بسم الله الرحمن الرحيم

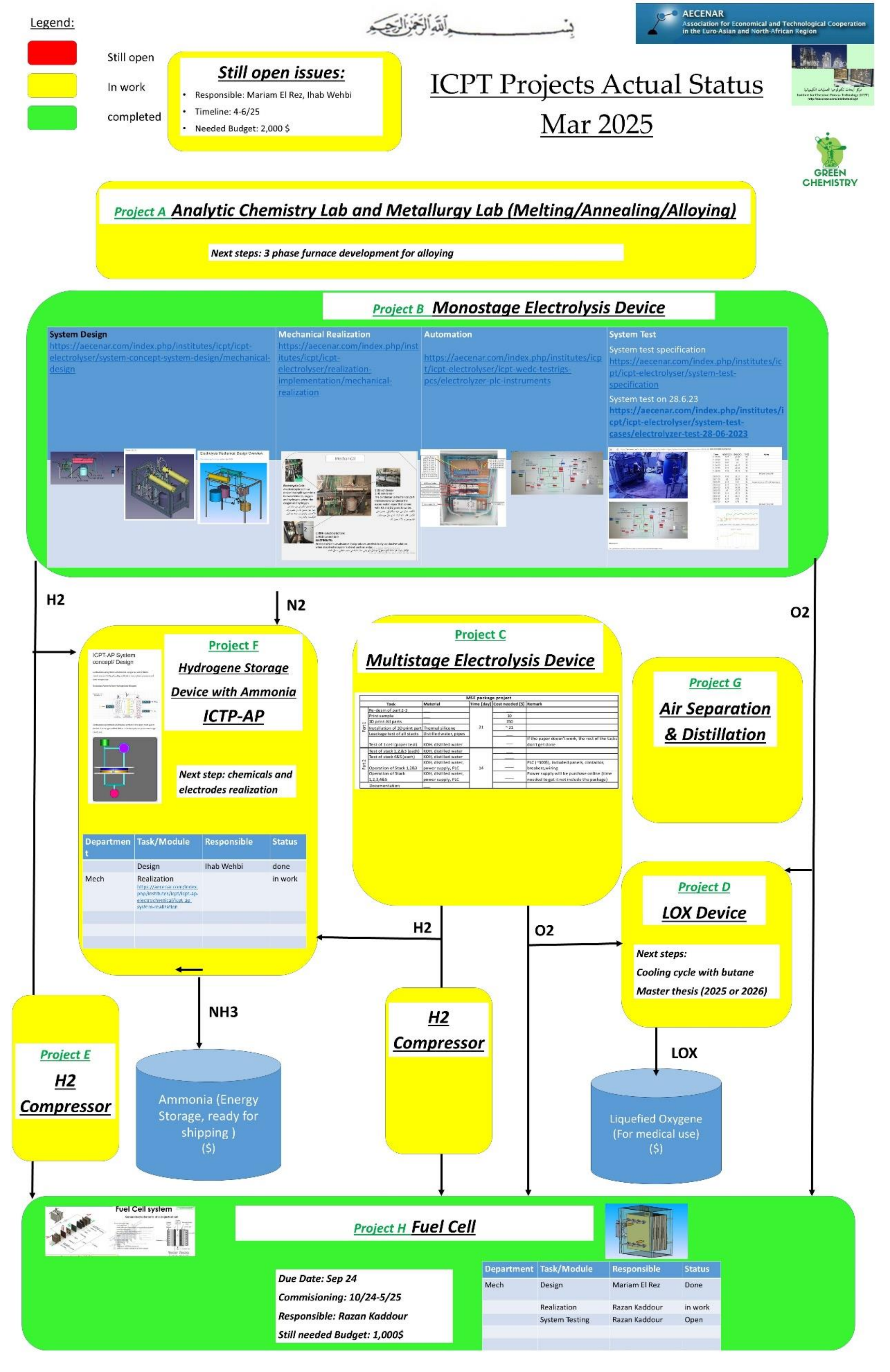
TECDA

AECENAR
Association for Economical and Technological Cooperation in the Euro-Asian and North-African Region

مركز أبحاث تكنولوجيا العمليات الكيميائية
Institute for Chemical Process Technology (ICPT)
http://aecenar.com/institutes/icpt

ICPT Final Report (2021 – Apr 2025)

Editor: Dr. Samir Mourad



Legend:

🟥 Still open
🟨 In work
🟩 completed

بسم الله الرحمن الرحيم

AECENAR Association for Economical and Technological Cooperation in the Euro-Asian and North-African Region

Still open issues:

- Responsible: Mariam El Rez, Ihab Wehbi
- Timeline: 4-6/25
- Needed Budget: 2,000 $

ICPT Projects Actual Status Mar 2025

Project A ***Analytic Chemistry Lab and Metallurgy Lab (Melting/Annealing/Alloying)***

Next steps: 3 phase furnace development for alloying

Project B ***Monostage Electrolysis Device***

System Design	Mechanical Realization	Automation	System Test
https://aecenar.com/index.php/institutes/icpt/icpt-electrolyser/system-concept-system-design/mechanical-design	https://aecenar.com/index.php/institutes/icpt/icpt-electrolyser/realization-implementation/mechanical-realization	https://aecenar.com/index.php/institutes/icpt/icpt-electrolyser/icpt-wedc-testrigs-pcs/electrolyzer-plc-instruments	System test specification https://aecenar.com/index.php/institutes/icpt/icpt-electrolyser/system-test-specification System test on 28.6.23 https://aecenar.com/index.php/institutes/icpt/icpt-electrolyser/system-test-cases/electrolyzer-test-28-06-2023

Project F

Hydrogene Storage Device with Ammonia ICTP-AP

Next step: chemicals and electrodes realization

Department	Task/Module	Responsible	Status
	Design	Ihab Wehbi	done
Mech	Realization https://aecenar.com/index.php/institutes/icpt/icpt-ap-electrochemical/icpt-ap-system-realization		in work

Project C

Multistage Electrolysis Device

MSE package project

	Task	Material	Time [day]	Cost needed [$]	Remark
Part 1	Re-desin of part 2-3	—	21	—	
	Print sample	—		30	
	3D print All parts	—		150	
	Installation of 3D print part	Thermal silicone		~21	
	Leackage test of all stacks	Distilled water, pipes		—	
	Test of 1 cell (paper test)	KOH, distilled water		—	If the paper doesn't work, the rest of the tasks don't get done
Part 2	Test of stack 1,2,&3 (each)	KOH, distilled water	14	—	
	Test of stack 4&5 (each)	KOH, distilled water		—	
	Operation of Stack 1,2&3	KOH, distilled water, power supply, PLC		—	PLC (~300$), included panels, contactor, breakers,wiring
	Operation of Stack 1,2,3,4&5	KOH, distilled water, power supply, PLC		—	Power supply will be purchase online (time needed to get it not include the package)
	Documentation	—			

Project G

Air Separation & Distillation

Project D

LOX Device

Next steps:
Cooling cycle with butane
Master thesis (2025 or 2026)

Project E

H2 Compressor

Ammonia (Energy Storage, ready for shipping) ($)

H2 Compressor

Liquefied Oxygene (For medical use) ($)

Project H ***Fuel Cell***

Due Date: Sep 24
Commisioning: 10/24-5/25
Responsible: Razan Kaddour
Still needed Budget: 1,000$

Department	Task/Module	Responsible	Status
Mech	Design	Mariam El Rez	Done
	Realization	Razan Kaddour	in work
	System Testing	Razan Kaddour	Open

With contributions of:

Maysaa Kamareddine
Siham Aisha
Mariam El Rez
Abdullah Kassem
Ihab Wahbi
Jana Hammoud
Othman Dhaybi
Abdel Rahman Hammoud
Abdullah Mourad
Amro Zawit
Razan Youssef Kaddour
Rawan ABDELMAJID
Muhamad AMOUD
Oussama DHAIBI
Tarek Tertanni
Ghaith al Ali
Ali DIB
Othman Dhaiby

Content in Short

Content

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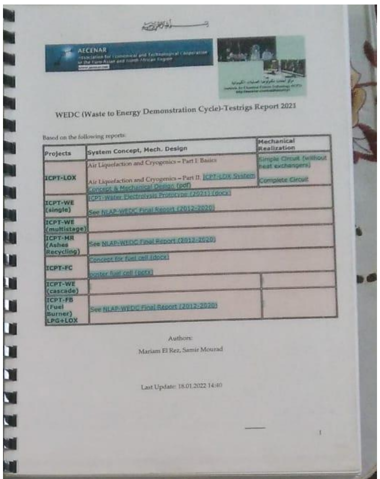
1 List of reports and relevant articles on www.aecenar.com



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WEDC (Waste to Energy Demonstration Cycle)-Testrigs Report 2021

Based on the following reports:

Projects	System Concept, Mech. Design	Mechanical Realization
ICPT-LOX	Air Liquefaction and Cryogenics – Part I: Basics Air Liquefaction and Cryogenics – Part II: ICPT-LOX System Concept & Mechanical Design (pdf)	Simple Circuit (without heat exchangers) Complete Circuit
ICPT-WE (single)	ICPT-Water Electrolysis Prototype (2021) (docx) See NLAP-WEDC Final Report (2012-2020)	
ICPT-WE (multistage)		
ICPT-MR (Ashes Recycling)	See NLAP-WEDC Final Report (2012-2020)	
ICPT-FC	Concept for fuel cell (docx) poster fuel cell (pptx)	
ICPT-WE (cascade)		
ICPT-FB (Fuel Burner) LPG+LOX	See NLAP-WEDC Final Report (2012-2020)	

Authors:
Mariam El Rez, Samir Mourad

Last Update: 18.01.2022 14:40

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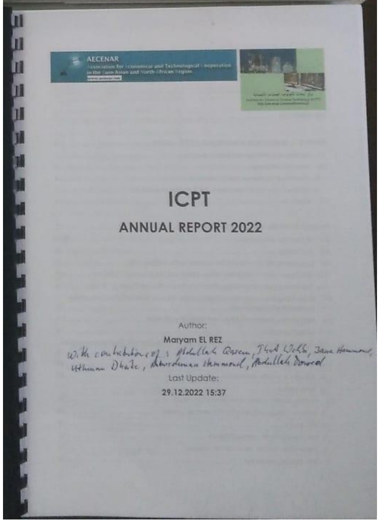

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ICPT
ANNUAL REPORT 2022

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Maryam EL REZ
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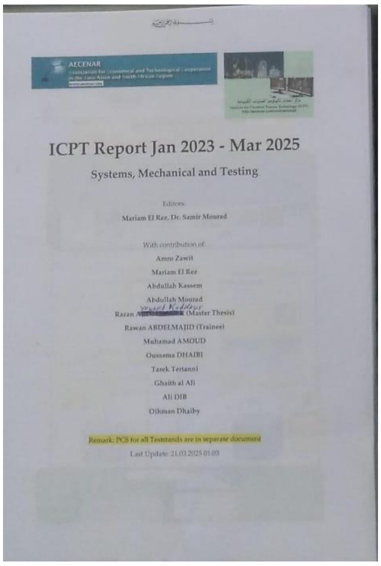
Last Update:
29.12.2022 15:37



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ICPT Report Jan 2023 - Mar 2025
Systems, Mechanical and Testing

Editors:
Mariam El Rez, Dr. Samir Mourad

With contribution of:
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Mariam El Rez
Abdullah Kassem
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Yousef Kaddour
Razan A[redacted] (Master Thesis)
Rawan ABDELMAJID (Trainee)
Muhamad AMOUD
Oussama DHAIBI
Tarek Tertanni
Ghaith al Ali
Ali DIB
Othman Dhaiby

Remark: PCS for all Teststands are in separate document
Last Update: 21.03.2025 01:03

1.1 WEDC Testrigs Report 2021

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WEDC (Waste to Energy Demonstration Cycle)-Testrigs Report 2021

Based on the following reports:

Projects	**System Concept, Mech. Design**	**Mechanical Realization**
ICPT-LOX	Air Liquefaction and Cryogenics – Part I: Basics Air Liquefaction and Cryogenics – Part II: ICPT-LOX System Concept & Mechanical Design (pdf)	Simple Circuit (without heat exchangers) Complete Circuit
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Authors:

Mariam El Rez, Samir Mourad

1.2 ICPT Report 2022

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ICPT

ANNUAL REPORT 2022

Editor:

Maryam EL REZ

With contribution of:

Abdullah Kassem

Ihab Wahbi

Jana Hammoud

Othman Dhaybi

Abdel Rahman Hammoud

Abdullah Mourad

This report contains details of the ICPT Institute projects that we carried out for the year 2022. These projects include the old ones that have been continued, such as the Electrolyser project, the Oxygen liquefaction project and the Ashes recycling project. It also reviews new projects such as the

Multistage electrolysis, Ammonia project, the Biogas project, the Gas turbine project, the Analytical Lab and the metallurgical Lab.

In 2022, the ICPT Institute will be responsible for **9 projects**; Three of them were started in the past years and this year they were continued, and four new projects were attached to the institute this year.

For projects started in previous years (2021 and earlier) and continued in 2022: **Electrolyser project**, **Oxygen liquefaction project** and **Ashes recycling project**.

For the projects added to the ICPT Institute this year (2022): **Multistage electrolyser**, **Ammonia production project**, **Gas turbine project**, **Biogas project, Analytical Lab** and **Metallurgical Lab**.

In the following sections, we will talk about each project in detail; What is it, where did it arrive before 2022, details that were added this year, and finally what should be completed with it.

1.3 ICPT Report 2023-Apr 25

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ICPT Report Jan 2023 - Mar 2025

Systems, Mechanical and Testing

Editors:

Mariam El Rez, Dr. Samir Mourad

With contribution of:

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Ghaith al Ali

Ali DIB

Othman Dhaiby

Remark: PCS for all Teststands are in separate document

In 2023 and 2024, the ICPT Institute was responsible for **8 projects**; six were started in previous years and continued this year, and two new projects were attached to the institute this year.

For projects started in previous years (2022 and earlier) and continued in 2023 and 2024: **Electrolyser project, Ammonia production project, Multistage electrolyzer project,** and **Metallurgical Lab**. **Biogas project** and **Gas turbine project is now in NLAP.**

For the projects added to the ICPT Institute this year (2023 and 2024): **FuelCell**, and **Air Separation projects**.

In the following sections, we will discuss each project in detail: What it is, where it arrived before 2023, details that were added in 2023 and 2024, and finally, what should be completed in each project.

---

2 Lists of Abbreviations and Symbols

U_b	: Acceleration voltage	V
d	: Distance between cathode and anode	m
F	: Electric force	N
e	: Charge of an electron	C
W	: Electrical work between the cathode and the anode	I
E_c	: Kinetic energy	J or ev
m	: Mass of an electron	Kg
V	: Speed of the electron	ms^{-1}
V_f	: Final velocity of the electron	ms^{-1}
m_r	: Relativistic mass of an electron	Kg or $ev.C^{-2}$
C	: Speed of light	ms^{-1}
γ	: Lorentz factor	
V_r	: Relativistic speed of an electron	ms^{-1}
V_c	: Classical speed of an electron	ms^{-1}
X	: Position of the electron	m
t	: Time	s
has	: Acceleration of the electron	ms^{-2}
R	: Radius of the circular trajectory of the electrons	m
B	: Magnetic field	T
q	: Charge	C
E_K	: K-shell binding energy	ev
E_L	: Binding energy of the L layer	ev
E_M	: M-shell binding energy	ev
$E_{K\alpha}$	: Difference between K-shell energy and L-shell energy	ev
$E_{K\beta}$	: Difference between K-shell energy and M-shell energy	ev
I	: Intensity of the current flowing through the two coils	HAS
N	: Number of turns	
R'	: Radius of each coil	m
d'	: Distance between two coils	m

D	: Diameter of each coil	m
μ_0	: Vacuum permeability	Hm^{-1}
x	: Distance measured along the central axis of the coils	m

V	: Volume of the ionization chamber	m^3
IE1	: First ionization energy	ev
IE2	: Second ionization energy	ev
m	: Mass of an ion	Kg
Z	: Electric charge of an ion	
R	: radius of curvature of an ion	m
E_c	: Kinetic energy of an ion	J or ev
q	: Charge	C
U	: Potential difference	V
v	: Speed of an ion	ms^{-1}
F	: Magnetic force	N
B	: Magnetic field	T
Your	: Offset voltage offset	V
HAS	: Voltage gain	
CMRR	: Common mode rejection ratio	dB
μ_0	: Vacuum permeability	H/m
μ_r	: Relative permeability of magnetic material	
μ	: Magnetic permeability of the material	H/m

I	: Current intensity flowing through the two coils	HAS
D	: Diameter of each coil	m
N	: Number of turns	
R'	: Radius of each coil	m
d'	: Distance between two coils	m
X	: Distance measured along the central axis of the coils	m

3 Summary

3.1 Posters 2021

3.1.1 NLAP-WEDC Overview

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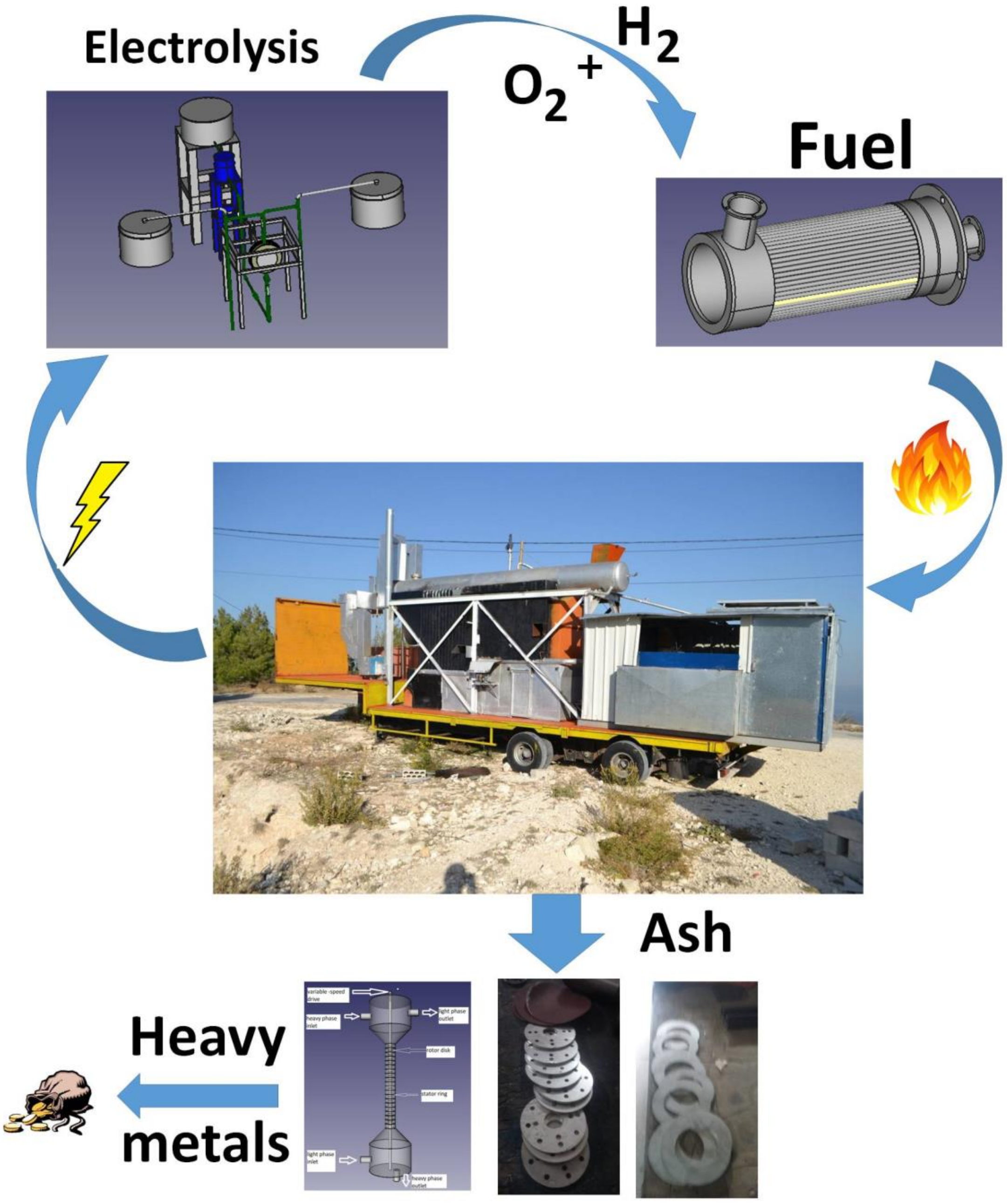
طاقة الشمال

North Lebanon Alternative Power

NLAP-WEDC **Waste** to **Electricity**

Demonstration cycle



Electrolysis

O_2 + H_2

Fuel

Ash

Heavy metals

3.1.2 NLAP-IPP (Incineration Power Plant)

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طاقة الشمال
North Lebanon Alternative Power
www.nlap-lb.com

Poster 1

NLAP-IPP

Introduction مقدمة

The heat that is generated by incineration can be used to generate electric power.
Waste-to-energy plants burn municipal solid waste (MSW), often called garbage or trash, to produce steam in a boiler that is used to generate electricity
Waste-to-energy uses trash as a fuel for generating power, just as other power plants use coal, oil, or natural gas. The burning fuel heats water into steam that drives a turbine then to the generator to create electricity. The process can reduce a community's landfill volume by up to 90 percent.

يمكن استخدام الحرارة الناتجة عن الحرق لتوليد الطاقة الكهربائية.
تحرق محطات تحويل النفايات إلى طاقة النفايات الصلبة البلدية، والتي تسمى غالبًا القمامة ، لإنتاج البخار في غلاية تُستخدم لتوليد الكهرباء
تستخدم عملية تحويل النفايات إلى طاقة القمامة كوقود لتوليد الطاقة ، تمامًا كما تستخدم محطات توليد الطاقة الأخرى الفحم أو الزيت أو الغاز الطبيعي. يعمل الوقود المحترق على تسخين الماء إلى بخار يدفع التوربينات ثم إلى المولد لتوليد الكهرباء.
يمكن أن تقلل هذه العملية من حجم مدافن المجتمع بنسبة تصل إلى 90 بالمائة.

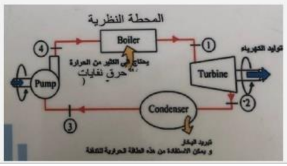
Control system نظام التحكم

The WTE (waste to energy) process uses specially developed boilers that burn non-hazardous waste in a closed circuit. The technology captures the heat generated during combustion and uses it to create steam that drives a turbine that generates electricity. The electricity is then be returned to the waste disposal facility to operate the equipment and sent to local utility companies, for use in households and businesses.
Sensors and instruments that have the ability to measure temperature and pressure within the same device.

How it works?
-Waste (fuel) burns and releases heat.
-Heat turns water into steam in a boiler
-High pressure steam turns the blades of a turbine generator to produce electricity
*To get energy efficiently from waste you need:
-An efficient incinerator: They range from small and portable to large on an industrial scale. We have a number of small business options.
-Sorted Waste: Any waste stream needs to be organized efficiently, removing metals and stones that cannot be incinerated and sorting materials that can be recycled.
-Shredded Waste: Another way to increase efficiency is to reduce the size of the waste before it is incinerated.
-**Biodegradable Components:** Adding renewable materials like wood, food, and paper to a waste stream can maximize energy production.
-**Low humidity waste:** the drier the waste stream, the less heat is required for incineration.

تستخدم العملية غلايات مطورة خصيصًا لحرق النفايات غير الخطرة في دائرة مغلقة. تلتقط هذه التقنية الحرارة المتولدة أثناء الاحتراق وتستخدمها لتوليد البخار الذي يدفع التوربين الذي يولد الكهرباء. ثم يتم إعادة الكهرباء إلى مرفق التخلص من النفايات لتشغيل المعدات وإرسالها إلى شركات المرافق المحلية ، لاستخدامها في المنازل والشركات.
أجهزة الاستشعار والأدوات التي لديها القدرة على قياس درجة الحرارة والضغط داخل نفس الجهاز.

كيف تعمل؟
-تحرق النفايات (الوقود) وينبعث منها حرارة.
-تحول الحرارة الماء إلى بخار في الغلاية
-يقوم بخار الضغط العالي بتحويل شفرات مولد التوربينات لتوليد الكهرباء.
*للحصول على الطاقة بكفاءة من النفايات ، أنت بحاجة إلى:
-**الحارق الفعالة:** تتراوح من الصغيرة والمحمولة إلى الكبيرة على نطاق صناعي.
– **فرز النفايات:** يجب تنظيم أي مجرى نفايات بشكل فعال وإزالة المعادن والأحجار التي لا يمكن حرقها وفرز المواد التي يمكن إعادة تدويرها.
– **النفايات المقطعة:** طريقة أخرى لزيادة الكفاءة هي تقليل حجم النفايات قبل حرقها.
– **المكونات القابلة للتحلل:** يمكن أن تؤدي إضافة مواد متجددة مثل الخشب والطعام والورق إلى تيار النفايات إلى زيادة إنتاج الطاقة إلى أقصى حد.
– **انخفاض نفايات الرطوبة:** كلما كان تيار النفايات أكثر جفافاً ، كلما قلت الحرارة **المطلوبة للحرق**.



Benefits فوائد

- **Environmental:**

-Reduces Landfill Waste,
By converting waste to energy, it substantially reduces the amount of waste entering landfills, which can curb greenhouse gases.
- Recycles Excess Waste,
The technology used to convert waste into energy also recycles any metal that remains after combustion, including steel and aluminum, further shrinking the amount of unusable waste.
-Sustainable Process,
The process itself is green, employing the latest pollution control equipment to scrub and filter emissions, preventing their release into the environment.

- **Economical:**

-Creates a Significant Amount of Energy,
One ton of waste can yield between 550 and 700 kilowatt hours—enough to power a person's home for almost a month. Additionally, the energy produced at waste-to-energy facilities is reliable base load power, meaning that it is generated 24 hours a day, seven days a week. That provides the opportunity to not only sell electricity onto the grid, but also provide steam delivered to houses, public buildings and industry.
-Gives careers,
According to the Energy Recovery Council, the average waste to energy facility in the US is responsible for the creation of 58 full time jobs. Generally, these are salaried, skilled positions with relatively high pay. And, these jobs have at least a 40 year projected life.
-New fuel sources,
Inevitably, we will always generate some waste. Turning this waste into energy means that we can create fuel sources that enable us to reduce our use of fossil fuels.
-Another benefit of waste-to-energy over landfilling is the opportunity to recover valuable resources such as metals post-incineration. They can then be sent for recycling and kept in the economy. This is even true of mixed materials, which are notoriously hard to recycle. Incineration burns away materials such as plastics leaving the metals behind, which can be considered better than landfills where recyclable materials are simply buried.

بيئي:
– **يقلل من نفايات المكب ،**
عن طريق تحويل النفايات إلى طاقة ، فإنه يقلل بشكل كبير من كمية النفايات التي تدخل مدافن النفايات ، والتي يمكن أن تحد من غازات الاحتباس الحراري.
– **إعادة تدوير النفايات الزائدة ،**
تعمل التقنية المستخدمة لتحويل النفايات إلى طاقة أيضًا على إعادة تدوير أي معدن متبقي بعد الاحتراق ، بما في ذلك الفولاذ والألمنيوم ، مما يؤدي إلى تقليص كمية النفايات غير القابلة للاستخدام.
– **عملية مستدامة ،**
العملية نفسها خضراء ، وتستخدم أحدث معدات مكافحة التلوث لتنظيف وتصفية الانبعاثات ، ومنع إطلاقها في البيئة.
اقتصاديا:
– **يخلق كمية كبيرة من الطاقة ،**
يمكن أن ينتج طن واحد من النفايات ما بين 550 و 700 كيلوواط ساعة – وهو ما يكفي لتزويد منزل الشخص بالطاقة لمدة شهر تقريبًا. بالإضافة إلى ذلك ، فإن الطاقة المنتجة في مرافق تحويل النفايات إلى طاقة هي طاقة يتم توليدها على مدار 24 ساعة في اليوم ، سبعة أيام في الأسبوع. يوفر ذلك الفرصة ليس فقط لبيع الكهرباء على الشبكة ، ولكن أيضًا توفير البخار الذي يتم توصيله إلى المنازل والمباني العامة والصناعة.
– **تؤمن وظائف ،**
وفقًا لمجلس استعادة الطاقة ، فإن متوسط معدل تحويل النفايات إلى طاقة في الولايات المتحدة مسؤول عن إنشاء 58 وظيفة بدوام كامل. بشكل عام ، هذه وظائف تتطلب مهارة وتتقاضى رواتب مرتفعة نسبيًا. وهذه الوظائف لها عمر متوقع 40 عامًا على الأقل.
– **مصادر وقود جديدة ،**
حتمًا ، سننتج دائمًا بعض النفايات. يعني تحويل هذه النفايات إلى طاقة أنه يمكننا إنشاء مصادر وقود تمكننا من تقليل استخدامنا للوقود الأحفوري.
–الميزة الأخرى لتحويل النفايات إلى طاقة على دفن النفايات هي فرصة استعادة الموارد القيمة مثل المعادن بعد الحرق. يمكن بعد ذلك إرسالها لإعادة التدوير والاحتفاظ بها في الاقتصاد.
وينطبق هذا أيضًا على المواد المختلطة ، والتي
يشتهر بصعوبة إعادة تدويرها. يحرق الحرق مواد مثل البلاستيك تاركًا المعادن ورائها ، والذي يمكن اعتباره أفضل من مدافن النفايات حيث يتم ببساطة دفن المواد القابلة لإعادة التدوير.

Challenges & Solutions
التحديات و الحلول

The disadvantages of waste-to-energy are numerous and have become more apparent in recent years. They include the pollution and particulates it generates, the destruction of useful materials, and the potential to disincentivize more sustainable waste management solutions and renewable energy sources.

Toxic gases,
Plastics and other oil-based products, which are burned in WTE, are equivalent to any other fossil fuel and emit damaging greenhouse gas emissions. So we should use advanced filters system (**chemical treatments**).

Ashes :

- There are 2 primary forms of ash left over from waste to energy incineration:

-Fly Ash.
This ash is taken out of the fumes that come from the incineration process. Removing this ash is done through an **electro filter** to ensure that the final gas which leaves the factory is just water vapor and Co2, i.e. completely safe for the surrounding population.
-INCINERATOR BOTTOM ASH,
Incinerator Bottom Ash is the ash from the bottom of the incinerator. You might expect that this waste is simply sent to landfill, with the successful job done of reducing its weight and size to 30% and 10% respectively. However, these unburnt remains from the combustion process contain a lot of value that can be removed, re-used and recycled. Your everyday municipal waste is surprisingly full of things that don't burn, such as broken porcelain, glass, and metal some of which are so toxic as lead that we cannot land them. Additionally, the incineration process leaves ash behind, no matter how complete the process is. So we should use an **ashes recycling** plant. **(poster 3)**

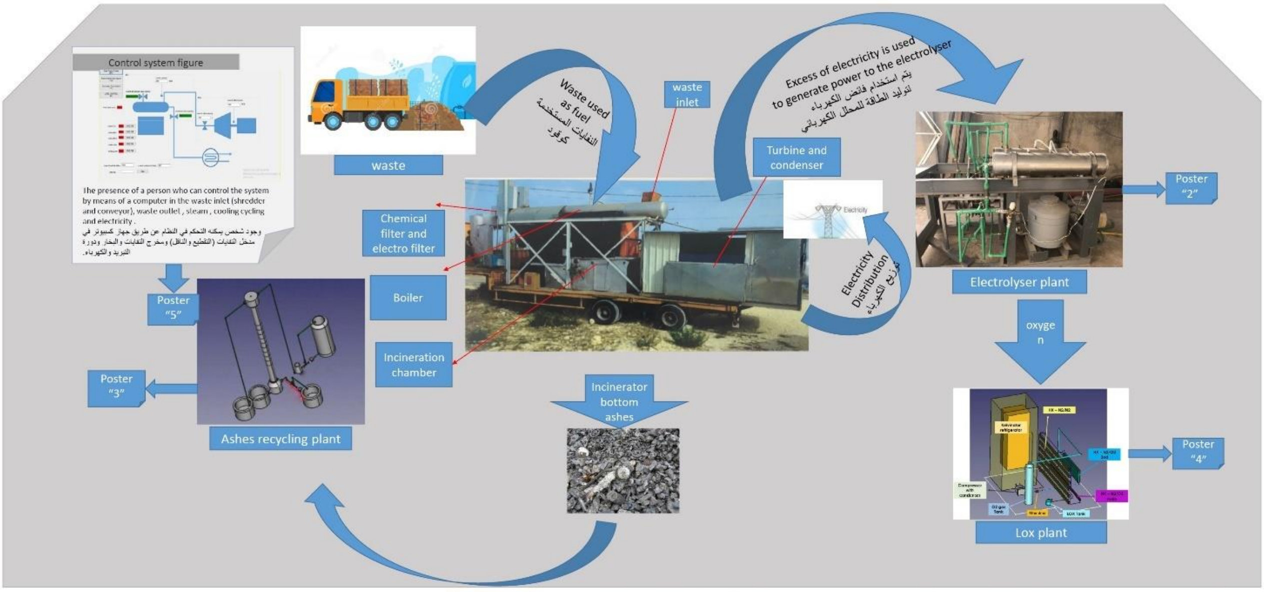
تتعدد مساوئ تحويل النفايات إلى طاقة وأصبحت أكثر وضوحًا في السنوات الأخيرة. وهي تشمل التلوث والجسيمات التي تولدها ، وتدمير المواد المفيدة ، وإمكانية تثبيط حلول إدارة النفايات الأكثر استدامة ومصادر الطاقة المتجددة.

الغازات السامة،
المواد البلاستيكية وغيرها من المنتجات القائمة على النفط ، والتي يتم حرقها تعادل أي وقود أحفوري آخر وتنبعث منها انبعاثات ضارة من غازات الاحتباس الحراري. لذلك يجب استخدام نظام الفلاتر المتقدم (**المعاجات الكيميائية**).

الرماد:
هناك نوعان أساسيان من الرماد المتبقي من حرق النفايات و تحويلها إلى الطاقة:

–الرماد المتطاير ،
يتم إخراج هذا الرماد من الأدخنة الناتجة عن عملية الحرق. تتم إزالة هذا الرماد من خلال **فلتر كهربائي** للتأكد من أن الغاز النهائي الذي يغادر المصنع هو مجرد بخار ماء وثاني أكسيد الكربون ، أي آمن تمامًا للسكان المحيطين.

–الرماد السفلي للمحرقة :
الرماد السفلي للمحرقة هو الرماد من قاع المحرقة. قد تتوقع أن يتم إرسال هذه النفايات ببساطة إلى مكب النفايات ؛ مع نجاح المهمة المتمثلة في تقليل وزنها وحجمها إلى 30٪ و 10٪ على التوالي.
ومع ذلك ، فإن هذه البقايا غير المحترقة من عملية الاحتراق تحتوي على الكثير من القيمة التي يمكن إزالتها وإعادة استخدامها وإعادة تدويرها. من المدهش أن نفايات البلدية اليومية مليئة بالأشياء التي لا تحترق ، مثل الخزف المكسور والزجاج والمعدن ، وبعضها شديد السمية مثل الرصاص بحيث لا يمكننا التخلص منها. بالإضافة إلى ذلك ، فإن عملية الحرق تترك الرماد وراءها ، بغض النظر عن مدى اكتمال العملية. لذلك يجب علينا استخدام مصنع إستخراج المعادن من **الرماد**.



The presence of a person who can control the system by means of a computer in the waste inlet (shredder and conveyor), waste outlet , steam , cooling cycling and electricity .
وجود شخص يمكنه التحكم في النظام عن طريق جهاز كمبيوتر في مدخل النفايات (التقطيع و الناقل) ومخرج النفايات والبخار ودورة التبريد والكهرباء.

Nidaa Fatfat/ Mounira Sayah ,AECENAR@November 2021

3.1.2.1 Process Control System of NLAP-IPP

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Poster 5

NLAP-IPP Process Control System

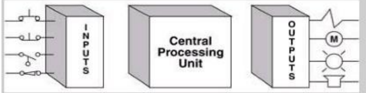
Introduction مقدمة

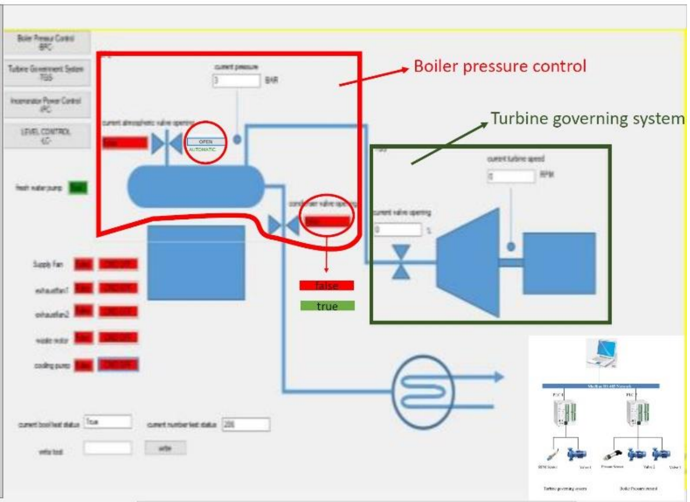
A programmable logic controller (PLC) is an industrial computer control system computer that has been ruggedized and adapted for the control of manufacturing processes, and that continuously monitors the state of input devices and makes decisions based upon a custom program to control the state of output devices.

A PLC's functions are divided into three main categories: inputs, outputs and the CPU (Figure 1). PLCs capture data from the plant floor by monitoring inputs that machines and devices are connected to. The input data is then processed by the CPU, which applies logic to the data, based on the input state. The CPU then executes the user-created program logic and outputs data or commands to the machines and devices it is connected to.

وحدة التحكم المنطقية القابلة للبرمجة هي عبارة عن جهاز كمبيوتر بنظام التحكم في الكمبيوتر الصناعي تم تهيئته وتكييفه للتحكم في عمليات التصنيع ، والذي يراقب باستمرار حالة أجهزة الإدخال ويتخذ القرارات بناءً على برنامج مخصص للتحكم في حالة مخرجات الأجهزة.

تنقسم الوظائف إلى ثلاث فئات رئيسية: المدخلات والمخرجات ووحدة المعالجة المركزية. تلتقط البيانات من أرضية المصنع من خلال مراقبة المدخلات التي تتصل بها الآلات والأجهزة. ثم تتم معالجة بيانات الإدخال بواسطة وحدة المعالجة المركزية ، والتي تطبق المنطق على البيانات ، بناءً على حالة الإدخال. تقوم وحدة المعالجة المركزية بعد ذلك بتنفيذ منطق البرنامج الذي أنشأه المستخدم وإخراج البيانات أو الأوامر إلى الأجهزة والأجهزة المتصلة بها.





Turbine Governing System نظام التحكم في التوربين

- **VALVE:** For the valve control there are 2 modes:

-AUTOMATIC: The valve will be controlled automatically depending on the turbine-speed-set point saved in the PLC (the set point can be either the default value or a manually written value).

- MANUAL: In this mode its possible to control the valve manually by writing an opening % to the PLC.

- **TURBINE SPEED:** Considering the setpoint there are 2 modes:
  - **AUTOMATIC:** The valve (if in automatic-mode) will be controlled depending on the default turbine-speed-set point saved in the PLC.
  - **-MANUAL:** In this mode its possible to set the setpoint manually. By writing a setpoint, the valve (if in automatic-mode) will be controlled depending on the written setpoint. For more details, see the PLC documentation.

- الصمام: للتحكم في الصمام ، هناك وضعان:

– آلي: سيتم التحكم في الصمام تلقائيًا اعتمادًا على نقطة ضبط سرعة التوربين المحفوظة في)PLCيمكن أن تكون نقطة الضبط إما القيمة الافتراضية أو قيمة مكتوبة يدويًا).

– يدوي: في هذا الوضع ، من الممكن التحكم في الصمام يدويًا عن طريق كتابة٪ الفتح إلى .PLC

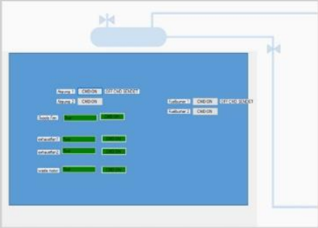
- سرعة التوربين: بالنظر إلى نقطة الضبط ، يوجد وضعان:

– آلي: سيتم التحكم في الصمام (إذا كان في الوضع التلقائي) اعتمادًا على نقطة ضبط سرعة التوربين الافتراضية المحفوظة في PLC.

–يدوي: من الممكن في هذا الوضع ضبط نقطة الضبط يدويًا. من خلال كتابة نقطة ضبط ، سيتم التحكم في الصمام (إذا كان في الوضع التلقائي) اعتمادًا على نقطة الضبط المكتوبة. لمزيد من التفاصيل ، راجع وثائق .PLC

Incinerator Regulating System نظام تنظيم المحارق

Boiler Level control التحكم في المستوى



- Color indication for states (Text fields): For supply fan, exhaust fans, waste motor:

-Red → False/OFF
-Green → True/ON

- Color indication for control commands (Buttons): For supply fan, exhaust fans, waste motor:

-Red→False/OFF Command is send (the state field should also be red (OFF))
-Green→True/ON Command is send (the state field should also be green (ON))

إشارة اللون للحالات: لمروحة الإمداد ، ومراوح العادم ، ومحرك النفايات:
- → Redخطأ / إيقاف
- → Greenصحيح / تشغيل
مؤشر اللون للتحكم
الأوامر (الأزرار): لمروحة الإمداد ، ومراوح العادم ، ومحرك النفايات:
- أحمر ← خطأ / إيقاف يتم إرسال الأمر (يجب أن يكون حقل الحالة أحمر أيضًا (إيقاف))
- أخضر ← صحيح / أمر تشغيل يتم الإرسال (يجب أن يكون حقل الحالة أخضر (تشغيل))

IMPORTANT NOTE:
- If the buttons have a different color than the state fields, that means something is wrong with the sensor or the actuator.
- If the buttons don't change the color by clicking, that means something is wrong with the connection.

– إذا كان للأزرار لون مختلف عن حقول الحالة ، فهذا يعني أن هناك خطأ ما في المستشعر أو المشغل.
– إذا لم تغير الأزرار اللون عن طريق النقر ، فهذا يعني وجود خطأ ما في الاتصال.

Boiler Pressure Control التحكم في ضغط الغلاية

- **VALVES:**

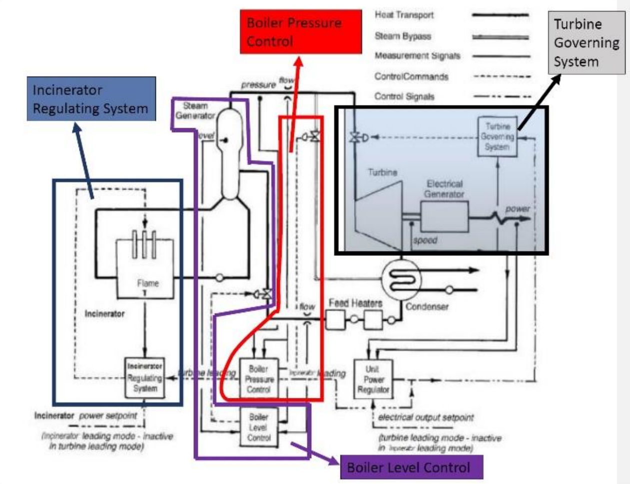
For atmospheric and condenser valves:
➢ Color indication for states (Text fields):
-Red→False/CLOSED
-Green→ True/OPEN
➢ Control indications (Buttons):
By clicking the Buttons its possible to open the valves manually. There can be 2 situations:

- OPEN AUTOMATIC That means the valve is in AUTOMATIC mode. Clicking the button will open the valve manually and turn into MANUAL mode.
- AUTOMATIC MANUAL OPEN CMD SENT That means the valve is in MANUAL mode (and OPEN). The valve will never close until returning into AUTOMATIC mode. Clicking the button will return into AUTOMATIC mode.

- **PRESSURE:**

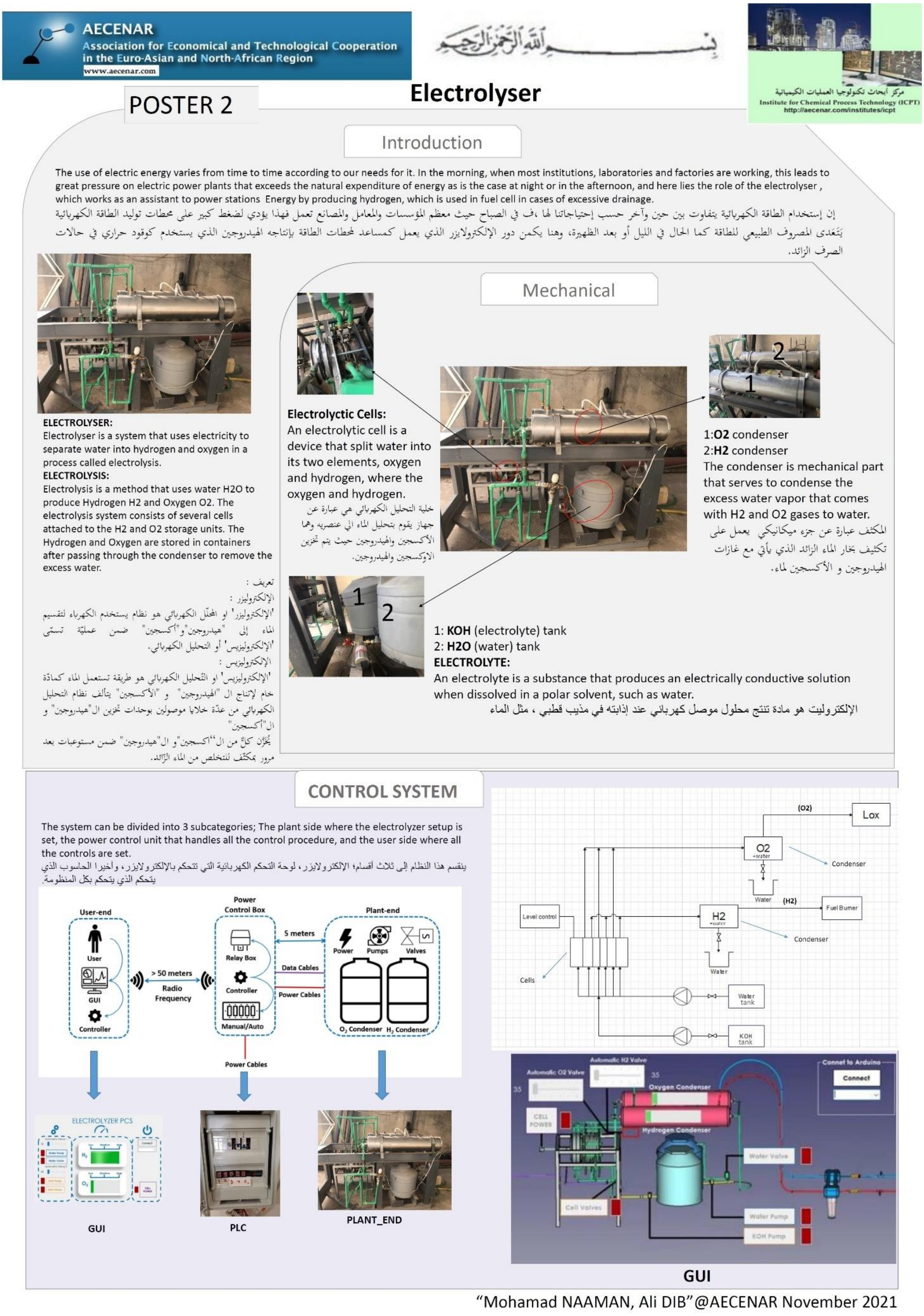
The current pressure is monitored in bar: Considering the setpoints there are 2 modes:
-AUTOMATIC: In this mode its not possible to set any setpoint manually. The valves will be controlled depending on the default pressure-set points saved in the PLC.
-MANUAL: In this mode its possible to set the setpoints manually. By writing a setpoint, the valves will be controlled depending on the written setpoints.

الصمامات:
لصمامات الغلاف الجوي وصمامات المكثف:
إشارة اللون للحالات (الحقول النصية):
- أحمر → خطأ / مغلق
- أخضر → صحيح / مفتوح
مؤشرات التحكم (الأزرار):
من خلال النقر فوق الأزرار ، من الممكن فتح الصمامات يدويًا. يمكن أن يكون هناك حالتان:
– هذا يعني أن الصمام في الوضع التلقائي. سيؤدي النقر فوق الزر إلى فتح الصمام يدويًا ويتحول إلى الوضع اليدوي.
– هذا يعني أن الصمام في الوضع اليدوي (ومفتوح). لن يغلق الصمام أبدًا حتى يعود إلى الوضع التلقائي. سيؤدي النقر فوق الزر إلى العودة إلى الوضع التلقائي.
الضغط:
يتم مراقبة الضغط الحالي في شريط: بالنظر إلى نقاط الضبط ، يوجد وضعان:
–التلقائي: في هذا الوضع لا يمكن ضبط أي نقطة ضبط يدويًا. سيتم التحكم في الصمامات وفقًا لنقاط ضبط الضغط الافتراضية المحفوظة في .PLC
يدوي: من الممكن في هذا الوضع ضبط – نقاط الضبط يدويًا. من خلال كتابة نقطة ضبط ، سيتم التحكم في الصمامات اعتمادًا على نقاط الضبط المكتوبة.



Mounira Sayah, Nidaa Fatfat/ AECENAR@November 2021

3.1.2.2 Water Electrolysis



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POSTER 2

Electrolyser

Introduction

The use of electric energy varies from time to time according to our needs for it. In the morning, when most institutions, laboratories and factories are working, this leads to great pressure on electric power plants that exceeds the natural expenditure of energy as is the case at night or in the afternoon, and here lies the role of the electrolyser , which works as an assistant to power stations Energy by producing hydrogen, which is used in fuel cell in cases of excessive drainage.

إن إستخدام الطاقة الكهربائية يتفاوت بين حين وآخر حسب إحتياجاتنا لها ،ف في الصباح حيث معظم المؤسسات والمعامل والمصانع تعمل فهذا يؤدي لضغط كبير على محطات توليد الطاقة الكهربائية يَتَعَدى المصروف الطبيعي للطاقة كما الحال في الليل أو بعد الظهيرة، وهنا يكمن دور الإلكترولايزر الذي يعمل كمساعد لمحطات الطاقة بإنتاجه الهيدروجين الذي يستخدم كوقود حراري في حالات الصرف الزائد.

ELECTROLYSER:
Electrolyser is a system that uses electricity to separate water into hydrogen and oxygen in a process called electrolysis.

ELECTROLYSIS:
Electrolysis is a method that uses water H2O to produce Hydrogen H2 and Oxygen O2. The electrolysis system consists of several cells attached to the H2 and O2 storage units. The Hydrogen and Oxygen are stored in containers after passing through the condenser to remove the excess water.

تعريف :

الإلكتروليزر :

'الإلكتروليزر' او المحلّل الكهربائي هو نظام يستخدم الكهرباء لتقسيم الماء إلى "هيدروجين"و"أكسجين" ضمن عمليّة تسمّى 'الإلكتروليزيس' أو التحليل الكهربائي.

الإلكتروليزيس :

'الإلكتروليزيس' او التّحليل الكهربائي هو طريقة تستعمل الماء كمادّة خام لإنتاج ال "الهيدروجين" و "الأكسجين" يتألف نظام التحليل الكهربائي من عدّة خلايا موصولين بوحدات تخزين ال"هيدروجين" و ال"أكسجين"

يُخَزّن كلٌّ من ال"اكسجين"و ال"هيدروجين" ضمن مستوعبات بعد مرور بمكثّف للتخلص من الماء الزّائد.

Mechanical

Electrolyctic Cells:
An electrolytic cell is a device that split water into its two elements, oxygen and hydrogen, where the oxygen and hydrogen.

خلية التحليل الكهربائي هي عبارة عن جهاز يقوم بتحليل الماء الي عنصريه وهما الأكسجين والهيدروجين حيث يتم تخزين الاوكسجين والهيدروجين.

1:**O2** condenser
2:**H2** condenser
The condenser is mechanical part that serves to condense the excess water vapor that comes with H2 and O2 gases to water.

المكثف عبارة عن جزء ميكانيكي يعمل على تكثيف بخار الماء الزائد الذي يأتي مع غازات الهيدروجين و الأكسجين لماء.

1: **KOH** (electrolyte) tank
2: **H2O** (water) tank

ELECTROLYTE:
An electrolyte is a substance that produces an electrically conductive solution when dissolved in a polar solvent, such as water.

الإلكتروليت هو مادة تنتج محلول موصل كهربائي عند إذابته في مذيب قطبي ، مثل الماء

CONTROL SYSTEM

The system can be divided into 3 subcategories; The plant side where the electrolyzer setup is set, the power control unit that handles all the control procedure, and the user side where all the controls are set.

ينقسم هذا النظام إلى ثلاث أقسام؛ الإلكترولايزر، لوحة التحكم الكهربائية التي تتحكم بالإلكترولايزر، وأخيرا الحاسوب الذي يتحكم الذي يتحكم بكل المنظومة.

GUI

PLC

PLANT_END

GUI

“Mohamad NAAMAN, Ali DIB”@AECENAR November 2021

Single Stage Water Electrolysis

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منظومة التحليل الكهربائي للماء (Alkaline Electrolysis)

I. المدخل

- *مبدأ التحليل الكهربائي للماء هو تطبيق التيار المباشر على الماء المقطر (distilled water)، مع وجود electrolyte اللذي بدوره يساعد على تقسيم المياه إلى الهيدروجين والأكسجين.*
- *في التحليل الكهربائي للمياه القلوية (Alkaline water electrolysis) ، يتم استخدام potassium hydroxide solution 20-40% (electrolyte) بدلاً من الماء النقي ، لأن الماء النقي مقاوم للكهرباء.*

Through this reaction, two molecules of water are decomposed and hydrogen evolves in the cathode. In the anode, oxygen evolves and at the same time one molecule of water is regenerated. As a result, one molecule of water is decomposed and another molecule of water moves to the anode.

$$\text{(Cathode)}\quad 2H_2O + 2e^- \rightarrow 2OH^- + H_2 \uparrow$$

$$\text{(Anode)}\quad 2OH^- \rightarrow H_2O + 2e^- + \frac{1}{2}O_2 \uparrow$$

$$\text{(Total)}\quad 2H_2O \rightarrow H_2 + \frac{1}{2}O_2 \ + H_2O$$

The principle of water electrolysis is rather simple. Applying direct current to water causes electrolysis, splitting water into hydrogen and oxygen through the reaction.

II. الخطوات الاساسية لتشغيل المنظومة (Basic steps to apply the electrolysis)

صورة لجميع قطع المنظومة (Picture of all parts electrolysis)

الخطوة الاولى: وضع الالكتروليت الكهرباني (electrolyte KOH) في الخزان الظاهر في الصورة
First step: prepare the electrolyte KOH solution, put it in first tank

الخطوة الثانية: يتم خلط محلول الإلكتروليت والماء المقطر (distilled water) ووضعه في خزان صغير آخر للتحكم بكمية الماء
Second step: The electrolyte solution and distilled water are mixed and put in other small tank to control quantity of water

يمكن أن تحتوي هذه الخلية على حوالى 2.8 لتر من الماء بما في ذلك 1.12 لتر (= 2.37 كجم) من محلول KOH.
This cell can contain about 2.8 liter of water including 1.12 liter (=2.37 kg) of KOH solution.

الخطوة الثالثة: تطبيق 2 فولت من الجهد و 141 أمبير إلى الخلية
Third step: Apply 2 V of voltage and 141 A current to the cell

الخطوة الرابعة: بعد عملية تحلل المياه ، سيبدأ الغاز في الطفو داخل الانابيب ، والتي سيتم تخزينها في خزان الضغط، كل واحدة من هذه الخزانين يحتوي على غازات مختلفة (H2، O2)
After the decomposition water process, gas will start floating inside the pipes, which will eventually be stocked in the pressure chamber by a specific water method, each one of this 2 chambers contains different gases (H_2, O_2)

Voltage	2 V
Current	141 A
Power	282 W
Temperature	25°C
Pressure	1 bar
KOH	2.37 Kg
Distilled water	2.8 liter
Resistance	

@AECENAR/NLAP Feb 2019

Cascaded Multi-Stage Water Electrolysis

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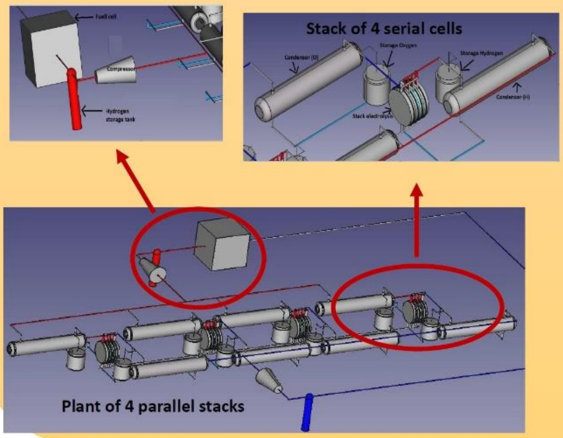
(Alkaline Electrolysis) منظومة التحليل الكهربائي للماء

I. Electrolysis design

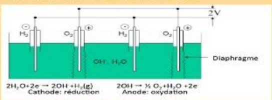
A. Introduction

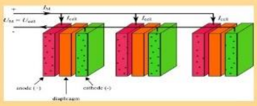
The single cell alkaline electrolysis is generated low amount of hydrogen gas per a minute. Hence, it is important to design alkaline electrolysis stack in order to produce high amount of hydrogen gas. Thus, we focuses on the designing of bipolar configuration of alkaline electrolysis stack.



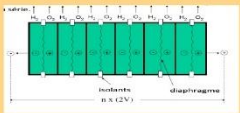
B. Technologies: Monopolar and bipolar structures

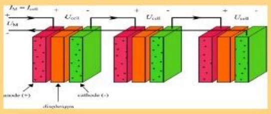
In monopolar configuration, each electrolysis cells are connected in parallel to form a large module of electrolysis stack as shown in figure below. Hence, the voltage between individual pairs of electrodes is directly equal to the total cell voltage and the sum of cell current is equal to the total cell current. Furthermore, in this configuration same electrochemical reaction is occurred on both sides of each electrode. The reaction may be either the hydrogen evolution reaction or the oxygen evolution reaction, depend on the polarity of relevant electrodes.





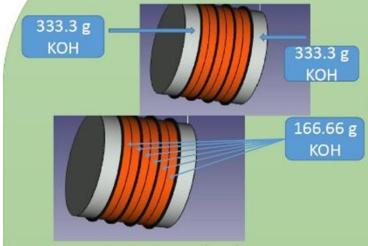
In bipolar configuration, each electrolysis cells are connected in series to form a large module of electrolysis stack as shown in Figure. Hence, the sum of all the voltages between individual pairs of electrodes is equal to the total cell voltage and the cell current is directly equal to the current which is passed through each individual cell. Furthermore, in this configuration two different electrochemical reactions, the hydrogen evolution reaction and the oxygen evolution reaction are occurred on both sides of each electrode. Thus, one side of electrode act as a cathode and other as anode at the same time.



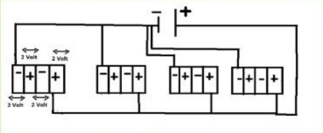


II. Electrolysis calculation

A. KOH



B. Power supplied



- Current density per cell: 0.2 – 0.4 A/cm²
- Our cell capacity 0.5 liter correspond to 250 cm²
- Current applied for each cell = $250\ cm^2 * 0.3\ A/cm^2 = 75\ A$
- Voltage applied for each cell is 2V
- Each stack has 4 serial cell => voltage = 4*2 V = 8 V

Current = 75A

- The total is 4 parallel stack => voltage = 8 V Current = 4 * 75 A = 300 A

C. Gas flow rate of Hydrogen

The maximum cell current value of 75 A is selected for the calculation. Faraday constant (F= 96485 C. mol^{-1} or C: coulomb (1C = 1A.s)). Moreover, Eq. 1 is used to calculate the number of hydrogen moles as follows.

$$n_{(H_2)} = \frac{I * t}{2F}$$
$$= \frac{75\,(C/s) * 60(s/min)}{2(electrons) * 96485\,C.mol^{-1}}$$
$$= 0.0233\,mol/min$$

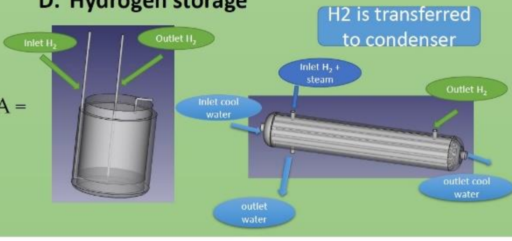
Considering Eq. 2, assuming the pressure of 1 atm and the operating temperature of 25°C, the theoretical $V_{H2(g)}$ can be determined as,

$$V_{H_{2(g)}} = \frac{n_{H_2}RT}{P}$$
$$= \frac{0.023\,mol/\min * 0.082\,Latm\,K^{-1}mol^{-1} * 298\,K}{1\,atm}$$

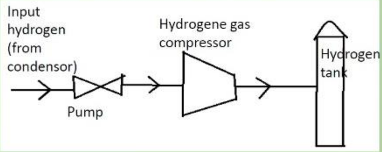
$$V_{H_2} = 0.569\,L.min^{-1}$$

Each stack produce 0.569 L.min^{-1} => 4 stack produce = 0.569 L.min^{-1} * 4 (stacks) = 2.279 L.min^{-1}

D. Hydrogen storage



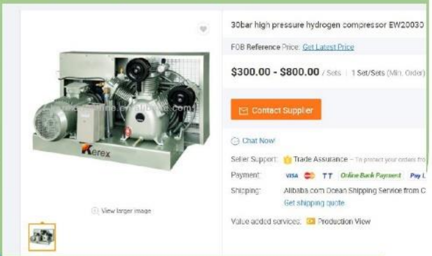
When Hydrogen gas exits from the condenser, it is pumped to the compressor at 30 bar then it storage in hydrogen tank



Connect the Hydrogen source to the diaphragm compressor inlet using a tapped hose, and leave the tap closed to prevent the gas from flowing. Use an external pump to push the gas into the compressor since the compressor itself sucks the gas from the inlet into its hydraulic pump. Make sure that the connection between the Hydrogen source and the compressor is air tight.

Prepare the gas tank and check for any cracks. Make sure the valve is not damaged in any way once again to prevent any accidents. Join the compressor to the tank using a hose with a pressure gauge. The pressure gauge is used to measure the pressure in the tank so that you may tell at what point you should stop pumping the gas into the tank. It is advisable to store Hydrogen at 800 atmospheres (the units can also be expressed in bars).

Hydrogen compressor supplier



30bar high pressure hydrogen compressor EW20030

FOB Reference Price: Get Latest Price

$300.00 - $800.00 / Sets | 1 Set/Sets (Min. Order)

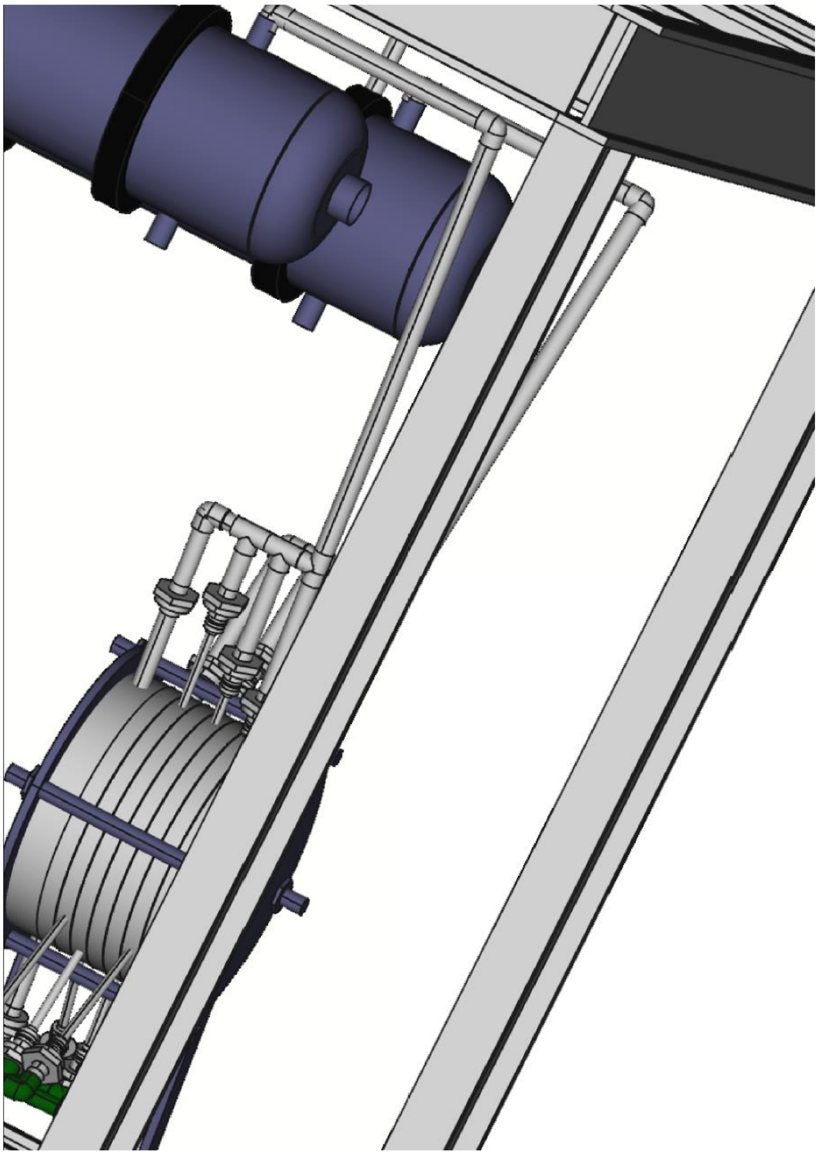
Seller Support: Trade Assurance – To protect your orders fro

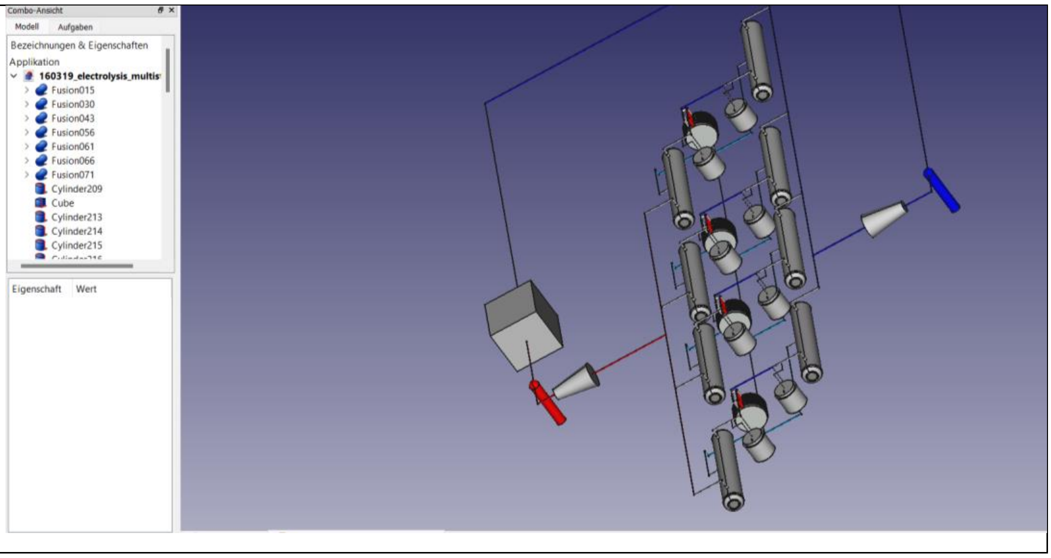
Payment: VISA TT Online Bank Payment Pay L

Shipping: Alibaba.com Ocean Shipping Service from C
Get shipping quote

Value added services: Production View

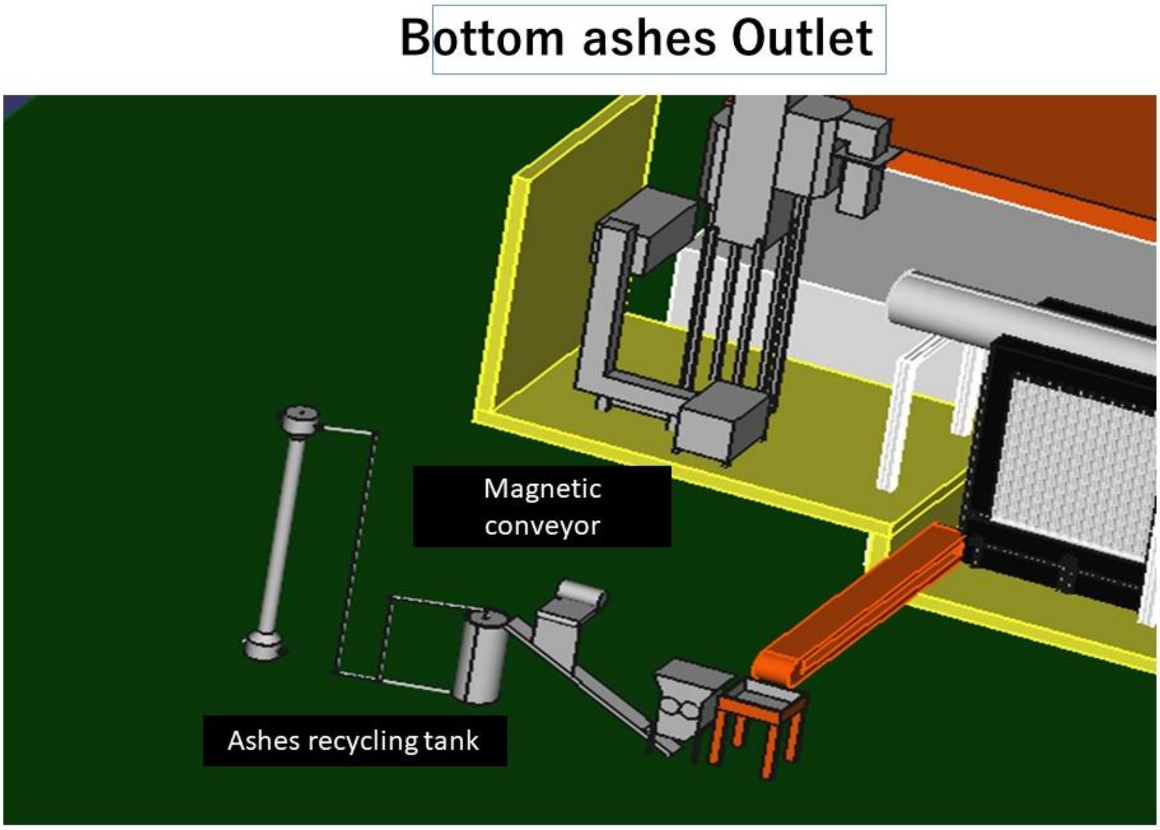
Siham Aisha/ AECENAR March 2019



160319_electrolysis_ multistack.FCStd	

Hydrogene Storage

3.1.2.3 Ashes Recycling



بسم الله الرحمن الرحيم

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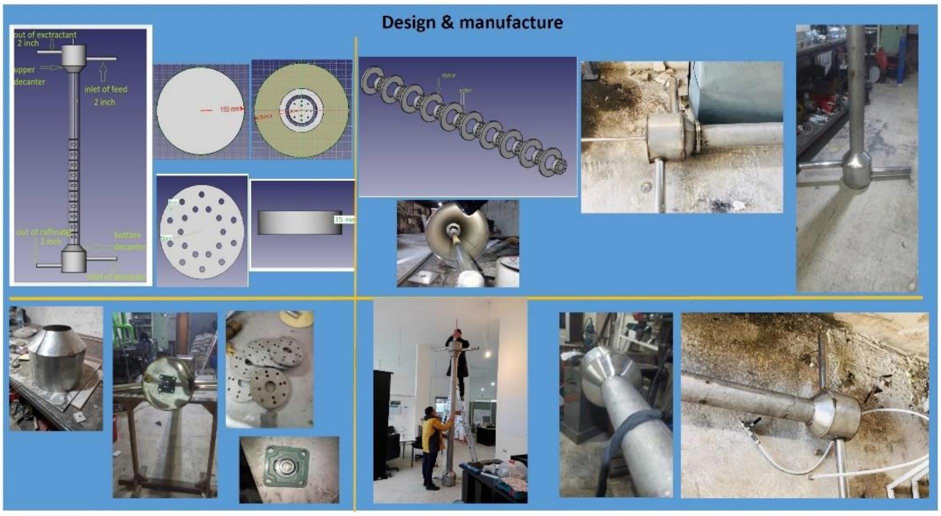
Heavy Metals Recycling Unit for NLAP-IPP Demonstration Plant

Lists of metals (mg/kg)

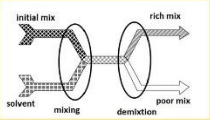
Element bottom ash	Bottom ash	Fly ash	Dry / quasi-dry	wet
Al	22.000-73.000	49.000 - 90.000	12.000-83.000	21.000-39.000
Cd	0.3-70	50-450	140-300	150-1.400
Cu	190-8.200	600-3.200	16-1.700	440-2.400
Fe	4.100-1500	12.000 - 44.000	2.600-71.000	20.000-97.000
Hg	0,02-8	0,7-30	0,1-51	2,2-2.300
Mo	2-280	15-150	9-29	2-44
Pb	100-13.700	5.300-26.000	2.500-10.000	3.300-22.000
Zn	61-7.800	7.000-70.000	7.000-20.000	8.100-53.000

Design & manufacture



Process

Solvent extraction, or liquid-liquid extraction is a separation technique isothermal in a heterogeneous liquid medium.
The method is based on the existence of a difference in the solubility of a substance in two immiscible liquids. The process has three steps, as shown in next figure :
- Mixture of the two immiscible liquids, one of them containing the solute,
- Obtaining physico -chemical equilibrium, leading to demixing ,
Separation of the two new liquid phases obtained based on the difference of



EXTRACTANTS

Oxime based extractants for copper are largely based on salicyaldoximes which have been modified with one of three modifier types. Examples of the three main extractant types currently in use are:

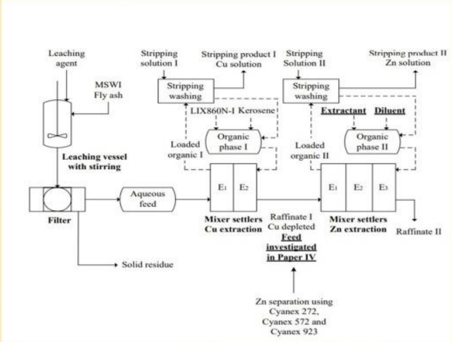
1. LIX® 984N
A mixture of 2-hydroxy-5-nonylacetophenone oxime and 5-nonylsalicylaldoxime in a high flash diluent. The acetophenone oxime modifies the aldoxime and also performs as an extractant in its own right. Molecular Weight:262.393 g/mol.

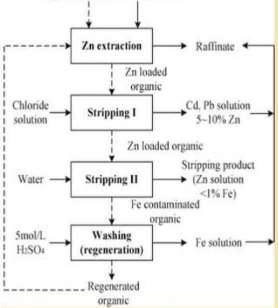
2. Acorga® M5640
5-Nonylsalicylaldoxime modified with an ester, 2,2,4-Trimethyl-1,3-pentanediol Diisobutyrate (TXIB) in a high flash diluent.

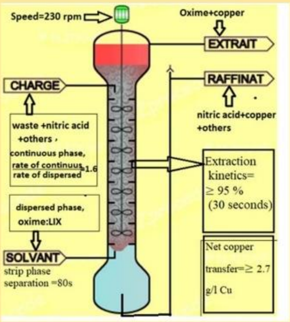
3. LIX® 622N
5-Nonylsalicylaldoxime modified with tridecyl alcohol in a high flash diluent.
Each of the extractants marketed by the major chemical suppliers has been designed for a specific type of PLS with regard to pH and copper tenor. Used under the conditions for which they were designed they all deliver very similar copper net transfer values. The physical properties of the various types of extractant do show some differences with the aldoxime/ketoxime mixtures such as LIX984N showing lower entrainments and greater tolerance to crud than the other reagents when treating some types of PLS. The vol% concentration of the commercially available extractants is limited by organic viscosity constraints to about 30-33% and this means that the maximum net transfer of copper will be about 10g/l. For leach solutions containing significantly higher copper tenors than this the throughput O/A ratio will have to be increased above 1.0.

1. Direct solvent extraction of **copper, cobalt and nickel from acid leach solutions using oximes, phosphinic acids and versatic acids to extract copper, cobalt and nickel in sequence.**

Steps of extraction

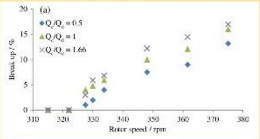


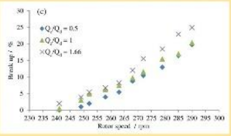




materials	Density (kg/m³)
Copper	999
Nitric acid	1510
Oxime LIX	806

The breakage probabilities versus rotor speed for mentioned chemical systems using glassy nozzles with different inner diameters (1.2 and 2.5 mm) to form various drop sizes by adjusting the Qc/Qd ratios and continuous phase heights are presented in next figure regarding to these graphs, the drop breakage increases by increasing the volumetric phase ratio that leads to decrease of the first critical rotor speed. It could be justified with increasing this ratio, the drag forces between the continuous phase and dispersed drops increase results to enhance the probability of drop break up due to collision with the rotors.





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Institute for Chemical Process Technology (ICPT)
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Ashes Recycling

Poster 3

INTRODUCTION مقدمة

Waste to energy is an environmentally friendly method of reducing the mass and volume of non-recyclable waste that would otherwise require landfill. The resulting ash, although largely inert, may contain heavy metal concentrations that require processing to comply with regulations, meet production standards for a usable product, and ensure the long-term stability of the metals when the ash is used. Heavy metals such as lead and cadmium can be toxic to biological systems if they are present in high enough concentrations. Fly and bottom ashes from fuel oil power plants and oil refineries may contain hazardous trace elements, such as heavy metals, which have a negative impact on the environment with time.

تحويل النفايات إلى طاقة هي طريقة صديقة للبيئة لتقليل كتلة وحجم النفايات غير القابلة لإعادة التدوير والتي قد تتطلب دفن النفايات. قد يحتوي الرماد الناتج ، على الرغم من أنه خامل إلى حد كبير ، على تركيزات معادن ثقيلة تتطلب معالجة لتتوافق مع اللوائح ، وتفي بمعايير الإنتاج لمنتج قابل للاستخدام ، وتضمن استقرار المعادن على المدى الطويل عند استخدام الرماد. يمكن أن تكون المعادن الثقيلة مثل الرصاص والكادميوم سامة للأنظمة البيولوجية إذا كانت موجودة بتركيزات عالية بما يكفي. قد يحتوي الرماد المتطاير ورماد القاع من محطات توليد الطاقة من زيت الوقود ومصافي النفط على عناصر خطرة ، مثل المعادن الثقيلة ، والتي لها تأثير سلبي على البيئة مع مرور الوقت.

Figure 1: Bottom ashes

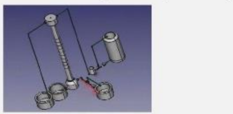


Figure 2: Ashes recycling plant

In order to recover usable materials from ashes, recycling technology must be used. (Figure 2)

من أجل استعادة المعادن الثقيلة ، يجب استخدام تقنية إعادة تدوير الرماد.

Technology of separation تقنية الفصل

Solvent extraction, or liquid-liquid extraction is a separation technique isothermal in a heterogeneous liquid medium.

The method is based on the existence of a difference in the solubility of a substance in two immiscible liquids. The process has three steps, as shown in Figure 3(b):

- Mixture of the two immiscible liquids, one of them containing the solute(ashes),
- Obtaining physico-chemical equilibrium, leading to demixing,
- Separation of the two new liquid phases obtained based on the difference of densities.

الاستخلاص بالمذيب ، أو الاستخلاص السائل – السائل هو تقنية فصل متساوي الحرارة في وسط سائل غير متجانس.

تعتمد الطريقة على وجود اختلاف في قابلية ذوبان مادة ما في سائلين غير قابلين للامتزاج.

تتكون العملية من ثلاث خطوات ، كما هو موضح في الشكل 3 (ب):

- خليط من سائلين غير قابلين للامتزاج يحتوي أحدهما على المذاب (الرماد).
- الحصول على توازن فيزيائي – كيميائي يؤدي إلى إزالة المزج.
- تم الحصول على فصل طورى السائل الجديدين على أساس اختلاف الكثافات.

System of recycling نظام إعادة التدوير

Samples of fresh bottom ash are taken from the incinerators and dried at 25 ° C. Then manually separate unburned parts such as screw, wire and plastic. The sample are reduced to a size of 500 µm using a shredder to remove the magnetic content (iron removal). Bottom ash samples (tailings and concentrates) were subjected to filtration tests in order to observe the mineral recoverability of the samples and to improve the parameters. It is important to reduce the size to 500 microns by using a shredder to remove the magnetic content. The solution is filtered and placed in a series of columns when the liquid is mixed with suitable liquid extractors to separate the minerals from the solution.

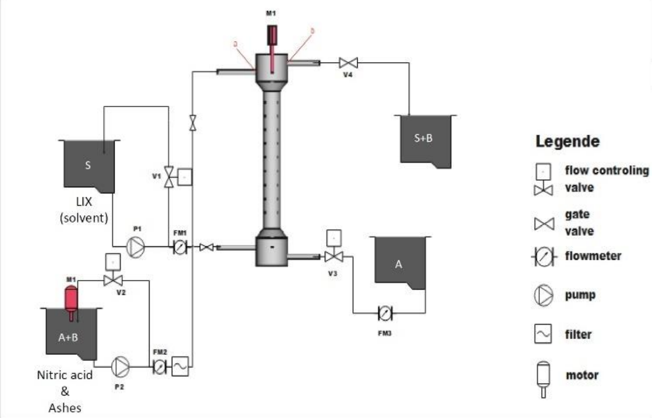
يتم أخذ عينات من رماد القاع الطازج من المحارق وتجفيفها عند 25 درجة مئوية ثم فصل الأجزاء غير المحترقة يدويًا مثل اللولب والأسلاك والبلاستيك. يتم تصغير العينة إلى حجم 500 ميكرومتر باستخدام آلة التقطيع لإزالة المحتوى المغناطيسي (إزالة الحديد). تم إخضاع عينات رماد القاع (المخلفات والمركزات) لاختبارات الترشيح من أجل مراقبة قابلية استعادة المعادن للعينات وتحسين المعلمات. من المهم تقليل الحجم إلى 500 ميكرون باستخدام آلة التقطيع لإزالة المحتوى المغناطيسي. يتم ترشيح المحلول ووضعه في سلسلة من الأعمدة عند خلط السائل بمستخلصات سائلة مناسبة لفصل المعادن عن المحلول.

Extraction column عمود الاستخراج

Extraction column is a kind of column extraction equipment of mechanical stirring, it is composed by upper settling chamber, emulsion chamber and bottom settling chamber. the emulsion chamber is cylinder type, and is divided into several extraction chambers by static ring baffle, there is a fixed turn plate between two static ring baffles, and rotating with shaft together. When work, heavy phase(aqueous)and light phase(organic phase) enter the equipment from column top and bottom respectively, and contact counter currently in column. Under fixed turn plate stirring, the dispersed phase formed small droplets, to enlarge mass transfer area and finished extraction process, and then Heavy phase and light phase discharge from the different exits.

عمود الاستخراج هو نوع من معدات استخراج العمود من التحريك الميكانيكي ، ويتكون من غرفة الترسيب العلوية ، وغرفة المستحلب ، وغرفة الاستقرار السفلية. حجرة المستحلب من النوع الأسطواني ، وتنقسم إلى عدة غرف استخلاص بواسطة حاجز دائري ثابت ، وهناك لوحة دوران ثابتة بين اثنين من حواجز الحلقة الثابتة ، وتدور مع العمود معًا. عند العمل ، يدخل الطور الثقيل (المائي) والمرحلة الخفيفة (الطور العضوي) إلى المعدات من أعلى العمود وأسفله على التوالي ، وعداد التلامس الموجود حاليًا في العمود. تحت التحريك الثابت للصفائح الدورانية ، شكلت المرحلة المشتتة قطيرات صغيرة ، لتوسيع منطقة نقل الكتلة وعملية الاستخراج النهائية ، ثم تفريغ الطور الثقيل والمرحلة الخفيفة من المخارج المختلفة.

Process control system نظام التحكم في العمليات



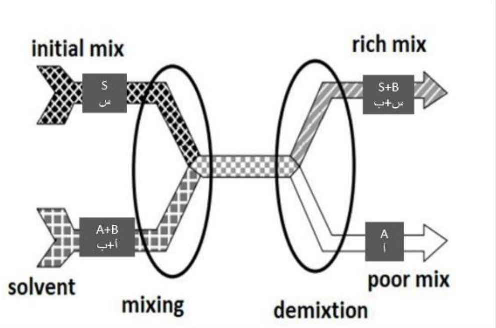


Figure 3: Principle of a separationstage by obtaining a balance

Practically, the initial mix ,containing solute B dissolved in the diluent A, is contacted with the solvent S. The solute B (generally more soluble in the solvent 'S' than in the diluent 'A'), passes from the solution (A+B) in the solvent (S+B) , the solvent enriched in solute (S+B) is the extract (rich mix) while the diluent depleted solute is the residue (poor mix).

So the substance B placed in contact with two partially miscible solvents or immiscible S and A is distributed unequally between the two phases that are formed when the physicochemical balance is reached.

In order to transport the material as quickly as possible, the area of the transfer surface is increased by various artifices. These objectives can be obtained in a column.

عمليًا ، المزيج الأولي ، المحتوي على المذاب «ب» المذاب في المادة المخففة «أ»، يتم ملامسته للمذيب «س» . والمذاب «ب» (بشكل عام أكثر قابلية للذوبان في المذيب «س» منه في المادة المخففة «أ») ، يمر من المحلول «أ+ب» في المذيب «س+ب»، المذيب المخصب في المذاب هو المستخلص (المزيج الغني) بينما المادة المخففة المستنفدة المذابة هي البقايا (المزيج الفقير).

لذلك فإن المادة «ب» الملامسة لمذيبين قابلين للامتزاج جزئيًا «أ» و «س» أو غير قابلين للامتزاج يتم توزيعها بشكل غير متساو بين المرحلتين اللتين تتشكلان عند الوصول إلى التوازن الفيزيائي الكيميائي.

من أجل نقل المواد في أسرع وقت ممكن ، يتم زيادة مساحة سطح النقل بواسطة مصنوعات مختلفة. يمكن الحصول على هذه الأهداف في عمود.

Mounira Sayah / Nidaa Fatfat, Aecenar November 2021

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Heavy metals recycling 8 columns for 8 metals (Cu,Zn,Pb,Cd,Cr,Ni,Hg,As)

Ashes:
Bottom ashes
Fly ashes

Considering that each hour 800 kg of waste will be incinerate which forms 338 kg of ashes (bottom ash and fly ash) that includes the following amount of metals :

Metals	Quantity in ash(mg/kg)	metals in 338 of ash(g)	Percentage of metals in 70 L of mixed =4.414, the amount of metals(g)
Cu	2678	905.164	37.4737896
Zn	7378	2467.4	102.15036
Pb	7760	2622.88	108.587232
Ni	1906	642.2	26.58708
Cd	56.6	18.928	0.7836192
Cr	1512	510.38	21.129732
As	253.35	85.514	3.5402796
Hg Ph=9.5	6.67	2.28488	0.094594032

Type of Extractant

Nouns of extractants	The amount of extractant (ml)
LIX® 984N (mixture of 2-hydroxy-5-nonylacetophenone oxime and 5-nonylsalicylaldoxime in a high flash diluent),	74.9475792
Cyanex273(Phosphonic acid)	204.30072
Cyanex 272(Bis(2,4,4-trimethylpentyl)phosphinic acid)	217.174464
Cyanex 272(Bis(2,4,4-trimethylpentyl)phosphinic acid)	53.17416
Cyanex273(Phosphonic acid)	1.5672384
nitrilotriacetic acid (NTA)-	42.259464
Cyanex273(Phosphonic acid)	7.0805592
By Cyanex 301 (Bis(2,4,4-trimethylpentyl)dithiophosphinic acid) and cyanex 302(Bis(2,4,4-trimethylpentyl)thiophosphinic acid	0.189188064

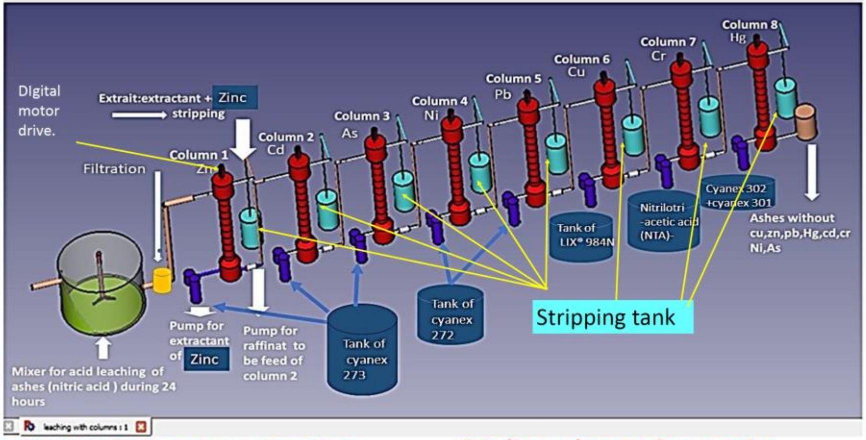
Leaching

Comparison of extraction of elements by different acids (%) (liquid/solid ratio 40:1 ml/g, concentration of organic acid 0.1 M, temperature 25°C, leaching time 60 min)

Leaching reagent	Final pH	Al	Ca	Fe	Cu	Zn	Pb
Citric acid	3.13	100	93.1	67.0	100	100	96.9
Malic acid	3.07	99.7	100	80.2	100	100	97.0
Acetic acid	3.02	88.4	100	23.2	100	100	70.1
Lactic acid	3.06	92.2	100	40.7	100	100	62.0
Oxalic acid	3.09	43.3	0.41	46.5	45.8	44.9	2.7
Tartaric acid	2.98	30.3	6.7	24.4	32.7	35.7	4.0
Sulfuric acid	3.03	44.2	100	5.8	52.4	57.9	28.3
Hydrochloric acid	3.10	42.5	100	2.9	50.2	54.3	14.8
Nitric acid	3.01	41.6	100	2.2	52.8	56.9	25.3

We choose the nitric acid to prevent the leaching of Fe).
Leaching during 24 hours with concentration =15,8 mol/l.
The ash was extracted at a liquid-to-solid ratio (L/S)=5 correspond to 5L of nitric acid to leach 1 kg of ash .

The rotor speed was adjusted to the desired value in the range of 0-375 rpm by use of a digital motor drive.



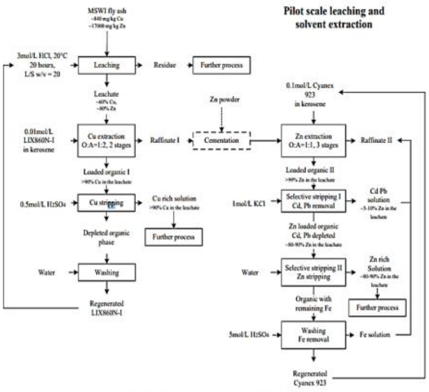
1.Operating the Column

- Open the pump and reach the column with 44 l of ash mixed with nitric acid
- When the liquid level in the column reaches the top right nozzle (turn the feed flowrate down to the desired set point.
- Turn on and set the extractant flowrate to the desired set point by adjusting the pump speed.
- Close the extrait out rotameter when the liquid level reaches the top left (extrait out) nozzle.
- Allow the interface to form between the top mesh and the top left nozzle (extrait out). The interface appears as an immiscible layer between acid and extractant with droplets
- Once the interface is formed in the desired location, open the extrait out rotameter slowly until there are flowrates out of the column.
- Adjusting this rotameter is used to control the interface level. Opening the rotameter causes the interface to rise, while closing it causes the interface to drop.
- The optimum setting of this rotameter will allow for a semi-stable interface and give a minimal amount of drift in the interface level.
- Small adjustments should be made in order to keep the interface constant.
- Set the stirrer speed to a setting of 5 using the dial on the top right of the lab equipment panel. Make sure the motor is powered with the top center switch on the right power panel.
- Allow the column to run until steady state is achieved (about hour).

To feed the column in our case with extractant,we need 9890 cm³

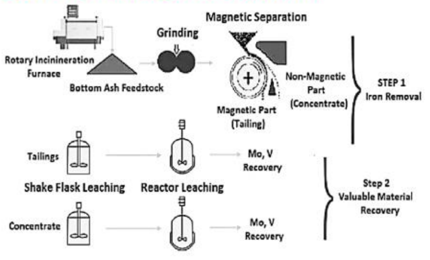
1-فتح المضخة لتغذية العامود مع 44 لتر من الرماد مختلطة مع حمض النتريك.
2-عندما يصل مستوى السائل في العامود إلى الفوهة اليمنى العليا (قم بتدفق التغذية لأسفل إلى نقطة الضبط المطلوبة.
3-قم بتشغيل وضبط تدفق المستخرج إلى نقطة الضبط المرغوبة عن طريق ضبط سرعة المضخة.
4-أغلق أداة قياس التدوير الإضافية عندما يصل مستوى السائل إلى أعلى اليسار (فوهة الخروج).
5-اسمح للواجهة بالتشكل بين الشبكة العلوية والفوهة اليسرى العلوية (خروج إضافي). تظهر الواجهة كطبقة غير قابلة للامتزاج بين الحمض والمستخرج باستخدام قطرات
6-بمجرد تشكيل الواجهة في الموقع المرغوب ، افتح مقياس التدريج الإضافي ببطء حتى تتدفق خارج العمود.
7-يستخدم ضبط هذا القياس للتحكم في مستوى الواجهة. يؤدي فتح أداة قياس الدوران إلى ارتفاع الواجهة ، بينما يؤدي إغلاقها إلى انخفاض الواجهة.
8-يسمح الإعداد الأمثل لمقياس الدوران هذا بواجهة شبه مستقرة وإعطاء قدر ضئيل من الانحراف في مستوى الواجهة.
8-يجب إجراء تعديلات صغيرة للحفاظ على الواجهة ثابتة.
9-اضبط سرعة التحريك على إعداد 5 باستخدام الاتصال الهاتفي أعلى يمين لوحة معدات المختبر. تأكد من تشغيل المحرك مع مفتاح التبديل العلوي في لوحة الطاقة اليمنى.
10-اسمح للعامود بالعمل حتى يتم تحقيق حالة مستقرة (حوالي الساعة).
11- بعد كل عامود يحول المحلول الى غرفة للتنظيف(stripping)

Leaching and solvent extraction plant



بعد تجميع الرماد ،يتم طحنه أولا ثم يدخل في غرفة للفرز المغناطيسي لازالة الحديد.بعد ذلك،يدخل في الخلاط حيث نزيد حامض النتريك بمعدل 5 ليتر لكل كيلومن الرماد لمدة 24 ساعة.ثم ،يحوّل الى العامود الاول للتصفية من المعدن الثقيل الاول حيث يصب عليه مستخرج المعدن الخاص (extractant).كل عامود يتوعب ما يقارب 44 ليتر من خليط الحامض والرماد.

Grinding and magnetic separation



Maysaa kamaredine
24 -04-2019

3.1.2.4 Liquefication of Oxygen

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بسم الله الرحمن الرحيم


مركز أبحاث تكنولوجيا العمليات الكيميائية
Institute for Chemical Process Technology (ICPT)
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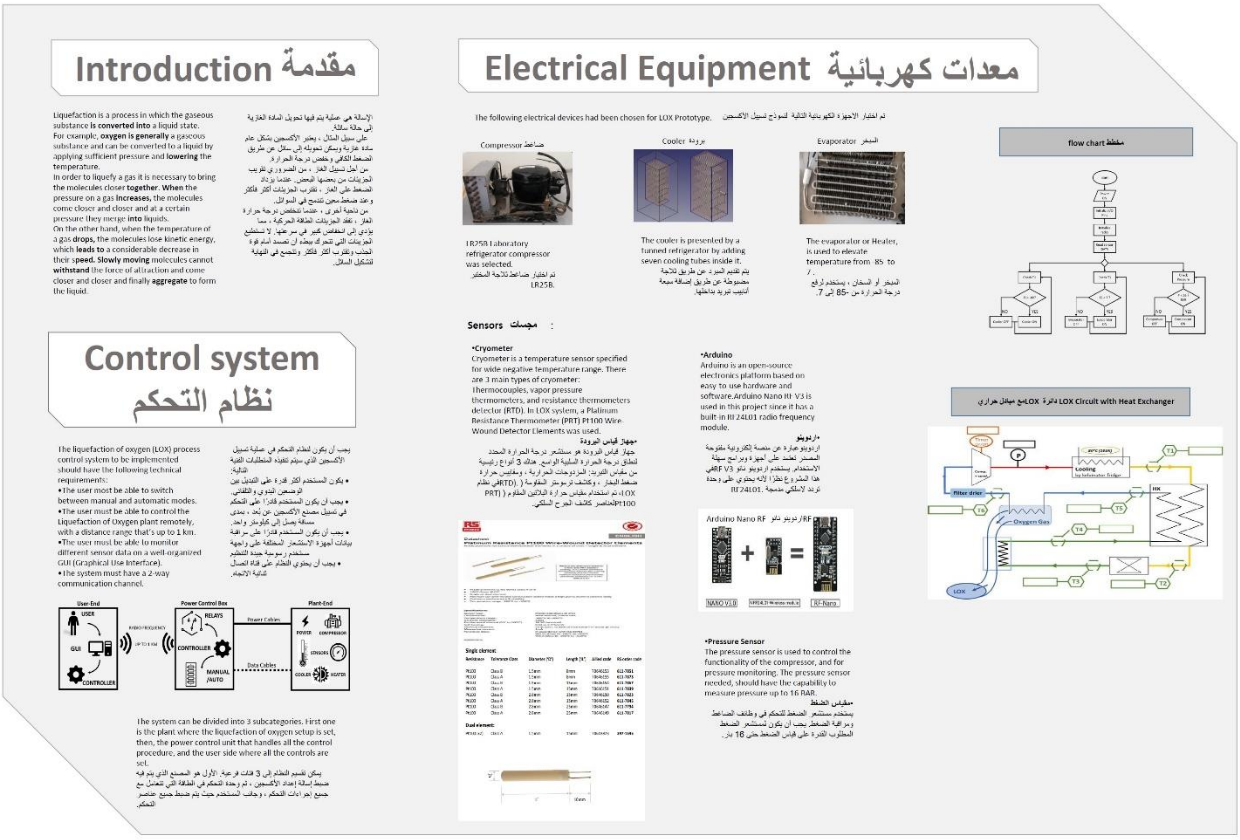
Air Liquefaction and Cryogenic



Introduction مقدمة

Liquefaction is a process in which the gaseous substance **is converted into** a liquid state.
For example, **oxygen is generally** a gaseous substance and can be converted to a liquid by applying sufficient pressure and **lowering** the temperature.
In order to liquefy a gas it is necessary to bring the molecules closer **together**. **When** the pressure on a gas **increases,** the molecules come closer and closer and at a certain pressure they merge **into** liquids.
On the other hand, when the temperature of a gas **drops,** the molecules lose kinetic energy, which **leads to** a considerable decrease in their s**peed. Slowly moving** molecules cannot **withstand** the force of attraction and come closer and closer and finally **aggregate** to form the liquid.

الإسالة هي عملية يتم فيها تحويل المادة الغازية إلى حالة سائلة.
على سبيل المثال ، يعتبر الأكسجين بشكل عام مادة غازية ويمكن تحويله إلى سائل عن طريق الضغط الكافي وخفض درجة الحرارة.
من أجل تسييل الغاز ، من الضروري تقريب الجزيئات من بعضها البعض. عندما يزداد الضغط على الغاز ، تقترب الجزيئات أكثر فأكثر وعند ضغط معين تندمج في السوائل.
من ناحية أخرى ، عندما تنخفض درجة حرارة الغاز ، تفقد الجزيئات الطاقة الحركية ، مما يؤدي إلى انخفاض كبير في سرعتها. لا تستطيع الجزيئات التي تتحرك ببطء أن تصمد أمام قوة الجذب وتقترب أكثر فأكثر وتتجمع في النهاية لتشكيل السائل.

Control system نظام التحكم

The liquefaction of oxygen (LOX) process control system to be implemented should have the following technical requirements:
- The user most be able to switch between manual and automatic modes.
- The user must be able to control the Liquefaction of Oxygen plant remotely, with a distance range that's up to 1 km.
- The user must be able to monitor different sensor data on a well-organized GUI (Graphical Use Interface).
- The system must have a 2-way communication channel.

يجب أن يكون لنظام التحكم في عملية تسييل الأكسجين الذي سيتم تنفيذه المتطلبات الفنية التالية:
- يكون المستخدم أكثر قدرة على التبديل بين الوضعين اليدوي والتلقائي.
- يجب أن يكون المستخدم قادرًا على التحكم في تسييل مصنع الأكسجين عن بُعد ، بمدى مسافة يصل إلى كيلومتر واحد.
- يجب أن يكون المستخدم قادرًا على مراقبة بيانات أجهزة الاستشعار المختلفة على واجهة مستخدم رسومية جيدة التنظيم
- يجب أن يحتوي النظام على قناة اتصال ثنائية الاتجاه.

The system can be divided into 3 subcategories. First one is the plant where the liquefaction of oxygen setup is set, then, the power control unit that handles all the control procedure, and the user side where all the controls are set.

يمكن تقسيم النظام إلى 3 فئات فرعية. الأول هو المصنع الذي يتم فيه ضبط إسالة إعداد الأكسجين ، ثم وحدة التحكم في الطاقة التي تتعامل مع جميع إجراءات التحكم ، وجانب المستخدم حيث يتم ضبط جميع عناصر التحكم.

Electrical Equipment معدات كهربائية

The following electrical devices had been chosen for LOX Prototype. تم اختيار الاجهزة الكهربائية التالية لنموذج تسيل الاكسجين

Compressor ضاغط

LR25B Laboratory refrigerator compressor was selected.
تم اختيار ضاغط ثلاجة المختبر LR25B.

Cooler برودة

The cooler is presented by a tunned refrigerator by adding seven cooling tubes inside it.
يتم تقديم المبرد عن طريق ثلاجة مضبوطة عن طريق إضافة سبعة أنابيب تبريد بداخلها.

Evaporator المبخر

The evaporator or Heater, is used to elevate temperature from -85 to 7 .
المبخر أو السخان ، يستخدم لرفع درجة الحرارة من -85 إلى 7.

Sensors مجسات :

•Cryometer
Cryometer is a temperature sensor specified for wide negative temperature range. There are 3 main types of cryometer: Thermocouples, vapor pressure thermometers, and resistance thermometers detector (RTD). In LOX system, a Platinum Resistance Thermometer (PRT) Pt100 Wire-Wound Detector Elements was used.

•جهاز قياس البرودة
جهاز قياس البرودة هو مستشعر درجة الحرارة المحدد لنطاق درجة الحرارة السلبية الواسع. هناك 3 أنواع رئيسية من مقياس التبريد: المزدوجات الحرارية ، ومقاييس حرارة ضغط البخار ، وكاشف ترمومتر المقاومة (RTD). في نظام LOX، تم استخدام مقياس حرارة البلاتين المقاوم (PRT) Pt100 لعناصر كاشف الجرح السلكي.

•Arduino
Arduino is an open-source electronics platform based on easy to use hardware and software.Arduino Nano RF V3 is used in this project since it has a built-in RF24L01 radio frequency module.

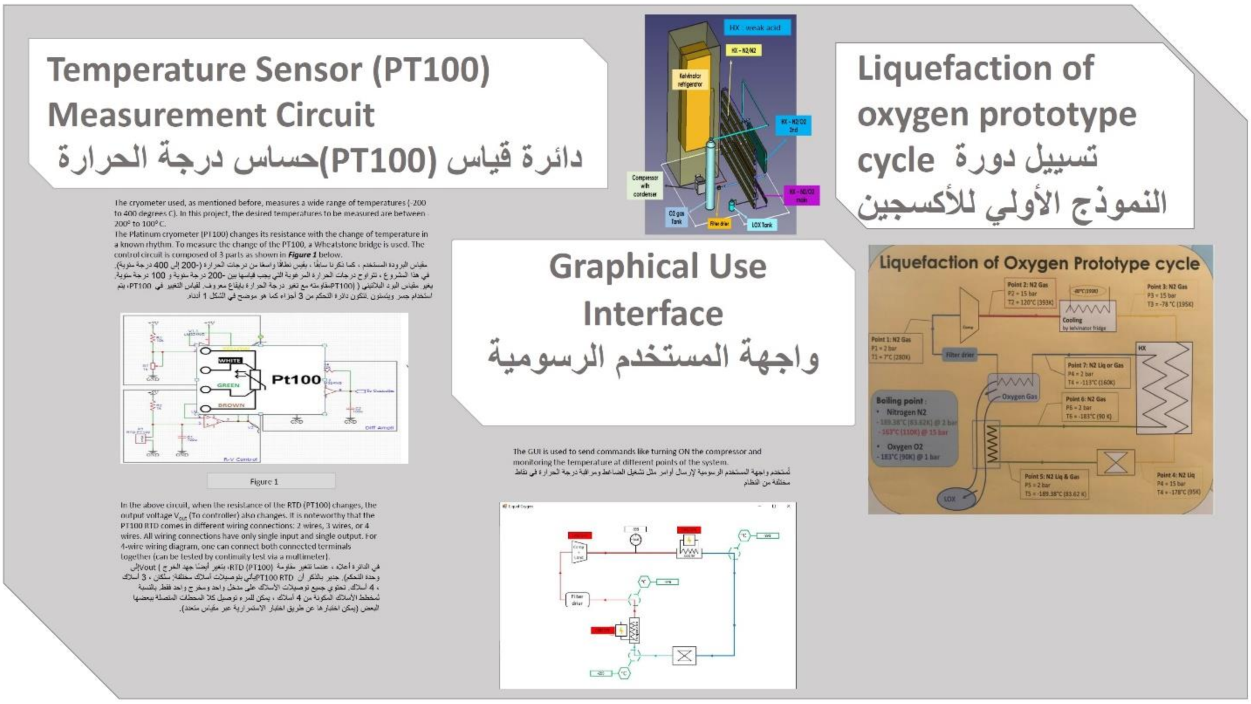
•اردوينو
اردوينو عبارة عن منصة إلكترونية مفتوحة المصدر تعتمد على أجهزة وبرامج سهلة الاستخدام. يستخدم اردوينو نانو RF V3 في هذا المشروع نظرًا لأنه يحتوي على وحدة تردد لاسلكي مدمجة RF24L01.

•Pressure Sensor
The pressure sensor is used to control the functionality of the compressor, and for pressure monitoring. The pressure sensor needed, should have the capability to measure pressure up to 16 BAR.

•مقياس الضغط
يستخدم مستشعر الضغط للتحكم في وظائف الضاغط ومراقبة الضغط يجب أن يكون لمستشعر الضغط المطلوب القدرة على قياس الضغط حتى 16 بار.

flow chart مخطط

LOX Circuit with Heat Exchanger دائرة LOX مع مبادل حراري



Temperature Sensor (PT100) Measurement Circuit دائرة قياس (PT100)حساس درجة الحرارة

The cryometer used, as mentioned before, measures a wide range of temperatures (-200 to 400 degrees C). In this project, the desired temperatures to be measured are between -200° to 100° C.
The Platinum cryometer (PT100) changes its resistance with the change of temperature in a known rhythm. To measure the change of the PT100, a Wheatstone bridge is used. The control circuit is composed of 3 parts as shown in ***Figure 1*** below.

مقياس البرودة المستخدم ، كما ذكرنا سابقًا ، يقيس نطاقًا واسعًا من درجات الحرارة (-200 إلى 400 درجة مئوية). في هذا المشروع ، تتراوح درجات الحرارة المرغوبة التي يجب قياسها بين -200 درجة مئوية و 100 درجة مئوية. يغير مقياس البرد البلاتيني (PT100) مقاومته مع تغير درجة الحرارة بإيقاع معروف. لقياس التغيير في PT100، يتم استخدام جسر ويتستون .تتكون دائرة التحكم من 3 أجزاء كما هو موضح في الشكل 1 أدناه.

Figure 1

In the above circuit, when the resistance of the RTD (PT100) changes, the output voltage V_{out} (To controller) also changes. It is noteworthy that the PT100 RTD comes in different wiring connections: 2 wires, 3 wires, or 4 wires. All wiring connections have only single input and single output. For 4-wire wiring diagram, one can connect both connected terminals together (can be tested by continuity test via a multimeter).

في الدائرة أعلاه ، عندما تتغير مقاومة RTD (PT100)، يتغير أيضًا جهد الخرج (Vout إلى وحدة التحكم). جدير بالذكر أن PT100 RTD يأتي بتوصيلات أسلاك مختلفة: سلكان ، 3 أسلاك ، 4 أسلاك. تحتوي جميع توصيلات الأسلاك على مدخل واحد ومخرج واحد فقط. بالنسبة لمخطط الأسلاك المكونة من 4 أسلاك ، يمكن للمرء توصيل كلا المحطات المتصلة ببعضها البعض (يمكن اختبارها عن طريق اختبار الاستمرارية عبر مقياس متعدد).

Liquefaction of oxygen prototype cycle تسييل دورة النموذج الأولي للأكسجين

Liquefaction of Oxygen Prototype cycle

Graphical Use Interface واجهة المستخدم الرسومية

The GUI is used to send commands like turning ON the compressor and monitoring the temperature at different points of the system.
تُستخدم واجهة المستخدم الرسومية لإرسال أوامر مثل تشغيل الضاغط ومراقبة درجة الحرارة في نقاط مختلفة من النظام

Nidaa Fatfat Mounira Sayah
/Aecenar November 2021

بسم الله الرحمن الرحيم

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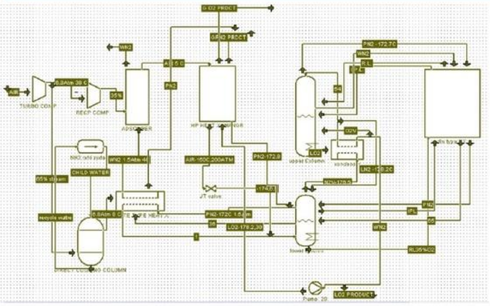
Liquefaction of air(oxygen)

Process of purification and liquefaction of air :



In this process at first air is **filtered & compressed to 6.8 atm** in turbo compressor. During the compression cooling is done to maintain the temp to **35 - 40°C.**

After compression the air is divided into two streams. One is **65% stream** & the other **is 35%,** now the larger stream is then passed through after cooler and heat exchanger where it is cooled to **-150°C to -170°C** by the incoming pure nitrogen & waste nitrogen streams produced from rectification columns.

The smaller stream is passed through **reciprocating compressor** to increase the pressure to about **200atm.**Here the air temp is maintained at **4-8°C** by intermediate cooling between stages using **cold water obtained by ammonia refrigeration.**

Then the air goes through **high pressure heat exchanger** where the temp of air is brought down to about **-120 -140°C.** Now the air undergoes expansion to about **6.5 atm in the expansion engine**.

The temperature of air is brought down from **-170 to -174°C by joule Thompson effect.**

Now the air will be in liquid state & mixes with the larger stream & changes the whole air stream into saturated liquid state.

This saturation liquid is fed to **Linde rectification column**. This column may be **single, double** or compound depending on requirement. the liquid product coming out will have a purity of about **99.4 -99.99%.**

This liquid is partially vaporized in condenser, to **liquefy the nitrogen vapor** &the rest may be taken as liquid product or it may be obtained in gaseous state if it is used for cooling of incoming air, the other products that obtained are pure **nitrogen of purity above 98% &** waste nitrogen product of purity of about 92-96%.

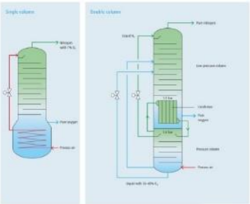


TABLE 5.6a: Specification sheet for Compressor

Power of Compressor	364.355KW
Rotational Speed	2300.0698rpm
Inlet absolute velocity from Imp	50.45m/s
Outlet absolute velocity from Imp	74.726m/s
Radius of Impeller 1 tip	0.0755m
Radius of Impeller 2 tip	0.151m
Number of impeller blades	20
Width of diffuser 1	0.033m
Width of diffuser 2	0.00938

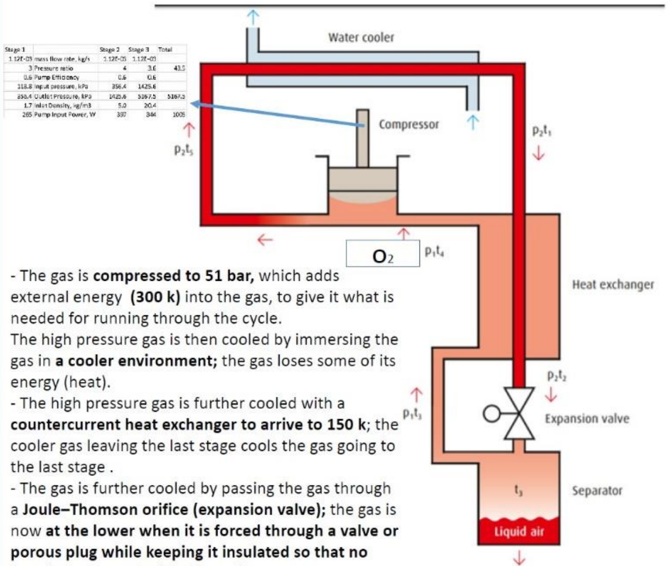
TABLE 5.6c: Specification sheet for the main heat exchanger

fin thickness(t)	30mm
fin frequency (f)	0.7425 fin per meter
fin length (l)	250mm
fin height (h)	50mm
fin spacing (s)	110mm
plate thickness (b)	80mm
free flow area (Aff)	4000mm^2
frontal area (A)	11200mm^2
heat transfer area (As)	83000mm^2
fin area (Af)	28000mm^2
equilibrium diameter (Dh)	48.19mm
fin area/total surface area	0.3373
frontal area ratio (ζ)	0.3571
height-spacing ratio (α)	0.45453
length- spacing ratio (δ)	2.7272
thickness-spacing (ν)	0.27273

HIGH PRESSURE COLUMN, P = 5.0 atm			
COMPONENT	FEED, F1	DISTILLATE, D1	BOTTOM, B1
OXYGEN	0.21	0.005	0.4
NITROGEN	0.79	0.995	0.6
FLOWRATES (Kmol/h)			
F1 = 145.379	D1 = 69.92	B1 = 75.459	
Vn1 = 209.76	Ln1 = 139.84	Vm1 = 209.76	Lm1 = 285.219
FEED TEMPERATURE : -200°C			
FEED POINT : 2			
NUMBER OF STAGES, N = 7			
MINIMUM REFLUX RATIO, Rm = 0.5			
REFLUX RATIO, R = 2			
MINIMUM NUMBER OF STAGES, Nm = 4			
LOW PRESSURE COLUMN, P = 1.4 atm			
COMPONENT	FEED, F2	DISTILLATE, D2	BOTTOM, B2
OXYGEN	0.6	0.005	0.01
NITROGEN	0.4	0.995	0.99
FLOWRATES (Kmol/h)	D2 = 45.20	B2 = 30.26	
F2 = 75.459	Ln2 = 0	Vm2 = 185.039	Lm2 = 215.299
Vn1 = 209.76			
FEED POINT : 5			

NUMBER OF STAGES, N = 7			
PLATE SIZING	PLATE SPACING: 500mm	PLATE THICKNESS: 5mm	
PLATE EFFIENCY : 50%			
HOLE SIZING	HOLE PITCH, LP : 15mm	AREA OF PITCH, : 218.2mm²	
HOLE SIZE, dh : 5mm			
COLUMN SIZING	COLUMN EFFICIENCY : 70%		
COLUMN DIAMETER, Dc : 4700mm			
WEIR/DOWNCOMER SIZING	WEIR LIQUID CREST, how : 50mm liquid	LENGTH OF WEIR, Lw :3619mm	
HEIGHT OF WEIR, hw : 50.0mm			
DOWNCOMER CLEARANCE, hcl : 13mm			
VAPOUR LIQUID FLOW RATE, FLV : 0.62			
FLOOD VELOCITY, Uf : 7.366mm/s			
NUMBER OF REAL STAGES, N : 19			

Process of liquefaction of oxygen



Stage 1		Stage 2	Stage 3	Total
1.12E-03	mass flow rate, kg/s	1.12E-03	1.12E-03	
3	Pressure ratio	4	3.6	43.5
0.6	Pump Efficiency	0.6	0.6	
118.8	Input pressure, kPa	356.4	1425.6	
356.4	Outlet Pressure, kPa	1425.6	5167.5	5167.5
1.7	Inlet Density, kg/m3	5.0	20.4	
265	Pump Input Power, W	397	344	1005

- The gas is **compressed to 51 bar,** which adds external energy **(300 k)** into the gas, to give it what is needed for running through the cycle.

The high pressure gas is then cooled by immersing the gas in **a cooler environment;** the gas loses some of its energy (heat).

- The high pressure gas is further cooled with a **countercurrent heat exchanger to arrive to 150 k**; the cooler gas leaving the last stage cools the gas going to the last stage .

- The gas is further cooled by passing the gas through a **Joule–Thomson orifice (expansion valve);** the gas is now **at the lower when it is forced through a valve or porous plug while keeping it insulated so that no heat is exchanged with the environment.**

- The low pressure gas is now at its coolest in the current cycle.

Some of the gas may condense and become output product.

The low pressure gas is directed back to the countercurrent heat exchanger to cool the warmer, incoming, high-pressure gas.

After leaving the countercurrent heat exchanger, the gas is warmer than it was at its coldest, but cooler than it started out at step 1.

The gas is sent back to the compressor to make another trip through the cycle (and become still colder).

Oxygen properties

OXYGEN IN SOLID STATE: It is a hard, pale blue, doubly refracting crystalline solid.

Melting point:	-218.81°C
Density at -252.5°C:	1.4256 gm/cc
Specific heat at -256°C:	0.078 cal
Heat of fusion at -219°C:	313 cal/gm

OXYGEN IN LIQUID STATE: It is a pale steel blue, transparent and very mobile liquid

Boiling point:	-182.02°C
Density at boiling point:	1.14gm/cc
Surface tension at B.P.:	13074 dynes/cm

It is a non-conductor of electricity and strongly magnetic when compared to iron.

OXYGEN IN GASEOUS STATE: It is a colourless, odourless, tasteless, diatomic gas, a volume of it slightly heavier than equal volume of air. One Litre of oxygen under standard condition weighs 1.42901gm and the corresponding weight of air is 1.2929gm. The oxygen is only slightly soluble in water at ordinary temperature and pressures

Table 12 Work Required to Liquefy Selected Gases[a]

Substance	Work			Thermal Energy (Btu/lb)	Electricity	
	cal/mole	J/mole	Btu/lb		kWh/lb	kWh/kg
Air	5,000	20,900	310	930	0.091	0.20
Oxygen	4,800	20,300	273	819	0.080	0.18
Nitrogen	5,100	21,400	328	984	0.096	0.21
Helium	6,500	27,200	2,935	8,805	0.86	1.89
Hydrogen	5,700	23,800	5,119	15,357	1.50	3.30

[a] Using ideal (thermodynamically reversible) process: $W_{rev} = T_a\Delta S - \Delta H$, where $T_a = 298$ K (25°C), and $P_a = 1$ atm.

Note: The values given for each gas are equivalent amounts of energy (or work) expressed in several units of measure.

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Liquefaction of Oxygen

Simple refrigeration cycle

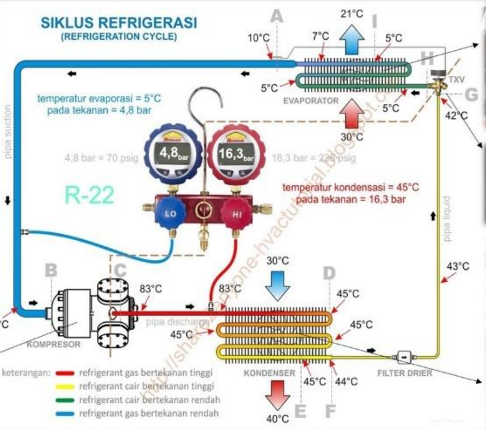
R-22

- **Nomenclature:** *Chlorodifluoromethane*
- **Symbol:** *$CHClF_2$*
- **Boiling point :**

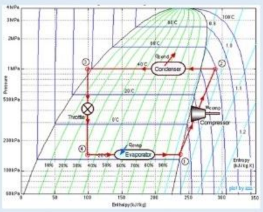
T= *- 40.7°C* (232.5 K) @ *1 bar*

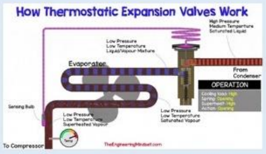
T= *4.9°C* (278.05 K) @ 4.8 bar

T= 45.6°C (318.75 K) @ 16.3 bar



Basic components of refrigeration are: Compressor, Condenser, expansion valve(throttle) and evaporator





Based on the Ideal gas Law: **PV=nRT**

In a constant volume V, when P increases → T increases

The variation of pressure has influence on the degree of boiling point of a refrigerant

The TXV is used in many refrigeration systems, they can be found in the same location which is just before the evaporator.

The valve decreases the pressure to allow the refrigerant to boil at lower temperatures. The boiling is essential as the refrigerant will absorb the heat from the ambient air and carry this away to the compressor. Just remember that refrigerants have a much lower boiling point than water.

The high pressure liquid refrigerant is forced through a small orifice which causes a pressure reduction as it passes through. During this pressure reduction, some of the refrigerant will vaporise and the rest will remain as liquid.

Refrigeration with cascade to reaching a lower temperature

(kelvinator refrigerator)

The cascade refrigeration system consists of a low-temperature loop (Low stage) and a high-temperature loop (high stage).

Each stage consists of a compressor, condenser, expansion valve and evaporator

The high stage condenser is cooled by air cooled, while the low stage condenser is cooled by the high stage evaporator.

So the high stage evaporator acts as a coolant for the pressurized refrigerant in the low stage.

Advantages of a cascade cooling system:

- Repair is easy
- The Cascade refrigeration allows to low-temperature operation.
- You can reduce the use of power up to 10% with the help of cascade refrigeration.

Point 4: Gas
P4= 1 bar
T4= -16°C (> -20 °C)

R-502 (Higher stage)

- **Chemical formula:**
  $C_3HCl_2F_7$
- **Boiling point:**

- 45.5°C @ 1 bar

+ 61.5 °C @ 25.85 bar (375 psi)

R-503 (Lower stage)

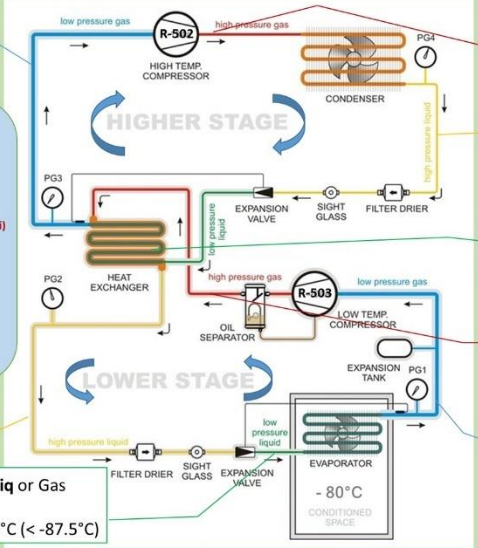
- **Chemical formula:**
  CC1F3,CHF3
- **Boiling point:**

- 87.5°C @ 1 bar

- 20°C @ 25.85 bar (375 psi)

Point B: Liq
PB= 25.85 bar
TB= -30 (< -20 °C)

Point C: Liq or Gas
PC= 1 bar
TC= - 90.5°C (< -87.5°C)



Point 1: Gas
P1= 25.85 bar
T1= 90°C (>60 °C)

Point 2: Liq
P2= 25.85 bar
T2= 50°C (<60 °C)

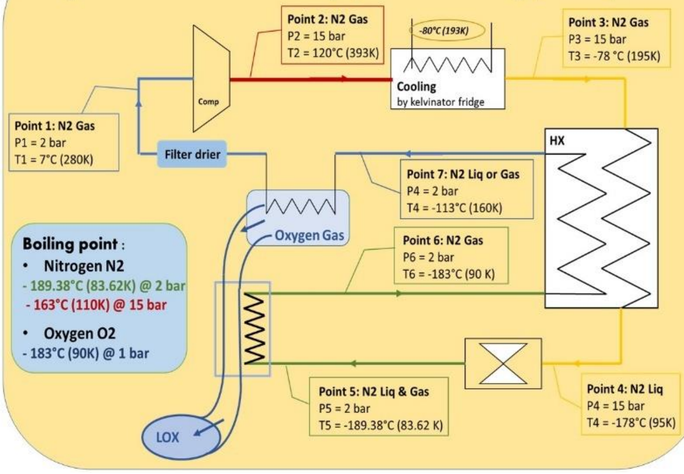
Point 3: Liq or Gas
P3= 1 bar
T3= - 50°C (< - 45.5 °C)

Point A: Gas
PA= 25.85 bar
TA= 10°C (> -20 °C)

Point D: Gas
PD= 1 bar
TD= - 83°C (> -87.50 °C)

Cryogenic

Liquefaction of Oxygen Prototype cycle



Point 1: N2 Gas
P1 = 2 bar
T1 = 7°C (280K)

Point 2: N2 Gas
P2 = 15 bar
T2 = 120°C (393K)

Point 3: N2 Gas
P3 = 15 bar
T3 = -78 °C (195K)

Point 4: N2 Liq
P4 = 15 bar
T4 = -178°C (95K)

Point 5: N2 Liq & Gas
P5 = 2 bar
T5 = -189.38°C (83.62 K)

Point 6: N2 Gas
P6 = 2 bar
T6 = -183°C (90 K)

Point 7: N2 Liq or Gas
P4 = 2 bar
T4 = -113°C (160K)

Boiling point :

- **Nitrogen N2**

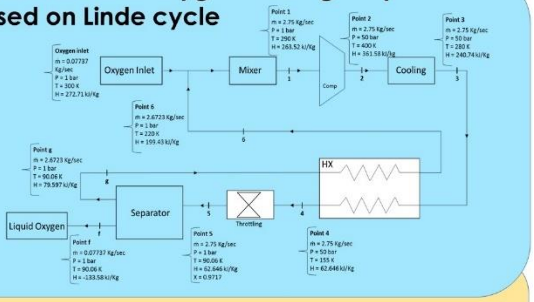
- 189.38°C (83.62K) @ 2 bar

- 163°C (110K) @ 15 bar

- **Oxygen O2**

- 183°C (90K) @ 1 bar

Liquefaction of Oxygen in a big shape based on Linde cycle



Oxygen inlet
m = 0.07737 Kg/sec
P = 1 bar
T = 300 K
H = 272.71 kJ/Kg

Point 1
m = 2.75 Kg/sec
P = 1 bar
T = 290 K
H = 263.52 kJ/Kg

Point 2
m = 2.75 Kg/sec
P = 50 bar
T = 400 K
H = 361.58 kJ/kg

Point 3
m = 2.75 Kg/sec
P = 50 bar
T = 280 K
H = 240.74 kJ/Kg

Point 4
m = 2.75 Kg/sec
P = 50 bar
T = 155 K
H = 62.646 kJ/Kg

Point 5
m = 2.75 Kg/sec
P = 1 bar
T = 90.06 K
H = 62.646 kJ/Kg
X = 0.9717

Point 6
m = 2.6723 Kg/sec
P = 1 bar
T = 220 K
H = 199.43 kJ/Kg

Point g
m = 2.6723 Kg/sec
P = 1 bar
T = 90.06 K
H = 79.597 kJ/Kg

Point f
m = 0.07737 Kg/sec
P = 1 bar
T = 90.06 K
H = -133.58 kJ/Kg

In this prototype the oxygen will be liquefied by cascade cooling of nitrogen.
The nitrogen gas will be compressed (from 2 bar to about 15 bar)[use for that the laboratory refrigerator], The nitrogen will then be cooled down to 195 K by means of a Kelvinator fridge operated with a cascade of R-502 and R-503 refrigerants.

Then the nitrogen will be cooled to lower temperatures (83.6 K) using the expansion valve and heat exchanger.
This nitrogen temperature (<90 K) would be sufficient to liquefy the oxygen at 1atm.

Oxygen gas can also be prepared and cooled to about 170 K in nitrogen before returning directly to the compressor (160 K).

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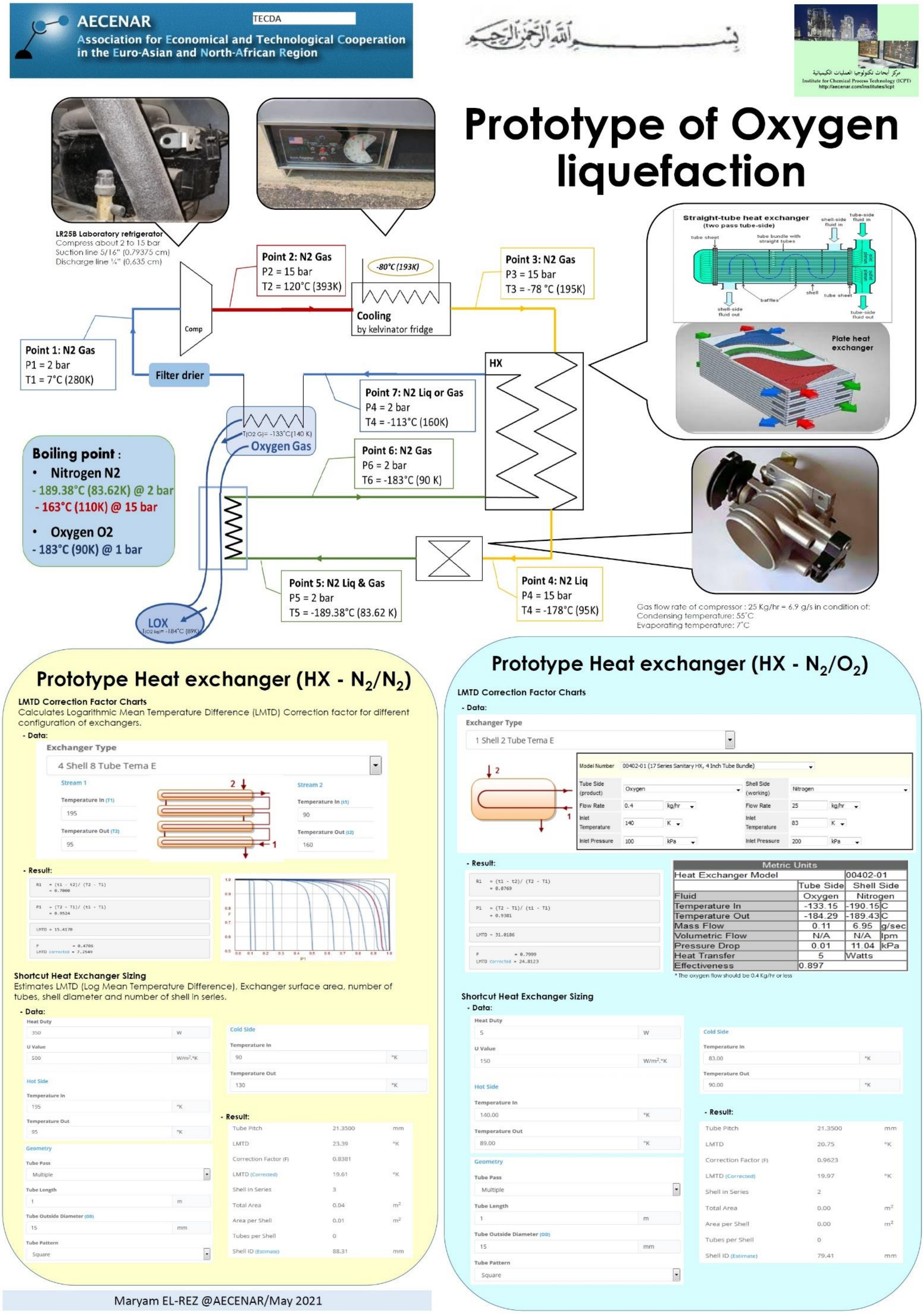

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Prototype of Oxygen liquefaction

LR25B Laboratory refrigerator
Compress about 2 to 15 bar
Suction line 5/16" (0.79375 cm)
Discharge line ¼" (0,635 cm)

Point 1: N2 Gas
P1 = 2 bar
T1 = 7°C (280K)

Point 2: N2 Gas
P2 = 15 bar
T2 = 120°C (393K)

Cooling
by kelvinator fridge

Point 3: N2 Gas
P3 = 15 bar
T3 = -78 °C (195K)

Filter drier

Point 7: N2 Liq or Gas
P4 = 2 bar
T4 = -113°C (160K)

Oxygen Gas

Point 6: N2 Gas
P6 = 2 bar
T6 = -183°C (90 K)

Boiling point :
- **Nitrogen N2**
- 189.38°C (83.62K) @ 2 bar
- 163°C (110K) @ 15 bar
- **Oxygen O2**
- 183°C (90K) @ 1 bar

Point 5: N2 Liq & Gas
P5 = 2 bar
T5 = -189.38°C (83.62 K)

Point 4: N2 Liq
P4 = 15 bar
T4 = -178°C (95K)

Gas flow rate of compressor : 25 Kg/hr = 6.9 g/s in condition of:
Condensing temperature: 55°C
Evaporating temperature: 7°C

Prototype Heat exchanger (HX - N_2/N_2)

LMTD Correction Factor Charts
Calculates Logarithmic Mean Temperature Difference (LMTD) Correction factor for different configuration of exchangers.

- **Data:**

Exchanger Type
4 Shell 8 Tube Tema E

Stream 1
Temperature In (T1): 195
Temperature Out (T2): 95

Stream 2
Temperature In (t1): 90
Temperature Out (t2): 160

- **Result:**

```
R1   = (t1 - t2)/ (T2 - T1)
     = 0.7000

P1   = (T2 - T1)/ (t1 - T1)
     = 0.9524

LMTD = 15.4170

F              = 0.4706
LMTD corrected = 7.2549
```

Shortcut Heat Exchanger Sizing
Estimates LMTD (Log Mean Temperature Difference), Exchanger surface area, number of tubes, shell diameter and number of shell in series.

- **Data:**

Heat Duty: 350 W
U Value: 500 W/m².°K

Hot Side
Temperature In: 195 °K
Temperature Out: 95 °K

Geometry
Tube Pass: Multiple
Tube Length: 1 m
Tube Outside Diameter (OD): 15 mm
Tube Pattern: Square

Cold Side
Temperature In: 90 °K
Temperature Out: 130 °K

- **Result:**

Tube Pitch	21.3500	mm
LMTD	23.39	°K
Correction Factor (F)	0.8381	
LMTD (Corrected)	19.61	°K
Shell in Series	3	
Total Area	0.04	m²
Area per Shell	0.01	m²
Tubes per Shell	0	
Shell ID (Estimate)	88.31	mm

Prototype Heat exchanger (HX - N_2/O_2)

LMTD Correction Factor Charts

- **Data:**

Exchanger Type
1 Shell 2 Tube Tema E

Model Number: 00402-01 (17 Series Sanitary HX, 4 Inch Tube Bundle)

Tube Side (product)	Oxygen		Shell Side (working)	Nitrogen	
Flow Rate	0.4	kg/hr	Flow Rate	25	kg/hr
Inlet Temperature	140	K	Inlet Temperature	83	K
Inlet Pressure	100	kPa	Inlet Pressure	200	kPa

- **Result:**

```
R1   = (t1 - t2)/ (T2 - T1)
     = 0.0769

P1   = (T2 - T1)/ (t1 - T1)
     = 0.9381

LMTD = 31.0186

F              = 0.7999
LMTD corrected = 24.8123
```

Metric Units			
Heat Exchanger Model		00402-01	
	Tube Side	Shell Side	
Fluid	Oxygen	Nitrogen	
Temperature In	-133.15	-190.15	C
Temperature Out	-184.29	-189.43	C
Mass Flow	0.11	6.95	g/sec
Volumetric Flow	N/A	N/A	lpm
Pressure Drop	0.01	11.04	kPa
Heat Transfer	5	Watts	
Effectiveness	0.897		

* The oxygen flow should be 0.4 Kg/hr or less

Shortcut Heat Exchanger Sizing

- **Data:**

Heat Duty: 5 W
U Value: 150 W/m².°K

Hot Side
Temperature In: 140.00 °K
Temperature Out: 89.00 °K

Geometry
Tube Pass: Multiple
Tube Length: 1 m
Tube Outside Diameter (OD): 15 mm
Tube Pattern: Square

Cold Side
Temperature In: 83.00 °K
Temperature Out: 90.00 °K

- **Result:**

Tube Pitch	21.3500	mm
LMTD	20.75	°K
Correction Factor (F)	0.9623	
LMTD (Corrected)	19.97	°K
Shell in Series	2	
Total Area	0.00	m²
Area per Shell	0.00	m²
Tubes per Shell	0	
Shell ID (Estimate)	79.41	mm

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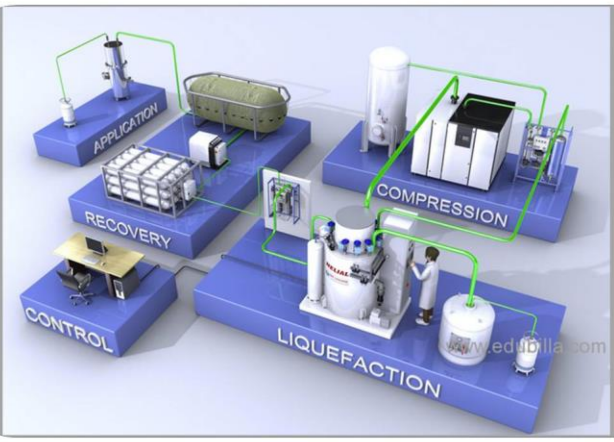
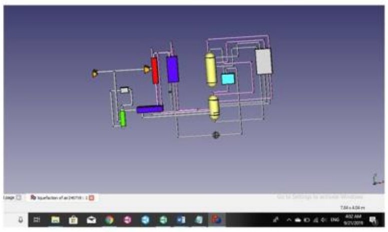
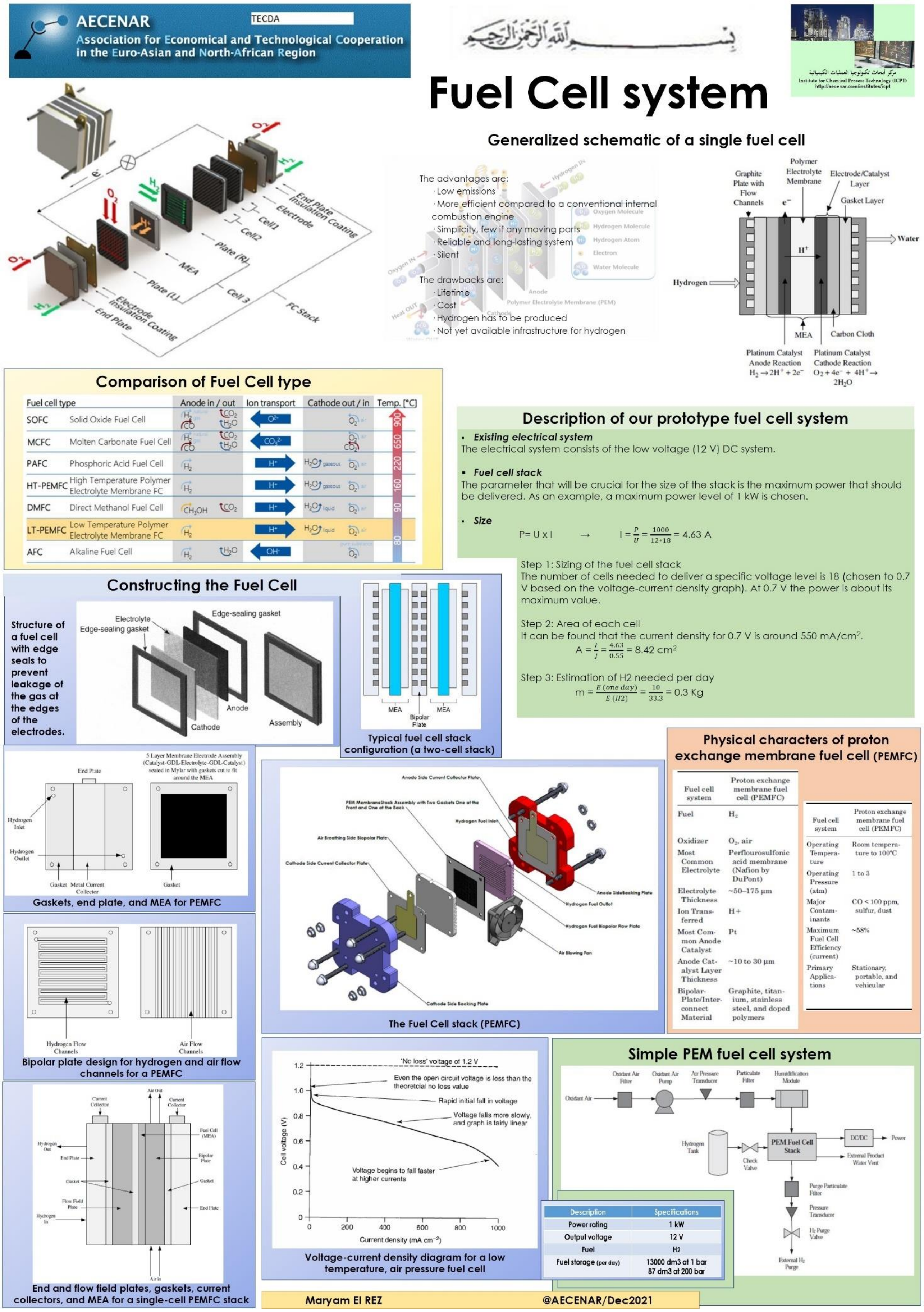
AIR LIQUEFACTION

Principle of Production





3.1.2.5 Fuel Cell



Fuel Cell system

Generalized schematic of a single fuel cell

The advantages are:
- Low emissions
- More efficient compared to a conventional internal combustion engine
- Simplicity, few if any moving parts
- Reliable and long-lasting system
- Silent

The drawbacks are:
- Lifetime
- Cost
- Hydrogen has to be produced
- Not yet available infrastructure for hydrogen

Platinum Catalyst Anode Reaction $H_2 \rightarrow 2H^+ + 2e^-$

Platinum Catalyst Cathode Reaction $O_2 + 4e^- + 4H^+ \rightarrow 2H_2O$

Comparison of Fuel Cell type

Fuel cell type		Anode in / out		Ion transport	Cathode out / in		Temp. [°C]
SOFC	Solid Oxide Fuel Cell	H_2 natural gas CO	CO_2 H_2O	← O^{2-}		O_2 air	900
MCFC	Molten Carbonate Fuel Cell	H_2 natural gas CO	CO_2 H_2O	← CO_3^{2-}		O_2 air CO_2	650
PAFC	Phosphoric Acid Fuel Cell	H_2		H^+ →	H_2O gaseous	O_2 air	220
HT-PEMFC	High Temperature Polymer Electrolyte Membrane FC	H_2		H^+ →	H_2O gaseous	O_2 air	160
DMFC	Direct Methanol Fuel Cell	CH_3OH	CO_2	H^+ →	H_2O liquid	O_2 air	90
LT-PEMFC	Low Temperature Polymer Electrolyte Membrane FC	H_2		H^+ →	H_2O liquid	O_2 air	80
AFC	Alkaline Fuel Cell	H_2	H_2O	← OH^-		O_2 pure substance	

Description of our prototype fuel cell system

- ***Existing electrical system***

The electrical system consists of the low voltage (12 V) DC system.

- ***Fuel cell stack***

The parameter that will be crucial for the size of the stack is the maximum power that should be delivered. As an example, a maximum power level of 1 kW is chosen.

- ***Size***

$$P = U \times I \quad \rightarrow \quad I = \frac{P}{U} = \frac{1000}{12 \cdot 18} = 4.63\ A$$

Step 1: Sizing of the fuel cell stack
The number of cells needed to deliver a specific voltage level is 18 (chosen to 0.7 V based on the voltage-current density graph). At 0.7 V the power is about its maximum value.

Step 2: Area of each cell
It can be found that the current density for 0.7 V is around 550 mA/cm².

$$A = \frac{I}{J} = \frac{4.63}{0.55} = 8.42\ cm^2$$

Step 3: Estimation of H2 needed per day

$$m = \frac{E\ (one\ day)}{E\ (H2)} = \frac{10}{33.3} = 0.3\ Kg$$

Constructing the Fuel Cell

Structure of a fuel cell with edge seals to prevent leakage of the gas at the edges of the electrodes.

Typical fuel cell stack configuration (a two-cell stack)

Gaskets, end plate, and MEA for PEMFC

Bipolar plate design for hydrogen and air flow channels for a PEMFC

End and flow field plates, gaskets, current collectors, and MEA for a single-cell PEMFC stack

The Fuel Cell stack (PEMFC)

Voltage-current density diagram for a low temperature, air pressure fuel cell

Physical characters of proton exchange membrane fuel cell (PEMFC)

Fuel cell system	Proton exchange membrane fuel cell (PEMFC)
Fuel	H_2
Oxidizer	O_2, air
Most Common Electrolyte	Perflourosulfonic acid membrane (Nafion by DuPont)
Electrolyte Thickness	~50–175 µm
Ion Transferred	H+
Most Common Anode Catalyst	Pt
Anode Catalyst Layer Thickness	~10 to 30 µm
Bipolar-Plate/Interconnect Material	Graphite, titanium, stainless steel, and doped polymers

Fuel cell system	Proton exchange membrane fuel cell (PEMFC)
Operating Temperature	Room temperature to 100°C
Operating Pressure (atm)	1 to 3
Major Contaminants	CO < 100 ppm, sulfur, dust
Maximum Fuel Cell Efficiency (current)	~58%
Primary Applications	Stationary, portable, and vehicular

Simple PEM fuel cell system

Description	Specifications
Power rating	1 kW
Output voltage	12 V
Fuel	H2
Fuel storage (per day)	13000 dm3 at 1 bar 87 dm3 at 200 bar

Maryam El REZ @AECENAR/Dec2021

3.1.2.6 Fuel Burner

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طاقة الشمال
North Lebanon Alternative Power
www.nlap-lb.com

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The Fuel Burner:

I. Introduction:

A burner is the mechanical element that ensures the production of heat by mixing a fuel (gaseous, liquid or solid) with an oxidant (usually air, naturally containing oxygen), thus producing a combustion . The mixture requires the best adjustment so that the combustion efficiency is maximum and the combustion is the best possible, that is to say, generating the least possible unburnts and pollutants.

The fuel supplying a burner may be gaseous, liquid or solid, alone or as a mixture, for example:
hydrogen
methane (natural gas);
butane;
propane ;
oil;
oil (fossil, plant, animal);
pulverized coal;
wood pellets and crushed biomass waste;
waste (in cement burners for example).

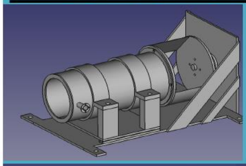
Natural gas burner equipping an industrial cooking oven

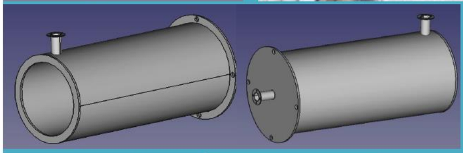
Combustion fan with frequency variator for gas / oil burners

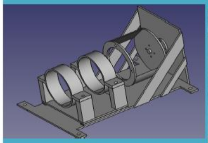
Properties of the inlet of fuel	
number	9
diameter(cm)	1
length (cm)	7
volume of 1 tube (cm2)	5.495
volume of 9 tubes	49.455
Properties of the inlet of air	
diameter of pores(cm)	0.2
number of pores around each tube	6
total number	54
surface of pore	0.0314
total volume	1.6956
chamber of air	
length (cm)	5
diameter (cm)	23
volume (cm2)	2076.325
chamber of fuel	
length (cm)	5
diameter	23
volume	2076.325
dimension of the tube related flask to burner	
diameter(cm)	1
surface of section	0.785
length (cm)	400
combustion value of butane (MJ/m³)	120
flow rate of fuel (g/s)	556
flow rate of oxygen (g/s)	30442
velocity of fuel (m/s)	0.948
velocity of oxygen(m/s)	17.12

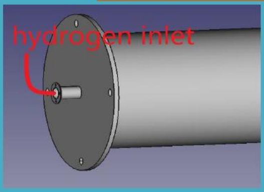
II. burner functionality :

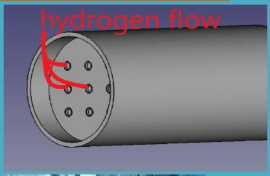
This burner is powered by oxygen and hydrogen

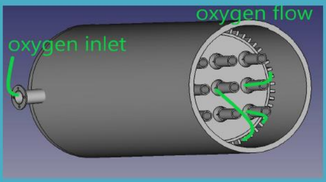


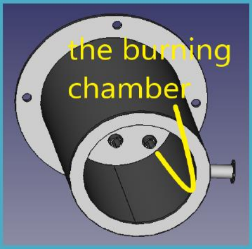




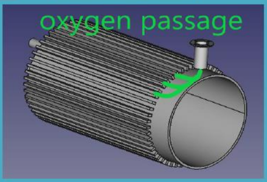








the flow of oxygen on the wall leads to its cooling



3.1.2.7 Fuel Burner Mixing Test Rig

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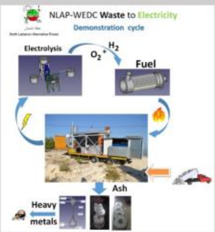
طاقة الشمال
North Lebanon Alternative Power

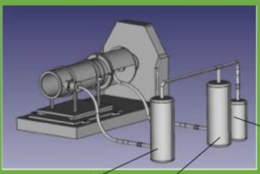
Fuel Burner Mixing Testrig

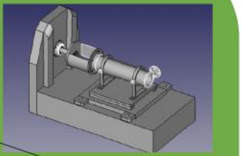
1. Introduction



To be able to operate the NLAP Waste to Electricity Demonstration Cycle by Night without incinerating municipal waste, an electrolysis unit produces by day O2 and H2. O2 is liquefied to LOX. This is the oxidizer for the fuel burner. The fuel can be liquefied Methane (liquefied waste gas from landfill) or propan gas (غاز البيوت).

2. Testrig mechanical system design



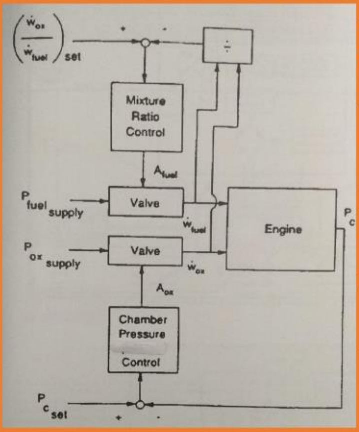


The methane and oxygen are mixed together, and from high pressure gas supply tank (He), a feed mechanism to force the the fuel and the oxidizer from the tanks into the burning chamber

Components:

- Oxidizer Tank
- Fuel Tank
- High pressure gas supply tank
- Burning chamber
- Restriction Orifice (RO) – Flow Control Instrument
- Propellant valves
- Bleed valve
- Filters
- Drain valves
- Gas fill valve
- Pressure regulator

3. Control System Design and Required Instruments



Two variables are controlled: *mixture ratio* and *chamber pressure*

Instruments needed:

Sensors:
2 Flowmeters
1 pressure sensor

Actuators:
2 Automatic valves

1 Central Control Unit

نحن نريد التحكم بنوعين من السوائل لذلك هذه الخطوة ستكون مشابهة للخطوة الأولى فهي عبارة عن تحكم بكمية السائل الذي نحتاجه سنحتاج بهذا العمل الى

- 2 relays for DC motors (automatic valves, variant 2)
- Raspberry pi
- Battery 12V
- Wires
- Flow sensors, pressure sensor

4. Hardware Realization of Mixing Control System

Flowmeter

Automatic valve with DC motor

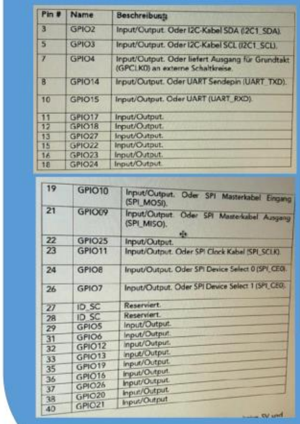
To be operated, a 12 V battery and two relais iwith H bridge are needed.

pressure sensor

Integration

Central Control Unit:
Rasberry Pi 3

Raspberry Pi 3, General Purpose I/O Pins



Pin #	Name	Beschreibung
3	GPIO2	Input/Output. Oder I2C-Kabel SDA (I2C1_SDA).
5	GPIO3	Input/Output. Oder I2C-Kabel SCL (I2C1_SCL).
7	GPIO4	Input/Output. Oder liefert Ausgang für Grundtakt (GPCLK0) an externe Schaltkreise.
8	GPIO14	Input/Output. Oder UART Sendepin (UART_TXD).
10	GPIO15	Input/Output. Oder UART (UART_RXD).
11	GPIO17	Input/Output.
12	GPIO18	Input/Output.
13	GPIO27	Input/Output.
15	GPIO22	Input/Output.
16	GPIO23	Input/Output.
18	GPIO24	Input/Output.
19	GPIO10	Input/Output. Oder SPI Masterkabel Eingang (SPI_MOSI).
21	GPIO09	Input/Output. Oder SPI Masterkabel Ausgang (SPI_MISO).
22	GPIO25	Input/Output.
23	GPIO11	Input/Output. Oder SPI Clock Kabel (SPI_SCLK).
24	GPIO8	Input/Output. Oder SPI Device Select 0 (SPI_CE0).
26	GPIO7	Input/Output. Oder SPI Device Select 1 (SPI_CE0).
27	ID_SC	Reserviert.
28	ID_SC	Reserviert.
29	GPIO5	Input/Output.
31	GPIO6	Input/Output.
32	GPIO12	Input/Output.
33	GPIO13	Input/Output.
35	GPIO19	Input/Output.
36	GPIO16	Input/Output.
37	GPIO26	Input/Output.
38	GPIO20	Input/Output.
40	GPIO21	Input/Output.

5. Control Software on Central Control Unit (python program on Raspberry Pi 3)

```
import RPi.GPIO as GPIO
import time, sys
RELAY_2_GPIO = 27
FLOW_SENSOR = 23
RELAY_1_GPIO = 17
GPIO.setmode(GPIO.BCM)
GPIO.setup(FLOW_SENSOR, GPIO.IN, pull_up_down = GPIO.PUD_UP)
GPIO.setup(RELAY_1_GPIO, GPIO.OUT) # GPIO Assign mode
GPIO.setup(RELAY_2_GPIO, GPIO.OUT)
GPIO.output(RELAY_1_GPIO, GPIO.LOW)
GPIO.output(RELAY_2_GPIO, GPIO.LOW)
global count
count = 0
def countPulse(channel):
global count
if start_counter == 1:
count = count+1
# print count
flow = count / (60 * 7.5)
# print(flow)
GPIO.add_event_detect(FLOW_SENSOR, GPIO.FALLING, callback=countPulse)
while True:
try:
start_counter = 1
time.sleep(1)
start_counter = 0
flow = (count * 60 * 2.25 / 1000)
print ("The flow is: " + str(flow) + " Liter/min" )
if flow == 0: # 0.0
GPIO.output(RELAY_1_GPIO, GPIO.LOW)
GPIO.output(RELAY_2_GPIO, GPIO.LOW)
elif flow < 15: # 1.9
GPIO.output(RELAY_1_GPIO, GPIO.LOW)
GPIO.output(RELAY_2_GPIO, GPIO.HIGH)
elif flow < 20: # 2.1
GPIO.output(RELAY_1_GPIO, GPIO.LOW)
GPIO.output(RELAY_2_GPIO, GPIO.LOW)
else:
GPIO.output(RELAY_1_GPIO, GPIO.HIGH)
GPIO.output(RELAY_2_GPIO, GPIO.LOW)
count = 0
time.sleep(5)
except KeyboardInterrupt:
print ("caught keyboard interrupt!")
GPIO.cleanup()
sys.exit()
```

For more details see *NLAP-WEDC Final Report (2012 – 2020) - Waste Incineration Electrical Power Plant Technology*

@AECENAR/ICPT June-Dec 2020 علي ابراهيم و علي عوض و د. سمير مراد

3.2 Posters of projects 23 - 25

3.2.1 Project H: Fuel Cell

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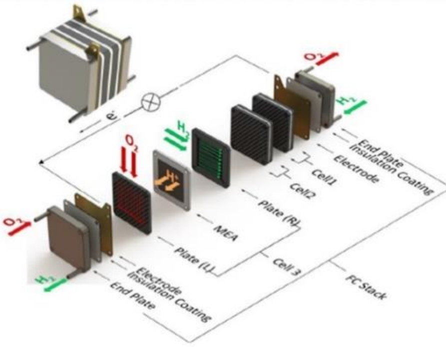
بسم الله الرحمن الرحيم

مركز أبحاث تكنولوجيا العمليات الكيميائية
Institute for Chemical Process Technology (ICPT)
http://aecenar.com/institutes/icpt

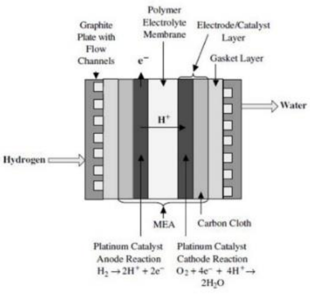
Fuel Cell system



Generalized schematic of a single fuel cell

The advantages are:
- Low emissions
- More efficient compared to a conventional internal combustion engine
- Simplicity, few if any moving parts
- Reliable and long-lasting system
- Silent

The drawbacks are:
- Lifetime
- Cost
- Hydrogen has to be produced
- Not yet available infrastructure for hydrogen



Comparison of Fuel Cell type

Fuel cell type		Anode in / out		Ion transport	Cathode out / in		Temp. [°C]
SOFC	Solid Oxide Fuel Cell	H_2 CO	CO_2 H_2O	← O^{2-}		O_2	900
MCFC	Molten Carbonate Fuel Cell	H_2 CO	CO_2 H_2O	← CO_3^{2-}		O_2 CO_2	650
PAFC	Phosphoric Acid Fuel Cell	H_2		H^+ →	H_2O gaseous	O_2	220
HT-PEMFC	High Temperature Polymer Electrolyte Membrane FC	H_2		H^+ →	H_2O gaseous	O_2	160
DMFC	Direct Methanol Fuel Cell	CH_3OH	CO_2	H^+ →	H_2O liquid	O_2	90
LT-PEMFC	Low Temperature Polymer Electrolyte Membrane FC	H_2		H^+ →	H_2O liquid	O_2	80
AFC	Alkaline Fuel Cell	H_2	H_2O	← OH^-		O_2	

Description of our prototype fuel cell system

- ***Existing electrical system***

The electrical system consists of the low voltage (12 V) DC system.

- ***Fuel cell stack***

The parameter that will be crucial for the size of the stack is the maximum power that should be delivered. As an example, a maximum power level of 1 kW is chosen.

- ***Size***

$$P = U \times I \quad \rightarrow \quad I = \frac{P}{U} = \frac{1000}{12 \cdot 18} = 4.63\ A$$

Step 1: Sizing of the fuel cell stack
The number of cells needed to deliver a specific voltage level is 18 (chosen to 0.7 V based on the voltage-current density graph). At 0.7 V the power is about its maximum value.

Step 2: Area of each cell
It can be found that the current density for 0.7 V is around 550 mA/cm².

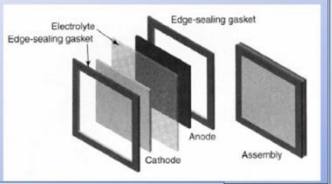
$$A = \frac{I}{J} = \frac{4.63}{0.55} = 8.42\ cm^2$$

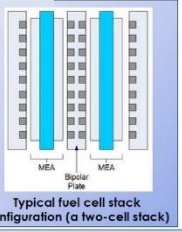
Step 3: Estimation of H2 needed per day

$$m = \frac{E\ (one\ day)}{E\ (H2)} = \frac{10}{33.3} = 0.3\ Kg$$

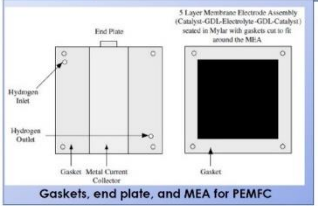
Constructing the Fuel Cell

Structure of a fuel cell with edge seals to prevent leakage of the gas at the edges of the electrodes.

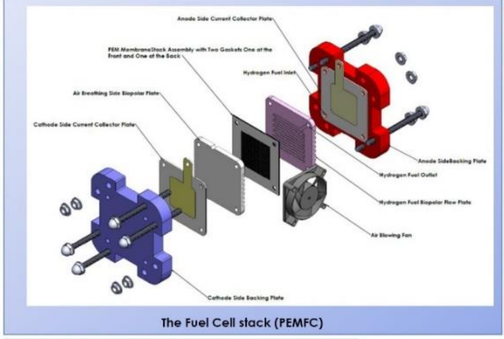




Typical fuel cell stack configuration (a two-cell stack)



Gaskets, end plate, and MEA for PEMFC

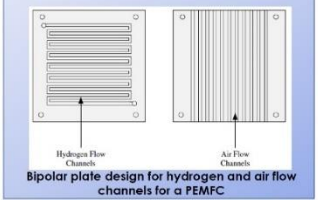


The Fuel Cell stack (PEMFC)

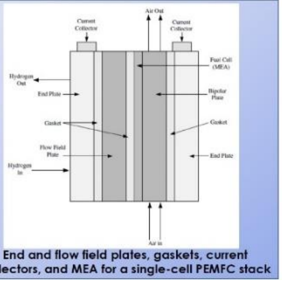
Physical characters of proton exchange membrane fuel cell (PEMFC)

Fuel cell system	Proton exchange membrane fuel cell (PEMFC)
Fuel	H_2
Oxidizer	O_2, air
Most Common Electrolyte	Perflourosulfonic acid membrane (Nafion by DuPont)
Electrolyte Thickness	~50–175 µm
Ion Transferred	H+
Most Common Anode Catalyst	Pt
Anode Catalyst Layer Thickness	~10 to 30 µm
Bipolar-Plate/Interconnect Material	Graphite, titanium, stainless steel, and doped polymers

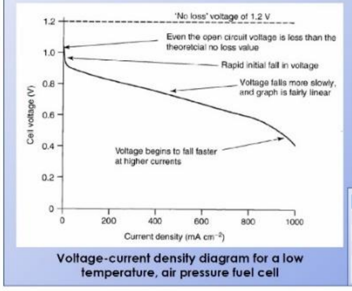
Fuel cell system	Proton exchange membrane fuel cell (PEMFC)
Operating Temperature	Room temperature to 100°C
Operating Pressure (atm)	1 to 3
Major Contaminants	CO < 100 ppm, sulfur, dust
Maximum Fuel Cell Efficiency (current)	~58%
Primary Applications	Stationary, portable, and vehicular



Bipolar plate design for hydrogen and air flow channels for a PEMFC

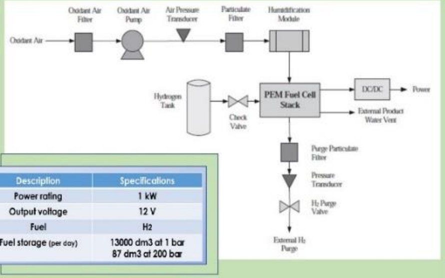


End and flow field plates, gaskets, current collectors, and MEA for a single-cell PEMFC stack



Voltage-current density diagram for a low temperature, air pressure fuel cell

Simple PEM fuel cell system



Description	Specifications
Power rating	1 kW
Output voltage	12 V
Fuel	H2
Fuel storage (per day)	13000 dm3 at 1 bar 87 dm3 at 200 bar

Maryam El REZ @AECENAR/Dec2021

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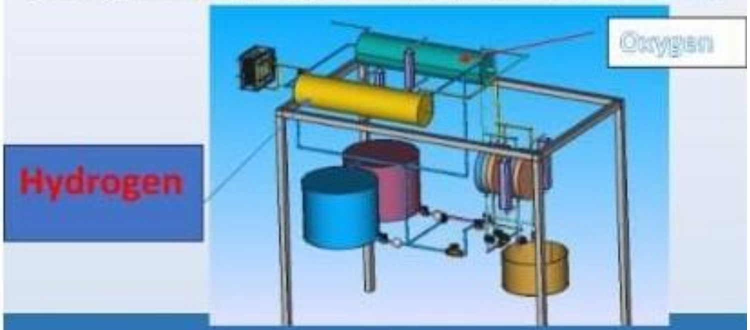
بسم الله الرحمن الرحيم

Fuel Cell & Electrolyser

.Introduction:

Electrolyzer and fuel cells are necessary for the management of hydrogen in various industrial processes as an alternative energy carrier. Electrolyzer produce hydrogen by decomposing water into oxygen and hydrogen through electrolysis. The hydrogen gas is then sent to fuel cells, which convert the chemical energy into alternating current, heat, and water, requiring a supply of fuel and oxidant in return.

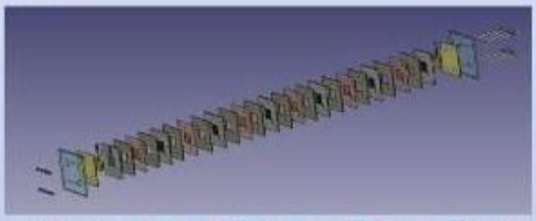
.Design- Electrolyser & Fuel Cell Free Cad.



Hydrogen from electrolysis will be used on one side and air on the other side.

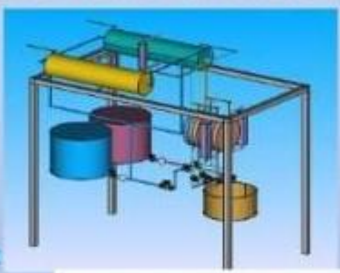
Fuel Cell realization

+



Conducting Test of Fuel Cell and measurements the cell Voltage,Power,Current,and efficiency.

Design of Electrolysis-Free CAD



Design of fuel Cell Free CAD

Simulation of Fuel Cell and carry out measurements under different conditions (temperature ,pressure, gas flow)

Fuel Cell Propulsion System for Automobiles incl. Balance-of-Plant

Photos of electrolysis

Graphite plates for the Fuel Cell

MEA plate

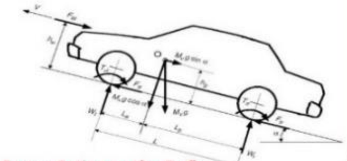
June 2024 ***Razan Youssef Kaddour.***

Vehicle Dynamics MATLAB Simulation

Vehicle Dynamics

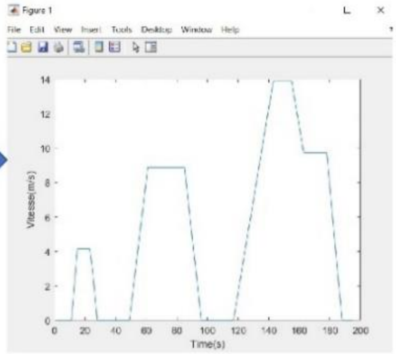
The purpose of this series of practical exercises in "Electric Transmission and Hybrid Motorization" is to develop a model of a hybrid vehicle using batteries and a fuel cell as the energy source , using Matlab/Simulink software.

"To create the speed versus time plot in MATLAB Simulink for a vehicle, enter the time and speed values into MATLAB."



Forces Acting on the Car"

```
t=City(:,1) %time [s]
V=City(:,2) %Vitesse [m/s]
simtemps=length(t)-1;
plot(t,V)
xlabel('time',(s))
ylabel ('Vitesse',(m/s))
```



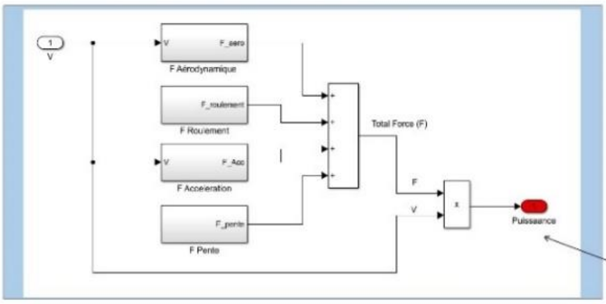
·CALCULATE THE FORCE AND THE POWER·

$$F = F\_aerodynamic + F\_rolling + F\_acceleration + F\_slope$$

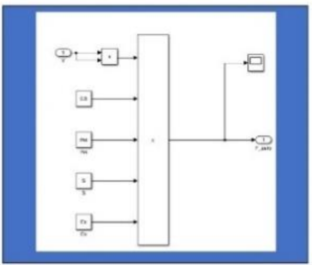
$$=(0{,}5.\rho.s.Cx.V2) + (mv.g.\mu) + (mv.a) + mv.g.\sin\alpha$$

THE STRUCTURE OF THE COMPLETE MODEL 'POWER CALCULATION'"

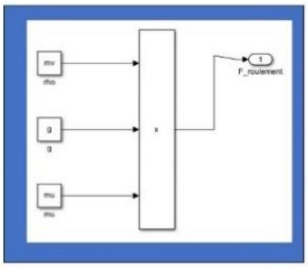
Model in MATLAB Simulink



Force aerodynamic in MATLAB Simulink

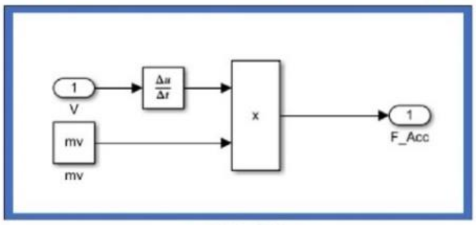


Force rolling in MATLAB Simulink

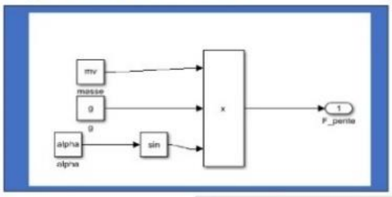


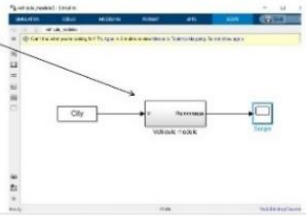
Vehicle model in MATLAB Simulink

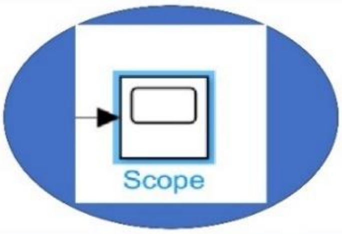
Force acceleration in MATLAB Simulink

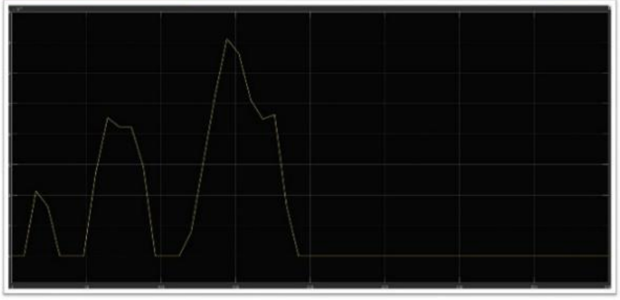


Force slope in MATLAB Simulink









@AECENAR/July 2024 *Razan Youssef Kaddour*

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Institute for Chemical Process Technology (ICPT)
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الجامعة اللبنانية
كلية العلوم

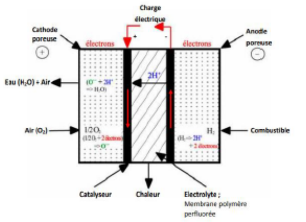
Fuel Cell System Simulation in Electric vehicle

Problem

The limitation of resources and climate change caused by polluting vehicles that release a large amount of CO_2 impose a change in the mode of personal transportation. Therefore, hybrid electric vehicle technologies are considered as one of the most favorable solutions to face the environmental and energy problems caused by the automobile industry.

Objective

The objective of this study is to determine the mass of hydrogen, m_{H2}, needed to operate a vehicle during a driving cycle. We will need to use the vehicle dynamics Simulink model and extract the power and the power required by the fuel cell. The transmission efficiency is 80%. We are implementing a fuel cell in an electric vehicle.



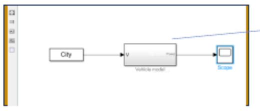
Fuel cell unit

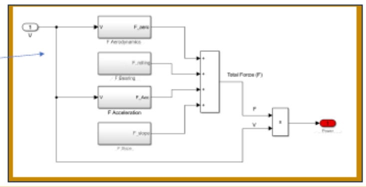
A fuel cell is a potentially clean energy source because it only produces water and consumes hydrogen gas (H_2). However, whether the system is considered clean depends on how the hydrogen is produced. The production process is very expensive due to the large quantities of platinum required and the complexities of its synthesis. Additionally, hydrogen must be compressed into gas cylinders at pressures between 350 and 700 bars, liquefied, or chemically produced onboard from methanol or methane.

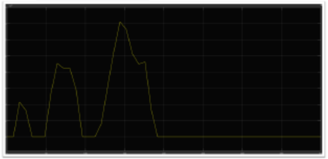
Characteristic of electric vehicle

F = F_aerodynamic + F_rolling + F_acceleration + F_slope $=(0{,}5.\rho.s.C_x.V^2) + (m_v.g.\mu) + (m_v.a) + m_v.g.\sin\alpha$

P=FxV







Vehicle Power

Modelling of fuel cell

1) Current of fuel cell [A]:

$$I_{fc} = \frac{P_{fc}}{V_{fc}}$$

2) Voltage of fuel cell [V]:

Vc (voltage of cells) $=1.031-2.45\times10^{-4}\times j - 0.03\ln(j+3)-2.11\times10^{-5}e^{(8\times10-3j)}$

J (current density mA/cm²) $= \frac{I_{fc}}{S_{fc}}$;

S_{fc} (surface of cell = 480cm²)

n_c (number of cells = 180)

$V_{fc} = V_c \times n_c$

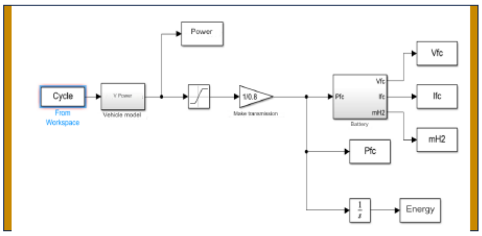
3) Mass of H_2 [kg]

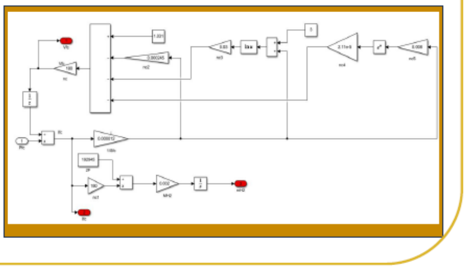
$m_{H2} = \int n_{H2} * MH_2\, dt$

M_{H2}= molar mass of dihydrogen=2*10⁻³[kg/mol]

n_{H2}= molar flow rate[mol/s]

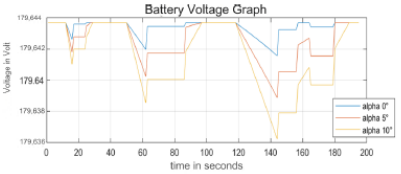
Model of fuel cell in MATLAB Simulink

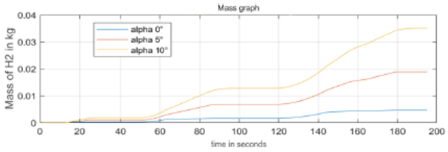


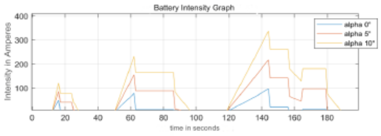


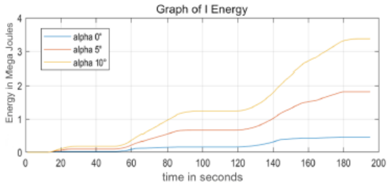
Results of simulation

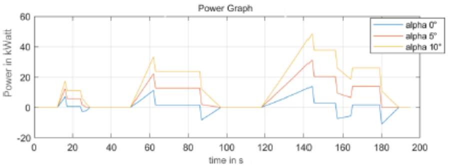
We simulate the following parameters at different angles alpha 0°, 5°, 10°

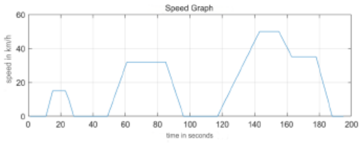












Conclusion

The simulation shows that the voltage of the fuel cell decreases with time for different α values and provides valuable insights into system performance and management under various configurations. The consumption of H_2 during one cycle is 0.036 kg for $\alpha = 10°$ and its deceases when α decreases. The fuel cell solution seems to be an excellent solution because consumption is not very high, however, it is necessary to compress the dihydrogen to store it.

@AECENAR/August 2024 Razan Youssef Kaddour

3.2.2 Ammonia production project

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بسم الله الرحمن الرحيم

Laboratory name: AECENAR
Laboratory website: www.aecenar.com
Location: Ras Masqat/Tripoli

Hydrogen Storage device
ICPT-AP

Supervisor: - Dr. Berna Hamad
- Dr. Samir Mourad
Presented by: Ghayth Ali
Department of Petroleum Chemistry

Title: Ammonia production System Using Solid Electrolyze

Introduction:

Solid electrolytes are materials that allow ionic conduction but not electronic conduction. They are characterized by the type of conducting ion (eg: proton (H+), oxygen (O2-)).They have potential applications in gas separation, chemical sensing, fuel cells, batteries, ammonia synthesis and decomposition.

Principle:

Electrolysis is a method that allows chemical reactions to be carried out using an electric current. It consists of passing a direct current through an electrolytic cell, composed of two electrodes in the sides of the electrolyte (Dielectric material).

- The formation of Ammonia requires a reaction between Hydrogen (H_2) and Nitrogen (N_2) which have the following Chemical equation:

Anode: $3H_2 \longrightarrow 6H^+ + 6e^-$
Cathode: $N_2 + 6H^+ + 6e^- \longrightarrow 2NH_3$

Overall : $3H_2(g) + N_2(g) \longleftrightarrow 2NH_3(l) + \Delta H \quad (\Delta H < 0)$

- The double arrow ($\leftrightarrow$) indicates that this reaction is reversible. Which means that the ammonia produced can decompose back into nitrogen and hydrogen.
- The symbol $\Delta H < 0$ indicates that the reaction is exothermic (releases heat).

Figure 1 shows a schematic of electrolyze, that the unite responsible for the ammonia reaction. It contains an ion exchange membrane which allows the passage of protons to react with N_2.

Factors influencing electrolysis:
- The electrolyte material
- The Electrode material
- Temperature during the process

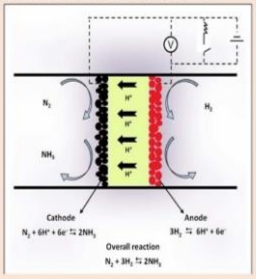

Figure 1

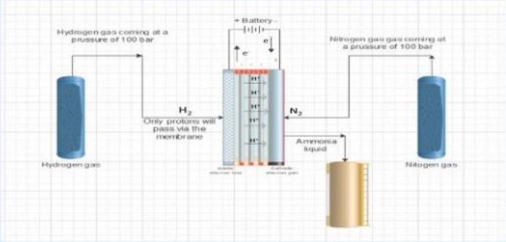

Figure 2

Material properties to be considered:

- Electrolyte properties:
- A material of high proton conductivity as polymers.
- Polymer electrolytes allow the synthesis of ammonia at low temperature and atmospheric pressure.
- They have advantages over high temperature electrolytes (HTPC) in avoiding ammonia decomposition.
- Reducing thickness of the electrolyte decrease operating temperature, manufacturing cost while increasing its life span.

The table below shows types of polymer electrolytes with there proton conductivity at a specific temperature in (C^0)

Proton Conductor	Electrolytic Cell	Temperature (°C)	NH_3 Formation rate (mol s^{-1} cm^{-2})
Nafion	H_2O, Pt |Nafion| Ru, N_2, NH_3	90	2.12×10^{-11}
Nafion	H_2, Ni-SDC |Nafion| SFCN, N_2, NH_3	80	1.13×10^{-8}
SPSF	H_2, Ni-SDC |Nafion| SSCO, N_2, NH_3	80	6.5×10^{-9}
Nafion	H_2, Ni-SDC |Nafion| SSN, N_2, NH_3	80	1.05×10^{-8}
Nafion	H_2, Ni-SDC |Nafion| SSC, N_2, NH_3	80	0.98×10^{-8}
Nafion	H_2, Ni-SDC |Nafion| SSF, N_2, NH_3	80	0.92×10^{-8}
Nafion	H_2, Ni-SDC |Nafion| SSN, N_2, NH_3	80	1.05×10^{-8}
SPSF	H_2, Ni-SDC | SPSF | SSN, N_2, NH_3	80	1.03×10^{-8}
Nafion	H_2, Ni-SDC |Nafion| SBCF, N_2, NH_3	80	7.0×10^{-9}
Nafion	H_2, Ni-SDC |Nafion| SBCC, N_2, NH_3	80	7.5×10^{-9}
Nafion	H_2, Ni-SDC |Nafion| SBCN, N_2, NH_3	80	8.7×10^{-9}

Figure 3

- Electrode properties:
- Depending on the type of electrode, the rate of ammonia production can be increased.
- Both electrodes must be stable at the operating temperature and have suitable porosity and pore size to improve the catalyst surface area and enhance the catalytic activity.
- Certain electrodes can act as catalysts, accelerating NH_3 reactions occurring on their surface.
- The electrodes must not react with H^+ or NH_3.

- Potential difference across the electrodes:
- Minimum voltage difference: There is a voltage limit below which ammonia production is impossible.
- **$\Delta G_R^0 = -nFE^0$**
  equation used to calculate the minimum voltage used to produce NH_3.
  $\Delta G°r$: Change in Gibbs free energy for the reaction
  F: Faraday constant
  n: Number of electrons
  E^0: Standard electromotive force
- Effect of applied potential: Increasing the potential to a certain point increases the rate of ammonia production.

Figures 4 and 5 shows the 3D design of the Solid electrolyze using FreeCAD program.

The Voltage of the battery is equal to 2V.
And the current density = 5.97 mA

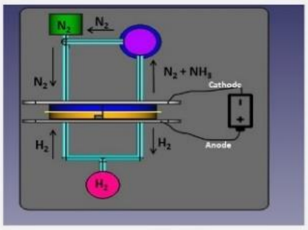

Figure 4

The Area of electrodes = 132.73 cm^2
The solid electrolyte is Nafion.
The operating temperature of the system is 80 °C.

Cathode used $SmFe_{0.7}Cu_{0.1}Ni_{0.2}$
Anode used is $NiCe_{0.8}Sm_{0.2}$

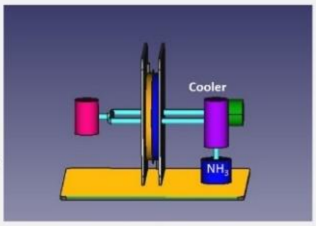

Figure 5

@AECENAR/ June 2024

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TECDA
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مركز أبحاث تكنولوجيا العمليات الكيميائية
Institute for Chemical Process Technology (ICPT)
http://aecenar.com/institutes/icpt

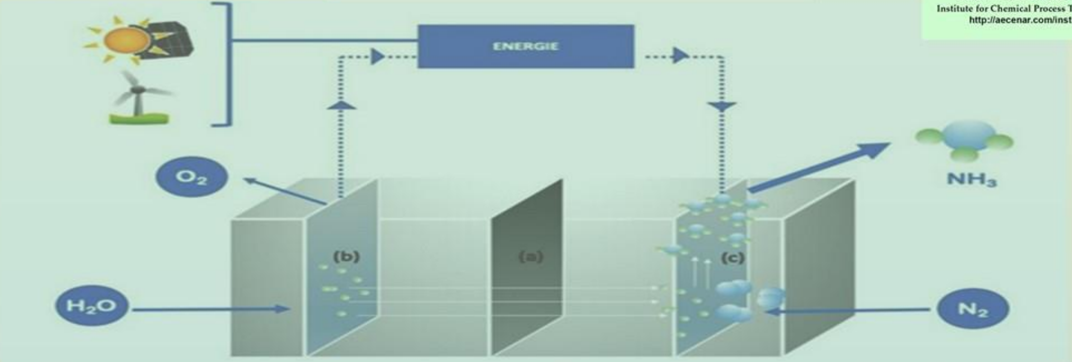


Figure : Alternative ammonia production at low T° and pressure in an electrolysis unit powered by renewable energy. (a) = separation membrane; (b) = anode; (c) = cathode. The dotted arrows indicate the path of the electrons within the device.

Anode Preparation

Chemical Formula: Ni-Ce0.8Sm0.2
Volume of the anode (disc shape):
Radius = 6.5 cm **Height** = 0.1 cm or more
V = π r²h = π*6.52*0.1 = 13.273 cm3 = 13273 mm3
Total volume for 100g mass of this alloy = 13.53 cm3
ρ = 100/13,53 = 7.391 g/cm3
M1 = ρ V = 7.391*13.273 = 98.100743 g

Metal	Melting point (°C)	Density (g/cm^3)
Nickel	1455	8.902
Cerium	795	6.76
Samarium	1072	7.52

Metal	Mass (g)	%W	N° of moles	Xi
Nickel	286	30.33	4.873	0.5134
Cerium	510	54.08	3.640	0.3835
Samarium	147	15.59	0.978	0.1030
Alloy	943	100	9.491	1

Ni-Ce0.8Sm0.2

Nickel (58.5g)

Cerium (510g)

Samarium (147g)

Cathode Preparation

Chemical Formula: SmFe0.7Cu0.1Ni0.2
Volume of the anode (disc shape):
Radius = 6.5 cm **Height** = 0.1 cm or more
V = π r2h = π*6.52*0.1 = 13.273 cm3 = 13273 mm3
Total volume for 100g mass of this alloy = 13.01 cm3
ρ = 100/13.01 = 7.69 g/cm3
M2 = ρ V = 7.69*13.273 = 102.06937 g

Metal	Melting point (°C)	Density (g/cm^3)
Samarium	1072	7.52
Iron	1538	7.874
Copper	1538	8.96
Nickel	1455	8.902

Metal	Mass (g)	%W	N° of moles	Xi
Samarium	147	15.59	0.978	0.1030
Iron	192	18.78	3.4381	0.35
Copper	31.5	3.08	0.5	0.05
Nickel	286	30.33	4.873	0.5134
Alloy	1022.29	100	9.8537	1

Samarium (740g)

Copper (31.5g)

Nickel(286g)

Alloy producing stages :

1)Melting nickel with a torch
2)After dissolving the nickel well, add the remaining iron to the melted nickel to incorporate it.

Melting metal

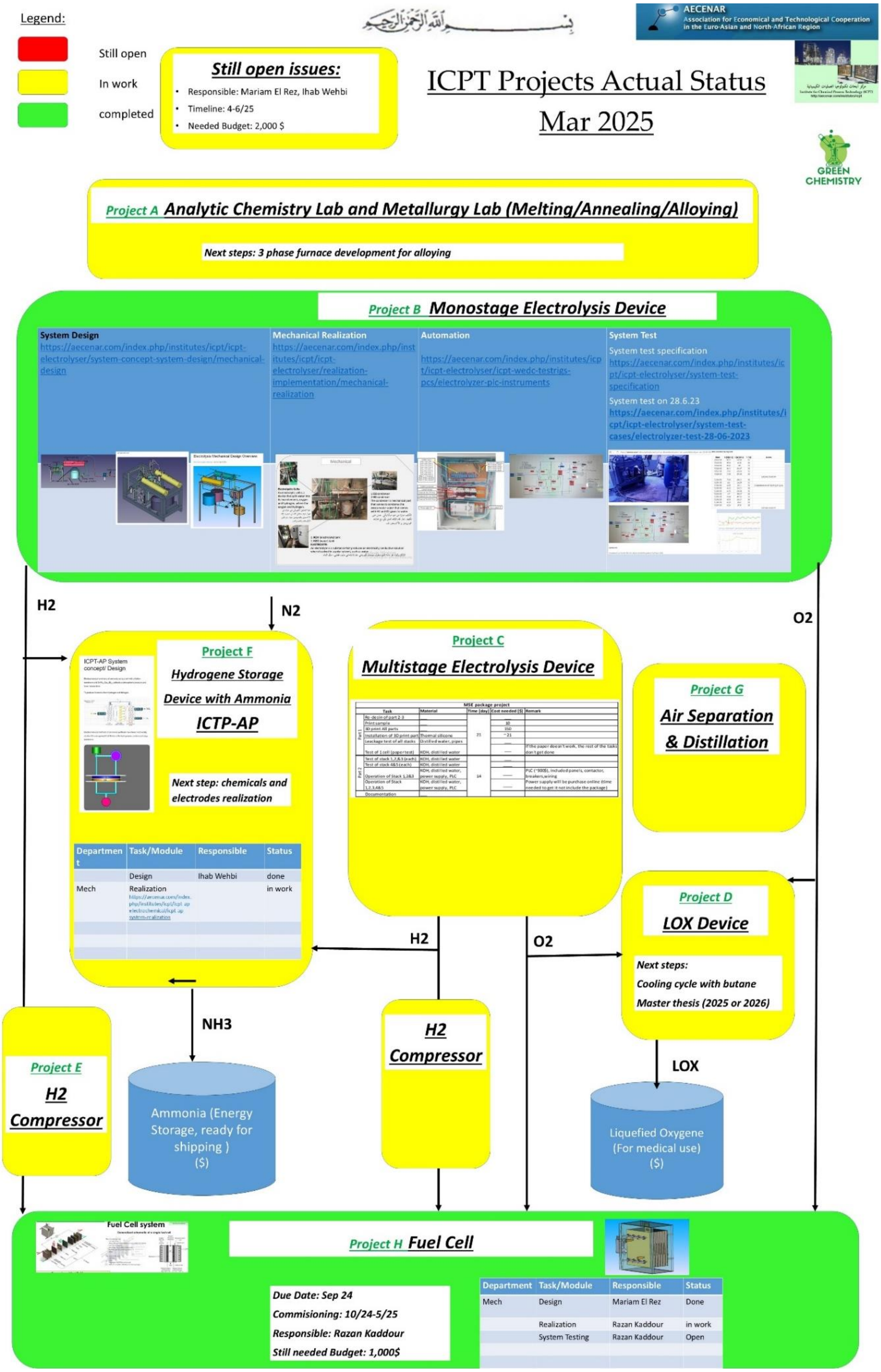
Pouring molten metal

Alloy

Oussama Mostapha Al Dahabi

@AECENAR_ICPT_AP 20/Aug/2024

3.3 Actual Status of Projects in Apr 2025



Legend:

- 🟥 Still open
- 🟨 In work
- 🟩 completed

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GREEN CHEMISTRY

Still open issues:

- Responsible: Mariam El Rez, Ihab Wehbi
- Timeline: 4-6/25
- Needed Budget: 2,000 $

ICPT Projects Actual Status Mar 2025

Project A Analytic Chemistry Lab and Metallurgy Lab (Melting/Annealing/Alloying)

Next steps: 3 phase furnace development for alloying

Project B Monostage Electrolysis Device

System Design	Mechanical Realization	Automation	System Test
https://aecenar.com/index.php/institutes/icpt/icpt-electrolyser/system-concept-system-design/mechanical-design	https://aecenar.com/index.php/institutes/icpt/icpt-electrolyser/realization-implementation/mechanical-realization	https://aecenar.com/index.php/institutes/icpt/icpt-electrolyser/icpt-wedc-testrigs-pcs/electrolyzer-plc-instruments	System test specification https://aecenar.com/index.php/institutes/icpt/icpt-electrolyser/system-test-specification System test on 28.6.23 https://aecenar.com/index.php/institutes/icpt/icpt-electrolyser/system-test-cases/electrolyzer-test-28-06-2023

Project F

Hydrogene Storage Device with Ammonia

ICTP-AP

ICPT-AP System concept/ Design

Next step: chemicals and electrodes realization

Department	Task/Module	Responsible	Status
	Design	Ihab Wehbi	done
Mech	Realization https://aecenar.com/index.php/institutes/icpt/icpt-ap-electrochemical/icpt-ap-system-realization		in work

Project C

Multistage Electrolysis Device

MSE package project

	Task	Material	Time (day)	Cost needed ($)	Remark
Part 1	Re-desin of part 2-3	—	21	—	
	Print sample	—		10	
	3D print All parts	—		150	
	Installation of 3D print part	Thermal silicone		~21	
	Leackage test of all stacks	Distilled water, pipes		—	
	Test of 1 cell (paper test)	KOH, distilled water		—	If the paper doesn't work, the rest of the tasks don't get done
Part 2	Test of stack 1,2,&3 (each)	KOH, distilled water	14	—	
	Test of stack 4&5 (each)	KOH, distilled water		—	
	Operation of Stack 1,2&3	KOH, distilled water, power supply, PLC		—	PLC (~300$), included panels, contactor, breakers,wiring
	Operation of Stack 1,2,3,4&5	KOH, distilled water, power supply, PLC		—	Power supply will be purchase online (time needed to get it not include the package)
	Documentation	—			

Project G

Air Separation & Distillation

Project D

LOX Device

Next steps:

Cooling cycle with butane

Master thesis (2025 or 2026)

Project E

H2 Compressor

H2 Compressor

Ammonia (Energy Storage, ready for shipping) ($)

Liquefied Oxygene (For medical use) ($)

Project H Fuel Cell

Fuel Cell system

Due Date: Sep 24

Commisioning: 10/24-5/25

Responsible: Razan Kaddour

Still needed Budget: 1,000$

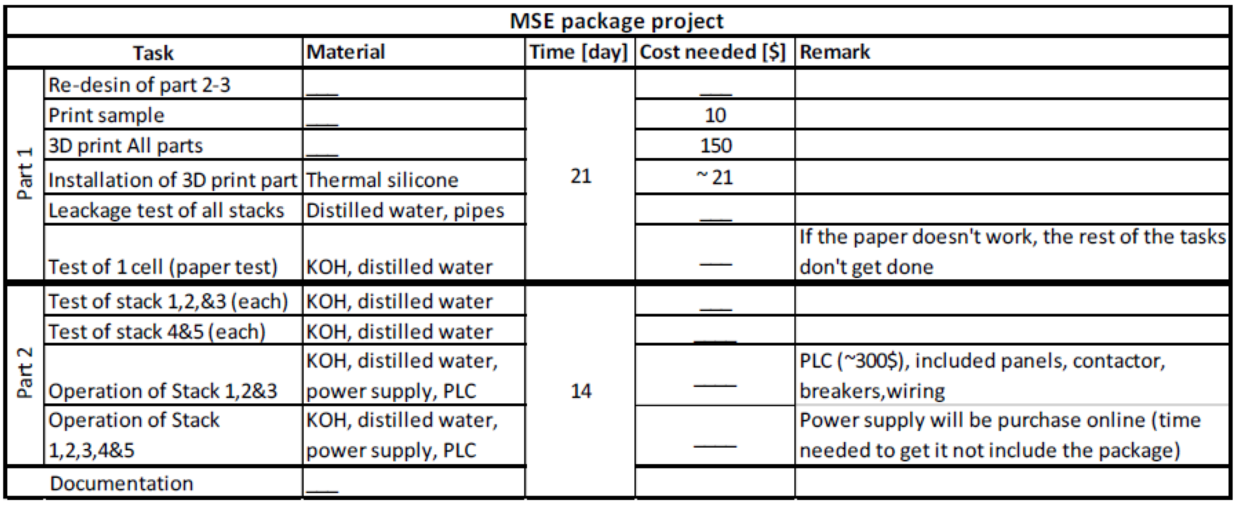
Department	Task/Module	Responsible	Status
Mech	Design	Mariam El Rez	Done
	Realization	Razan Kaddour	in work
	System Testing	Razan Kaddour	Open

Summary

3.4 Next TODO

Offer to AECENAR:

Multistage project package



MSE package project					
	Task	Material	Time [day]	Cost needed [$]	Remark
Part 1	Re-desin of part 2-3	___	21	___	
	Print sample	___		10	
	3D print All parts	___		150	
	Installation of 3D print part	Thermal silicone		~ 21	
	Leackage test of all stacks	Distilled water, pipes		___	
	Test of 1 cell (paper test)	KOH, distilled water		——	If the paper doesn't work, the rest of the tasks don't get done
Part 2	Test of stack 1,2,&3 (each)	KOH, distilled water	14	___	
	Test of stack 4&5 (each)	KOH, distilled water		___	
	Operation of Stack 1,2&3	KOH, distilled water, power supply, PLC		——	PLC (~300$), included panels, contactor, breakers,wiring
	Operation of Stack 1,2,3,4&5	KOH, distilled water, power supply, PLC		——	Power supply will be purchase online (time needed to get it not include the package)
	Documentation	___			

Status: In the opinion of AECENAR responsible staff the packages should not take 21+14 = 35 person days, but max. (4 days + 4 days)*2 persons = 16 person days

4 Project A: Analytical Chemistry Lab and Metallurgical Lab

4.1 Analytical Chemistry Lab

4.2 Metallurgical Lab

4.2.1 Position of Metallurgical Lab project

This project was designed to serve several projects under implementation or proposed. It is an implementation project that aims to form multiple types of mineral mixtures, where the type and quantity (percentage) of minerals combined with each other varies. Work on this project began this year (2022), and work on it will be completed when needed.

4.2.2 Iron melting Test

- Video 1:

WhatsApp Video
2022-12-24 at 14.03.

- Video 2:

WhatsApp Video
2022-12-24 at 14.04.

4.2.3 Metallurgical test 2 _ 31.01.2023

4.2.3.1 Melting System Test Specification

- **<u>Pre-Starting</u>**

Please read these instructions thoroughly. This will make sure you obtain full safe use, Keep this instruction manual in a handy place for future reference.

- **<u>Safety precaution</u>**

Wear the thermal gloves

Wear the face shield

Keep a safe distance (1m_1.5m)

- **Caution**

- Never leave a hot graphite crucible with metal liquid cooling in the machine naturally, otherwise it will damage the machine. grab the crucible out immediately when the melting is finished.
- Anytime when the water circulation is stopped or fails if the crucible is hot and stays in the coil. Ensure it immediately leaves the coil, otherwise, the coil will be damaged.
- This melting furnace must use ceramic and graphite crucible together. other kinds and shapes crucible alone must use both or the coil might be damaged.
- Turn off the working switch before pouring the liquid metal.
- After completion of smelting, turn off the operating switch on the melting furnace. Keep the water cycle cooling system running for more than 20 seconds, then turn off the power switch on the melting furnace and water chiller.
- When using the machine with a pump (without a chiller) for cooling, do not reuse the outlet hot water, need to change new water whenever one crucible melting finishes.

4.2.3.2 Test 002: 31012023_ Iron melting – Test steps

Step	Step Description	Expected Result
Precondition	System is Off	
Switch on the system	Turn on the heating switch	System is On
Heating of the melting pot	Heating should be in three stages: - Low heat for three minutes (500 °C), - Double heat for 5 minutes (1000°C), - Melting heat for 2 minutes (1600° C)	Melting pot is ready

Put the iron pieces	The heat must be reduced before putting the pieces and reheated after putting the pieces	The iron is melting
Switch off the system	Turn off the heating switch	System is off
Postcondition	System is Off	

4.2.3.3 Operation steps

1. Starting: 1: 55 pm
2. Heating stage 1: 1600 watts for 3 min
3. Heating stage 2: 3000 watts for 5 min

4. Heating stage 3: 5000 watts for 2 min
5. Putting the pieces 500 g of iron within 10 min
6. Melting iron within 10 min
7. Cooling of system within 10 min
8. Switch off the system

4.2.3.4 Result

- The Iron melted within 10 min.

4.2.3.5 Analysis of the test results

The reason we couldn't get the desired disc shape was the use of an unsuitable sand shape.

4.2.3.6 What we have to do:

Repeat the experiment using a refractory sand mold.

4.2.4 Metallurgical Test 003: 11022023_ iron melting

Step	Step Description	Expected Result	result
Precondition	System is Off		
Switch on the system	Turn on the heating switch	System is on	positive
Heating of the melting pot	Heating should be in three stages: - Low heat for three minutes (500°C), - Double heat for 5 minutes (1000°C), - Melting heat for 2 minutes (1600°C)	Melting pot is ready	positive
Put the iron pieces	The heat must be reduced before putting the pieces and reheated after putting the pieces	The iron is melting	positive
Switch off the system	Turn off the heating switch	System is off	positive
Postcondition	System is Off		positive

4.2.4.1 Operating steps

Sand operation steps:

1. Sand purification
2. Put the sand in an iron pot
3. Pour a little water on the sand (helps create the sand shape)
4. Create the sand shape
5. Heating the sand in three stages to dry it and conserve shape

Iron preparation steps:

1. Cutting iron (30*60)
2. The weight of the iron
3. Heating iron (low degree)

Iron melting operation steps

1. Starting: 1: 32 pm
2. Heating stage 1: 1600 watts for 3 min

3. Heating stage 2: 3000 watts for 5 min

4. Heating stage 3: 5000 watts for 2 min

5. Putting the pieces 650 g of iron within 10 min

6. Melting iron within 10 min

7. Cooling of system within 10 min
8. Switch off the system

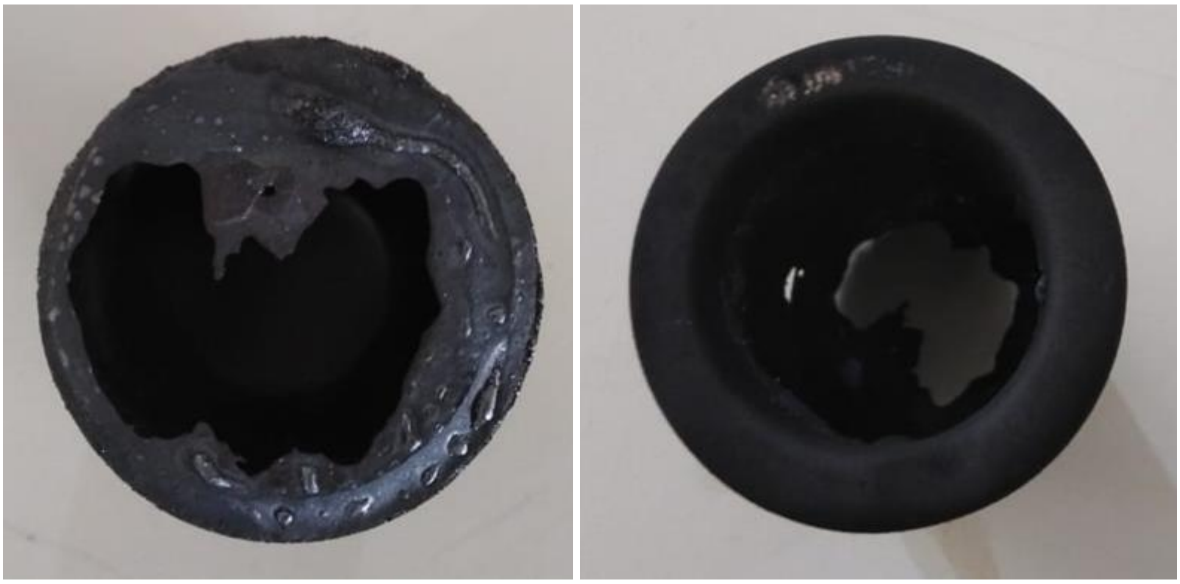
1.1.1. Result

Obtain a piece of iron that has the same shape as the sand and pure

---

A piece has some holes and voids

Corrosion of graphite crucible



4.2.4.2 Analysis of the test results

- The reason for piece holes and voids is to let the melting iron in the shape without pressure
- We get a graphite crucible corrosion because this crucible is not intended for melting iron

1.1.2. What we have to do

- Use a crucible for melting iron
- Manufacturing of a piston to press the melting iron in the sand shape

4.2.5 Metallurgical test 4_09092024

There was another test on September 9, 2024, and here are some pictures related to the test:

The steps we followed:

1. First, we mixed the soil and broke the larger parts.

2. We added water to the soil and mixed it well.
3. We placed the mixture into a mold to take the desired shape.

4. We dried the Soil Mold to remove the Moisture.

5. We placed the clay core pot and the lead pot with the Iron parts to melt them


1600

6. The problem occurred when we added too much iron into the pot, and the amount was more than necessary.

7. The iron expanded excessively due to this excess amount and resulting heat.

8. As a result, the clay pot exploded due to the pressure from the excessive expansion.

It’s essential to measure the right amount of iron, ensuring it fits within the lead pot. If the amount exceeds the capacity, the pressure and heat will cause expansion and explosion. and we should ensure that the lead pot can accommodate the molten iron, without exceeding its capacity. And another solution is that if larger amounts of iron are needed, consider using a pot with greater durability to withstand thermal stress.

Video of the Metallurgical test:

Metallurgical test
4_09092024.mp4

4.2.6 What‘s next

4.2.6.1 Development of prototype of a electrical furnace for making alloys:

Electric Arc Furnace for making alloys

ELECTRIC ARC STEEL MAKING

The electric arc furnace (EAF) has historically been used for high-grade steels and scrap melting, but it is growing in use for ordinary grades. It is an integral part of the 'mini-mill' steel making process consisting of an EAF along with a continuous caster to provide a small, low capital cost steel mill utilising abundant, inexpensive steel scrap. Today, mini-mills can produce over 80 per cent of all steel products. The electric arc furnace is also usually used to refine high alloy steels, such as stainless steels.

The electric arc furnace is illustrated in Figure 1-4 and is from 25 to more than 150 tonnes capacity. The charge can be of scrap of the required final composition although carbon is usually lost during the carbon boil. The carbon electrodes in the roof strike an arc directly with the metal to melt it. Reducing conditions allow for removal of sulphur in the slag, and alloying elements such as nickel, chromium, manganese, vanadium etc. can be added and will not be lost through oxidation. Oxygen can be blown into the furnace to purify the steel, and lime and fluorspar added to combine with impurities to form slag. At the end of the process, the furnace is tilted, first to pour off the slag, and then in the opposite direction where the molten steel is tapped into a ladle.

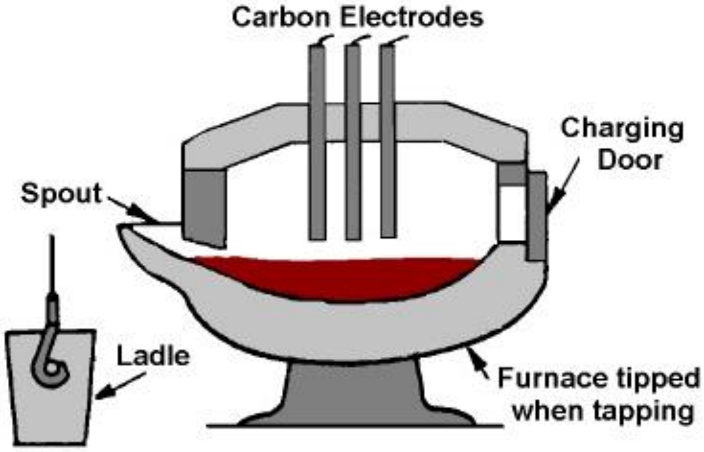
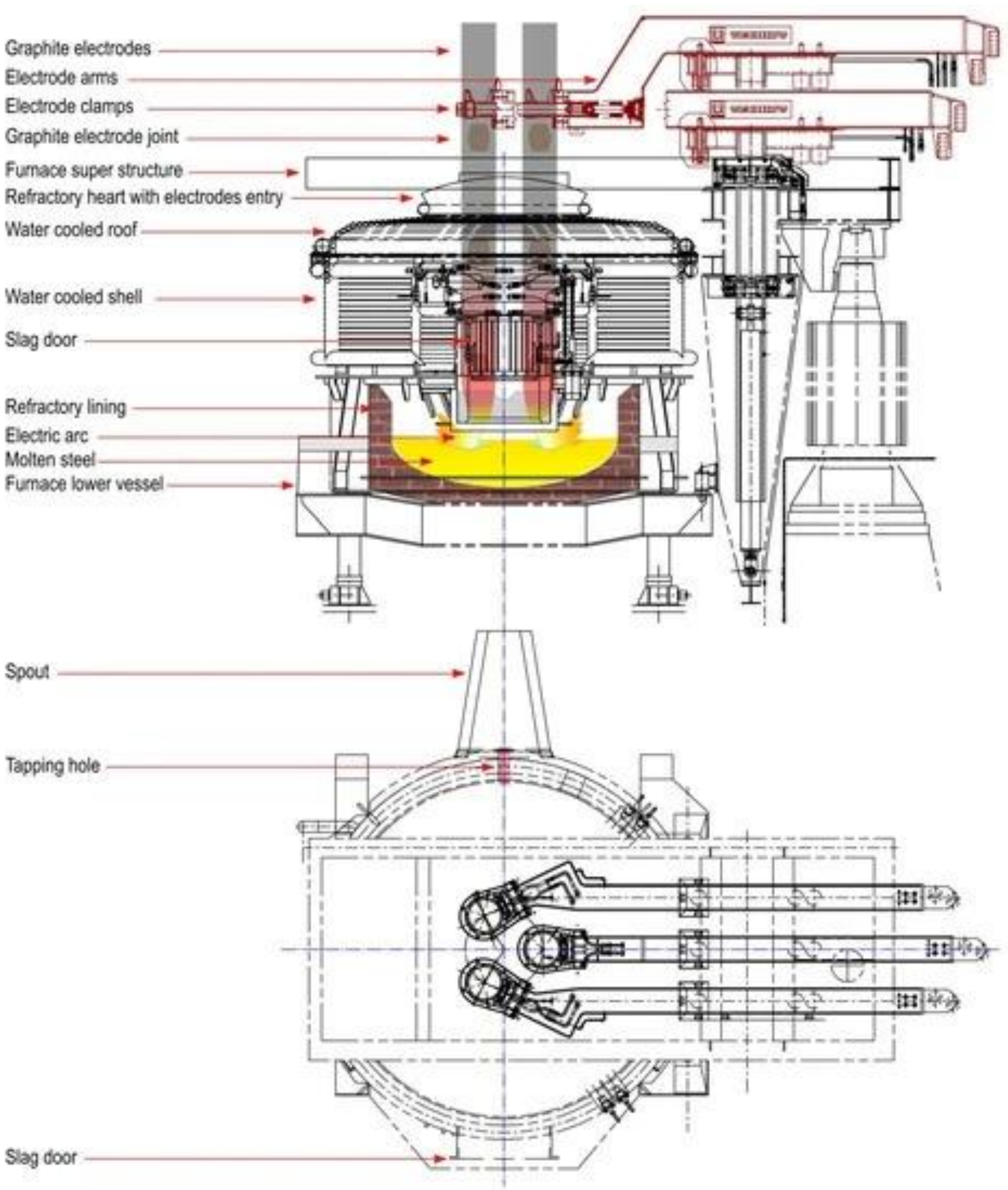
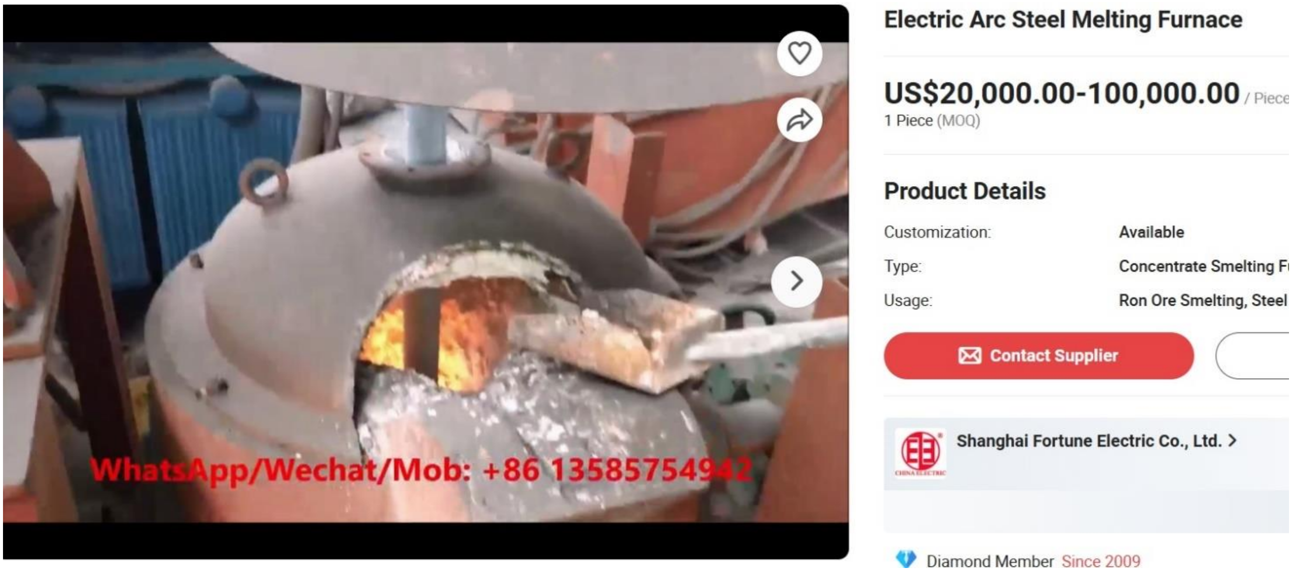


Figure 1-4: Electric arc furnace.

The efficiency of electric arc steel making has been substantially improved in recent years. As well as adopting oxygen injection, oxy fuel burners, coal powder injection, high-power transformers, preheating scrap and new systems of cooling and protecting furnace walls have been introduced, enabling production efficiency increases from 80 to 120 tonnes per hour.


Graphite electrodes
Electrode arms
Electrode clamps
Graphite electrode joint
Furnace super structure
Refractory heart with electrodes entry
Water cooled roof
Water cooled shell
Slag door
Refractory lining
Electric arc
Molten steel
Furnace lower vessel
Spout
Tapping hole
Slag door



Electric Arc Steel Melting Furnace

US$20,000.00-100,000.00 / Piece
1 Piece (MOQ)

Product Details

Customization:	Available
Type:	Concentrate Smelting F
Usage:	Ron Ore Smelting, Steel

Shanghai Fortune Electric Co., Ltd. >

Diamond Member Since 2009

From: [Electric Arc Steel Melting Furnace - Eaf and Electric Arc Furnace (made-in-china.com)]()

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5 Project B 21: Monostage Water Electrolysis (ICPT-WE)

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POSTER 2

Electrolyser

Introduction

The use of electric energy varies from time to time according to our needs for it. In the morning, when most institutions, laboratories and factories are working, this leads to great pressure on electric power plants that exceeds the natural expenditure of energy as is the case at night or in the afternoon, and here lies the role of the electrolyser , which works as an assistant to power stations Energy by producing hydrogen, which is used in fuel cell in cases of excessive drainage.

إن إستخدام الطاقة الكهربائية يتفاوت بين حين وآخر حسب إحتياجاتنا لها ،ف في الصباح حيث معظم المؤسسات والمعامل والمصانع تعمل فهذا يؤدي لضغط كبير على محطات توليد الطاقة الكهربائية يَتَعَدى المصروف الطبيعي للطاقة كما الحال في الليل أو بعد الظهيرة، وهنا يكمن دور الإلكترولايزر الذي يعمل كمساعد لمحطات الطاقة بإنتاجه الهيدروجين الذي يستخدم كوقود حراري في حالات الصرف الزائد.

ELECTROLYSER:
Electrolyser is a system that uses electricity to separate water into hydrogen and oxygen in a process called electrolysis.
ELECTROLYSIS:
Electrolysis is a method that uses water H2O to produce Hydrogen H2 and Oxygen O2. The electrolysis system consists of several cells attached to the H2 and O2 storage units. The Hydrogen and Oxygen are stored in containers after passing through the condenser to remove the excess water.

تعريف :
الإلكتروليزر :
'الإلكتروليزر' او المحلّل الكهربائي هو نظام يستخدم الكهرباء لتقسيم الماء إلى "هيدروجين"و"أكسجين" ضمن عمليّة تسمّى 'الإلكتروليزيس' أو التحليل الكهربائي.
الإلكتروليزيس :
'الإلكتروليزيس' او التّحليل الكهربائي هو طريقة تستعمل الماء كمادّة خام لإنتاج ال "الهيدروجين" و "الأكسجين" يتألف نظام التحليل الكهربائي من عدّة خلايا موصولين بوحدات تخزين ال"هيدروجين" و ال"أكسجين"
يُخزّن كلٌّ من ال"اكسجين"و ال"هيدروجين" ضمن مستوعبات بعد مرور بمكثّف للتخلص من الماء الزّائد.

Mechanical

Electrolyctic Cells:
An electrolytic cell is a device that split water into its two elements, oxygen and hydrogen, where the oxygen and hydrogen.

خلية التحليل الكهربائي هي عبارة عن جهاز يقوم بتحليل الماء الي عنصريه وهما الأكسجين والهيدروجين حيث يتم تخزين الاوكسجين والهيدروجين.

1:**O2** condenser
2:**H2** condenser
The condenser is mechanical part that serves to condense the excess water vapor that comes with H2 and O2 gases to water.

المكثف عبارة عن جزء ميكانيكي يعمل على تكثيف بخار الماء الزائد الذي يأتي مع غازات الهيدروجين و الأكسجين لماء.

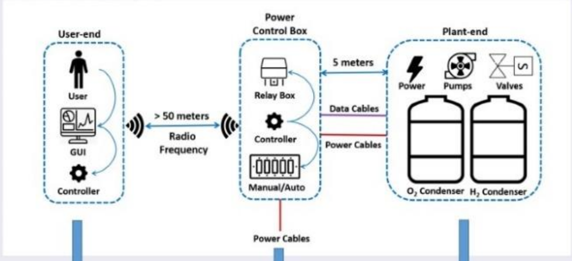
1: **KOH** (electrolyte) tank
2: **H2O** (water) tank
ELECTROLYTE:
An electrolyte is a substance that produces an electrically conductive solution when dissolved in a polar solvent, such as water.

الإلكتروليت هو مادة تنتج محلول موصل كهربائي عند إذابته في مذيب قطبي ، مثل الماء

CONTROL SYSTEM

The system can be divided into 3 subcategories; The plant side where the electrolyzer setup is set, the power control unit that handles all the control procedure, and the user side where all the controls are set.

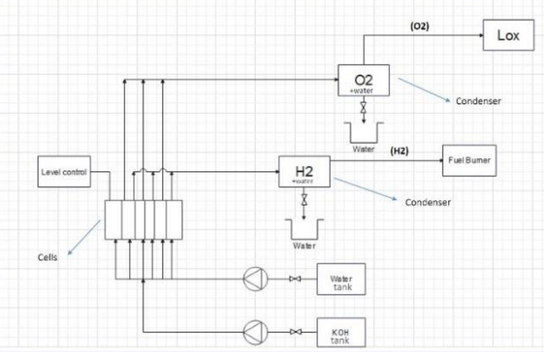
ينقسم هذا النظام إلى ثلاث أقسام؛ الإلكترولايزر، لوحة التحكم الكهربائية التي تتحكم بالإلكترولايزر، وأخيرا الحاسوب الذي يتحكم الذي يتحكم بكل المنظومة.

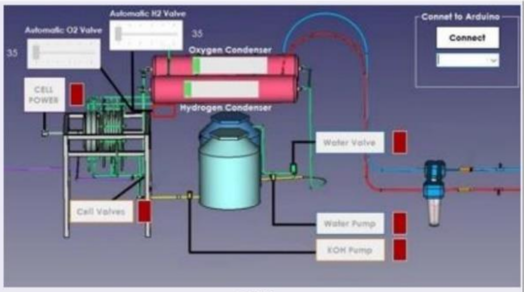


GUI

PLC

PLANT_END





GUI

"Mohamad NAAMAN, Ali DIB"@AECENAR November 2021

5.1 Calculation of Oxygen flow rate outlet by electrolysis

- Power :2.4 kW (voltage =4V; current = 150 A)
    - Gas flow rate Hydrogen all stacks = 2.27 L/min =136.2 L/hr
    - **Gas flow rate Oxygen all stacks = 1.13 L/min = 67.8 L/hr**
- Power : 25 kW
    - Gas flow rate Hydrogen all stacks = 23.65 L/min = 1418.75 L/hr
    - **Gas flow rate Oxygen all stacks = 11.77L/min = 706.25 L/hr**

6 Project B 22: Monostage Water Electrolysis (ICPT - WE)

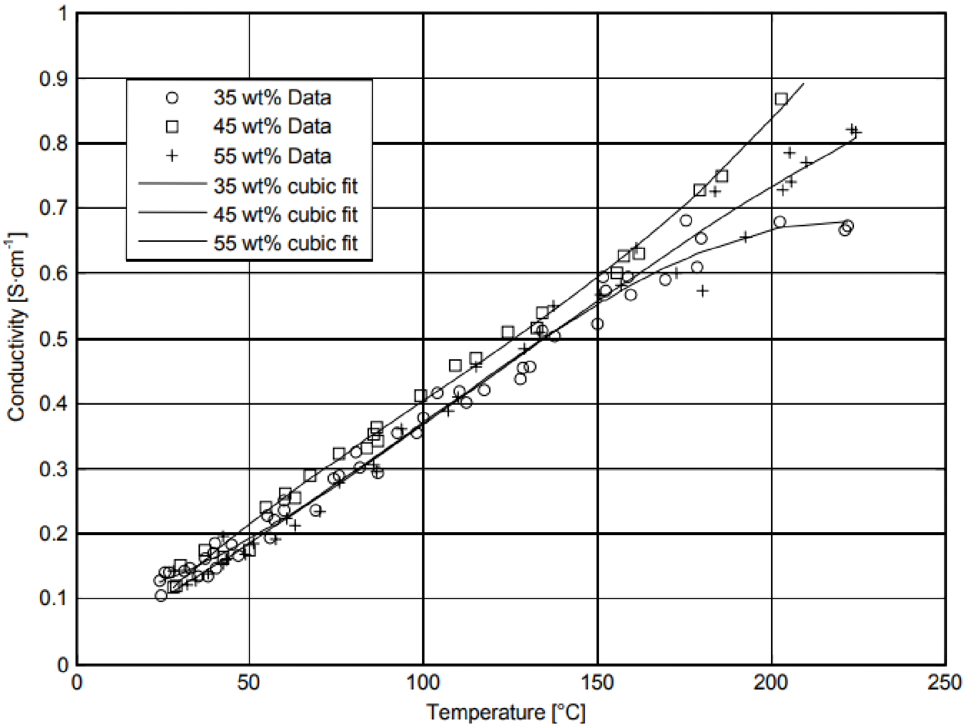
6.1 Electrolyser introduction

In the past years (2021 and before), and after the theoretical study and the implementation of an applied model, work was done in the year 2022 on the control and automatic system to control the operation of the electrolysis model from a distance. Several operational experiments were also carried out to test the performance of the model.

6.2 PCS design

Needed information for the design and the calculations:

The proposed spaces were 10.65, 9.20, 8.25, 7.25, 6.30, 6.05, 4.35, 4.15, and 3.40 millimeters. From the nine different analyzed distances between electrodes, it can be said that the best performance was reached by one of the smallest distances proposed, 4.15 mm. When the same distance between electrodes was compared (the same and different distance between electrodes and separator), the one that had almost twice the distance (negative compartment) presented an increase in current density of approximately 33% with respect to that where both distances (from electrodes to separator) are the same. That indicates that the stichometry of the electrolysis reaction influenced the performance [1].



[2]

Figure 13: Measured conductivity data and cubic regression analysis for 35,45 and 55 wt% immobilized KOH versus temperature

$$L = A \times \frac{R}{\rho}$$

$$R = \frac{L \times \rho}{A} = \frac{L}{A \times K}$$

When $K = \frac{1}{\rho}$

$U = R \times I$

Current density in alkaline electrolysis = 0,2 - 0,4 A/cm²

6.3 Calculating the current and the voltage for the existing cells

1) **The bigger cells in which the distance between the electrodes is 3,6 cm**

Cell details :

- The radius of the surface which touches the solution : 14,6 cm .
- The distance between the electrode and the membrane : 3,6 cm .
- We filled only 2/3 of the cell volume .
- Temperature = 25 °C

So R = (3,6 cm)/((446,21 cm² × 0,125)) = 0,0645 Ω .

I = 178,484 Amperes

U = 11,52 Volt

2) **The smaller cells in which the distance between the electrodes is 1,8 cm**

Cell details :

- L = 1,8 cm
- Inner Radius = 14,6 cm

So R =(1,8 cm)/((446,21 cm² × 0,125)) = 0,0322 Ω

I = 178,484 Amperes

U =5,747 volt

6.4 Calculating the current the voltage and the distance between electrodes of the multistage electrolyser cell

L= A x (6)/(A) x 0,3375 = 2,025 cm

I = 0,4 x the surface that touches the solution = 0,4 x A = 0,4 × 3,14 × r²

U = 2,4 Volt

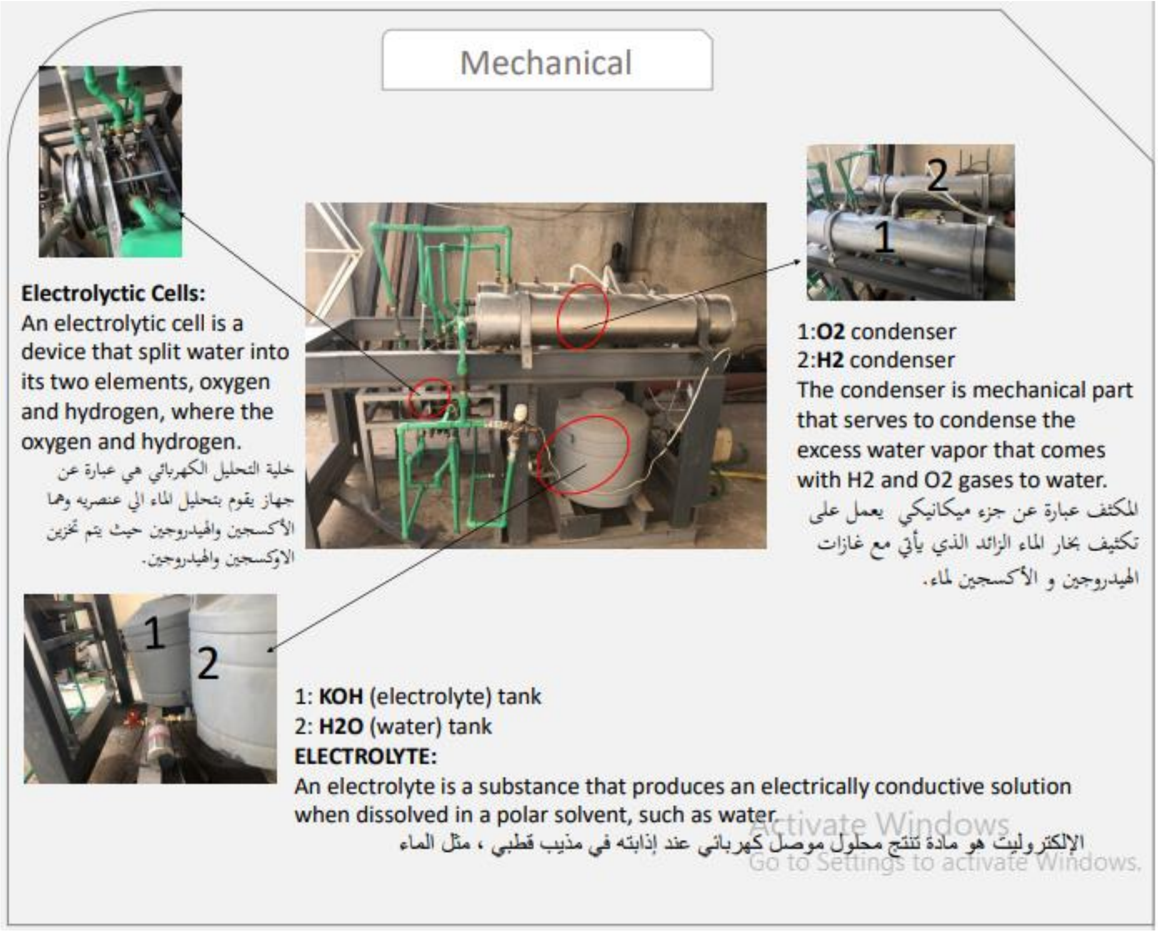
So the distance between the two electrodes shall be 2,025 cm .

And from the text above we seen that it is better to divide this distance into 3 parts 2 parts on the hydrogen production site and one on the oxygen production .

That means 0,675 cm from the anode to the membrane and 1,35 cm from the cathode to the membrane.

6.5 Realization / implementation - Mechanical realization

1) System overview



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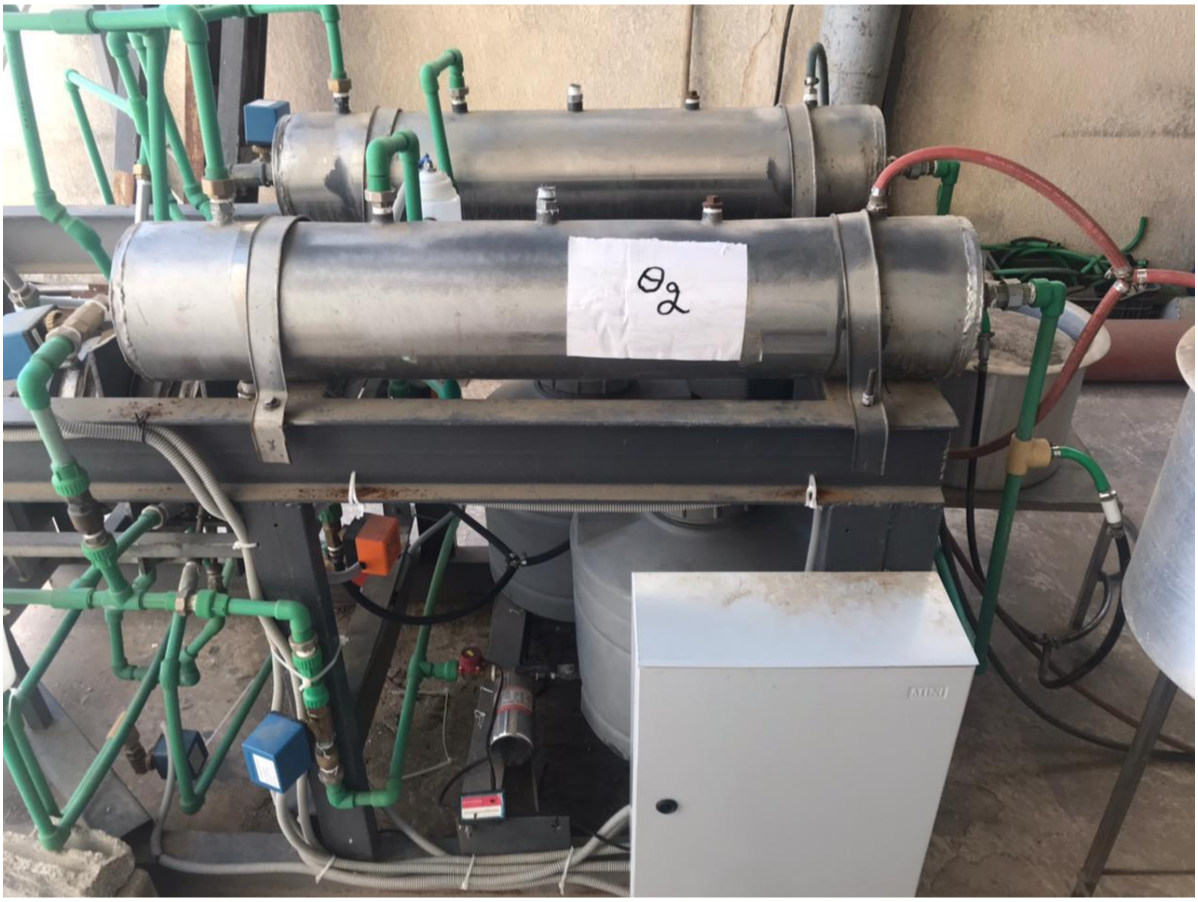
2) Pipe installation from O_2 and H_2 condenser to fuel burner with filters and expansion tanks

Project B 22: Monostage Water Electrolysis (ICPT - WE)



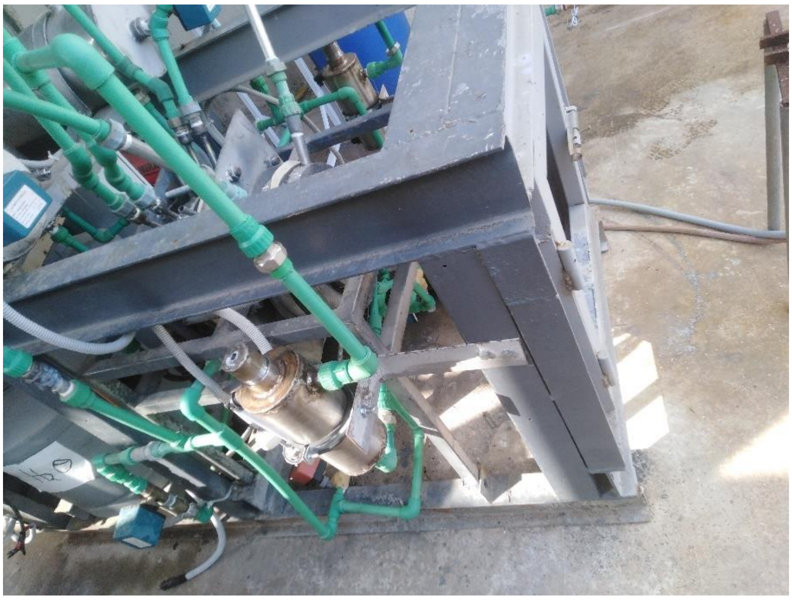

KOH

3) H_2 burning kit

4) Nitrogen can pipe installation

5) Level sensor


θ2



6.6 Process control system realization (PLC + GUI)

- PLC Code :

ICPT-Electrolyzer_PCS_PLC Code_270522.

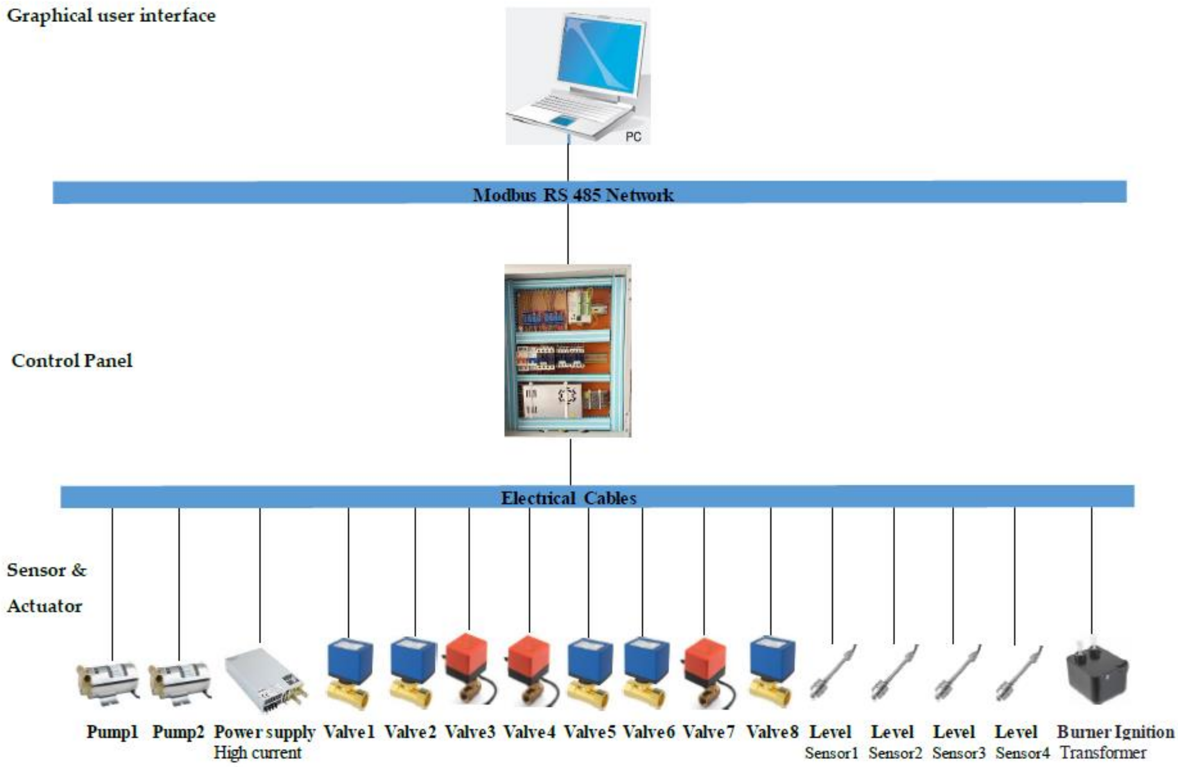
- Graphical User Interface code (C#) :

ICPT-Electrolyzer_PCS_GUI_070722.rar

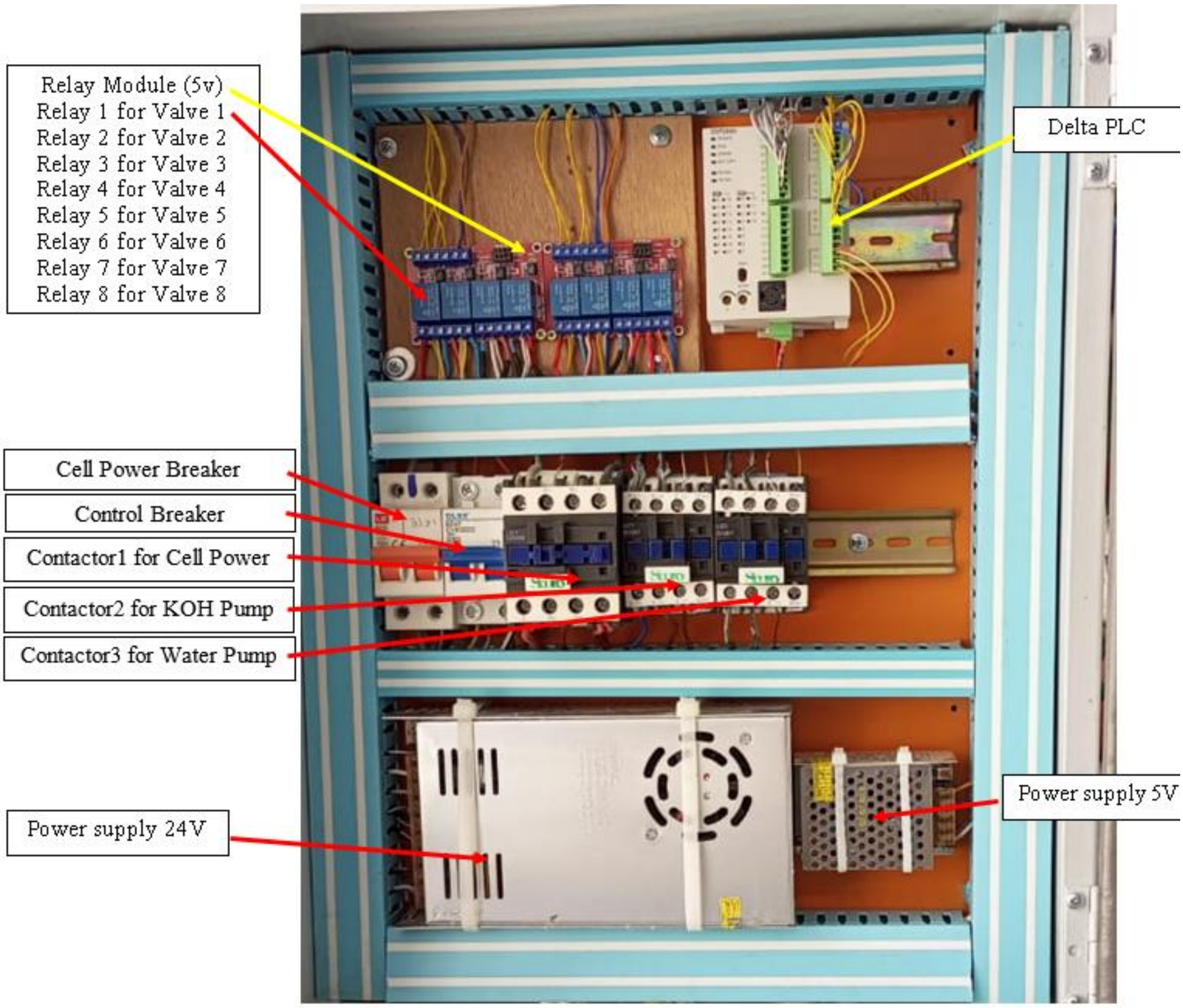
- ICPT Electrolyser PCS - PLC Modbus address :

ICPT-Electrolyzer PCS (MODBUS-addr

1) Process control system for the Electrolyzer system



2) PLC panel



- PLC Point Wiring

Project B 22: Monostage Water Electrolysis (ICPT - WE)

Input:

X0 connect to the Level sensor 1
X1 connect to the Level sensor 2
X0 connect to the Level sensor 3
X1 connect to the Level sensor 4

Output:

Y0 Connect to the Relay 1 for Valve 1
Y1 Connect to the Relay 2 for Valve 2
Y2 Connect to the Relay 3 for Valve 3
Y3 Connect to the Relay 4 for Valve 4
Y4 Connect to the Relay 5 for Valve 5
Y5 Connect to the Relay 6 for Valve 6
Y6 Connect to the Relay 7 for Valve 7
Y7 Connect to the Relay 8 for Valve 8
Y4 Connect to the Relay 5 for Valve 5
Y5 Connect to the Relay 6 for Valve 6
Y6 Connect to the Relay 7 for Valve 7
Y7 Connect to the Relay 8 for Valve 8
Y11 Connect to the Contactor 1 for Cell power
Y12 Connect to the Contactor 2 for KOH pump
Y13 Connect to the Contactor 3 for Water pump

V1: Water valve of half cells set of O2

V2: Water valve of half cells set of H2

V3: Water emptying valve of H2 Condenser

V4: Water emptying valve of O2 Condenser

V5: Electrolyte valve of half cells set of O2

V6: Electrolyte valve of half cells set of H2

V7: emptying valve of O2 half cells set

V8: emptying valve of H2 half cells set

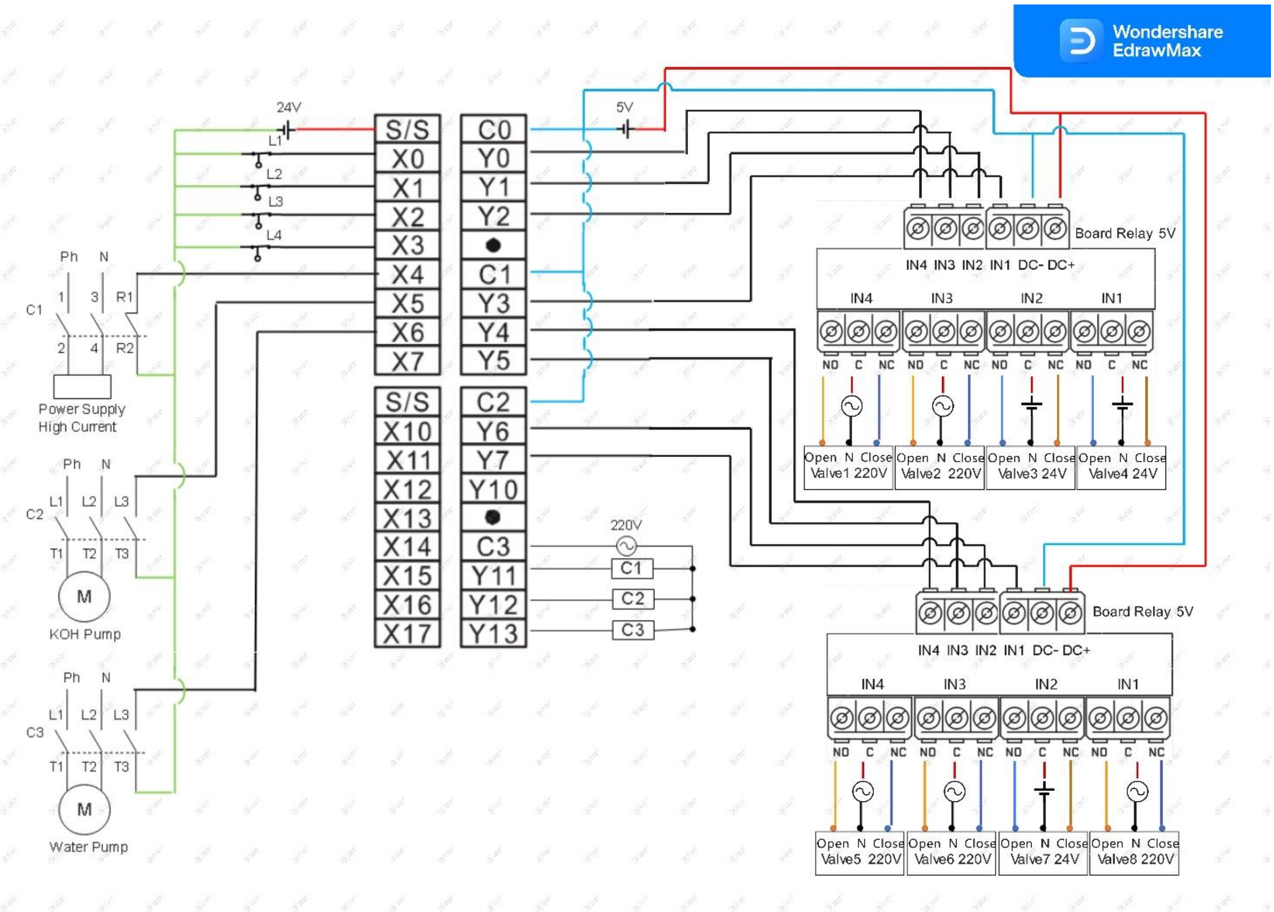
L1:H2 Condenser level

L2: O2 Condenser Level

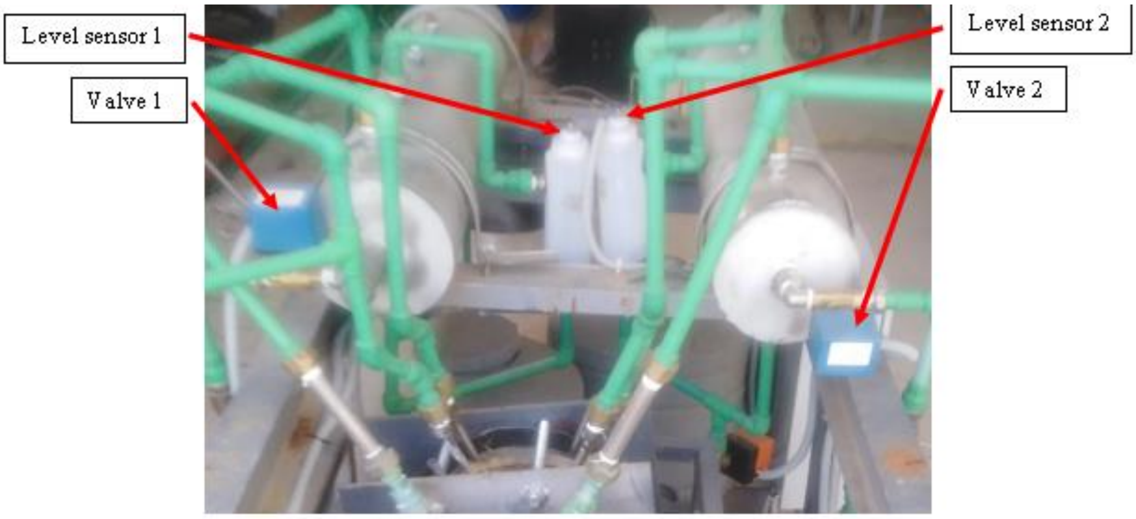
L3: H2 half cells set level

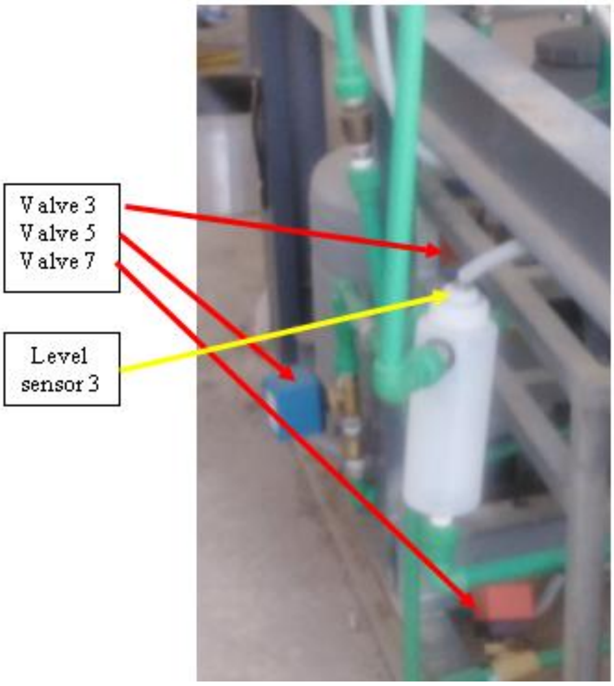
L4: O2 half cells set level

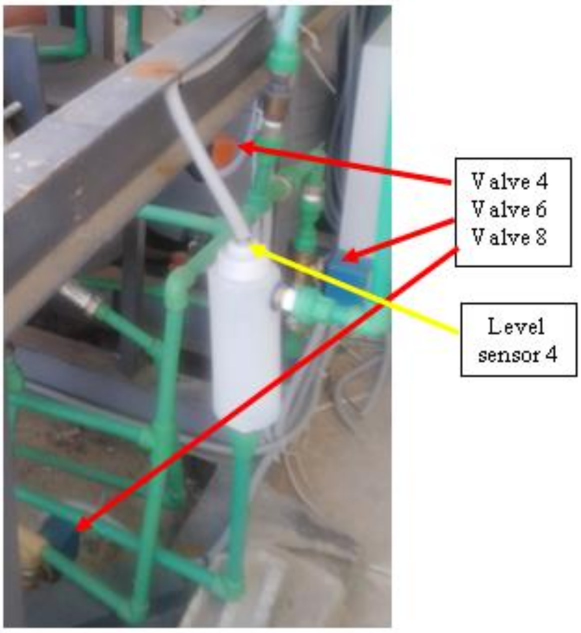
3) PLC Control Panel - Wiring Diagram



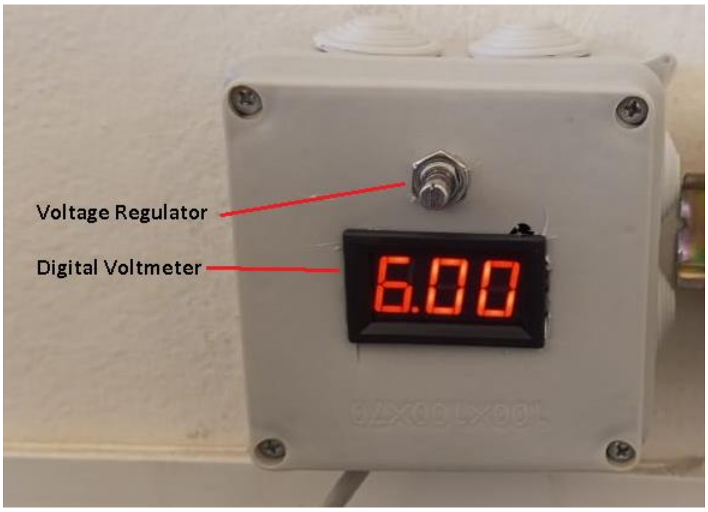
4) Instruments (Valves, Level Control Sensors)



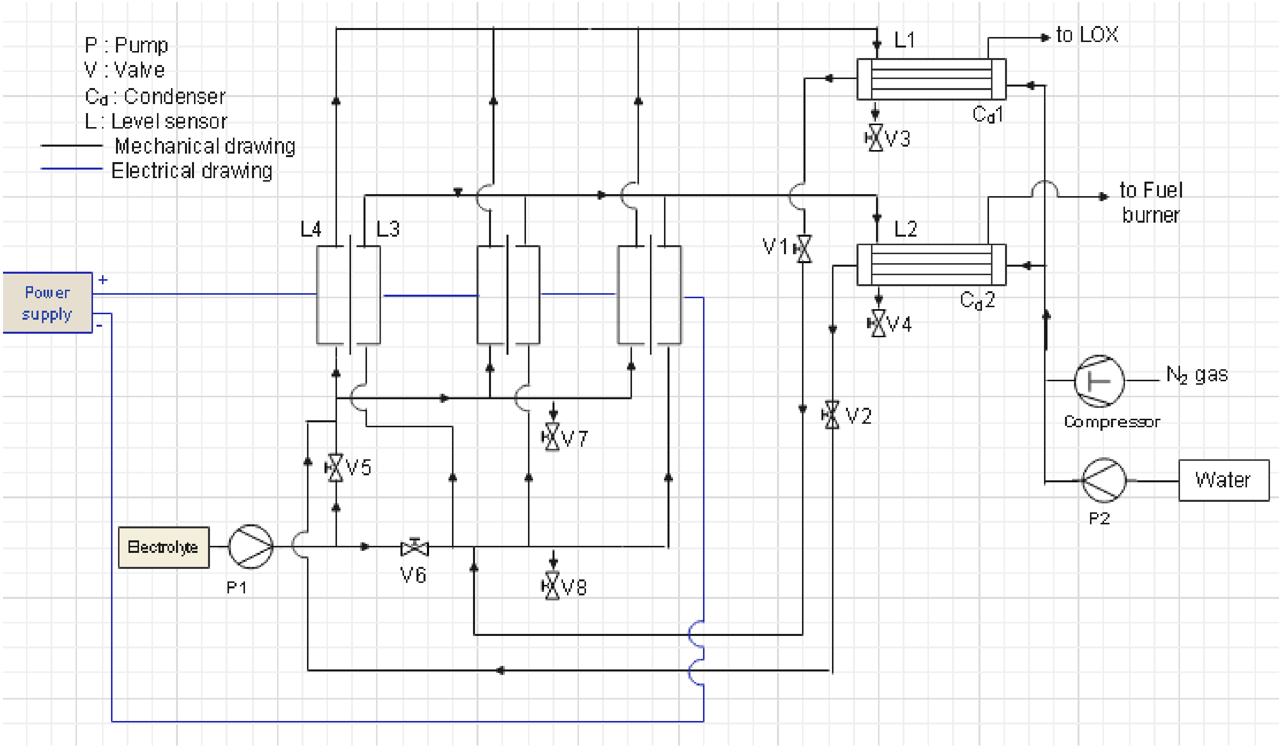




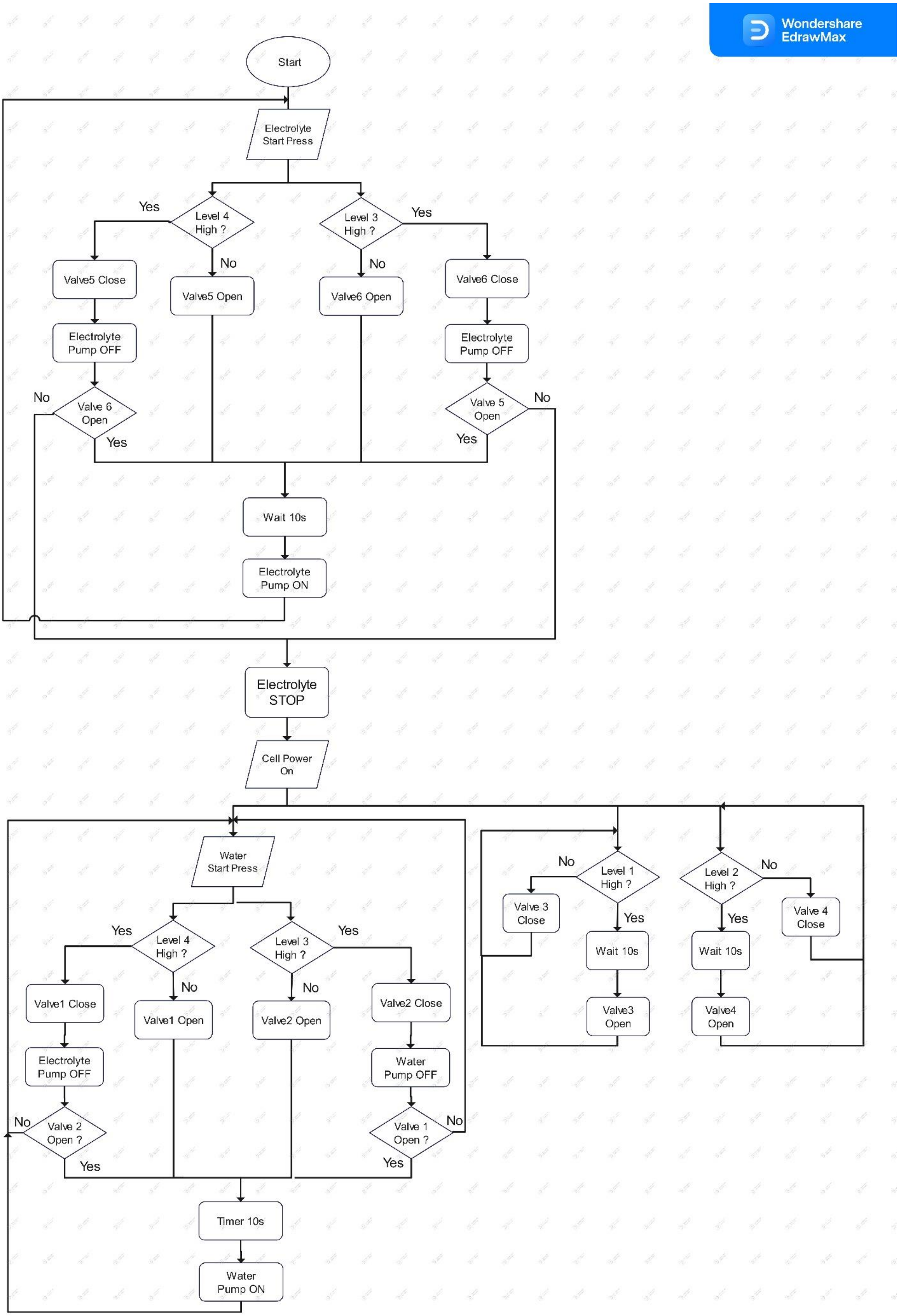
- **Power Supply High Current - Panel & Cable**



5) GUI- Electrolyzer Design

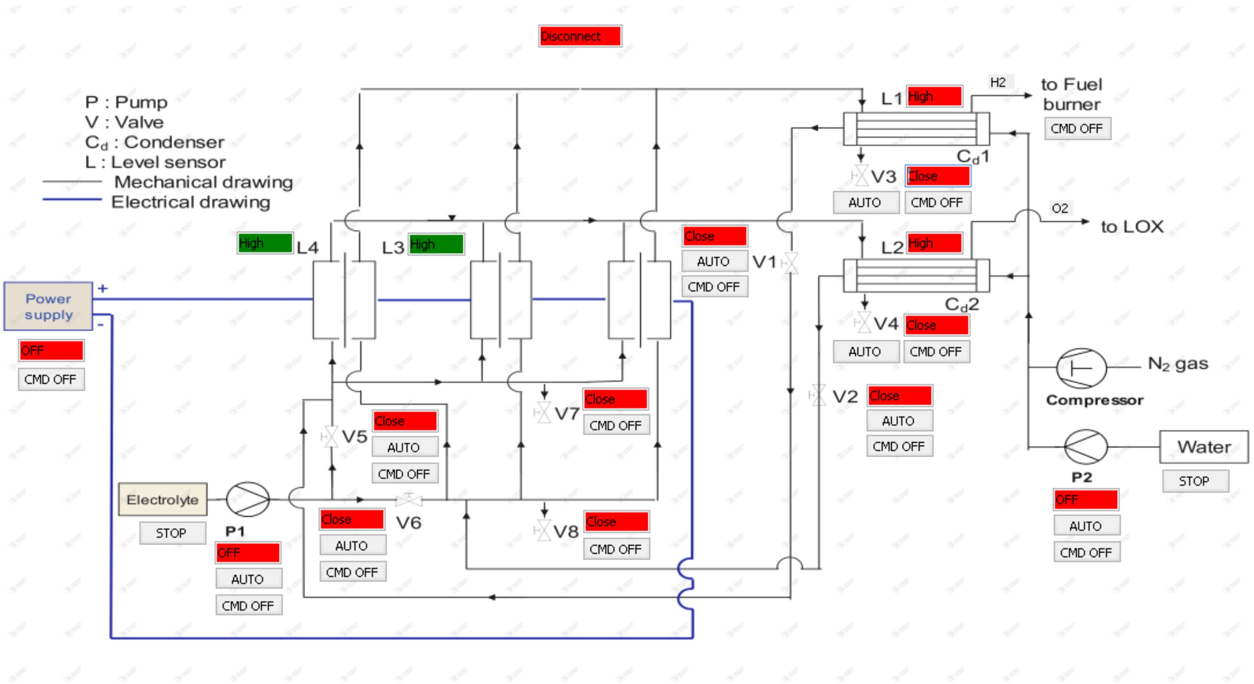


- **Algorithme electrolyser 16.6.2022**



- **<u>GUI 13.7.22</u>**

WhatsApp Video
2021-08-20 at 13.07.



6.7 Electrolysis system test specifications

1) Pre-Starting

Please read these instructions thoroughly. This will make sure you obtain full safe use, Keep this instruction manual in a handy place for future reference.

a) Nitrogen purging

1. Make sure the circuit is closed (all valves are closed)
2. Make sure the power is turned off
3. Connect the Nitrogen tank to the system
4. Open Nitrogen tank valve

   The amount of nitrogen needed for this process is based on how many times pressurized purges are needed to reduce the unwanted contaminant to the desired level.

5. Disconnect the nitrogen.

b) Tank

1. Make sure that the water tank has 60 liters of water
2. Make sure that the KOH tank has 60 liters of KOH

c) Safety precaution

Storage of H_2 is dangerous, for this reason, it should be burned using a fuel burner.

2) Electrolysis operation method

1- Ensure all sanitary connections

2- Fill the first tank with distilled water

3- Fill the second tank with KOH mixture with pH = 13.47

4- Ensure that all electrical connections are made, with no electricity connected to the device

5- Filling the device completely with nitrogen gas, starting with the entry of nitrogen gas at the electrodes and its exit from the hydrogen and oxygen vents, passing through the condensate

6- Operation of the distilled water pump

7- Operation of the KOH mixture pump

8- Connect electricity (continuous power) to the device

9- Wait a while and then start collecting the hydrogen and oxygen gases produced separately by connecting the outlets to specific tanks or connecting them directly to the burner.

6.8 Electrolyser system test

1) Test 22.06.2022 – Hydraulic test of pipes

Hydraulic test to detect Pipe Leakage using a 1.5 HP air compressor at a 2-3 Bar Pressure.

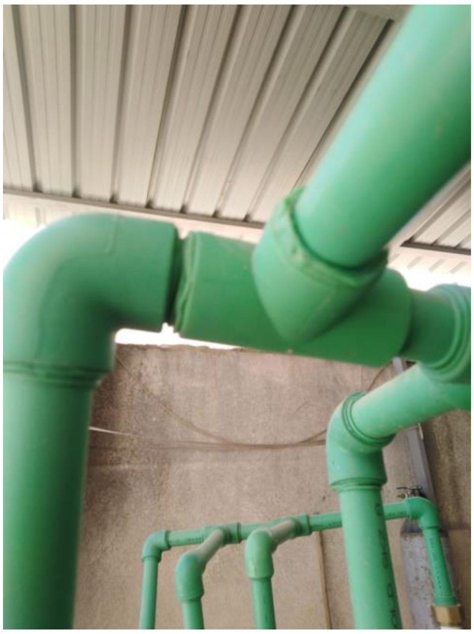
00001: The leck shall be detected when it exists

Step	Step Description	Expected Result	Result
Precondition	System is off		
Switch on the system	Turn on the air compressor	Air enters to the whole system	

Lack is detected	Air exit from the pie system	Lack position shall be detected with a marker
Switch off the system.	Turn off the air compressor	The air stops enter to the pipe system
Postcondition	System is off	

a) Place of leakage of stainless steel

b) Place of leakage of PPR pipes



2) Test 04.07.2022 – Electrolysis

00001: The leck shall be detected when it exists

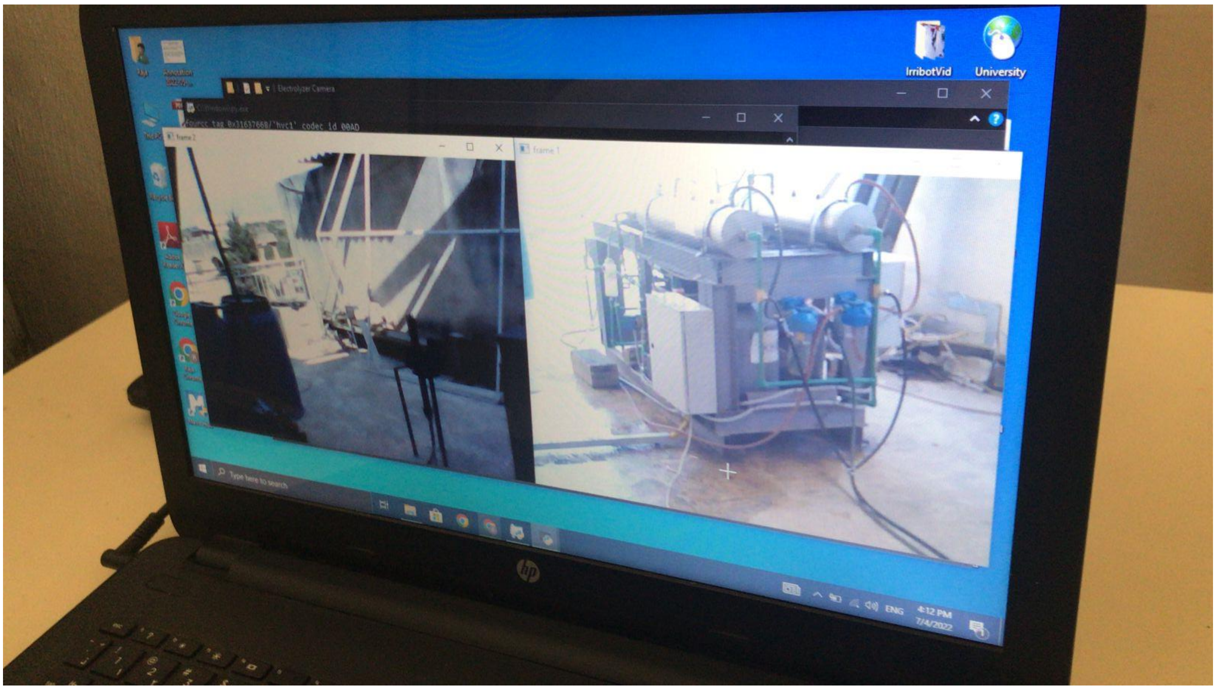
Step	Step Description	Expected Result	Result
Precondition	System is off		
Switch on the system	Turn on the air compressor	Air enters to the whole system	
Lack is detected	Air exit from the pie system	Lack position shall be detected with a marker	
Switch off the system.	Turn off the air compressor	The air stops enter to the pipe system	
Postcondition	System is off		

3) Test 04.07.2022 – Electrolysis whole system test

00002: WHOLE SYSTEM TEST

Step	**Step Description**	**Expected Result**	**Result**
Precondition	System is off		
Open the valves V_1 and V_2	**Open the valves V_1 and V_2 from the GUI**	The valve V_1 and V_2 are open and enable to let the nitrogen gas pass	Positive result
WASH THE SYSTEM WITH NITROGENE	Wash the system with Nitrogen for few minutes BY TURNING ON THE VALVE on the nitrogen tank	One can see that there is nitrogen exit from the gas outlets	Positive
Switch on the system	Turn off the nitrogen Turn on the system from the GUI	THE SYSTEM IS GENERATING hydrogen and oxygen	We turned on the system but no hydrogen or oxygen generation
Burn the hydrogen	Turn on the transformator	The Hydrogen is burning	Negative since no hydrogen generated
Switch off the system.	Switch off the system from the GUI Switch off the trans formator	The system goes down.	Positive
WASH THE SYSTEM WITH NITROGENE	Wash the system with Nitrogen for few minutes BY TURNING ON THE VALVE on the nitrogen tank	All the hydrogen existing in the pipe system exit	Positive
Postcondition	System is off		

Turning on the system through the GUI after nitrogen purging for more than 10 minutes



We watched everything through 2 cameras and found that nothing had happened.
This could be seen by the fact that no current was withdrawn from the power supply and that no bubbles formed in the 2 containers.

- Analysis of the test results:

The reason why no hydrogen was generated is that the KOH concentration was not high enough.

The desired concentration is 5 to 7 molar = 280,528 g/L

We had entered far too little KOH, which left the conductivity of the solution close to zero.

- What we have to do:

Increase the concertation of the KOH.

4) 05.07.2022 – Electrolysis whole system test

00002: WHOLE SYSTEM TEST

Step	Step Description	Expected Result	Result

Precondition	System is off		
Open the valves V_1 and V_2	**Open the valves V_1 and V_2 from the GUI**	The valve V_1 and V_2 are open and enable to let the nitrogen gas pass	Positive
WASH THE SYSTEM WITH NITROGENE	Wash the system with Nitrogen for few minutes BY TURNING ON THE VALVE on the nitrogen tank	One can see that there is nitrogen exit from the gas outlets	Positive
Switch on the system	Turn off the nitrogen Turn on the system from the GUI	THE SYSTEM IS GENERATING hydrogen and oxygen	Positive
Burn the hydrogen	Turn on the transformator	The Hydrogen is burning	Negative
Switch off the system.	Switch off the system from the GUI Switch off the transformator	The system goes down	Positive
WASH THE SYSTEM WITH NITROGEN	Wash the system with nitrogen for few minutes BY TURNING ON THE VALVE on the nitrogen tank	All the hydrogen existing in the pipe system exit	Positive
Postcondition	System is off		

After correcting the KOH concentration, we started the test and successfully generated hydrogen.
However, the quantity was very low, so ignition did not occur.

- Test analysis:

It can be 2 Reason for the low generated quantity:

1- Either the concentration is yet too low knowing that we rise it.

2- Or the current passing through the cells is too low.

or the two reasons together.

- What we have to do:

Do a test with the maximum possible concentration of the KOH. If this is not successful, we have to define which power supply should be used instead. this is done by installing measuring instruments to detect the voltage and the current passing through the cells.

5) Test #2: 05.07.2022 – Electrolysis whole system

00002: WHOLE SYSTEM TEST

Step	Step Description	Expected Result	Result
Precondition	System is off		
Open the valves V_1 and V_2	**Open the valves V_1 and V_2 from the GUI**	the valve V1 and V_2 are open and enable to let the nitrogen gas pass	
WASH THE SYSTEM WITH NITROGENE	Wash the system with Nitrogen for few minutes BY TURNING ON THE VALVE on the nitrogen tank	One can see that there is nitrogen exit from the gas outlets	
Switch on the system	Turn off the nitrogen Turn on the system from the GUI	THE SYSTEM IS GENERATING hydrogen and oxygen	
Burn the hydrogen	Turn on the transformator	The hydrogen is burning	
Switch off the system.	Switch off the system from the GUI Switch off the transformator	The system goes down.	
WASH THE SYSTEM WITH NITROGENE	Wash the system with Nitrogen for few minutes BY TURNING ON THE VALVE on the nitrogen tank	All the hydrogen existing in the pipe system exit	
Postcondition	System is off		

6) 19.07.2022 – Whole system test with another power supply

Tested according to test specification

00004: WHOLE SYSTEME TEST WITH ANOTHER POWER SUPPLY

WHOLE SYSTEME TEST WITH ANOTHER POWER SUPPLY 15.07.2022

Step	Step Description	Expected Result	RESULTS
Precondition	System is off		
THE CHANGING OF THE POWER SUPPLY WITH A POWER SUPPLY OF HIGHER VOLTAGE	Replacing the power supply with the welding machine	More hydrogen is generated	Positive
Open the valves V_1 and V_2	**open the valves V_1 and V_2 from the GUI**	The valve V_1 and V_2 are open and enable to let the nitrogen gas pass	Positive
WASH THE SYSTEM WITH NITROGEN	Wash the system with Nitrogen for few minutes BY TURNING ON THE VALVE on the nitrogen tank	One can see that there is nitrogen exit from the gas outlets	Positive
Switch on the system	Turn off the nitrogen Turn on the system from the GUI	THE SYSTEM IS GENERATING hydrogen and oxygen	The system is generating hydrogen but not oxygen
Burn the hydrogen	Turn on the transformator	The hydrogen is burning	Positive
Switch off the system.	Switch off the system from the GUI Switch off the transformator	The system goes down.	Positive
WASH THE SYSTEM WITH NITROGENE	Wash the system with nitrogen for few minutes BY TURNING ON THE VALVE on the nitrogen tank	All the hydrogen existing in the pipe system exit	Not done yet
Postcondition	System is off	system is off	

After replacing the power supply with the welding machine, we were able to generate enough hydrogen to burn it. see the pictures below.

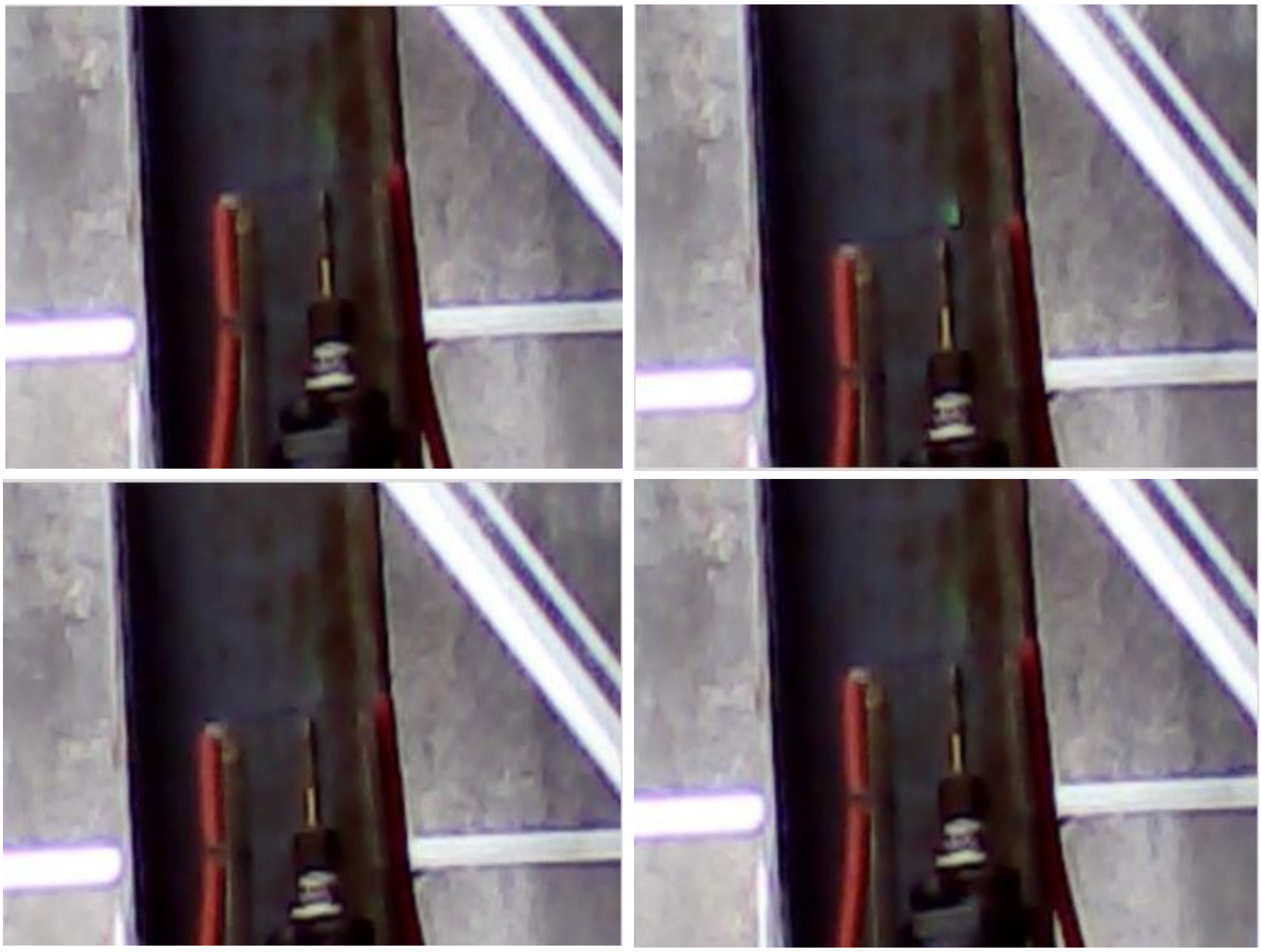


Fig. 1: The Hydrogen flame

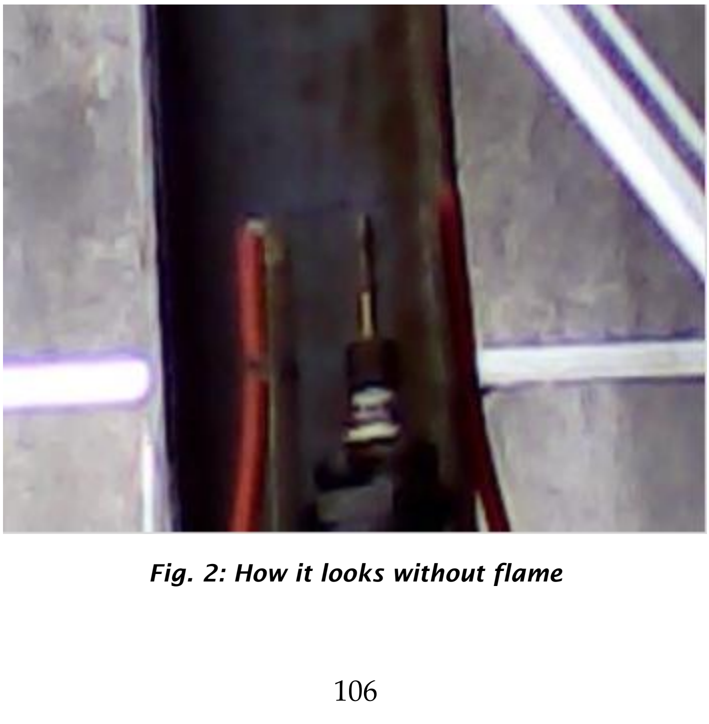


Fig. 2: How it looks without flame

But what we noticed is that the current going to the welding machine was only high at the beginning of the start-up (about 13 A at 230 V) and then it kept decreasing until it went down to 1,4 A at 230 V. see the pictures below:

Fig. 3: Just after starting the machine (1A is going to the transformator)

Fig. 4: After a while. One can see how much the current has decreased.

- <u>Test analysis:</u>

The welding machine is not good enough since it cannot withstand for long time.

At the highest power of the welding machine, hydrogen was generated and burned, but even then too little.

- It can be 2 Reason for the low generated quantity :

1- Either the concentration is yet too low knowing that we rise it .

2- Or the current passing through the cells is too low .

or the two reasons together .

- What we have to do :

1- Test whether the membranes are ruptured.

2 - Doing a test with the maximum possible concentration of the KOH. If this is not successful we have to define which power supply should be used instead . This is done by installing measuring instruments to detecct the voltage and the current passing through the cells.

7) 05.07.2022 – All system test with only one cell connected

Tested according test specification

00005: WHOLE SYSTEME TEST WITH WITH ONLY ONE CELL CONNECTED

Step	Step Description	Expected Result	RESULTS
Precondition	System is off		
CONNECTING THE COMPLETE VOLTAGE TO ONLY ONE CELL	DISCONNECT THE POWER SUPPLY FROM TWO CELLS AND CONNECT IT TO ONLY ONE CELL.	MORE CURRENT WILL DRIVE THROUGH THE CELL	Instead of 0.5 A, the power source has drawn up to 5 A from the 230 V socket.
Open the valves V_1 and V_2	**Open the valves V_1 and V_2 from the GUI**	the valve V_1 and V_2 are open and enable to let the nitrogen gas pass	Positive
WASH THE SYSTEM WITH NITROGENE	Wash the system with Nitrogen for few minutes BY TURNING ON THE VALVE on the nitrogen tank	One can see that there is nitrogen exit from the gas outlets	Positive

Switch on the system	Turn off the nitrogen Turn on the system from the GUI	THE SYSTEM IS GENERATING hydrogen and oxygen	There is seen that only hydrogen is generated but this is so also in all previous tests we done
Burn the hydrogen	Turn on the transformator	The hydrogen is burning	Negative
Switch off the system.	Switch off the system from the GUI Switch off the transformator	The system goes down.	Positive
WASH THE SYSTEM WITH NITROGENE	Wash the system with Nitrogen for few minutes BY TURNING ON THE VALVE on the nitrogen tank	All the hydrogen existing in the pipe system exit	Positive
Postcondition	System is off	System is off	

We have assumed that the voltage we give to one cell is too low, so we have connected all the voltage that was intended for all three cells to only one cell.

We expected more current to go through the one cell. And that is what happened and more hydrogen was generated. But the amount of hydrogen was not enough to burn it.

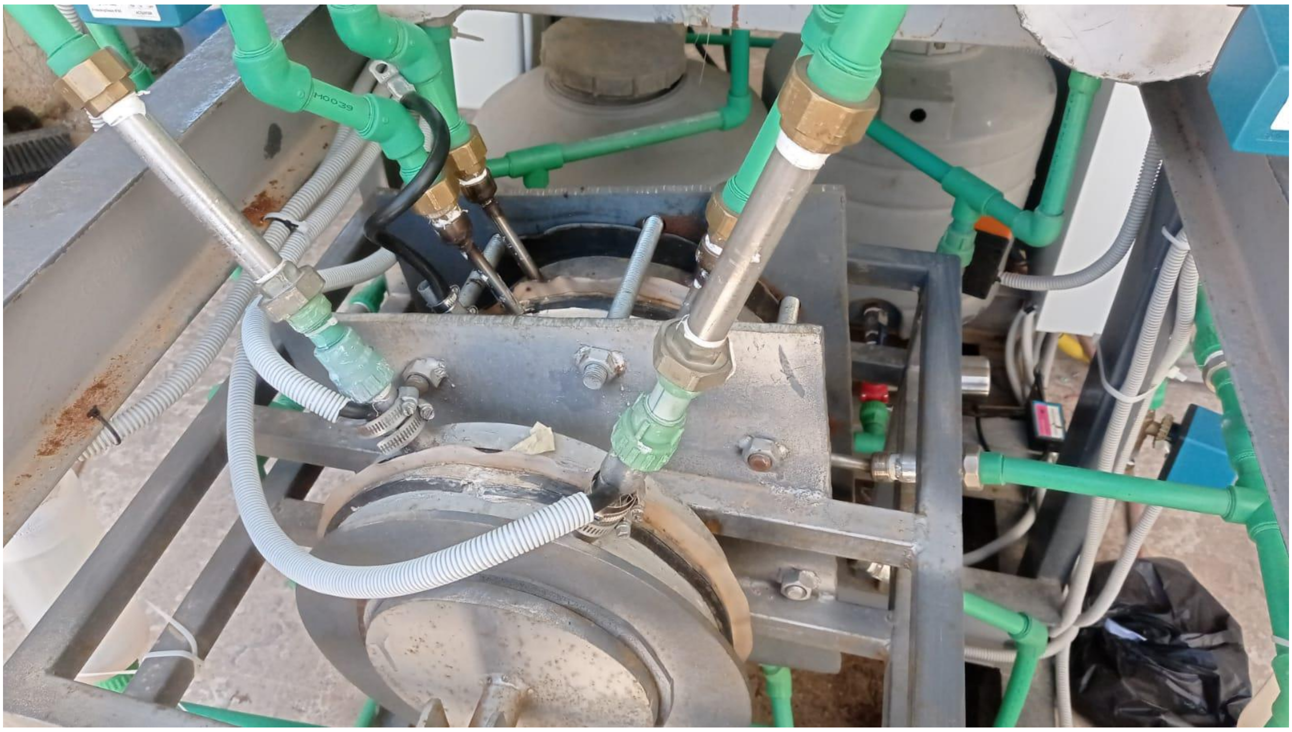


Fig 1: In this figure, it can be seen that only one cell is connected

- Test Analysis:

One can see that the resistance of the 3 cellls is too high .

- What to do:

1- Test whether the membranes are ruptured.
2- Rise the KOH concentration to the maximum.

8) 29.07.2022 – Test whether the membrane is ruptured

Testing according the test 00007: Test whether the membrane is ruptured.

If there are air bubbles from the hydrogen half cells set the membrane have to be changed.

Step	Step Description	Expected Result	Results
Precondition	System is off		
Emptying the cells	Placing a container under the two emptying valves and open the two emptying valves so that the containers are filled with the solution of the cells.	The solution flows into the containers.	Not done

Closing of the emptying valves.	Closing the emptying valves after the whole solution flowed from the cells into the containers.	The emptying valves are closed	Not done
Let the air enter to the half-cell set of oxygen.	Connect the air compressor to one set of the half-cell sets and tur on the compressor.	Air bubbles are seen only in the one set on which the air bubbles are connected	Not done
Stop the air	Turn off the compressor	The compressor is off	Not done
Postcondition	System is off	System is off	

Before we could start with the actual test, we first had to purge the electrolyser with nitrogen.

When we did this, water flowed out of one or more cells.

And the level of the water in the filters and in the containers for the level controllers has changed.

As one can see in the figures below:

Fig. 1: water sprays out of the cells

Fig. 2: the level change in the filters

fig 3 : the level changes in the level controlling containers

- Test Analysis:

Test analysis to be discussed further but we think that the membrane is ruppted and the pressure of the cells on each other has become weaker .

- What we have to do:

open the cells and change the membranes and refix the cells

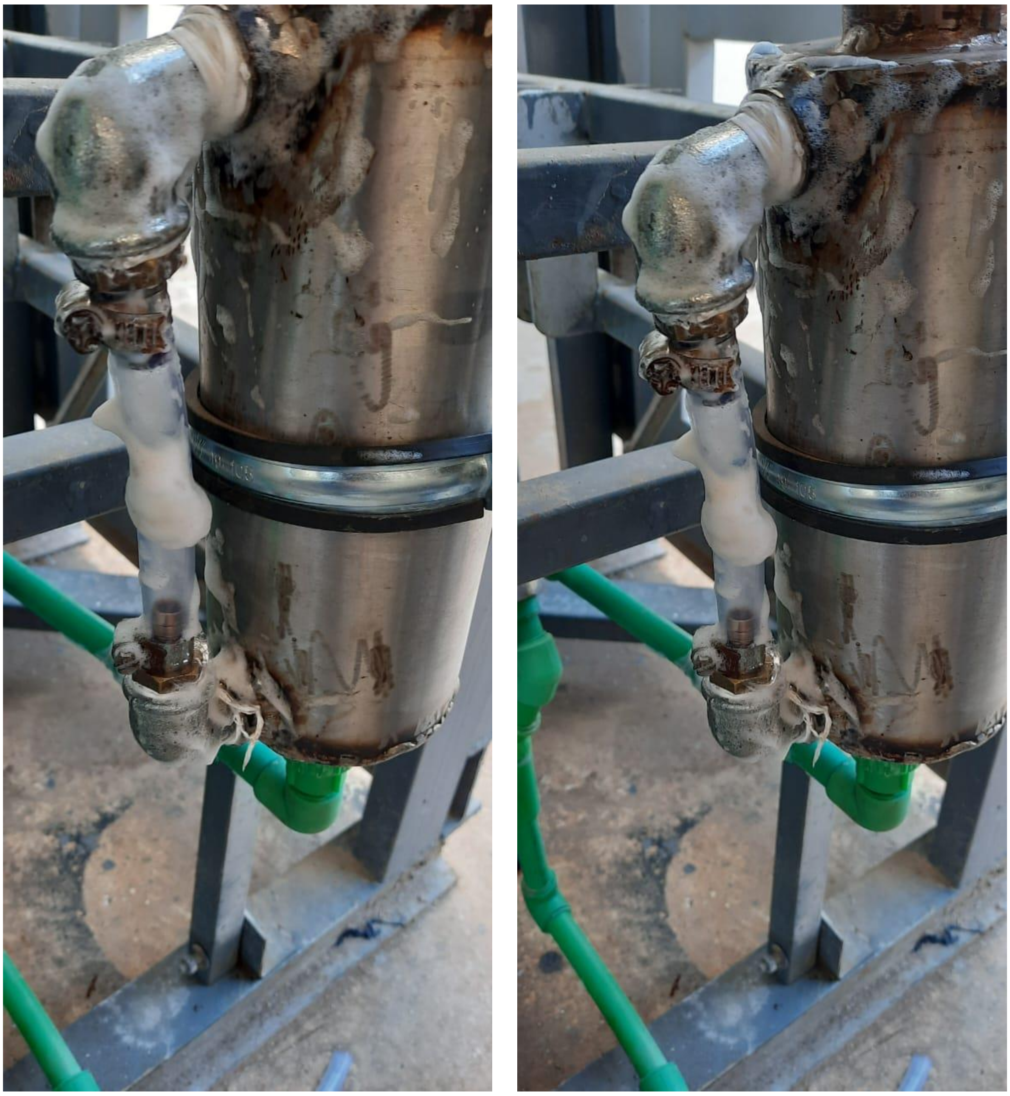
9) **14.11.2022 – Electrolysis test**

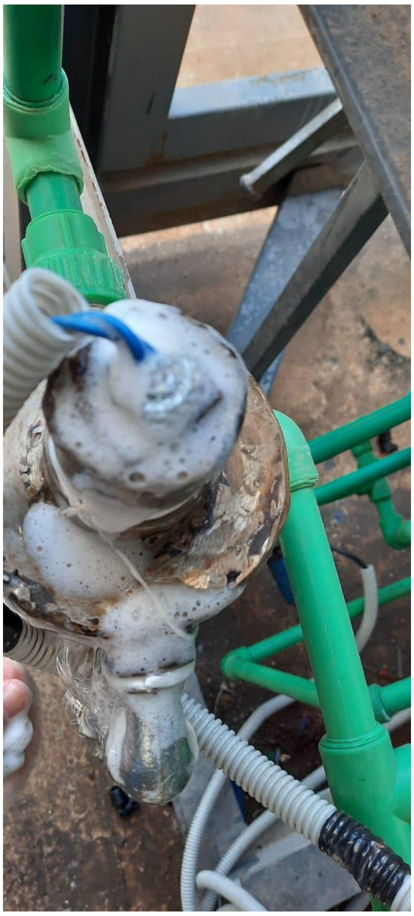
   15/12/2022 System test

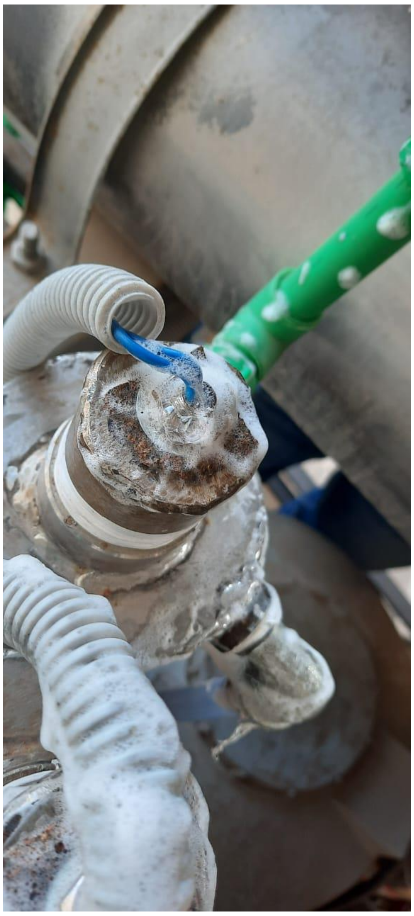
   Leakage places:

Also, we couldn't see air bubbles in the oxyegn water reciever, but we saw them a little in the hydrogen water reciever.

After changing the 4 tanks, we made Nitrogen purguing to test the new ones. The results were also negative and the new ones didn't work well. we have leakages.

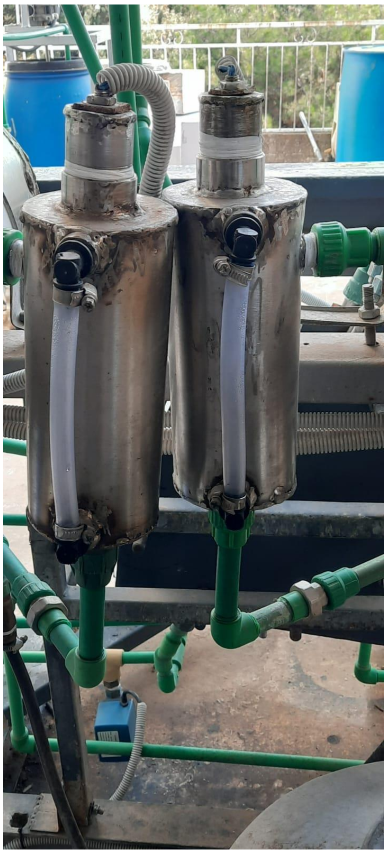






10) 15/12/2022 - System test

a) Leakage places:



Also, we couldn't see air bubbles in the oxyegn water reciever, but we saw them a little in the hydrogen water reciever.

After changing the 4 tanks, we made Nitrogen purguing to test the new ones. The results were also negative and the new ones didn't work well. we have leakages.

b) Electrolyser Test 14 December 2022 _ Results

No leakages observed

Greater flame

Both H_2 and O_2 gases water tanks showed air bubbles (for the first time).

Hydrogen took little time to appear, maybe because it's the time needed for the nitrogen gas to leave the system.

We noticed that the tanks 3 & 4 showed different levels of water after the test. The oxygen tank showed lower water level than the Hydrogen tank.

- Video 1 for the test:

WhatsApp Video
2022-12-16 at 11.06.

- Video 2:

WhatsApp Video
2022-12-16 at 11.06.

- Video 3:

WhatsApp Video
2022-12-16 at 11.05.

6.9 What's next

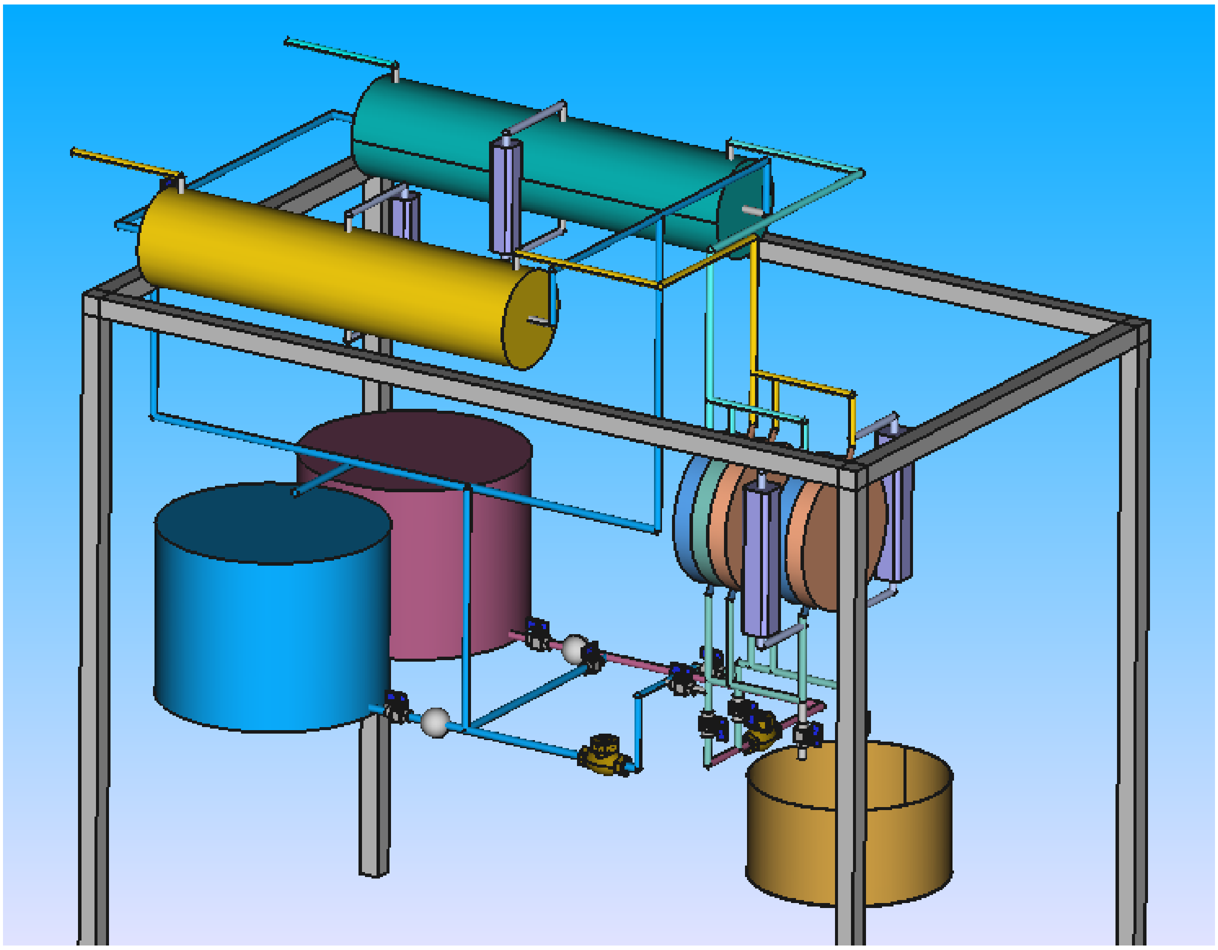
To complete the applied part of the electrolysis project, we only have to do a long-term experiment, showing us the endurance of the model and the amount of hydrogen and oxygen produced with respect to time. After completing this step, we will have successfully completed this project.

7 Project B 23-24: Monostage Water Electrolysis (ICPT - WE)

7.1 Position of ICPT-WE

The electrolysis project underwent an upgrade in 2023/2024 with the redesign and installation of new mechanical connections. The project also subsequently underwent testing of the Nafion membrane inside the electrolytic cell.

7.2 Re-design of electrolysis



FreeCAD file of Electrolysis re-design:

17042024_ELectrolysis - pipes redesign.

7.3 Electrolyze System Requirements[1]

System requirement

- The system shall be able to produce hydrogen and oxygen, separately.

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[1] from NLAP-WEDC Report 2023, Chapter 5

Physical requirements

- The electrodes shall be able to withstand the electrolysis temperature.

- The pipe system shall be able to withstand a temperature up to 100°C.

- The valves shall be able to resist the temperature and the pressure.

- The condensers shall be able to condense the vapor leaving the cell, with water.

Chemical requirements

- The electrodes shall be able to withstand the corrosion with KOH.

- The membrane shall be able to allows the ions to pass through so that electrolysis takes place when the current is connected.

- The membrane shall be able to insulate the two half-cells, chemically.

- The membrane shall be made of Nafion.

- The pipe system used shall be able to withstand the corrosion with KOH.

- The valves shall be able to withstand the corrosion with KOH.

- The metal of condenser used shall be able to withstand the corrosion with KOH.

Mechanical requirements

- The electrodes shall be thick enough to withstand the pressing (the pressing of the screw rods).

- The electrodes shall be thick enough to press the gaskets so that no gas can exit.

- The gaskets shall be able to prevent the leakage of gases and liquids from the cells.

- The gaskets shall be made of thermal caoutchouc.

- The pipes connections shall be able to resist the gas pressure without let gas exit through.

- The pressure of the pump shall be sufficient to fill the cells and not too high for the pipes system.

- The valves shall be able to close completely.

- The valves shall be able to open or close with independent pressure.

Electrical requirements

- For power supply, DC the current that pass through one cell shall be about 140 A DC and we have to test how much voltage shall be needed to make that.

- The power supply shall be able to let the electrolyze generates enough hydrogen so that we can burn it.

- The valves shall be able to be controlled from the GUI.

Safety requirement

- The hydrogen burner shall be able to burn the produced hydrogen gas to avoid the risk of its explosion.

7.4 Electrolyser System Test Specification[2]

WE_Automation_Process

Step 1: Camera connections

1- Connect the camera Adapter

2- Connect the camera with PC

On PC, open "Internet explorer", then enter the IP address "192.168.1.64"(written on the camera box), password: a1111111

Step 2: PLC

1- Connect wire of PLC.

2- Turn UP (Turn On) the PLC breaker.

GUI_Operation

1- Open file named "***Electrolysis GUI***" placed on the desktop of "*Mediston Laptop".*

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[2] from NLAP-WEDC Report 2023, Chapter 5

2- Through the GUI, we enter the solution.

3- When all valves are closed, turn on the power supply until burner is on.

If we find the voltage is up to 16V, the voltage must be reduced. *(Working on updates)*

7.4.1 System_test_cases

00001: The lack shall be detected when it exists

Step	Step Description	Expected Result
Precondition	System is off	
Switch ON the system	Turn on the air compressor manually	Air enters to the whole system
Lack is detected	Air exit from the pie system	Lack position shall be detected with a marker
Switch OFF the system	Turn off the air compressor manually	The air stops enter to the pipe system
Postcondition	System is OFF	

00002: WHOLE SYSTEM TEST

Step	Step Description	Expected Result
Precondition	System is off	
Open the valves V_1 and V_2	Open the valves V_1 and V_2 from the GUI	The valve V_1 and V_2 are open and enable to let the nitrogen gas pass
WASH THE SYSTEM WITH NITROGEN	Wash the system with Nitrogen for few minutes BY TURNING ON THE GLOBLE	One can see that there is nitrogen exit from the gas outlets

	VALVE on the nitrogen tank	
Switch ON the system	Turn Off the globle nitrogen valve Turn Up (Turn On) the breaker (behind the Kelvinator refrigerator) Turn Up (Turn On) the two breakers (red & blue breakers in PLC box) Turn ON the system from the GUI	THE SYSTEM IS GENERATING hydrogen and oxygen
Burn the hydrogen	Turn On the transformator	The Hydrogen is burning
Switch Off the system	Switch Off the system from the GUI Switch Off the transformator	The system goes down
WASH THE SYSTEM WITH NITROGEN	Wash the system with Nitrogen for few minutes BY TURNING ON THE VALVE on the nitrogen tank	All the hydrogen existing in the pipe system exit
Postcondition	Turn off the system	System is off

00003: KOH pipe system test

The lack have to be marked with a marker and fixed

Step	Step Description	Expected Result
Precondition	System is off (No LIN signal)	
Switch on the KOH system	Open the KOH valves Turn on the KOH pump	The water passes through the KOH pump to the cell

Lack is detected	Look at the KOH pump system and look if there is exiting of water from the system	There is entering of water from the pipe system
Switch off the system.	Switch off the the pump and then the 2 KOH vlves	The system goes down.
Postcondition	System is off	

00004: WHOLE SYSTEM TEST WITH ANOTHER POWER SUPPLY

Step	**Step Description**	**Expected Result**
Precondition	System is off	
THE CHANGING F THE POWER SUPPLY WIT A POWER SUPPLY OF HIGHER VOLTAGE	Replacing the power supply with the welding machine	More hydrogen is generated
Open the valves V_1 and V_2	**Open the valves V_1 and V_2 from the GUI**	The valve V_1 and V_2 are open and enable to let the nitrogen gas pass
WASH THE SYSTEM WITH NITROGENE	Wash the system with Nitrogen for few minutes BY TURNING ON THE VALVE on the nitrogen tank	One can see that there is nitrogen exit from the gas outlets
Switch on the system	Turn off the nitrogen Turn on the system from the GUI	THE SYSTEM IS GENERATING hydrogen and oxygen
Burn the hydrogen	Turn on the transformator	The Hydrogen is burning
Switch off the system.	Switch off the system from the GUI Switch off the transformator	The system goes down.

WASH THE SYSTEM WITH NITROGENE	Wash the system with Nitrogen for few minutes BY TURNING ON THE VALVE on the nitrogen tank	All the hydrogen existing in the pipe system exit
Postcondition	Turn off the system	System is off

00005: WHOLE SYSTEM TEST WITH ONLY ONE CELL CONNECTED

Step	**Step Description**	**Expected Result**
Precondition	System is off	
CONNECTING THE COMPLETE VOLTAGE TO ONLY ONE CELL	DISCONNECT THE POWER SUPPLY FROM TWO CELLS AND CONNECT IT TO ONLY ONE CELL.	MORE CURRENT WILL DRIVE THROUGH THE CELL
Open the valves V_1 and V_2	**Open the valves V_1 and V_2 from the GUI**	The valve V_1 and V_2 are open and enable to let the nitrogen gas pass
WASH THE SYSTEM WITH NITROGEN	Wash the system with Nitrogen for few minutes BY TURNING ON THE VALVE on the nitrogen tank	One can see that there is nitrogen exit from the gas outlets
Switch on the system	Turn off the nitrogen Turn on the system from the GUI	THE SYSTEM IS GENERATING hydrogen and oxygen
Burn the hydrogen	Turn on the transformator	The Hydrogen is burning
Switch off the system	Switch off the system from the GUI Switch off the transformator	The system goes down.
WASH THE SYSTEM WITH NITROGEN	Wash the system with Nitrogen for few minutes BY TURNING ON THE VALVE on the nitrogen tank	All the hydrogen existing in the pipe system exit
Postcondition	Turn off the system	System is off

00006: WHOLE SYSTEM TEST after increasing of the KOH concentration

Step	Step Description	Expected Result
Precondition	System is off	
Emptying the cells	Placing a container under the two emptying valves and open the two emptying valves so that the containers are filled with the solution of the cells.	The solution flows into the containers.
Closing of the emptying valves.	closing the emptying valves after the whole solution flowed from the cells into the containers.	The emptying valves are closed
Increase the KOH concentration.	For the solution from the cells into the KOH tank and increase the KOH concentration, by adding new KOH.	The KOH concentration increase
Open the valves V_1 and V_2	Open the valves V_1 and V_2 from the GUI	The valve V_1 and V_2 are open and enable to let the nitrogen gas pass
WASH THE SYSTEM WITH NITROGEN	Wash the system with Nitrogen for few minutes BY TURNING ON THE VALVE on the nitrogen tank	One can see that there is nitrogen exit from the gas outlets
Switch on the system	Turn off the nitrogen Turn on the system from the GUI	THE SYSTEM IS GENERATING hydrogen and oxygen
Burn the hydrogen	Turn on the transformator	The Hydrogen is burning
Switch off the system.	Switch off the system from the GUI Switch off the transformator	The system goes down.
WASH THE SYSTEM WITH NITROGEN	Wash the system with Nitrogen for few minutes BY TURNING ON THE VALVE on the nitrogen tank	All the hydrogen existing in the pipe system exit
Postcondition	Turn off the system	System is off

00007: Test whether the membrane is ruptured

If there are air bubbles from the hydrogen half cells set the membrane have to be changed.

Step	Step Description	Expected Result
Precondition	System is off	
Emptying the cells	Placing a container under the two emptying valves and open the two emptying valves so that the containers are filled with the solution of the cells .	The solution flows into the containers.
Closing of the emptying valves.	Closing the emptying valves after the whole solution flowed from the cells into the containers.	The emptying valves are closed
Let the air enter to the half-cell set of oxygen.	Connect the air compressor to one set of the half cell sets and tur on the compressor.	Air bubbles are seen only in the one set on which the air bubbles are connected
Stop the air	Turn off the compressor	The compressor is off
Postcondition	Turn off the system	System is off

00008: A simple test of an Electrolysis system -Case add water manually-

Steps	Steps description	Excepted result
Precondition	System is Off	
	The cells are partially filled with NaOH solution	
	Open the valves (V_3) & (V_4) from the GUI	(V_3) & (V_4) are opened and enable to let the electrolyte solution pass

Run pump to fill the cells with the NaOH solution	Click "Start" on the Electrolyte bottom from the GUI	The cells enable to filled with electrolyte solution
	Wait 5 seconds, the pump (P_1) run automatically	The pump (P_1) is turned On
Turn Off the pump when the cells are filled with NaOH solution	When (L_3) & (L_4) go from "Low" to "High", turn Off the pump from the GUI	The cells filled with electrolyte solution
		Pump (P_1) turned Off
Close the valves (V_3) & (V_4)	Turn Off the valves (V_3) & (V_4) from the GUI	The valves (V_3) & (V_4) are closed
Wash the system with Nitrogen gas	Open the valves (V_1) & (V_2) from the GUI	The valves (V_1) & (V_2) are open and enable to let the nitrogen gas pass
	Close the blue ball valve of the water tank manually	The blue ball valve is closed
	Open the bottle of Nitrogen gas 5 minutes @ 4 bars	The Nitrogen gas pass through the system
		The air bubbles appear (generate) in the Gas AutoSafety
	Turn Off the Nitrogen bottle by its gate valve manually	The Nitrogen bottle is closed
		The air bubbles disappear (doesn't generate) in the Gas AutoSafety
	Open the blue ball valve of water tank manually	The blue ball valve is opened
	Close the valves (V_1) & (V_2) from the GUI	The valves (V_1) & (V_2) are closed

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Turn ON the burner to burn the gas	Click "Start" on Fuel Burner from the GUI	The transformer is turned On
		The burner is turned On
		Redness of the metal strip of the burner
Connect the Power Supply on the system	Ensure that the pump (P_1) is turned Off	Pump (P_1) is closed
	Click "Start" on the Power Supply bottom from the GUI	The Power Supply is On
		The system is generating Hydrogen and Oxygen
		5 minutes after turning On the burner, a flame appears
Add water to the system	Click "Start" on Water from the GUI	
	Turn On the valves (V_1) & (V_2) from the GUI	The valves (V_1) & (V_2) are open and enable to let the water pass through the cells
	Turn On the pump (P_2)	Pump (P_2) is turned On
	After few minutes, Click "Stop" on the valves (V_1) & (V_2) with the Command OFF "CMD OFF" from the GUI	The valves (V_1) & (V_2) are closed
	When (L_3) & (L_4) go from "Low" to "High", turn Off the pump (P_2) from the GUI	The pump (P_2) is turned Off
	When (L_3) & (L_4) go from "Low" to "High", Turn Off the valves (V_1) & (V_2) from the GUI	The valves (V_1) & (V_2) are closed

Disconnect the Power Supply on the system	Click "Stop" on Power Supply bottom from the GUI	The electricity is turned Off from the system
		The generation of Hydrogen and Oxygen are stopped
Turn Off the fuel burner	Click "Stop" on the Fuel Burner bottom from the GUI	Burner (Transformer) is Off
	Click "Stop" on the valves (V_1) & (V_2) from the GUI	The valves (V_1) & (V_2) are closed
		Flame disappears (is Off)
Re-wash the system with Nitrogen gas	Open the valves (V_1) & (V_2) from the GUI	The valves (V_1) & (V_2) are open and enable to let the nitrogen gas pass
	Close the blue ball valve of the water tank manually	The blue ball valve is closed
	Open the bottle of Nitrogen gas 5 minutes @ 4 bars	The Nitrogen gas pass through the system
		The air bubbles appear (generate) in the Gas AutoSafety
	Turn Off the Nitrogen bottle by its gate valve manually	The Nitrogen bottle is closed
		The air bubbles disappear (doesn't generate) in the Gas AutoSafety
	Open the blue ball valve of water tank manually	The blue ball valve is opened
	Close the valves (V_1) & (V_2) from the GUI	The valves (V_1) & (V_2) are closed

	Turn Off the system	System is Off
Post condition	The cells are partially filled with NaOH solution	
	The cells are filled totally with NaOH solution	

00009: A simple test of an Electrolysis system -Case add water automatically-

Steps	**Steps description**	**Excepted result**
Precondition	System is Off	
	The cells are partially filled with NaOH solution	
Run pump to fill the cells with the NaOH solution	Open the valves (V_3) & (V_4) from the GUI	(V_3) & (V_4) are opened and enable to let the electrolyte solution pass
	Click "Start" on the Electrolyte bottom from the GUI	The cells enable to filled with electrolyte solution
	Wait 5 seconds, the pump (P_1) run automatically	The pump (P_1) is turned On
Turn Off the pump when the cells are filled with NaOH solution	When (L_3) & (L_4) go from "Low" to "High", turn Off the pump from the GUI	The cells filled with electrolyte solution
		Pump (P_1) turned Off
Close the valves (V_3) & (V_4)	Turn Off the valves (V_3) & (V_4) from the GUI	The valves (V_3) & (V_4) are closed

Wash the system with Nitrogen gas	Open the valves (V_1) & (V_2) from the GUI	The valves (V_1) & (V_2) are open and enable to let the nitrogen gas pass
	Close the blue ball valve of the water tank manually	The blue ball valve is closed
	Open the bottle of Nitrogen gas 5 minutes @ 4 bars	The Nitrogen gas pass through the system
		The air bubbles appear (generate) in the Gas AutoSafety
	Turn Off the Nitrogen bottle by its gate valve manually	The Nitrogen bottle is closed
		The air bubbles disappear (doesn't generate) in the Gas AutoSafety
	Open the blue ball valve of water tank manually	The blue ball valve is opened
	Close the valves (V_1) & (V_2) from the GUI	The valves (V_1) & (V_2) are closed
Turn ON the burner to burn the gas	Click "Start" on Fuel Burner from the GUI	The transformer is turned On
		The burner is turned On
		Redness of the metal strip of the burner
Connect the Power Supply on the system	Ensure that the pump (P_1) is turned Off	Pump (P_1) is closed
		The Power Supply is On

	Click "Start" on the Power Supply bottom from the GUI	The system is generating Hydrogen and Oxygen
		5 minutes after turning On the burner, a flame appears
Add water to the system	Click "Start" on Water from the GUI	
	Turn On the valves (V_1) & (V_2) from the GUI	The valves (V_1) & (V_2) are open and enable to let the water pass through the cells
	Turn On the pump (P_2)	Pump (P_2) is turned On
	When (L_3) & (L_4) go from "Low" to "High", the pump (P_2) is turned Off automatically from the GUI	Pump (P_2) is turned Off
	When (L_3) & (L_4) go from "Low" to "High", the valves (V_1) & (V_2) are turned Off automatically from the GUI	The valves (V_1) & (V_2) are closed
	Click "Stop" on Water from the GUI	
Disconnect the Power Supply on the system	Click "Stop" on Power Supply bottom from the GUI	The electricity is turned Off from the system
		The generation of Hydrogen and Oxygen are stopped
Turn Off the fuel burner	Click "Stop" on the Fuel Burner bottom from the GUI	Burner (Transformer) is Off
		The valves (V_1) & (V_2) are closed

	Click "Stop" on the valves (V_1) & (V_2) from the GUI	Flame disappears (is Off)
Re-wash the system with Nitrogen gas	Open the valves (V_1) & (V_2) from the GUI	The valves (V_1) & (V_2) are open and enable to let the nitrogen gas pass
	Close the blue ball valve of the water tank manually	The blue ball valve is closed
	Open the bottle of Nitrogen gas 5 minutes @ 4 bars	The Nitrogen gas pass through the system
		The air bubbles appear (generate) in the Gas AutoSafety
	Turn Off the Nitrogen bottle by its gate valve manually	The Nitrogen bottle is closed
		The air bubbles disappear (doesn't generate) in the Gas AutoSafety
	Open the blue ball valve of water tank manually	The blue ball valve is opened
	Close the valves (V_1) & (V_2) from the GUI	The valves (V_1) & (V_2) are closed
Post condition	Turn Off the system	System is Off
	The cells are partially filled with NaOH solution	
	The cells are filled totally with NaOH solution	

00010: A simple test of an Electrolysis system -Case without add water-

Steps	**Steps description**	**Excepted result**
Precondition	System is Off	
	The cells are partially filled with NaOH solution	
Run pump to fill the cells with the NaOH solution	Open the valves (V_3) & (V_4) from the GUI	(V_3) & (V_4) are opened and enable to let the electrolyte solution pass
	Click "Start" on the Electrolyte bottom from the GUI	The cells enable to filled with electrolyte solution
	Wait 5 seconds, the pump (P_1) run automatically	The pump (P_1) is turned On
Turn Off the pump when the cells are filled with NaOH solution	When (L_3) & (L_4) go from "Low" to "High", turn Off the pump from the GUI	The cells filled with electrolyte solution
		Pump (P_1) turned Off
Close the valves (V_3) & (V_4)	Turn Off the valves (V_3) & (V_4) from the GUI	The valves (V_3) & (V_4) are closed
Wash the system with Nitrogen gas	Open the valves (V_1) & (V_2) from the GUI	The valves (V_1) & (V_2) are open and enable to let the nitrogen gas pass
	Close the blue ball valve of the water tank manually	The blue ball valve is closed
	Open the bottle of Nitrogen gas 5 minutes @ 4 bars	The Nitrogen gas pass through the system
		The air bubbles appear (generate) in the Gas AutoSafety

	Turn Off the Nitrogen bottle by its gate valve manually	The Nitrogen bottle is closed
		The air bubbles disappear (doesn't generate) in the Gas AutoSafety
	Open the blue ball valve of water tank manually	The blue ball valve is opened
	Close the valves (V_1) & (V_2) from the GUI	The valves (V_1) & (V_2) are closed
Turn ON the burner to burn the gas	Click "Start" on Fuel Burner from the GUI	The transformer is turned On
		The burner is turned On
		Redness of the metal strip of the burner
Connect the Power Supply on the system	Ensure that the pump (P_1) is turned Off	Pump (P_1) is closed
	Click "Start" on the Power Supply bottom from the GUI	The Power Supply is On
		The system is generating Hydrogen and Oxygen
		5 minutes after turning On the burner, a flame appears
Disconnect the Power Supply on the system	Click "Stop" on Power Supply bottom from the GUI	The electricity is turned Off from the system
		The generation of Hydrogen and Oxygen are stopped
Turn Off the fuel burner	Click "Stop" on the Fuel Burner bottom from the GUI	Burner (Transformer) is Off

	Click "Stop" on the valves (V_1) & (V_2) from the GUI	The valves (V_1) & (V_2) are closed
		Flame disappears (is Off)
Re-wash the system with Nitrogen gas	Open the valves (V_1) & (V_2) from the GUI	The valves (V_1) & (V_2) are open and enable to let the nitrogen gas pass
	Close the blue ball valve of the water tank manually	The blue ball valve is closed
	Open the bottle of Nitrogen gas 5 minutes @ 4 bars	The Nitrogen gas pass through the system
		The air bubbles appear (generate) in the Gas AutoSafety
	Turn Off the Nitrogen bottle by its gate valve manually	The Nitrogen bottle is closed
		The air bubbles disappear (doesn't generate) in the Gas AutoSafety
	Open the blue ball valve of water tank manually	The blue ball valve is opened
	Close the valves (V_1) & (V_2) from the GUI	The valves (V_1) & (V_2) are closed
Post condition	Turn Off the system	System is Off
	The cells are partially filled with NaOH solution	
	The cells are filled totally with NaOH solution	

7.5 Electrolyzer System tests

7.5.1 Electrolyzer test (Test whether the pressure is equilibrium) 5.5.2023 [3]

If the water level sensors are in the parallel level throughout the test period, we have come to a solution to the problem of pressure difference within a single cell. Now we can replace the membrane with Nafion.

But if the water level sensors aren't in the parallel level throughout the test period, this means that there is a problem with suffocation (closed) in one of the condenser tubes.

Goal:

In the previous test, we had a problem with the pressure balance between the two half-cells, and to resolve this problem, we suggested placing flashback arrestor at the oxygen gas outlet. The aim of this test is to ensure the correctness of the pressure balance between the two half-cells.

Expected result:

In case of equilibrium between the two half-cells, the level sensor pointer for each half-cell (water level parallels between the cathodic half-cell and the anodic half-cell).

If there is a pressure difference between the two-level sensors, we should notice a difference in the level of the solution at the two sensors.

Operation Steps:

00008: A simple test of an Electrolysis system -Case add water manually-

Steps	Steps description	Excepted result	Result
Precondition	System is Off		✓
	The cells are partially filled with NaOH solution		✓
Run pump to fill the cells	Open the valves (V_3) & (V_4) from the GUI	(V_3) & (V_4) are opened and enable to let the electrolyte solution pass	✓

---

[3] from NLAP-WEDC Report 2023, Chapter 5

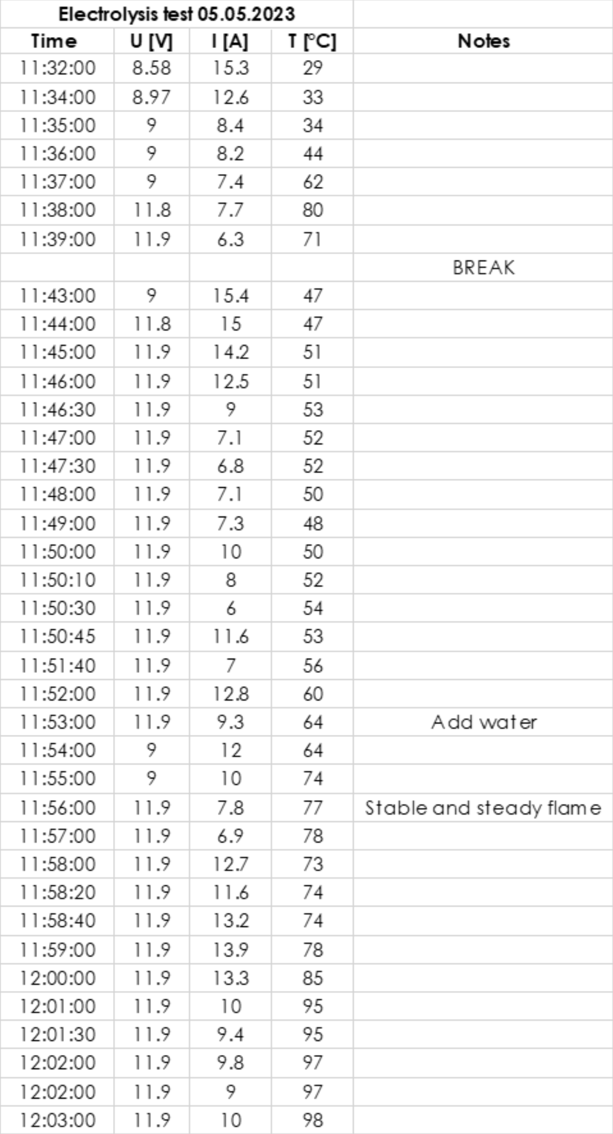
with the NaOH solution	Click "Start" on the Electrolyte bottom from the GUI	The cells enable to filled with electrolyte solution	✓
	Wait 5 seconds, the pump (P_1) run automatically	The pump (P_1) is turned On	✓
Turn Off the pump when the cells are filled with NaOH solution	When (L_3) & (L_4) go from "Low" to "High", turn Off the pump from the GUI	The cells filled with electrolyte solution	✓
		Pump (P_1) turned Off	✓
Close the valves (V_3) & (V_4)	Turn Off the valves (V_3) & (V_4) from the GUI	The valves (V_3) & (V_4) are closed	✓
Wash the system with Nitrogen gas	Open the valves (V_1) & (V_2) from the GUI	The valves (V_1) & (V_2) are open and enable to let the nitrogen gas pass	✓
	Close the blue ball valve of the water tank manually	The blue ball valve is closed	✓
	Open the bottle of Nitrogen gas 5 minutes @ 4 bars	The Nitrogen gas pass through the system	✓
		The air bubbles appear (generate) in the Gas AutoSafety	✓
	Turn Off the Nitrogen bottle by its gate valve manually	The Nitrogen bottle is closed	✓
		The air bubbles disappear (doesn't generate) in the Gas AutoSafety	✓

	Open the blue ball valve of water tank manually	The blue ball valve is opened	✓
	Close the valves (V_1) & (V_2) from the GUI	The valves (V_1) & (V_2) are closed	✓
Turn ON the burner to burn the gas	Click "Start" on Fuel Burner from the GUI	The transformer is turned On	✓
		The burner is turned On	✓
		Redness of the metal strip of the burner	✓
Connect the Power Supply on the system	Ensure that the pump (P_1) is turned Off	Pump (P_1) is closed	✓
	Click "Start" on the Power Supply bottom from the GUI	The Power Supply is On	✓
		The system is generating Hydrogen and Oxygen	✓
		5 minutes after turning On the burner, a flame appears	✓
Add water to the system	Click "Start" on Water from the GUI		✓
	Turn On the valves (V_1) & (V_2) from the GUI	The valves (V_1) & (V_2) are open and enable to let the water pass through the cells	✓
	Turn On the pump (P_2)	Pump (P_2) is turned On	✓
	After few minutes, Click "Stop" on the valves (V_1) & (V_2)	The valves (V_1) & (V_2) are closed	✓

	with the Command OFF "CMD OFF" from the GUI		
	When (L_3) & (L_4) go from "Low" to "High", turn Off the pump (P_2) from the GUI	The pump (P_2) is turned Off	✗
	When (L_3) & (L_4) go from "Low" to "High", Turn Off the valves (V_1) & (V_2) from the GUI	The valves (V_1) & (V_2) are closed	✗
Disconnect the Power Supply on the system	Click "Stop" on Power Supply bottom from the GUI	The electricity is turned Off from the system	✓
		The generation of Hydrogen and Oxygen are stopped	✓
Turn Off the fuel burner	Click "Stop" on the Fuel Burner bottom from the GUI	Burner (Transformer) is Off	✓
	Click "Stop" on the valves (V_1) & (V_2) from the GUI	The valves (V_1) & (V_2) are closed	✓
		Flame disappears (is Off)	✓
Re-wash the system with Nitrogen gas	Open the valves (V_1) & (V_2) from the GUI	The valves (V_1) & (V_2) are open and enable to let the nitrogen gas pass	✓
	Close the blue ball valve of the water tank manually	The blue ball valve is closed	✓
		The Nitrogen gas pass through the system	✓

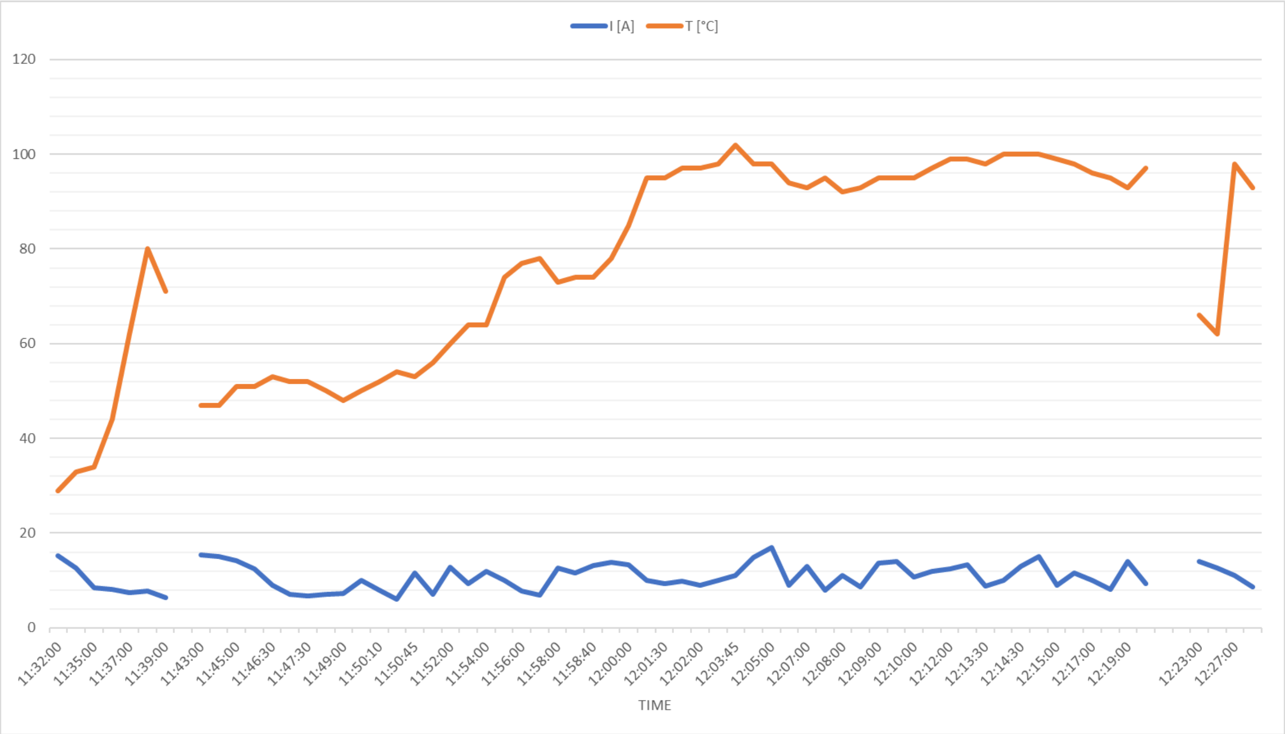
	Open the bottle of Nitrogen gas 5 minutes @ 4 bars	The air bubbles appear (generate) in the Gas AutoSafety	✓
	Turn Off the Nitrogen bottle by its gate valve manually	The Nitrogen bottle is closed	✓
		The air bubbles disappear (doesn't generate) in the Gas AutoSafety	✓
	Open the blue ball valve of water tank manually	The blue ball valve is opened	✓
	Close the valves (V_1) & (V_2) from the GUI	The valves (V_1) & (V_2) are closed	✓
Post condition	Turn Off the system	System is Off	✓
	The cells are partially filled with NaOH solution		✓
	The cells are filled totally with NaOH solution		✗

Data collected during test:



Electrolysis test 05.05.2023				
Time	**U [V]**	**I [A]**	**T [°C]**	**Notes**
11:32:00	8.58	15.3	29	
11:34:00	8.97	12.6	33	
11:35:00	9	8.4	34	
11:36:00	9	8.2	44	
11:37:00	9	7.4	62	
11:38:00	11.8	7.7	80	
11:39:00	11.9	6.3	71	
				BREAK
11:43:00	9	15.4	47	
11:44:00	11.8	15	47	
11:45:00	11.9	14.2	51	
11:46:00	11.9	12.5	51	
11:46:30	11.9	9	53	
11:47:00	11.9	7.1	52	
11:47:30	11.9	6.8	52	
11:48:00	11.9	7.1	50	
11:49:00	11.9	7.3	48	
11:50:00	11.9	10	50	
11:50:10	11.9	8	52	
11:50:30	11.9	6	54	
11:50:45	11.9	11.6	53	
11:51:40	11.9	7	56	
11:52:00	11.9	12.8	60	
11:53:00	11.9	9.3	64	Add water
11:54:00	9	12	64	
11:55:00	9	10	74	
11:56:00	11.9	7.8	77	Stable and steady flame
11:57:00	11.9	6.9	78	
11:58:00	11.9	12.7	73	
11:58:20	11.9	11.6	74	
11:58:40	11.9	13.2	74	
11:59:00	11.9	13.9	78	
12:00:00	11.9	13.3	85	
12:01:00	11.9	10	95	
12:01:30	11.9	9.4	95	
12:02:00	11.9	9.8	97	
12:02:00	11.9	9	97	
12:03:00	11.9	10	98	

12:03:45	11.9	11	102	
12:04:00	11.9	14.9	98	
12:05:00	11	17	98	
12:06:00	11	9	94	
12:07:00	11	13	93	
12:07:30	11.9	8	95	
12:08:00	11.9	11	92	
12:08:45	11.9	8.7	93	
12:09:00	11.9	13.6	95	
12:09:30	11.9	14	95	
12:10:00	11.9	10.8	95	
12:11:00	11.9	12	97	
12:12:00	11.9	12.5	99	
12:13:00	11.9	13.3	99	
12:13:30	11.9	8.8	98	
12:14:00	11.9	10	100	
12:14:30	11.9	13	100	
12:14:40	11.9	15	100	
12:15:00	11.9	9	99	
12:16:00	11.9	11.5	98	
12:17:00	11.9	10.1	96	
12:18:00	11.9	8.1	95	
12:19:00	11.9	14	93	
12:19:30	11.9	9.3	97	
				BREAK
				O2 condenser is more warm than H2 condenser
12:23:00	9.93	14	66	
12:25:00	9.93	12.7	62	
12:27:00	9.93	11	98	
12:29:00	9.93	8.7	93	



⚠ **Note:**

1. he intensity (I) measures the AC, while the voltage (V) measures the DC.

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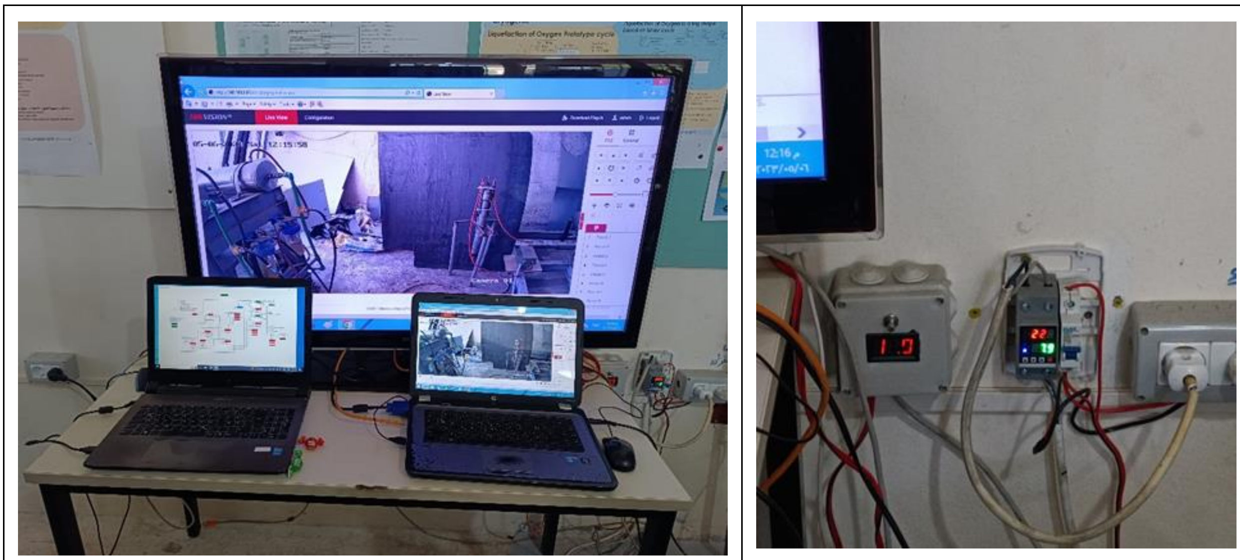
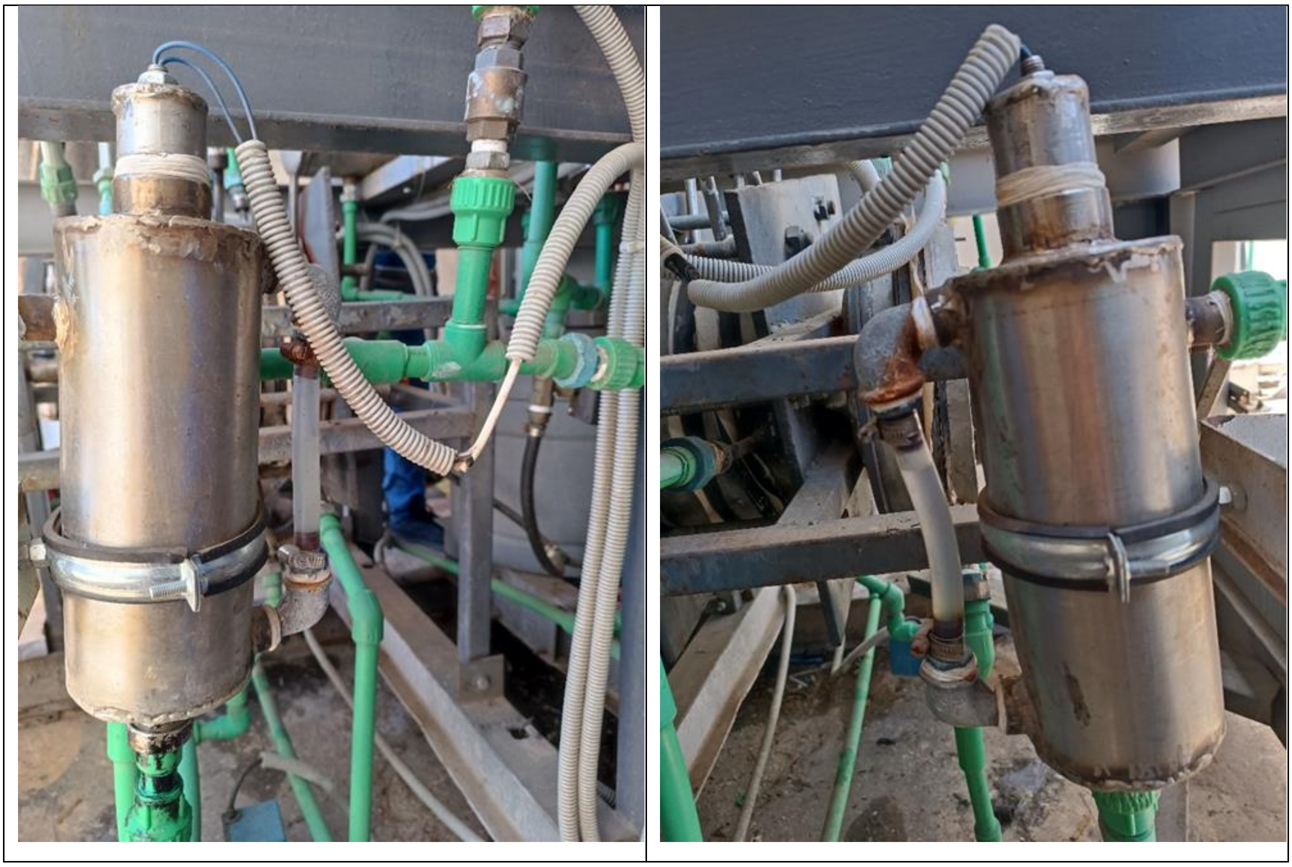
2. The inlet of O_2 condenser is too warm than inlet of H_2 condenser.

Result view:



Level sensors: on the left side, the level sensor placed on the anodic half-cell. On the right side, the level sensor placed on cathodic half-cell.



Conclusion:

At the end of the test, we found that the water level in the sensor was almost identical. Which means that the pressure differential problem has been preliminarily resolved.

7.5.2 Electrolyzer test 28.06.2023[4]

For the purpose of measuring the DC intensity of the cells system, an intensity sensor (Ammeter) with a capacity of 200 A has been installed.

Goal:

This test aims to collect the DC intensity data of the system cells during operation, in order to know the amount of hydrogen and oxygen gas generated.

Expected result:

Obtaining the required DC intensity data to balance it with the amount of Hydrogen and Oxygen gas generated.

If this is achieved, we can estimate the amount of hydrogen produced and thus select a suitable flowmeter for the hydrogen gas emitted

Test specifications:

00010: A simple test of an Electrolysis system -Case without add water-

Steps	Steps description	Excepted result	Result
Precondition	System is Off		✓
	The cells are partially filled with NaOH solution		✓
Run pump to fill the cells	Open the valves (V_3) & (V_4) from the GUI	(V_3) & (V_4) are opened and enable to let the	✓

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[4] from NLAP-WEDC Report 2023, Chapter 5

with the NaOH solution		electrolyte solution pass	
	Click "Start" on the Electrolyte bottom from the GUI	The cells enable to filled with electrolyte solution	✓
	Wait 5 seconds, the pump (P_1) run automatically	The pump (P_1) is turned On	✓
Turn Off the pump when the cells are filled with NaOH solution	When (L_3) & (L_4) go from "Low" to "High", turn Off the pump from the GUI	The cells filled with electrolyte solution	✓
		Pump (P_1) turned Off	✓
Close the valves (V_3) & (V_4)	Turn Off the valves (V_3) & (V_4) from the GUI	The valves (V_3) & (V_4) are closed	✓
Wash the system with Nitrogen gas	Open the valves (V_1) & (V_2) from the GUI	The valves (V_1) & (V_2) are open and enable to let the nitrogen gas pass	✓
	Close the blue ball valve of the water tank manually	The blue ball valve is closed	✓
		The Nitrogen gas pass through the system	✓

	Open the bottle of Nitrogen gas 5 minutes @ 4 bars	The air bubbles appear (generate) in the Gas AutoSafety	✓
	Turn Off the Nitrogen bottle by its gate valve manually	The Nitrogen bottle is closed	✓
		The air bubbles disappear (doesn't generate) in the Gas AutoSafety	✓
	Open the blue ball valve of water tank manually	The blue ball valve is opened	✓
	Close the valves (V_1) & (V_2) from the GUI	The valves (V_1) & (V_2) are closed	✓
Turn ON the burner to burn the gas	Click "Start" on Fuel Burner from the GUI	The transformer is turned On	✓
		The burner is turned On	✓
		Redness of the metal strip of the burner	✓
Connect the Power Supply on the system	Ensure that the pump (P_1) is turned Off	Pump (P_1) is closed	✓
		The Power Supply is On	✓

	Click "Start" on the Power Supply bottom from the GUI	The system is generating Hydrogen and Oxygen	✓
		5 minutes after turning On the burner, a flame appears	✓
Disconnect the Power Supply on the system	Click "Stop" on Power Supply bottom from the GUI	The electricity is turned Off from the system	✓
		The generation of Hydrogen and Oxygen are stopped	✓
Turn Off the fuel burner	Click "Stop" on the Fuel Burner bottom from the GUI	Burner (Transformer) is Off	✓
	Click "Stop" on the valves (V_1) & (V_2) from the GUI	The valves (V_1) & (V_2) are closed	✓
		Flame disappears (is Off)	✓
Re-wash the system with Nitrogen gas	Open the valves (V_1) & (V_2) from the GUI	The valves (V_1) & (V_2) are open and enable to let the nitrogen gas pass	✓
	Close the blue ball valve of the water tank manually	The blue ball valve is closed	✓

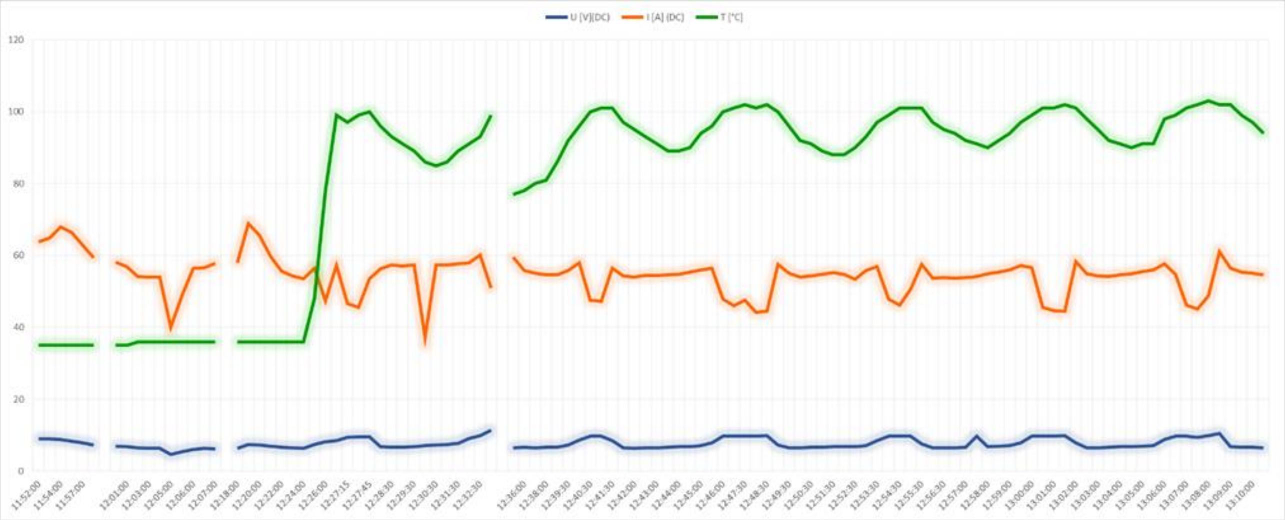
	Open the bottle of Nitrogen gas 5 minutes @ 4 bars	The Nitrogen gas pass through the system	✓
		The air bubbles appear (generate) in the Gas AutoSafety	✓
	Turn Off the Nitrogen bottle by its gate valve manually	The Nitrogen bottle is closed	✓
		The air bubbles disappear (doesn't generate) in the Gas AutoSafety	✓
	Open the blue ball valve of water tank manually	The blue ball valve is opened	✓
	Close the valves (V_1) & (V_2) from the GUI	The valves (V_1) & (V_2) are closed	✓
Post condition	Turn Off the system	System is Off	✓
	The cells are partially filled with NaOH solution		✓
	The cells are filled totally with NaOH solution		✗

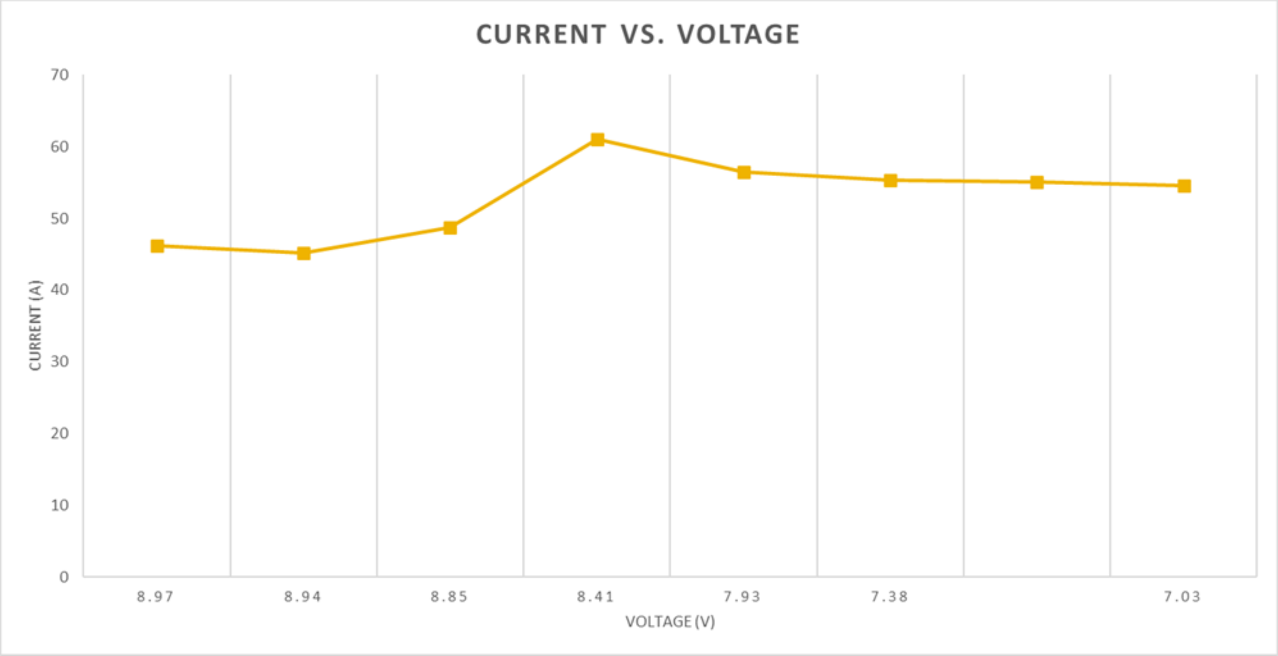
Data collected during test:

Time	U [V](DC)	I [A] (DC)	T [°C]	Notes
11:52:00	8.97	63.78	35	
11:53:00	8.94	64.8	35	
11:54:00	8.85	68	35	
11:56:00	8.41	66.47	35	
11:57:00	7.93	62.86	35	
11:58:00	7.38	59.43	35	
				BREAK ON/OFF
12:00:00	7.03	58.21	35	
12:01:00	6.8	56.89	35	
12:02:00	6.55	54.1	36	Appearance of Hydrogen gas
12:03:00	6.45	54.01	36	
12:04:00	6.32	54.08	36	
12:05:00	4.7	40.07	36	
12:05:30	5.44	49.15	36	
12:06:00	6.13	56.51	36	
12:06:30	6.36	56.6	36	
12:07:00	6.24	57.8	36	
				BREAK ON/OFF
12:18:00	6.41	58	36	
12:19:00	7.43	68.78	36	
12:20:00	7.36	65.57	36	
12:21:00	7.03	59.85	36	
12:22:00	6.7	55.74	36	
12:23:00	6.54	54.35	36	
12:24:00	6.39	53.53	36	
12:25:00	7.39	56.48	48	Stable and steady flame
12:26:00	8.19	47.44	78	
12:27:00	8.54	57.23	99	
12:27:15	9.51	46.7	97	
12:27:30	9.63	45.6	99	
12:27:45	9.55	53.55	100	
12:28:00	6.82	56.28	96	
12:28:30	6.7	57.35	93	
12:29:00	6.74	57	91	
12:29:30	6.9	57.35	89	
12:30:00	7.11	37.29	86	
12:30:30	7.23	57.42	85	
12:31:00	7.39	57.36	86	
12:31:30	7.81	57.67	89	
12:32:00	9.14	58	91	
12:32:30	9.95	60.06	93	
12:32:45	11.43	51	99	
				BREAK ON/OFF

12:35:00	6.5	59.56	77	
12:36:00	6.63	55.78	78	
12:37:00	6.6	55.08	80	
12:38:00	6.63	54.6	81	
12:39:00	6.73	54.6	86	
12:39:30	7.28	55.78	92	
12:40:00	8.62	58.01	96	
12:40:30	9.71	47.61	100	
12:41:00	9.77	47.22	101	
12:41:30	8.55	56.48	101	
12:41:45	6.53	54.3	97	
12:42:00	6.4	54.04	95	
12:42:30	6.49	54.41	93	
12:43:00	6.57	54.4	91	
12:43:30	6.67	54.57	89	
12:44:00	6.81	54.79	89	
12:44:30	6.91	55.37	90	
12:45:00	7.16	55.95	94	
12:45:30	7.94	56.53	96	
12:46:00	9.76	47.9	100	
12:47:00	9.8	46	101	
12:47:30	9.78	47.6	102	
12:48:00	9.82	44.23	101	
12:48:30	9.86	44.46	102	
12:49:00	7.23	57.55	100	
12:49:30	6.57	55.04	96	
12:50:00	6.6	54.04	92	
12:50:30	6.72	54.37	91	
12:51:00	6.73	54.81	89	
12:51:30	6.9	55.2	88	
12:52:00	6.83	54.71	88	flame
12:52:30	6.91	53.32	90	flame
12:53:00	7.17	55.77	93	flame
12:53:30	8.5	56.94	97	
12:54:00	9.72	47.87	99	
12:54:30	9.78	46.13	101	
12:55:00	9.81	50.7	101	
12:55:30	7.6	57.48	101	
12:56:00	6.5	53.63	97	
12:56:30	6.48	53.82	95	
12:56:45	6.5	53.74	94	
12:57:00	6.64	53.85	92	
12:57:30	9.75	54.2	91	
12:58:00	6.83	54.86	90	
12:58:30	7.02	55.45	92	

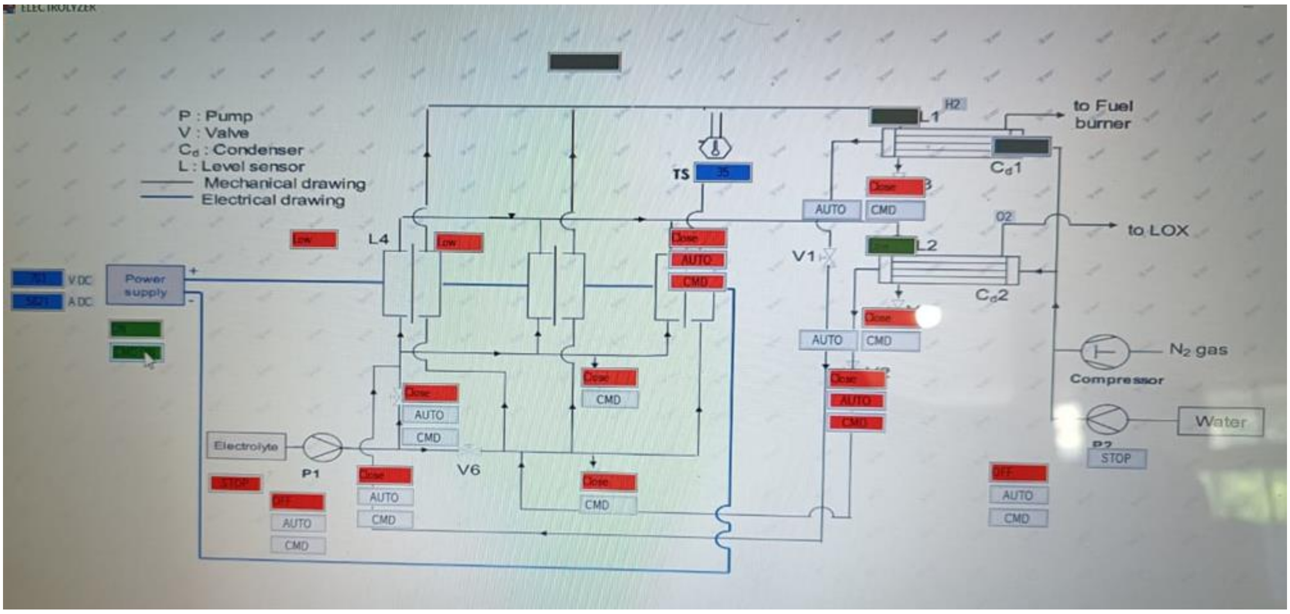
12:59:00	7.15	56.04	94	
12:59:30	7.87	57.25	97	Flame
13:00:00	9.76	56.6	99	
13:00:30	9.83	45.59	101	
13:01:00	9.83	44.68	101	
13:01:30	9.85	44.51	102	
13:02:00	7.92	58.23	101	
13:02:30	6.55	54.89	98	
13:03:00	6.59	54.24	95	
13:03:30	6.68	54.14	92	Flame
13:04:00	6.78	54.64	91	Flame
13:04:30	6.85	54.89	90	Flame
13:05:00	6.95	55.52	91	Flame
13:05:30	7.19	55.92	91	Flame
13:06:00	8.77	57.65	98	Flame
13:06:30	9.77	54.77	99	Flame
13:07:00	9.79	46.18	101	
13:07:30	9.48	45.12	102	
13:08:00	9.96	48.74	103	
13:08:30	10.59	61	102	
13:09:00	6.85	56.44	102	
13:09:30	6.64	55.39	99	
13:10:00	6.65	55.09	97	
13:10:30	6.61	54.59	94	




CURRENT VS. VOLTAGE
CURRENT (A)
70
60
50
40
30
20
10
0
8.97
8.94
8.85
8.41
7.93
7.38
7.03
VOLTAGE (V)

Result view:


Camera 01



Conclusion:

Test passed successfully. The next step is to install the produced hydrogen meter.

7.5.3 Membrane test

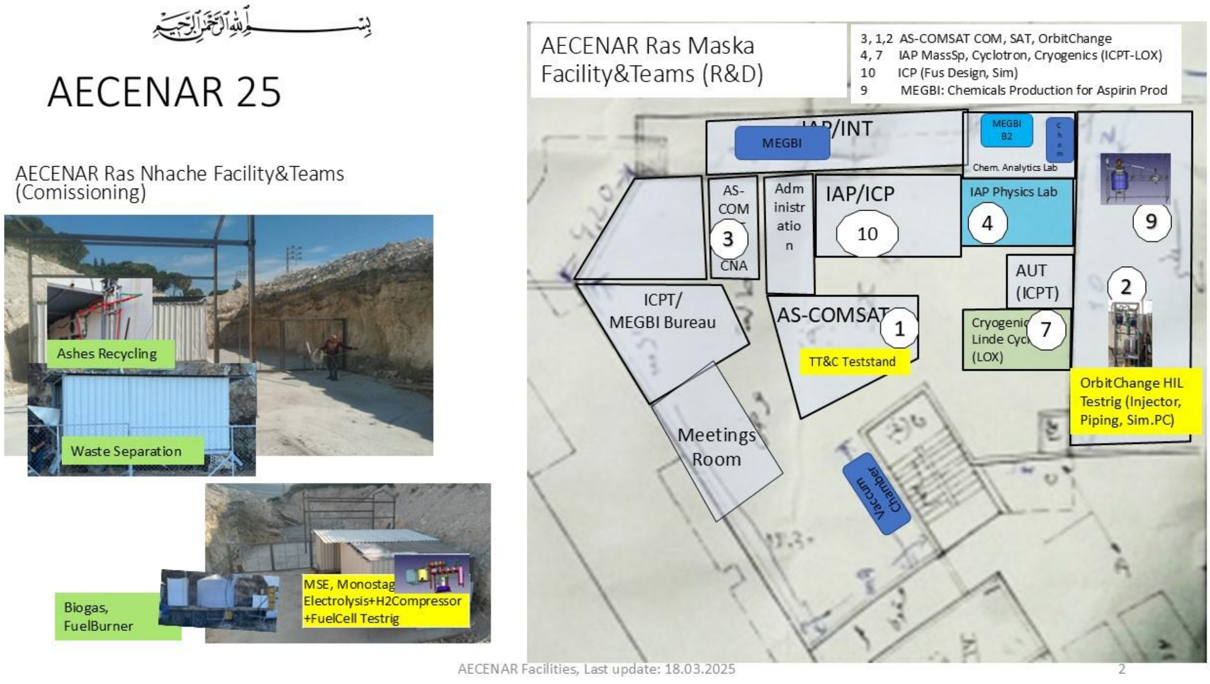
Following comprehensive modifications to the proposed connections, the existing membrane was replaced with a Nafion membrane. A subsequent electrolysis cell test revealed unsatisfactory performance. An investigation determined that the Nafion membrane, by its inherent nature, exhibits selective proton permeability while restricting anion passage. This characteristic rendered it unsuitable for our operational requirements. Consequently, the Nafion membrane must be replaced with an alternative, such as an Anion Exchange Membrane (AEM), which facilitates the passage of anions, thus enabling the desired electrochemical processes.

7.6 What’s next

To complete the applied part of the electrolysis project, we have to change the Nafion membrane to another from the type AEM membrane, and then test it.

After the test's success, we had to do a long-term experiment, which showed us the model's endurance and the amount of hydrogen and oxygen produced over time. After completing this step, we will move to operating several cells simultaneously.

7.7 What’s next



بسم الله الرحمن الرحيم

AECENAR 25

AECENAR Ras Nhache Facility&Teams (Comissioning)

AECENAR Ras Maska Facility&Teams (R&D)

3, 1,2 AS-COMSAT COM, SAT, OrbitChange
4, 7 IAP MassSp, Cyclotron, Cryogenics (ICPT-LOX)
10 ICP (Fus Design, Sim)
9 MEGBI: Chemicals Production for Aspirin Prod

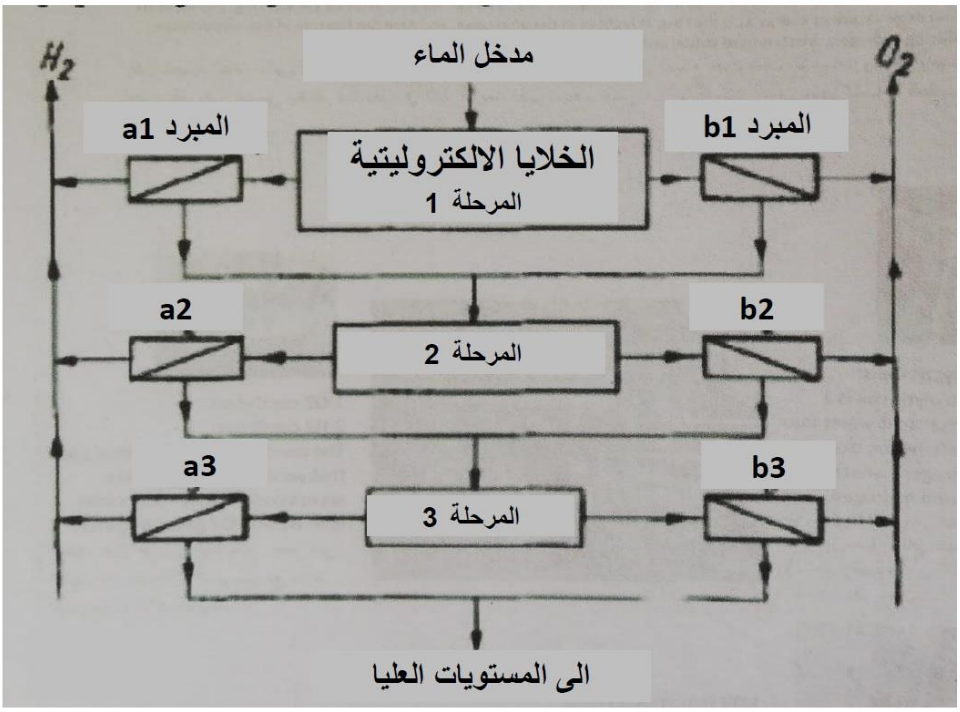
AECENAR Facilities, Last update: 18.03.2025 2

Commisioning at Ras Nhache

8 Project C 21: Multistage Electrolysis (ICPT-MSE)

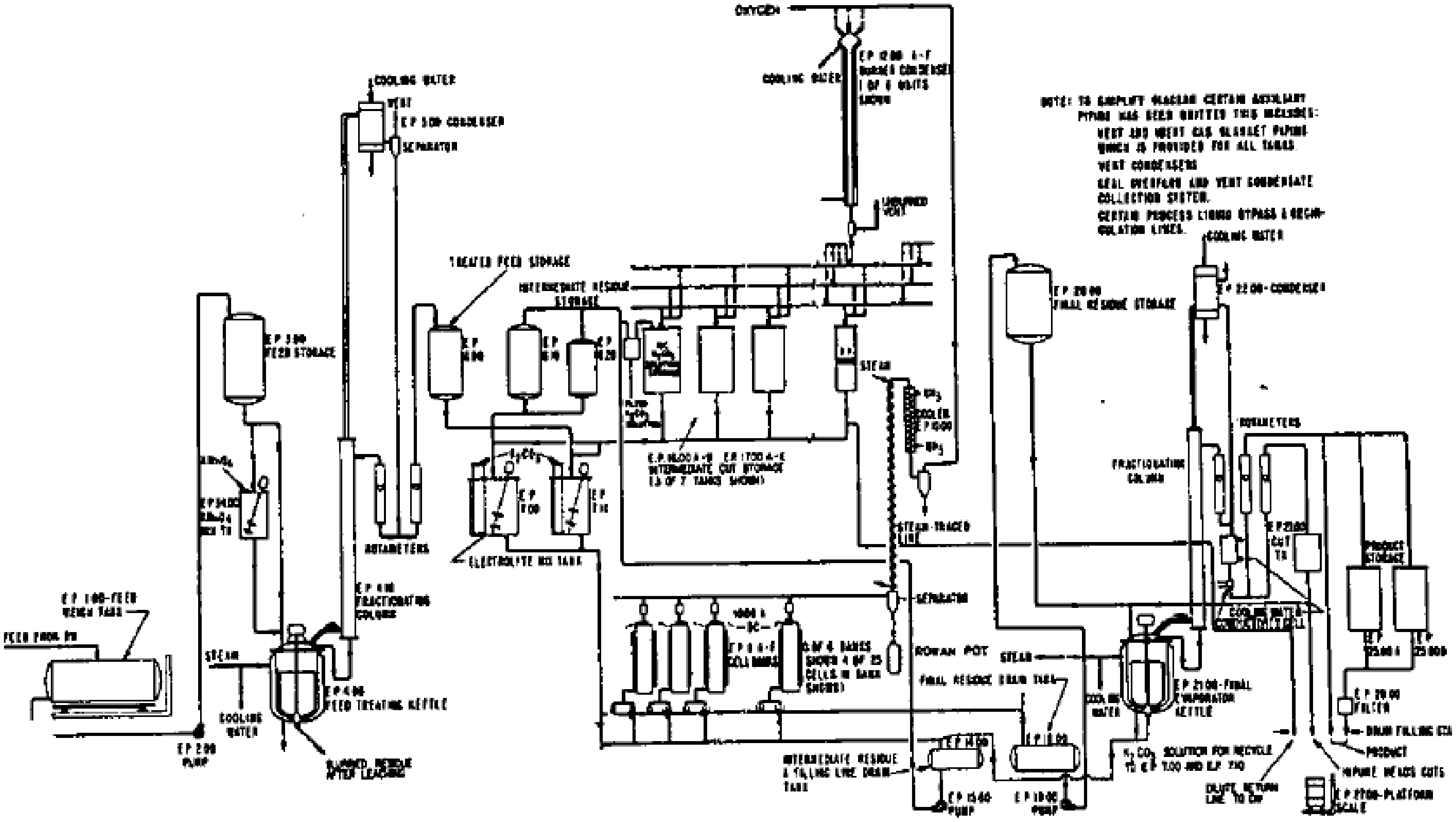
8.1 Stages 1-9

A continuously working plant is working as following: The level of the fresh water of the electrolysis cells 1 is hold constant, while the condensed water from the drying process of hydrogen and oxygen in the coolers a1 and b1 is going to the cells of stage 2. Stage 3 is fed by the coolers a2 and b2 etc. The throughput is getting lower the higher the stage is.



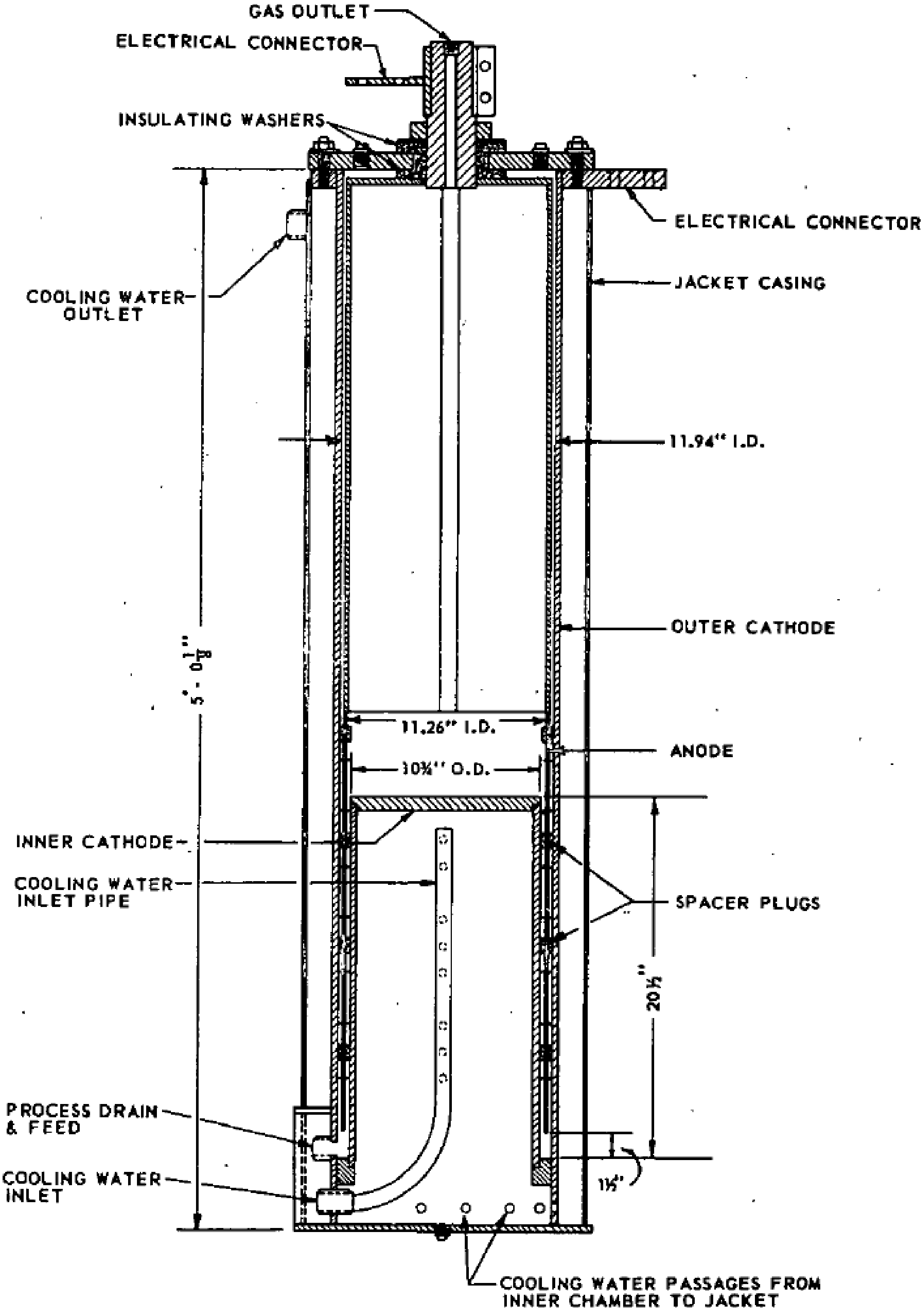
يعمل المصنع بشكل مستمر على النحو التالي: يدخل الماء العذب لخلايا التحليل الكهربائي 1 ثابت، بينما الماء المكثف من عملية تجفيف الهيدروجين والأكسجين في المبرداتa1 وb1 يذهب إلى خلايا المرحلة 2. يتم تغذية المرحلة 3 بواسطة المبردات a2 و b2 وما إلى ذلك. ينخفض معدل النقل كلما ارتفعت المرحلة.

8.2 Stages 10-14

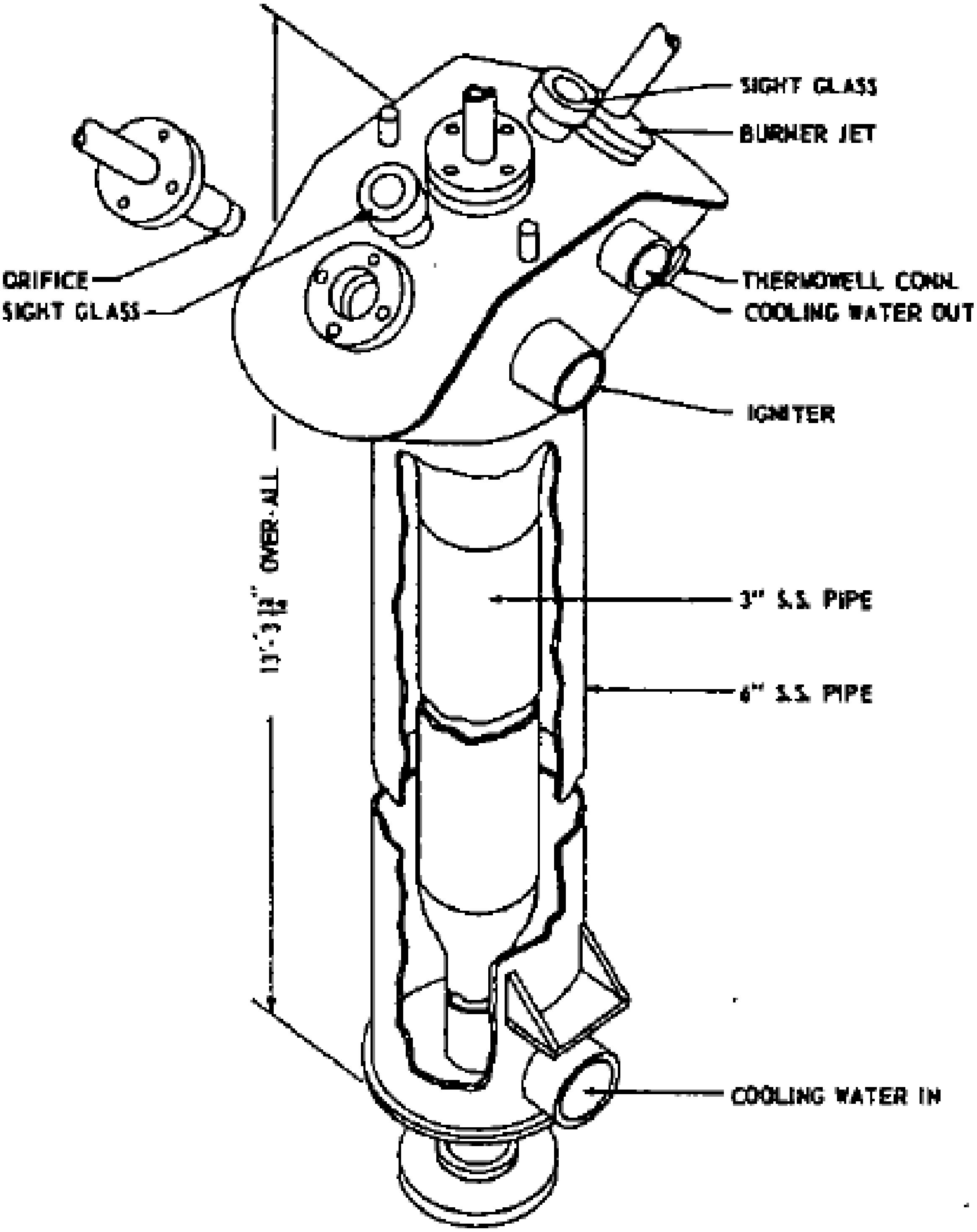


Project C 21: Multistage Electrolysis (ICPT-MSE)

Countious Electrolysis Plant with burning of the hydrogen.



Electrolytic Cell



Electrolytic burner-condenser. The nozzles are used singly. Burner chamber is stainless steel. The jacket is carbon steel.

---

9 Project C 22: Multistage Electrolysis (ICPT - MSE)

9.1 Position of Multistage electrolysis project

Work on this project will begin this year. The project was studied theoretically, and the first part of of the project was designed, but it was not implemented, provided that the first part and the remaining parts will be implemented in the following years.

9.2 Mechanical design

In this paragraph we will present the mechanical design of multistage electrolysis

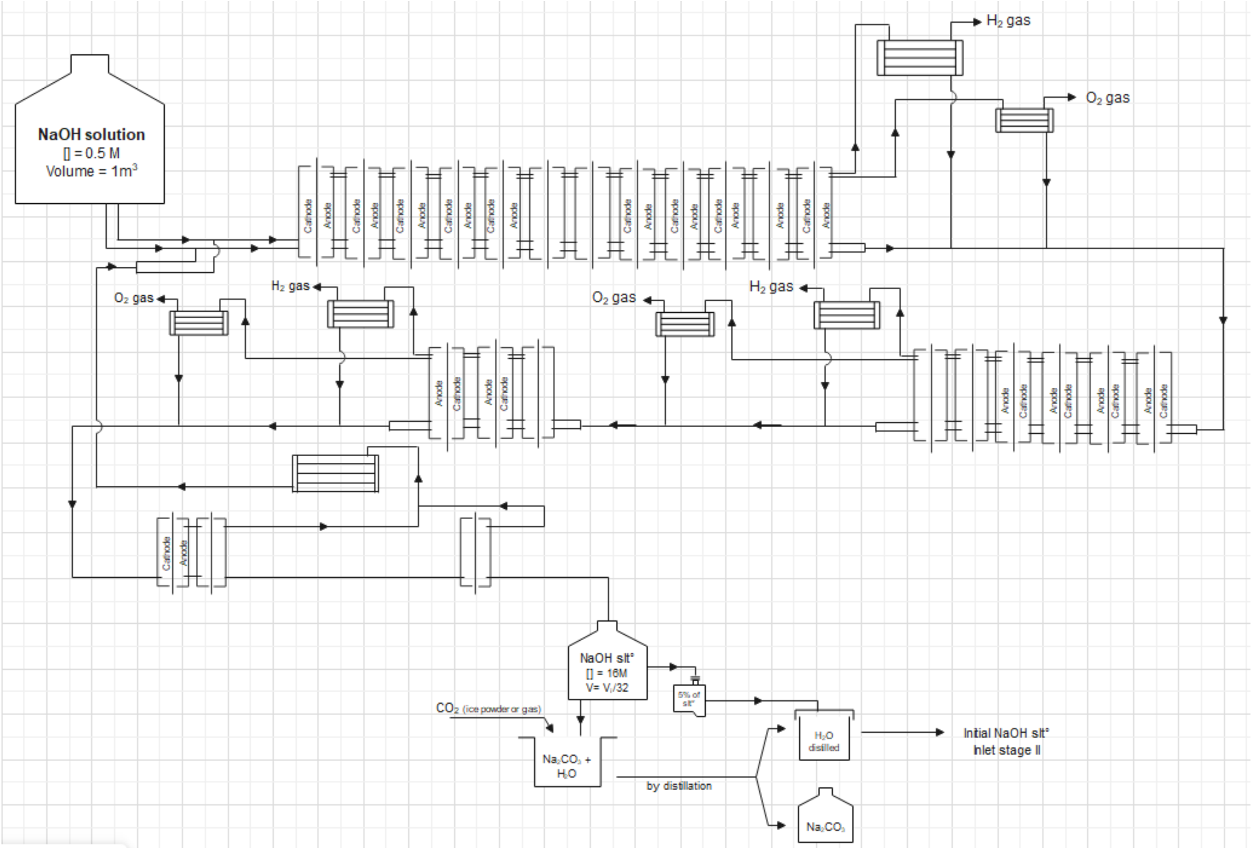
1) Electrolysis multistage design overview

The process is divided into 3 parts:

- Part I: Multistage electrolysis
- Part 2: Add carbon dioxide to the electrolyte solution
- Part 3: Distillation of the mixture

The multistage of electrolysis, as its name indicates, consists of several successive stages. The first part usually consists of five consecutive stages. The first three stages are similar to each other with a difference in volume as it shrinks to half in the second stage, and again to half in the next stage. As for the other two stages (stage 4 and 5), they are similar to each other and are not similar to the first three stages of design, while maintaining the size reduction in half between each stage and the next.

EDDX
25052022_multistag
e -GUI Stage 1.eddx



N.B.:

This Overview is not complete; it lacks pumps, compressors, sanitary installations for cooling water as well as electrical connections.

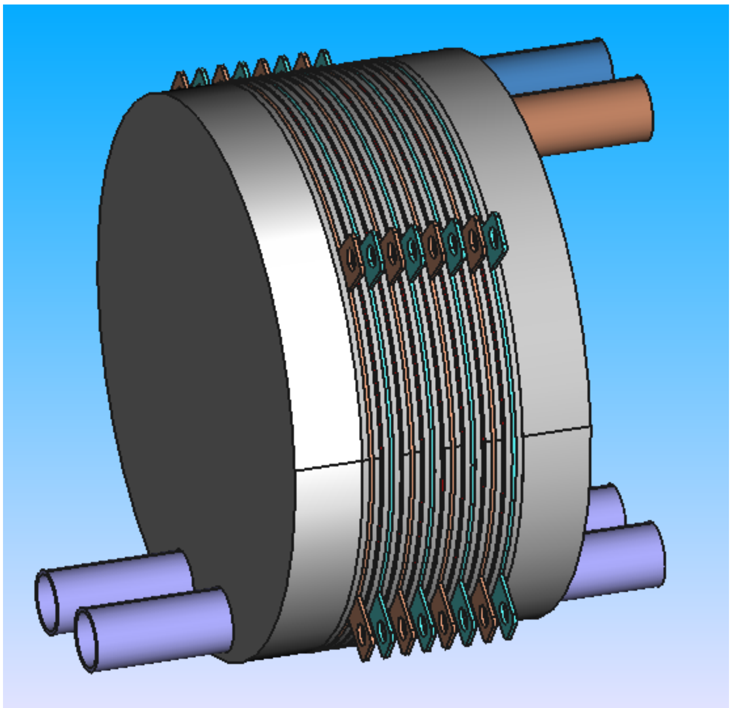
2) Design of electrolysis for steps 1, 2 & 3 and for steps 4 & 5

Electrolysis in stage 1 is divided to 5 steps. Step 1, 2 & 3 the production of hydrogen & oxygen separately, while each step 4 & 5 in which produces hydrogen and oxygen mixture to be burned.

In this paragraph, designs for each step of electrolysis multistage will be represented.

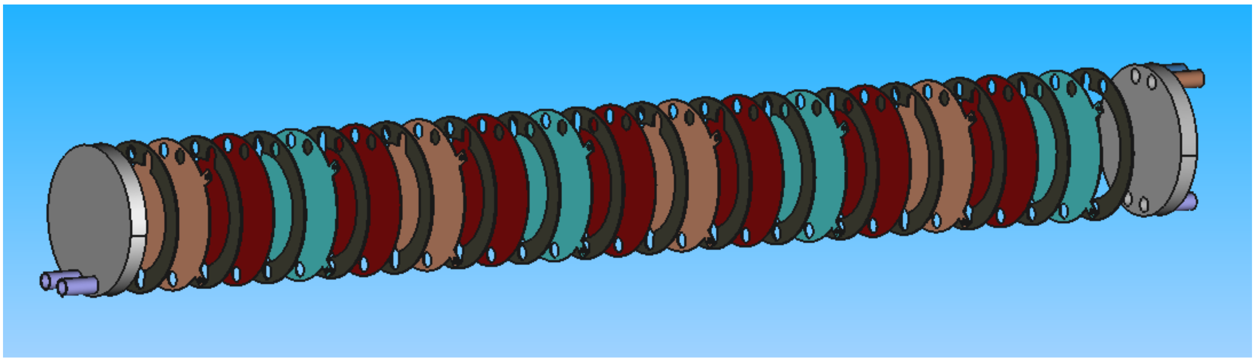
a) Electrolysis step 1, 2 & 3 _ All components -compressed-

20052022_all components COMPRESSED_step1,2,3.FCStd



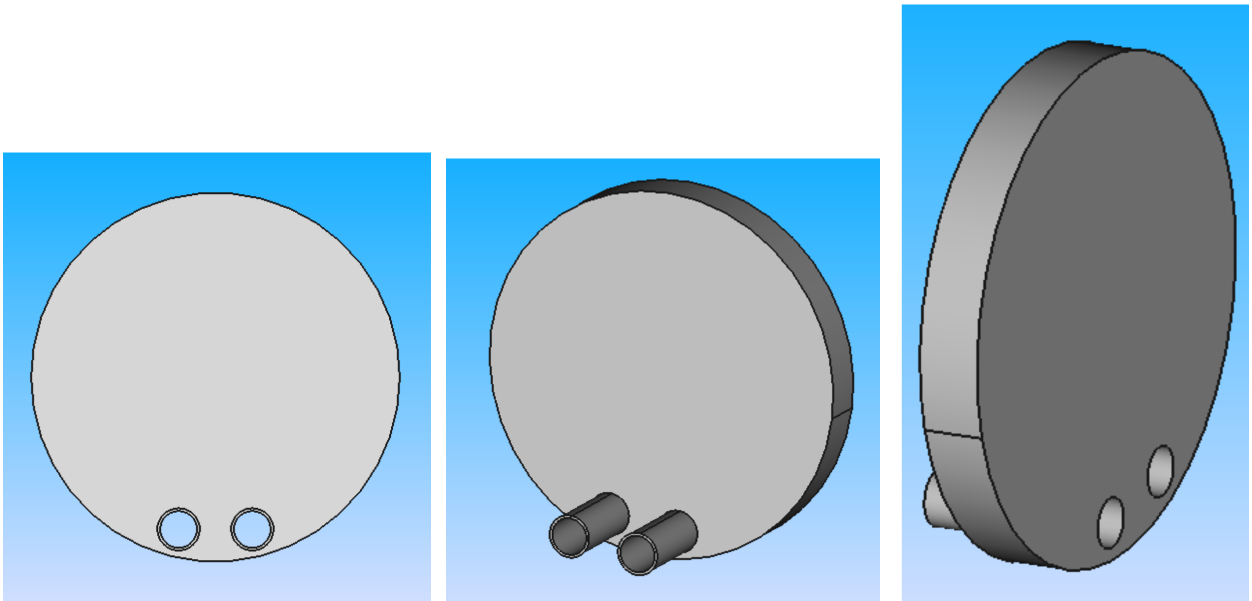
b) Electrolysis step 1, 2 & 3 _ All components -explosed-

20052022_all
components EXPLOS



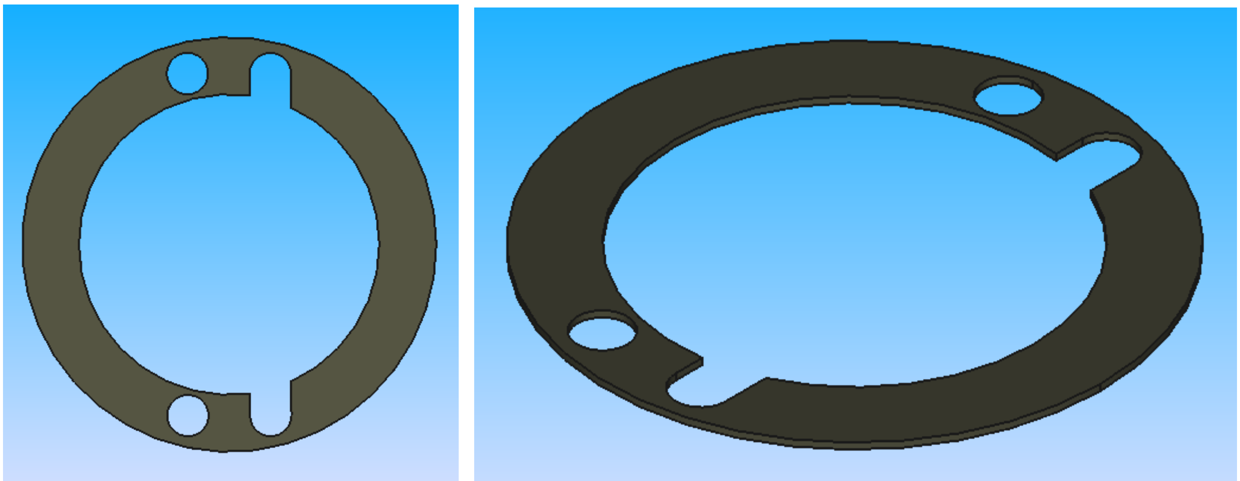
c) Electrolysis step 1, 2 & 3 _ End plate1 (inlet solution)

12052022_end plate
1 (jnlet slt)_ step1,2,



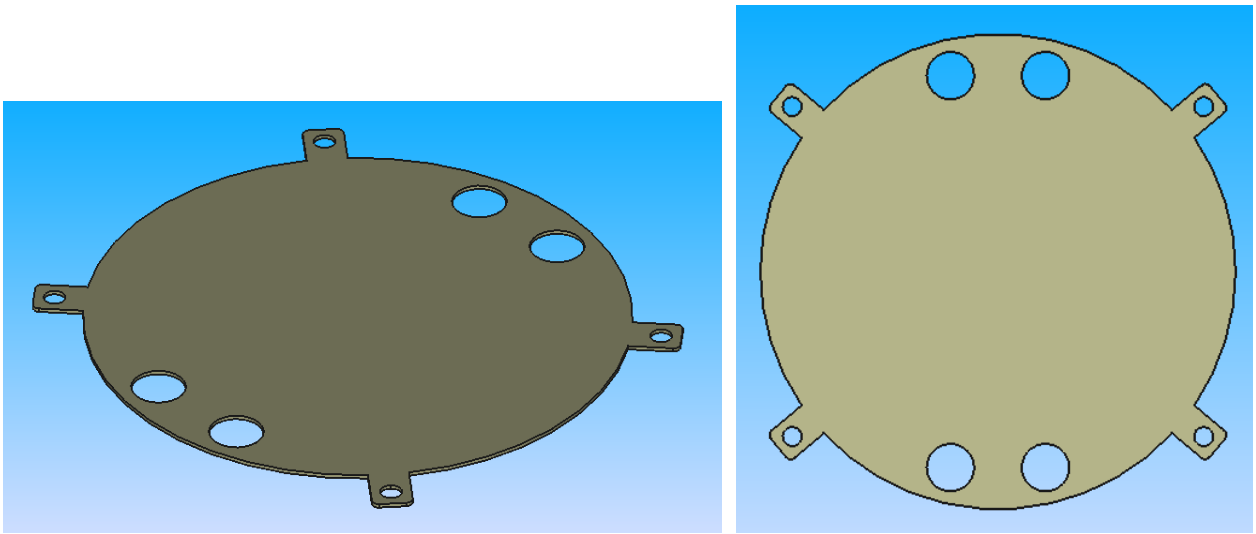
d) Electrolysis step 1, 2 & 3 _ Gasket

12052022_Gasket
_step1,2,3.FCStd



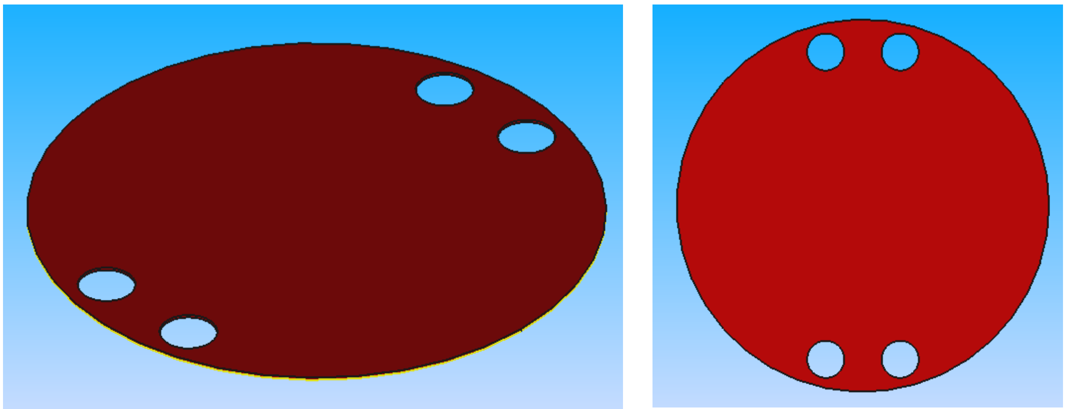
e) Electrolysis step 1, 2 & 3 _ Electrode

12052022_electrode
plate _step1,2,3.FCS



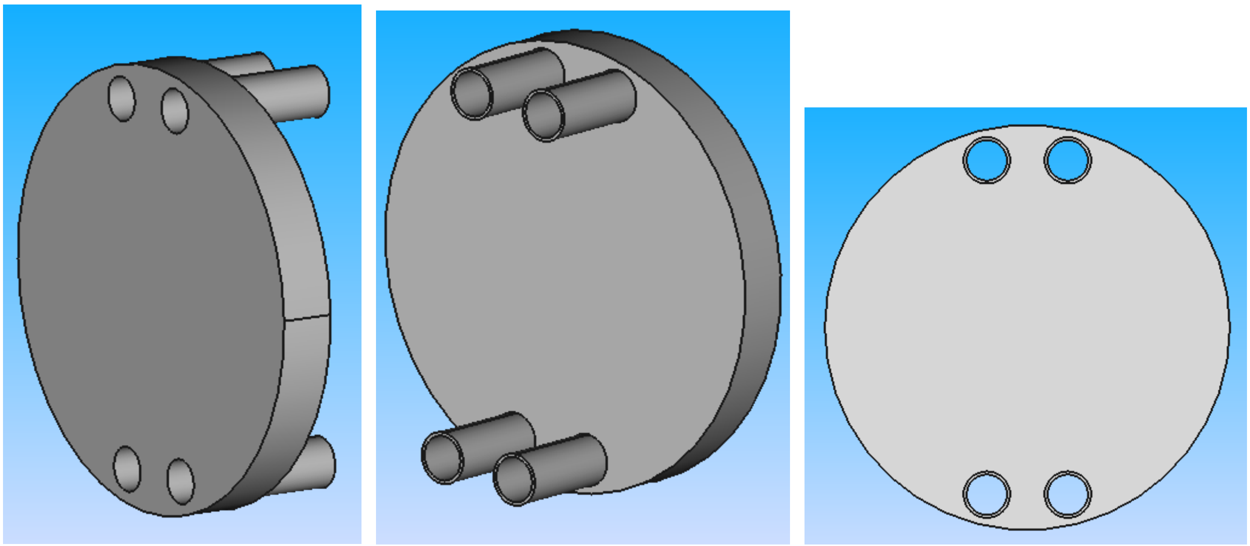
f) Electrolysis step 1, 2 & 3 _ Membrane

13052022_membrane _step 1,2,3.FCStd



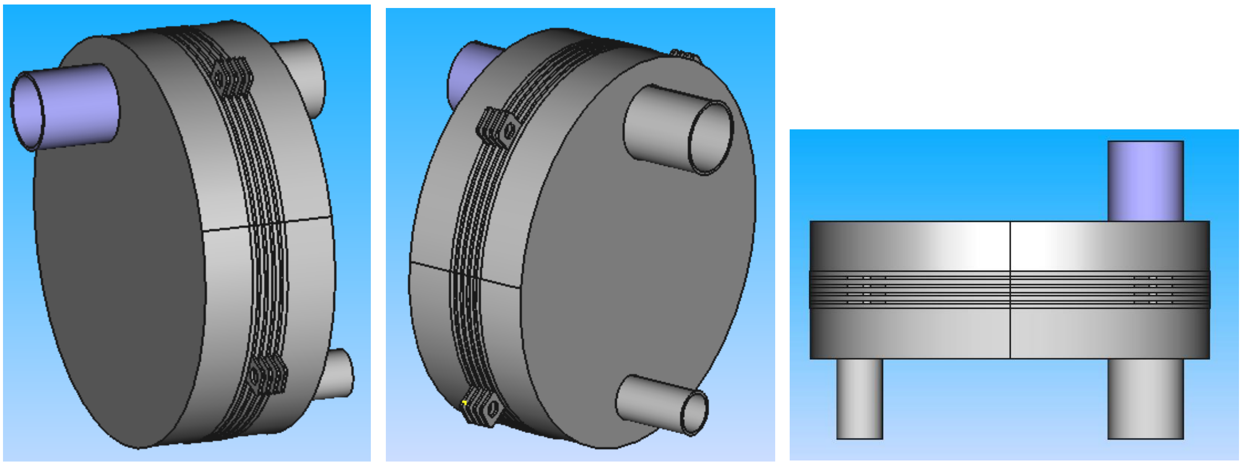
g) Electrolysis step 1, 2 & 3 _ End plate 2 (Outlet solution)

19052022_end plate 2 (outlet slt)_ step 1,



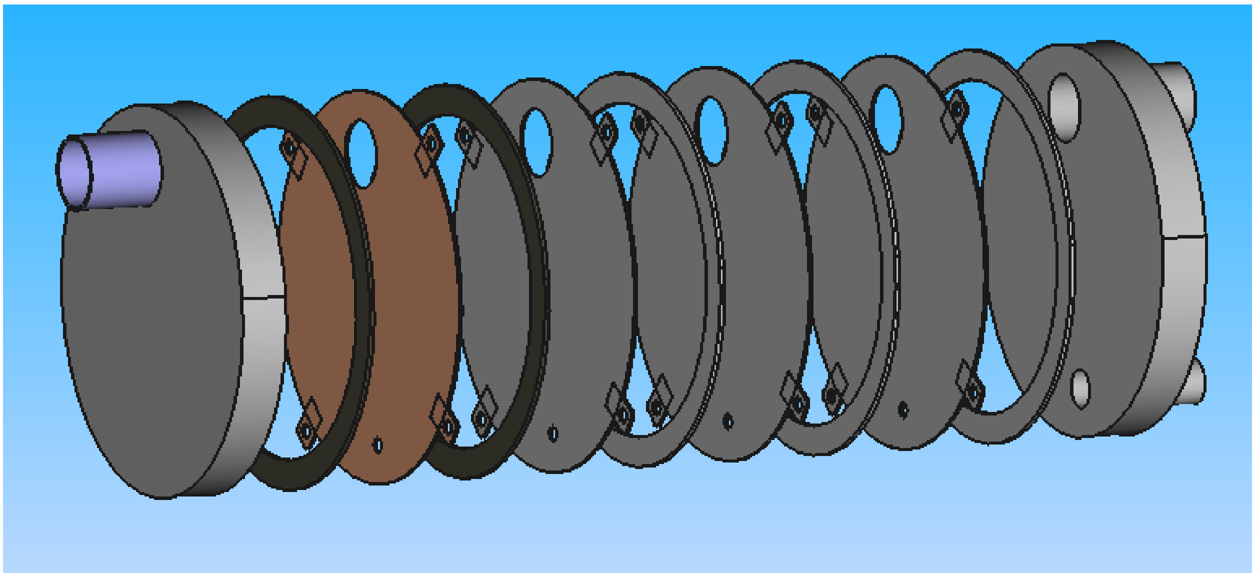
h) Electrolysis step 4 & 5 _ All components -compressed-

27052022_all
components COMP



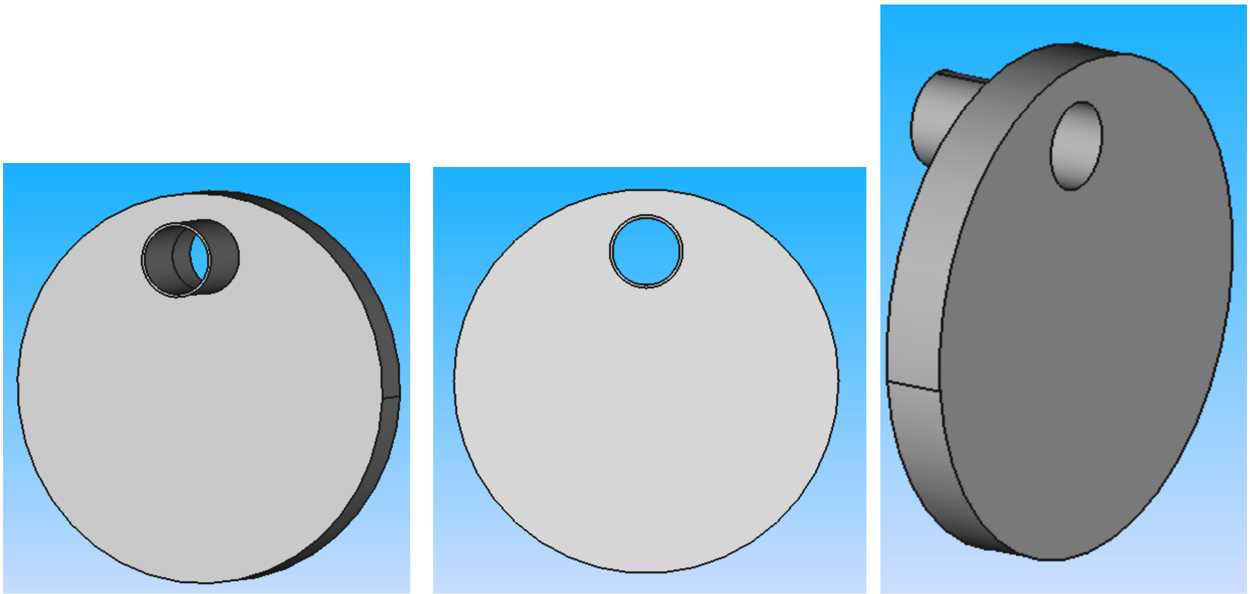
i) Electrolysis step 4 & 5 _ All components -Explosed-

27052022_all
components EXPLO



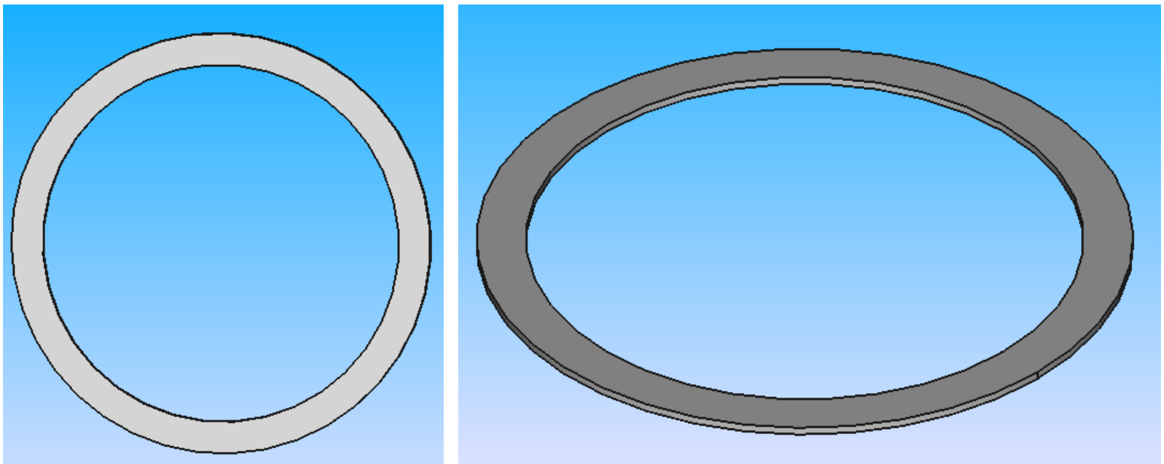
j) Electrolysis step 4 & 5 _ End plate1 (Intlet solution)

25052022_end plate
1 (inlet slt) _step 4,5.



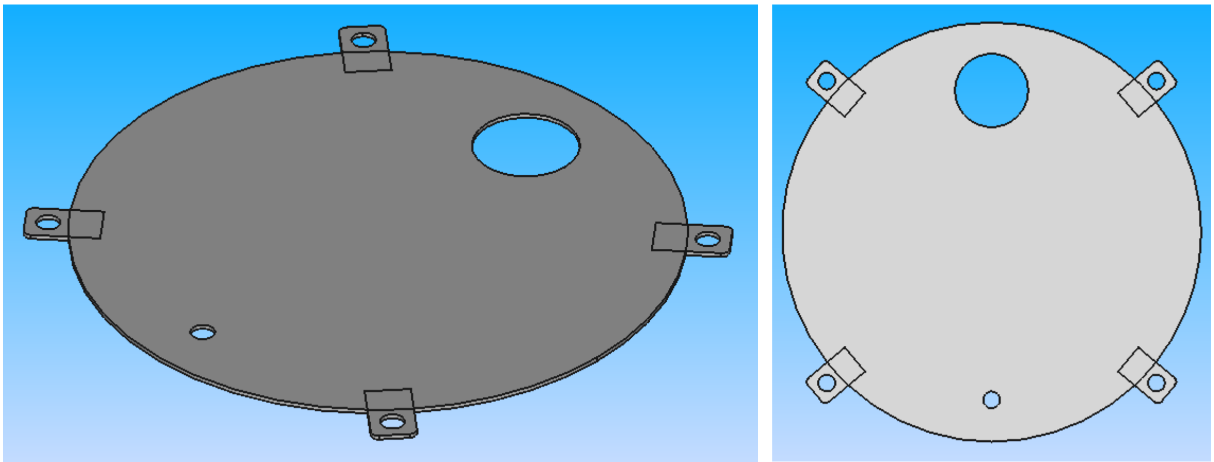
k) Electrolysis step 4 & 5 _ Gasket

25052022_gasket
_step4,5.FCStd



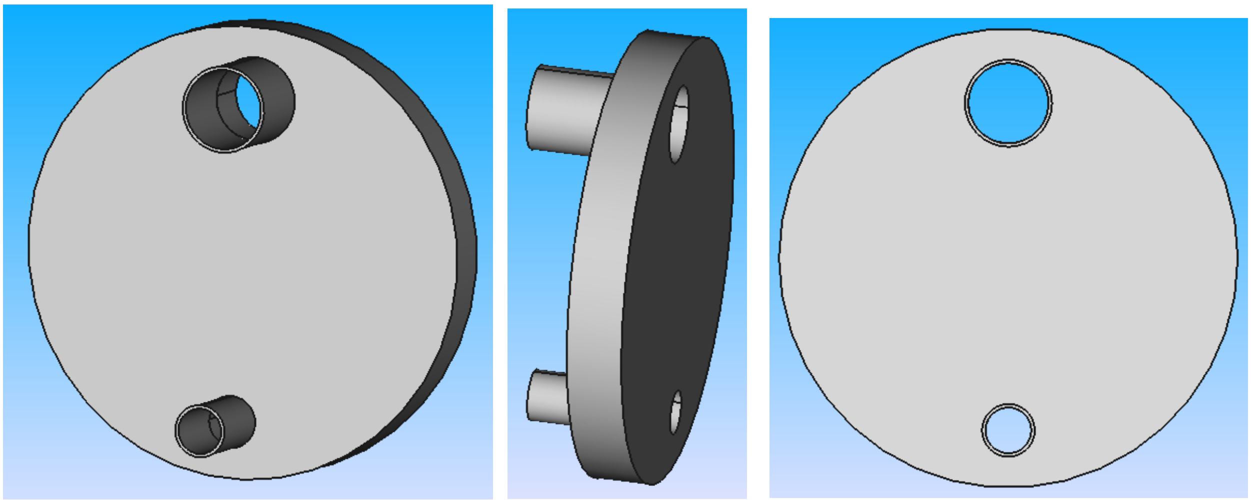
l) Electrolysis step 4 & 5 _ Electrode

25052022_electrode
_step4,5.FCStd



m) Electrolysis step 4 & 5 _ End plate 2 (Outlet solution)

25052022_end plate
2 (outlet slt) _step4,



9.3 What's Next

After completing the theoretical and design part of the first part of the project, in the future, the practical part must be started, where the required materials are purchased for the purpose of creating and operating the model

.

10 Project C 23: Multistage Electrolysis (ICPT - MSE)

10.1 Position of Multistage Electrolysis Project

The project's theoretical underpinnings were solidified in 2022, leading to the development of the initial design. Subsequent years, 2023 and 2024, were marked by the meticulous refinement of the design, encompassing detailed sizing calculations, strategic material selection, and efficient procurement. This culminated in the implementation of the pilot project model.

10.2 Requirements

10.2.1 Product requirements of the multistage electrolyse cell

The material of the electrolyze: stainless steel 304

The thickness of the electrodes: thick enough to withstand the pressing without change in shape

The dimensions of the electrodes: consider the current calculated

Taking into account the relation:

$I = 0{,}4$ x the surface that touches the solution$=0{,}4 \times A=0{,}4\times3{,}14\times r^2$

The cell voltage is $U = 2{,}4$ Volt

The thickness of the gasket:

On the cathode side: 0,5 cm

On the anode side: 0,25 cm

The calculations must be done again taking into account the conductivity of the stainless steel 304

The resistivity of the stainless steel 304 is very small ($0{,}72*10^{-6}$ (ohm meter)$^{-1}$) so it can be neglect and the calculations above are correct.

The dimension of the endplates: a bit bigger in dimension then the electrodes and thin enough to withstand the stress of the screws

The dimension of the wholes for the screw in the endplates: asking a mechanist

The dimensions of the screws: asking a mechanist

The type of the membrane: search it in google available and to be searched which one is the best:

Nafion n117 price: 340USD/pcs for 30*30cm. or 136USD for 15*15cm.

Nafion n115 price: 136USD/pcs for 20*20cm.

NR212 price is 303USD/pcs, 61cm*30cm.

NR211 price is 114USD/pcs, 20*20cm

Nafion N115 price is 136USD/pcs for 20*20cm

All the named Nafion membranes are from Alibaba:

https://www.alibaba.com/product-detail/Ion-Exchange-Membrane-Manufacturer-In-China_1600326782762.html

The diameter of the wholes

Of the water inlet:

Of gas outlet:

The dimensions of the whole of the gasket based on the

The dimensions of the catalyzer of the upcoming water vapor based on the calculation of the temperature of the cells and the amount of the water vapor upcoming.

The current = I = 0,4 x the surface that touches the solution=0,4 x A=$0{,}4 \times 3{,}14 \times r^2$.

10.2.2 System requirements

- The system shall be able to produce essentially the HW.

- It shall also be able to produce hydrogen and oxygen separately as a by-product.

10.2.3 Mechanical requirements

- The electrodes shall be thick enough to withstand the pressing (the pressing of the screw rods).
- The electrodes shall be thick enough to press the gaskets so that no gas can exit.
- The gasket shall be able to prevent the leakage of gases and liquids from the stack (cell group).
- The gases (H_2/O_2) shall be able the pass separately through the holes of the gaskets, the electrodes, and the membranes in the stack.
- The membrane shall be able to separate two types of gas [H_2/O_2].
- The Endplate shall be thick enough to withstand the pressing of the stack.
- The pipe connections shall be able to resist the gas pressure without letting gas exit through.
- The pressure of the pump shall be sufficient to fill the cells and not too high for the pipes system.

- The water pipe shall be able to deliver water to the KOH tank, distillation tank, and burner rooms from the water tank.

- The condenser shall be able to condense the gas formed through the KOH solution.

- The gases formed shall be able to pass through the pipes of the condensers.

- The Nitrogen pipe shall be able to pass Nitrogen gas through the stacks, condensers, and filters.

- The distillation tank shall be able to distill water from the K_2CO_3 solution.

- The distilled tank shall be able to contain the HW.

- The Nitrogen gas tank shall be able to fill the stacks, the condensers, and the filers with Nitrogen gas.

- The water tank shall be able to fill the KOH tank and sufficient to cool the distillation tank and burners.

- The igniter shall be able to burn mixed gas with the presence of Oxygen gas.

- The water shall be able to condense the water vapor.

- The condensate water shall be returned to the KOH tank.

- The burner shall be able to collect the liquid inside it.

- The water pump shall be able to deliver water from the water tank to the components.

- The valves shall be able to close completely.

- The valves shall be able to open or close with independent pressure.

- The ball valve shall be able to pass the solution from one component to the other.

- The check valve shall be able to pass the solution in one direction (without return).

- The level sensor shall be able to show the liquid level in the component [or tank].

- The Flashback Arrestor shall be able to avoid the explosion of H_2 gas.

- The Flashback Arrestor shall be installed at the H_2 gas outlet.

- The stand shall be able to support the MSE components.

- The distillation tank shall be formed into two parts: upper and lower.

- The epoxy shall be able to join the stainless plate with the caoutchouc pipe.

10.2.4 Chemical requirements

- The electrodes shall be able to withstand the corrosion with KOH.

- The membrane shall be able to allow the ions to pass through so that electrolysis takes place when the current is connected.

- The membrane shall be able to insulate the two half-cells, chemically.

- The membrane shall be made of AEM (Anion Exchange Membrane).

- The pipe system used shall be able to withstand the corrosion with KOH.

- The valves shall be able to withstand the corrosion with KOH.

- The metal of the condenser used shall be able to withstand the corrosion with KOH.

- The pH sensor shall be able to measure the high concentration of the solution.

- The O_2 gas pipe shall be able to withstand the corrosion with O_2.

- The KOH tank shall be able to withstand the corrosion with KOH solution.

- The gas filter shall be able to withstand the corrosion of O_2 gas.

- The water shall be unable to limescale.

- The dry ice shall be able to react with KOH solution.

- The dry ice tank shall be able to withstand the corrosion of KOH and K_2CO_3 solutions.

- The distillation tank shall be able to withstand the corrosion of K_2CO_3 solution.

- The KOH pump shall be able to withstand the corrosion of the KOH solution.

- The sensors shall be able to withstand the corrosion of the KOH solution.

- The level sensor shall be able to withstand the corrosion of the KOH solution.

- The distillation tank shall be able (especially the lower part) to withstand the high concentration of K_2CO_3 solution.

- The pH meter shall be able to measure the pH of the distilled water produced, of the KOH solution entering and exiting into/from each stack, and of the K_2CO_3 solution.

- The end plate should be prohibited and isolated from any contact with the KOH solution.

- The thermoplastic silicone should be able to resist corrosion.

- The thermoplastic silicone should be able to resist reaction with chemicals, especially KOH solution.

- The epoxy shall be able to withstand the KOH solution (no reaction between epoxy glue and KOH solution).

10.2.5 Electrical requirements

- The wires shall be connected in parallel.

- For power supply, DC the current that passes through one cell shall be about 26.6 A for each gram of Hydrogen gas produced and the voltage shall be 2V for each cell in the stack.

- The power supply shall be able to let the electrolyze generate enough hydrogen so that we can burn it.

- The GUI shall be able to control all electrical components: valves, sensors, and pumps.

- The igniter shall be connected to the electricity and shall be controlled by GUI.

- The system shall be connected with the earth by the Ground wire.

- The end plate should be electrically insulated.

- The thermoplastic silicone shall be able to insulate materials electrically.

- The epoxy shall be able to insulate materials electrically.

10.2.6 Physical requirements

- The electrodes shall be able to withstand the electrolysis temperature.
- The electrodes shall be made of Nickel.
- The endplate shall be made in Stainless [or Plexy].
- The gasket shall be made of Silicone (good chemical resistance to KOH).
- The membrane shall be made in AEM (Anion Exchange Membrane).
- The temperature sensor shall be able to measure the electrolyte temperature, gas amount temperature, and the KOH solution temperature pass in the condenser.
- The water pipes shall be made of PPR pipe [or PVDF/Plastic].
- The KOH solution pipe shall be made of PVDF.
- The KOH solution pipe shall be able to withstand the electrolysis temperature.
- The O_2 gas pipe shall be made in Stainless [PVDF / PPR/ Caoutchouc].
- The H_2 gas pipe shall be made of Stainless [PVDF / PPR/Caoutchouc].
- The N_2 pipe shall be made of Caoutchouc [or PPR].
- The KOH tank shall be made of Plastic [Stainless].
- The KOH tank shall be able to withstand the electrolysis temperature.
- The condenser shall be able to condense the gas formed by electrolysis.
- The condenser shall be made of Stainless.
- The gas filter shall be able to filter the gas (O_2/H_2).
- The Nitrogen pipe shall be made of Caoutchouc.
- The water shall be distilled.
- The water shall be unable to limescale (free of limescale).
- The dry ice shall be made in powder/finger.
- The dry ice tank shall be able to withstand the temperature of the reaction.
- The dry ice tank shall be made of stainless [or PTFE (Polytetrafluoroethylene)/ Polycarbonate/thermal glass].

- The distillation tank shall be able to condense the water vapor.
- The distillation tank shall be made of stainless.
- The distillation tank shall be thick enough (especially the lower part) to withstand the high concentration of K_2CO_3 solution
- The distilled tank shall be made of glass [or plastic/ stainless].
- The gas filter shall be made of Plastic [or Glass].
- The gas filter shall be able to withstand the temperature of the gas formed.
- The burner room shall be able to withstand the pressure of burn.
- The water shall be able to cool the burner room.
- The igniter shall be able to burn gas with the presence of the Oxygen gas.
- The burner shall be made of Glass (transparent material).
- The flashback arrestor shall be able to avoid the burn of gas (H_2 gas).
- The temperature sensor shall be able to measure the temperature.
- The pressure sensor shall be able to measure the pressure in the components.
- The liquid level reader shall be made of Transparent plastic to view the level of liquid.
- The pipe system shall withstand a temperature of up to 100°C.
- The valves shall be able to resist the temperature and the pressure.
- The condensers shall be able to condense the vapor leaving the cell, with KOH solution.
- The stove shall be with a variable temperature control.
- The water bath should be able to withstand heat (high temperature).
- The water bath shall be made in stainless/aluminum/iron/thermal glass.
- The thermoplastic silicone should be able to resist heat (temperature).
- The epoxy shall be able to withstand the high temperature (≤ 150℃).

10.2.7 Automation requirements

- All electrical parts of the system shall be controlled by GUI.
- All electrical valves of the system shall be controlled by GUI.
- All Sensors of the system shall be controlled by GUI.

10.2.8 Safety requirements

- The hydrogen burner shall be able to burn the produced hydrogen gas to avoid the risk of its explosion.
- The system shall be electrically isolated.
- The system shall be connected to Earth wire.
- The dry ice shall be thermally isolated with gloves.
- The dry ice tank shall be touched using thermally gloves only.
- The distillation tank shall be placed in a well-ventilated area.

10.2.8.1 Safety of Hydrogen Storage

Safety Tips for Hydrogen Storage

5 نصائح لضمان سلامة مصنع الهيدروجين

1. اختيار خزانات تخزين الهيدروجين المضغوط المناسبة

يمكن تخزين الهيدروجين كغاز أو سائل. وتتطلب الطريقة الأولى خزانات عالية الضغط (100–1,000 بار أو 1,400–14,500 رطلاً/بوصة مربعة)، بينما تتطلب الطريقة الثانية درجات حرارة تبريدية. وفي هذه المقالة، نركز على غاز الهيدروجين المضغوط.

لضمان السلامة المثلى لمصنع الهيدروجين، من الضروري استخدام **الخزانات المصنعة بمواد مناسبة**.

حسب الحجم والضغط، يجب استخدام أحد **الأنواع الأربعة** من أوعية الضغط لتخزين الهيدروجين المضغوط .

- **النوع الأول**

إن هذه الخزانات المعدنية مصنوعة عادةً من الفولاذ أو الألومنيوم. ويمكنها تحمل أقصى ضغط مقدَّر يبلغ 175 بار (للألومنيوم) و200 بار (للفولاذ). تتميز الخزانات من النوع الأول بأنها رخيصة الإنتاج، لكنها ثقيلة جدًا كونها مصنوعة بالكامل من المعدن. تُستخدم لتخزين الهيدروجين في حالتيه السائلة والغازية .

- **النوع الثاني**

إن هذه الخزانات المعدنية مصنوعة من الألومنيوم، لكنها تتميز بلفائف خيوط حول الأسطوانة المعدنية. ويمكن أن تتكون من الألياف الزجاجية/الأراميد أو ألياف الكربون. وحسب المادة المستخدمة، يمكنها تحمل أقصى ضغط يصل إلى 299 بار.

خزانات النوع الثاني أقل في الوزن وأقوى، لكنها أغلى ثمنًا .

- **النوع الثالث**

تتكون هذه الخزانات من مواد مركبة مزودة ببطانة معدنية، ويمكنها تحمل ضغط أعلى. على سبيل المثال، يمكن أن يتحمل خزان الألومنيوم/الأراميد ضغطًا يصل إلى 438 بار. ومن ناحية أخرى، فإن خزان الألومنيوم/الكربون المركب يمكن أن يتحمل الضغوط حتى 700 بار. ونتيجة لهذا فإنها أكثر تكلفة أيضًا .

- **النوع الرابع**

لا تحتوي هذه الخزانات على معادن، فهي مصنوعة بالكامل من ألياف الكربون مع بطانة من البوليمر. ويمكنها تحمل أقصى ضغط يبلغ 700 بار على الرغم من أن وزنها أقل من الأنواع الأخرى. والجانب السلبي هنا هو أن استخدام كميات كبيرة من ألياف الكربون يجعلها أكثر تكلفة أيضًا .

2. اختيار المواد المناسبة

إن للهيدروجين تأثيرًا ضارًا في الخصائص الميكانيكية لكل المواد. فعلى سبيل المثال، يمكن أن يسبب هشاشة المعادن. وهذا بدوره يمكن أن يؤدي إلى فقدان مقاومة الشد وقابلية الطرق والسحب ومتانة الكسر، ويؤدي إلى زيادة نمو تشققات الاجهاد.

تعتمد درجة هذا التدهور على المادة وضغط الهيدروجين ودرجة حرارته والحمل الميكانيكي. وهذا يعني أن بعض المواد أفضل من غيرها .

بشكل مثالي، يجب اختبار المواد لضمان أنها تعمل في ظروف التشغيل المتوقعة. إذا لم يكن ذلك ممكنًا، فإليك بعض المواد **المستخدمة بشكل شائع** :

- الفولاذ المقاوم للصدأ الأوستنيتي
- سبائك الألومنيوم
- فولاذ حديدي منخفض الخلائطية
- فولاذ حديدي من الكربون والمنجنيز
- سبائك النحاس

من ناحية أخرى، **ينبغي تجنب المواد الآتية** :

- الفولاذ الحديدي والمارتنسيتي عالي القوة
- حديد الزهر الرمادي والمطاوع واللدن
- سبائك النيكل

- سبائك التيتانيوم

3. اختيار الموقع الأمثل لإنشاء خزانات تخزين الهيدروجين

عندما يتعلق الأمر بسلامة مصنع الهيدروجين، من المهم اختيار وعاء التخزين المناسب وكذلك الموقع الأمثل لإنشائه .

على الرغم من **إمكانية تخزين أسطوانات الهيدروجين الصغيرة في الأماكن الداخلية**، فلا يوصى بذلك للكميات الكبيرة.

التخزين الخارجي أكثر أمانًا بشكل عام، بل هو ضروري لتخزين كميات كبيرة من الهيدروجين حيث يسمح بتبديد الغاز بسهولة في حال التسرب العرضي للهيدروجين.

فيما يأتي بعض خصائص الموقع المثالي لتخزين الهيدروجين المضغوط.

-التهوية الجيدة لمنع تراكم الهيدروجين

-الإنشاء على مسافة آمنة من الهياكل ومنافذ التهوية

-الحماية من حركة المركبات أو من الأجسام الساقطة

-تجنُّب التعرض لأشعة الشمس المباشرة، وألا تتجاوز درجة الحرارة المحيطة 52 درجة مئوية (126 درجة فهرنهايت تقريبًا)

-الحماية من الوصول غير المصرح به

4. منع تراكم غاز الهيدروجين في حاوية أو حيّز مغلق

حسبما ذُكر أعلاه، فإن التهوية أمر بالغ الأهمية عند التعامل مع الهيدروجين. حيث تضمن تبديد الغاز بسرعة وعدم التمكُّن من تشكيل مزيج قابل للاشتعال مع الأكسجين الموجود في الهواء .

ولأن الهيدروجين خفيف للغاية، **من المؤكد أن هذا التراكم سيحدث بالقرب من سقف الغرفة أو الحاوية.**

يجب مراعاة ذلك عند تصميم هذه المرافق.

يعني هذا أن هناك حاجة إلى وجود **تهوية مناسبة وأجهزة كشف وتدابير للسيطرة في المساحة العلوية** .

فضلاً عن ذلك، ولأنه لا يمكن استبعاد تسرب الهيدروجين تمامًا، من الضروري أيضًا **تركيب أجهزة كشف اللهب و/أو الغاز ونظام إخماد الحرائق** .

عند انطلاق غاز الهيدروجين في الهواء، سيصعد إلى الأعلى على الفور بسرعة 10 أمتار/ثانية، لذا فإنه ببساطة من الضروري **الكشف عن تركيز الهيدروجين عند أعلى نقطة في الغرفة** .وستحتاج أيضًا إلى **إعداد تهوية** الغرفة عند النقطة نفسها: يجب إخراج الهواء من أعلى نقطة. وإذا وضعت جهاز الكشف عند نقطة أدنى في الغرفة، فسيمتلئ أولاً الجزء من الغرفة أعلى جهاز الكشف بتركيز عالٍ جدًا من الهيدروجين، قبل الكشف عن الغاز. وينطبق الأمر نفسه على التهوية. إذا أدخلت الهواء من أعلى وأفرغته عند مستوى أقل، فلن تتخلص ببساطة من الهيدروجين. حيث يجب أن يكون تدفق التهوية من الأسفل إلى الأعلى.

خلال التشغيل العادي، يكون معدل التهوية منخفضًا نسبيًا، لكن عند الكشف عن الغاز في أعلى نقطة في الغرفة فقط، يجب عليك على الفور إخراج كمية هائلة من الهواء (الممزوج بالغاز). بالنسبة إلى المباني الجديدة المخصصة لتصنيع شاحنات الهيدروجين (التي تتم تعبئتها أيضًا داخل المبنى)، يمكن تركيب جهاز كشف الغاز بالقرب من السقف (على ارتفاع أكثر من 10 أمتار)، وعند الكشف عن الغاز، يُفتح السقف تلقائيًا.

5. منع تسرب الهيدروجين

تُعد حالات التسرب مشكلة رئيسية في العمليات التي تستخدم الهيدروجين حيث إن هذا عنصر صغير جدًا وهو مسؤول عن وقوع نسبة كبيرة من الحوادث .

تتمثل إحدى الطرق التي يمكن من خلالها منع حدوث التسرب في تركيب أجهزة كشف التسرب التي ينبغي صيانتها واختبارها بشكل دوري. وعلى أي حال، ينبغي إجراء اختبارات التسرب بشكل منتظم، بما في ذلك الفحوصات التشغيلية للصمامات .

هناك طريقتان شائعتان للاختبار وهما استخدام محلول فقاعات الصابون أو جهاز كشف الهيدروجين المحمول باليد. وبالإضافة إلى الاختبارات المنتظمة، يجب على مشغلي المصنع التحقق من وجود تسرب في كل مرة تتم فيها إعادة تجميع الوصلات. وعلاوة على ذلك، لا بد من فحص وصلات النظام بحثًا عن علامات التآكل والبلى والتشقق والانبعاج والتقشر أو أي شكل آخر من أشكال التلف.

Hydrogen, a highly flammable and explosive gas, requires careful storage and handling to prevent accidents. Here are some essential safety tips:

➢ Storage Location:

- Isolated Area: Store hydrogen cylinders in a well-ventilated, isolated area away from heat sources, sparks, and open flames.
- Secure Fastening: Ensure cylinders are securely fastened to prevent them from falling or being knocked over.
- Gas detector installation: It is installed at the highest point in the room (ceiling at a height of more than 10 meters) and when gas is detected, the ceiling will open automatically.
- Installing leak detection devices that should be maintained and tested periodically.
- Install leak tests regularly, including operational checks of valves.

➢ Cylinder Handling

- Protective Gear: Wear appropriate protective gear, including safety glasses, gloves, and closed-toe shoes, when handling hydrogen cylinders.
- Avoid Rough Handling: Handle cylinders gently to prevent damage to the valves or other components.
- Leak Checks: Regularly inspect cylinders for leaks using soap bubble solution or handheld Hydrogen Detector.
- Protection from vehicle movement and falling objects.
- Avoid exposure to direct sunlight, and the ambient temperature should not exceed 52°C.
- Protection from unauthorized access.

➢ Ventilation

- Adequate Ventilation: Ensure proper ventilation in the storage area to prevent the accumulation of hydrogen gas.
- Exhaust Fans: Consider installing exhaust fans to facilitate ventilation.

⚠ Note: Air must be brought in from the bottom to the top to ventilate the place.

➢ Fire Safety

- Fire Extinguishers: Keep fire extinguishers readily available and ensure personnel are trained properly.
- Emergency Plan: Develop and practice an emergency evacuation plan in case of a fire or other emergency.

➢ Electrical Safety

- Grounding: Ground all electrical equipment in the storage area to prevent static discharges.
- Avoid Sparks: Minimize electrical equipment near hydrogen cylinders to avoid creating sparks.

- **Signage**

Warning Signs: Mark the storage area with warning signs indicating the presence of hydrogen gas and the associated hazards.

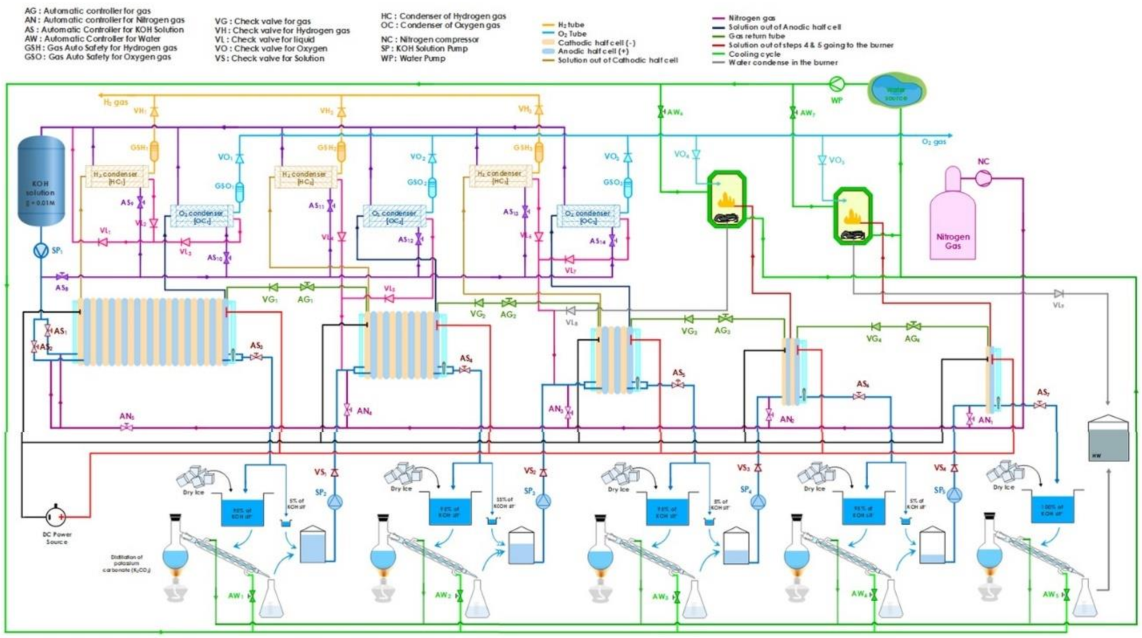
- **Regular Inspections**
    - Cylinder Inspections: Regularly inspect hydrogen cylinders for damage, leaks, or corrosion.
    - Plant operators must check for leaks each time connections are reassembled.
    - Inspect system connections for signs of wear, tear, cracking, denting, peeling, or any other form of damage.
    - Safety Equipment: Ensure that safety equipment, such as fire extinguishers and emergency shutoff valves, are in good working condition.
- **Training**

Personnel Training: Train all personnel in handling hydrogen gas on safety procedures, emergency response, and the proper use of equipment.

By following these safety tips, you can significantly reduce the risk of accidents associated with hydrogen storage and ensure a safe working environment.

10.3 System Design and Mechanical design

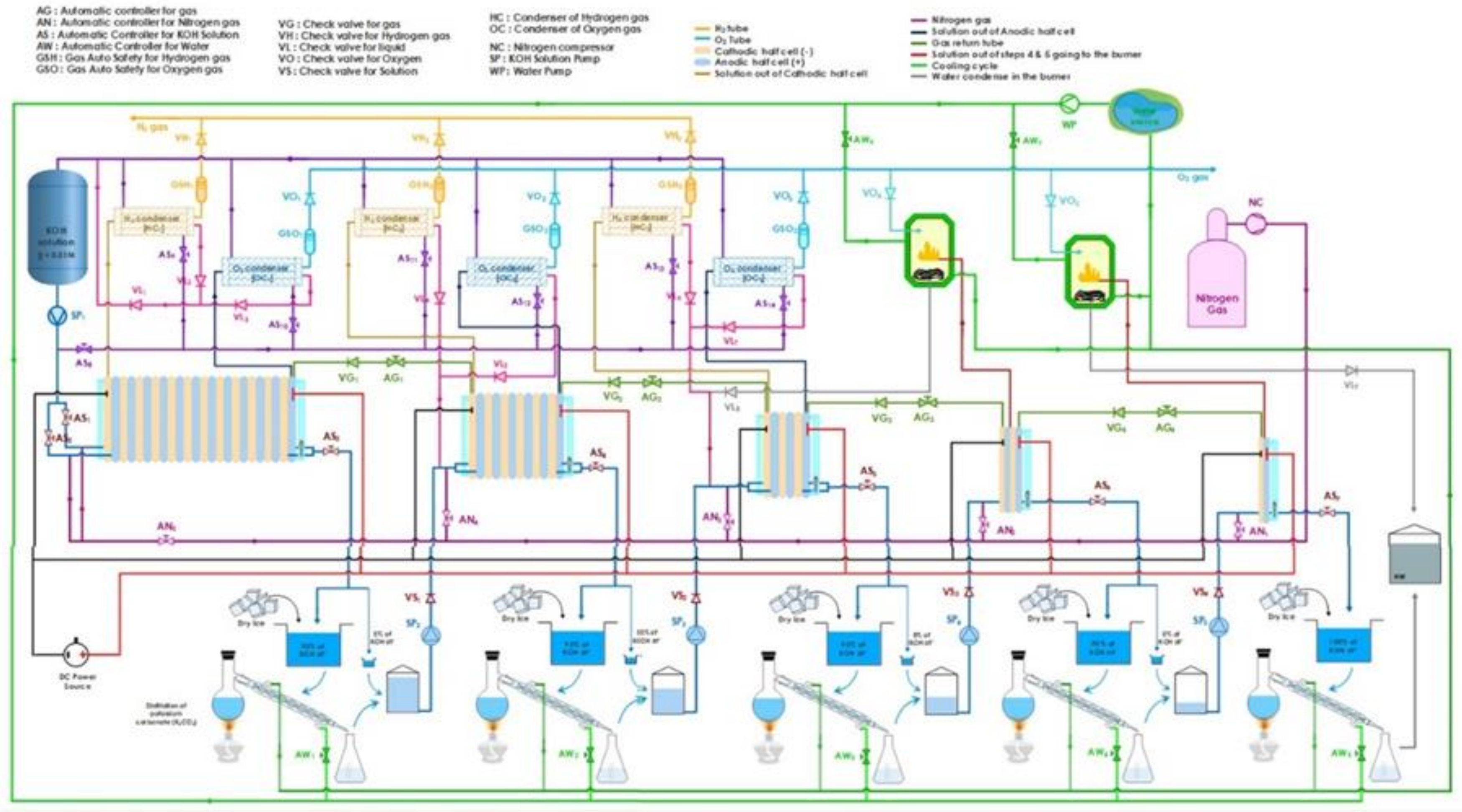
10.3.1 Electrolysis multistage design overview



Project C 23: Multistage Electrolysis (ICPT - MSE)

Multistage design (27072023) _ Edraw file

01082023_MSE flow
chart - with electricity.


AG : Automatic controller for gas
AN : Automatic controller for Nitrogen gas
AS : Automatic Controller for KOH Solution
AW : Automatic Controller for Water
GSH : Gas Auto Safety for Hydrogen gas
GSO : Gas Auto Safety for Oxygen gas
VG : Check valve for gas
VH : Check valve for Hydrogen gas
VL : Check valve for liquid
VO : Check valve for Oxygen
VS : Check valve for Solution
HC : Condenser of Hydrogen gas
OC : Condenser of Oxygen gas
NC : Nitrogen compressor
SP : KOH Solution Pump
WP : Water Pump
H₂ tube
O₂ Tube
Cathodic half cell (-)
Anodic half cell (+)
Solution out of Cathodic half cell
Nitrogen gas
Solution out of Anodic half cell
Gas return tube
Solution out of steps 4 & 5 going to the burner
Cooling cycle
Water condense in the burner
H₂ gas
O₂ gas
KOH solution
DC Power Source
Dry ice
Nitrogen Gas
WP
NC

10.3.2 FlowChart of MSE design

In this paragraph, we will present the mechanical design of multistage electrolysis using a burner room for the two last stages.

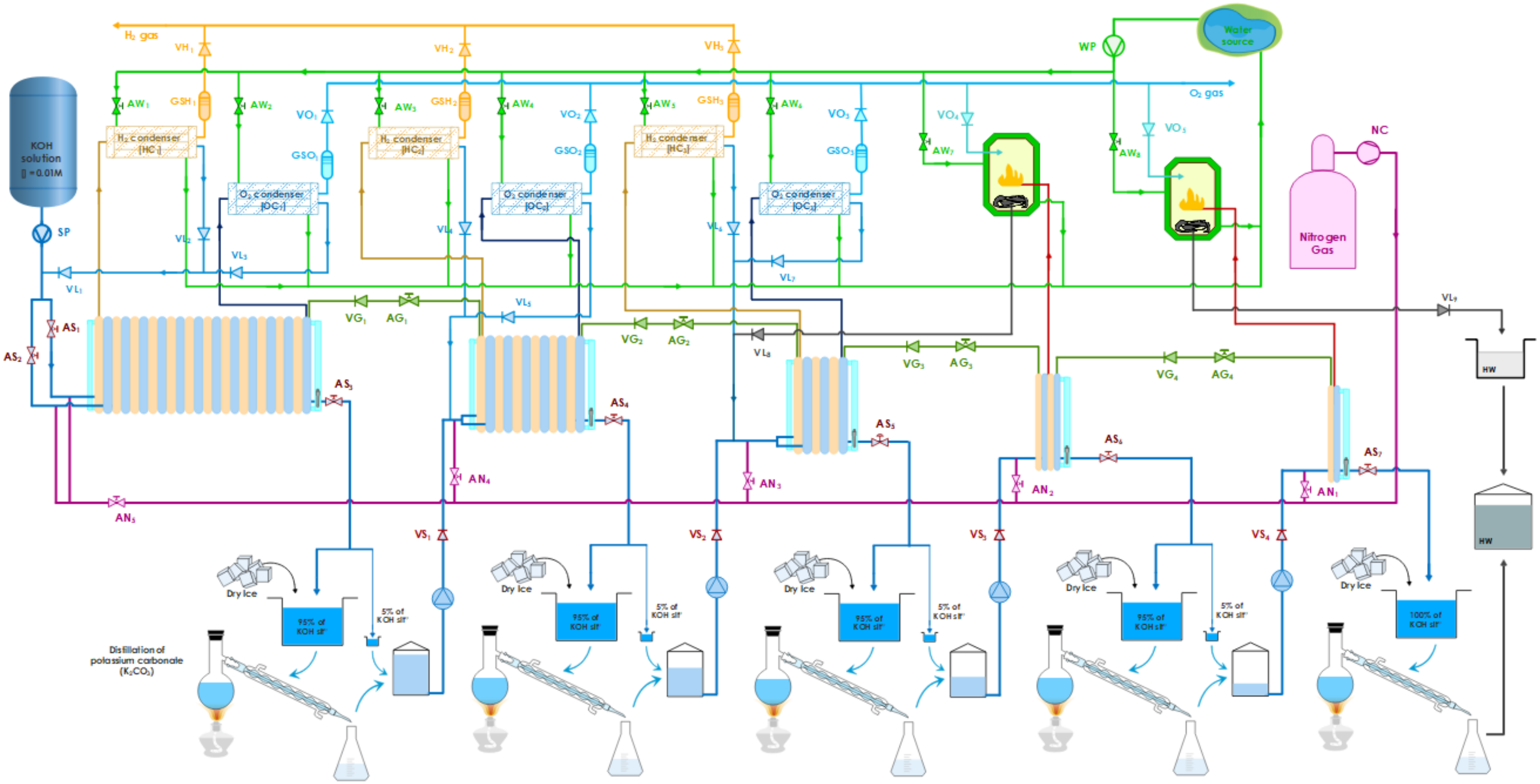


Figure: MSE using the burner rooms

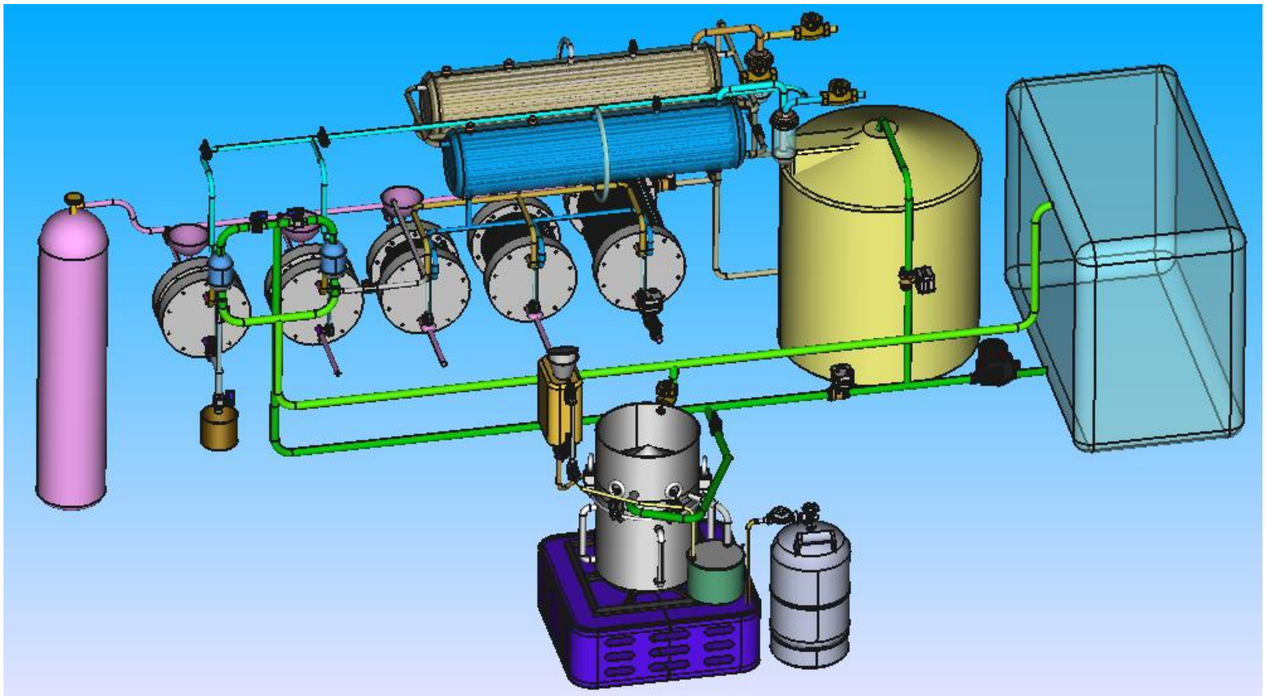
Project C 23: Multistage Electrolysis (ICPT - MSE)

The Edraw file contains the MSE details using burner rooms:

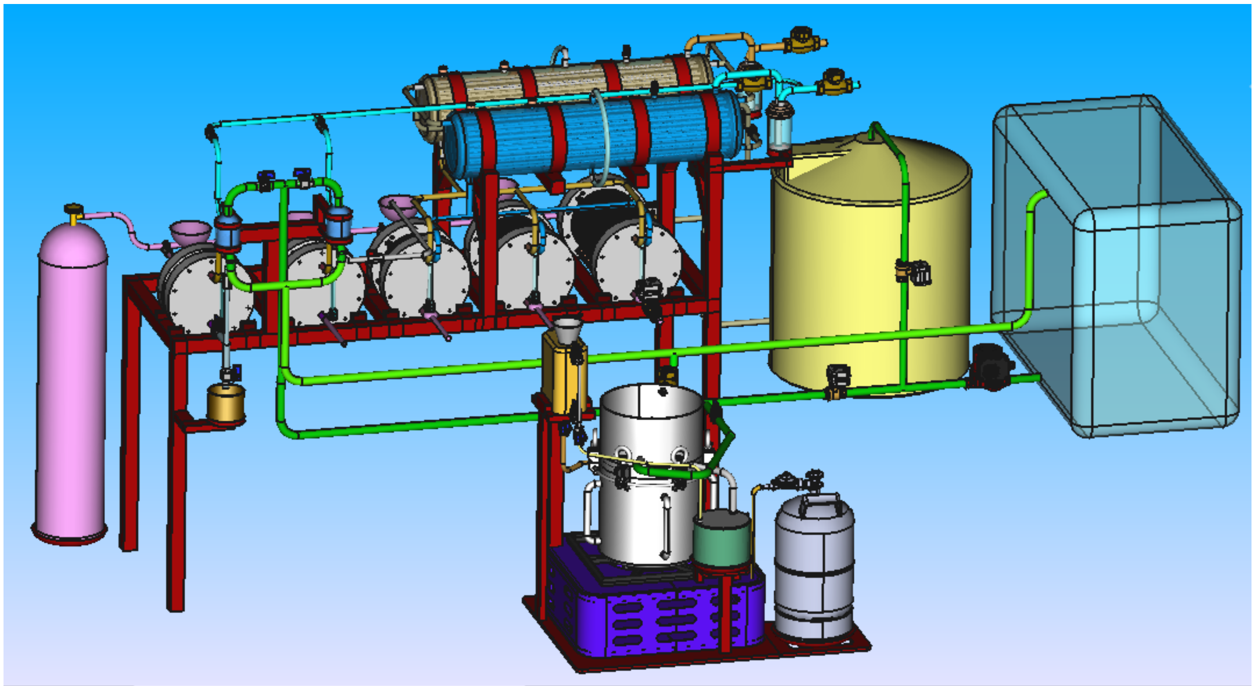
08052024_MSE flow
chart - with electrici

The FreeCAD file contains the MSE details using burner rooms:

10052024_MSE - All
components with pi



10.3.3 Design of the MSE with stand



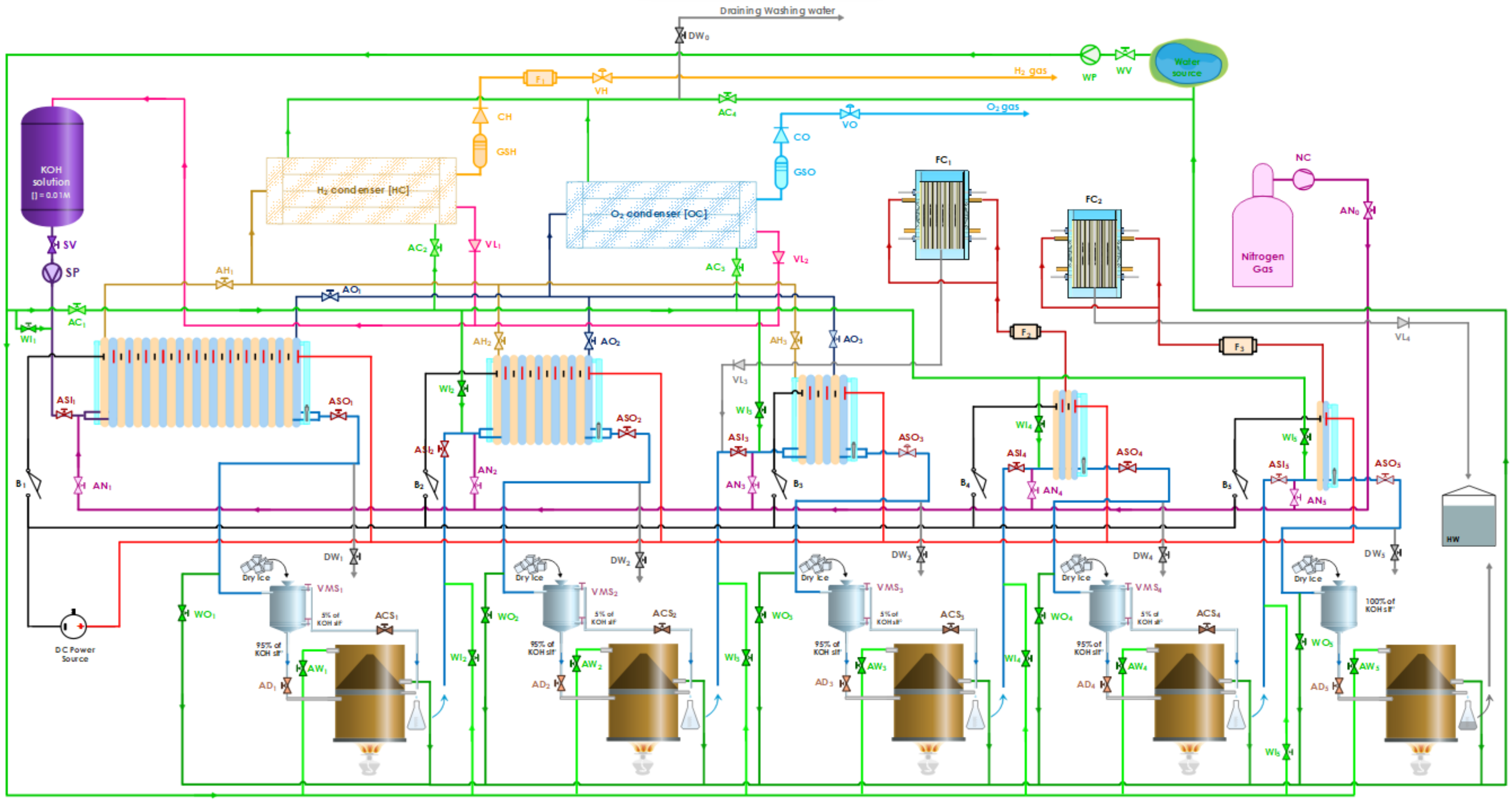
The FreeCAD file:

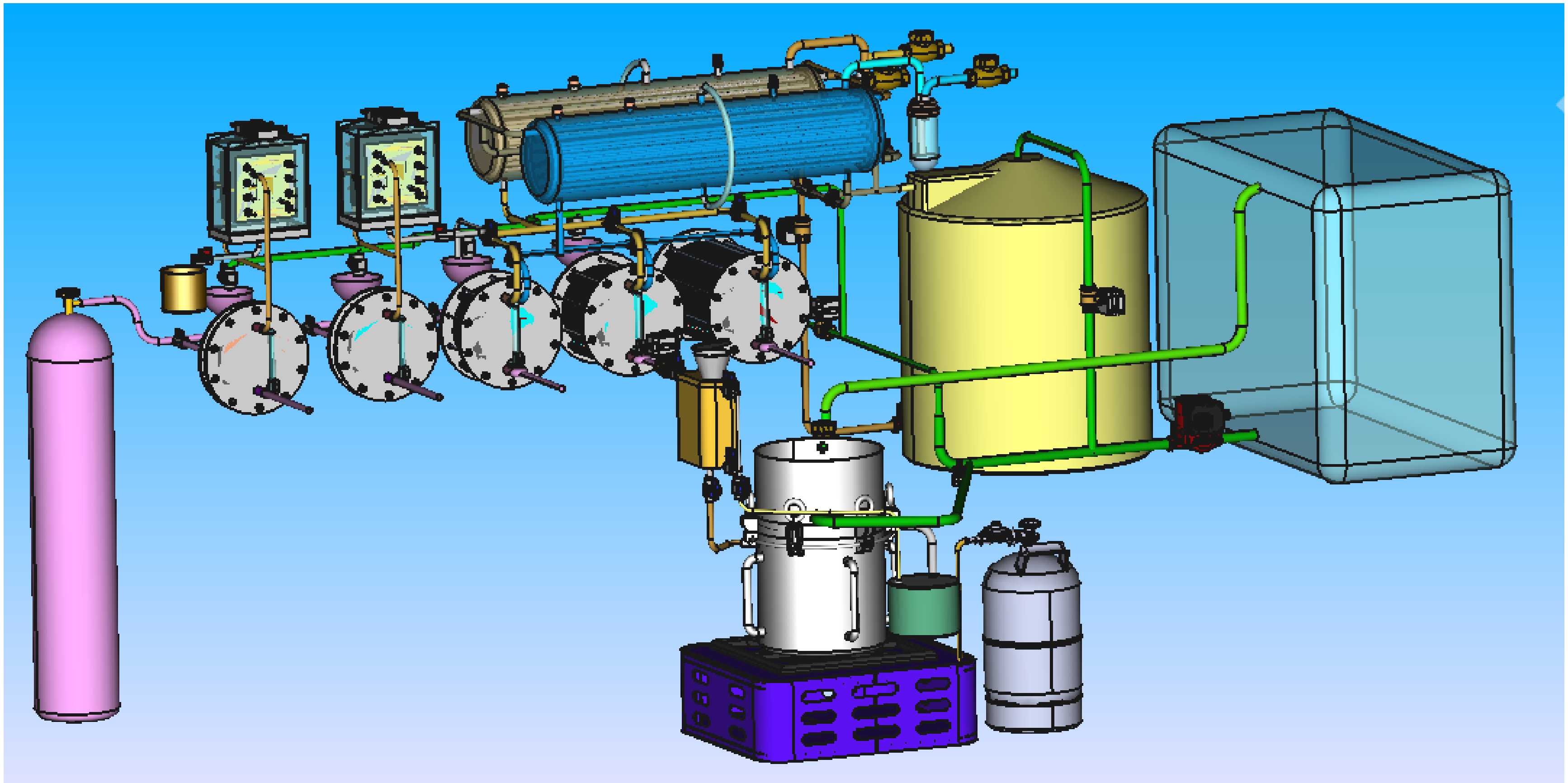
10052024_MSE - All components with pipes cnx.FCStd

10.3.4 Replacement of burners room by FuelCell

A to burn the gas mixture (consisting of hydrogen and oxygen gases) in a cold combustion manner by replacing the two combustion chambers with fuel cells (figure below) has been proposed, but this design is unrealistic and cannot be implemented. The main problem lies in the inherent selectivity of the membrane, which is specifically designed to facilitate the passage of hydrogen ions while strictly preventing the passage of oxygen molecules. This critical design constraint renders the proposed system inoperable. The presence of oxygen and deuterium within the fuel cell environment not only fails to contribute to the desired electrochemical reactions; but also poses a significant risk of blocking the membrane pores, impeding the flow of hydrogen ions and seriously compromising the fuel cell function.

Project C 23: Multistage Electrolysis (ICPT - MSE)



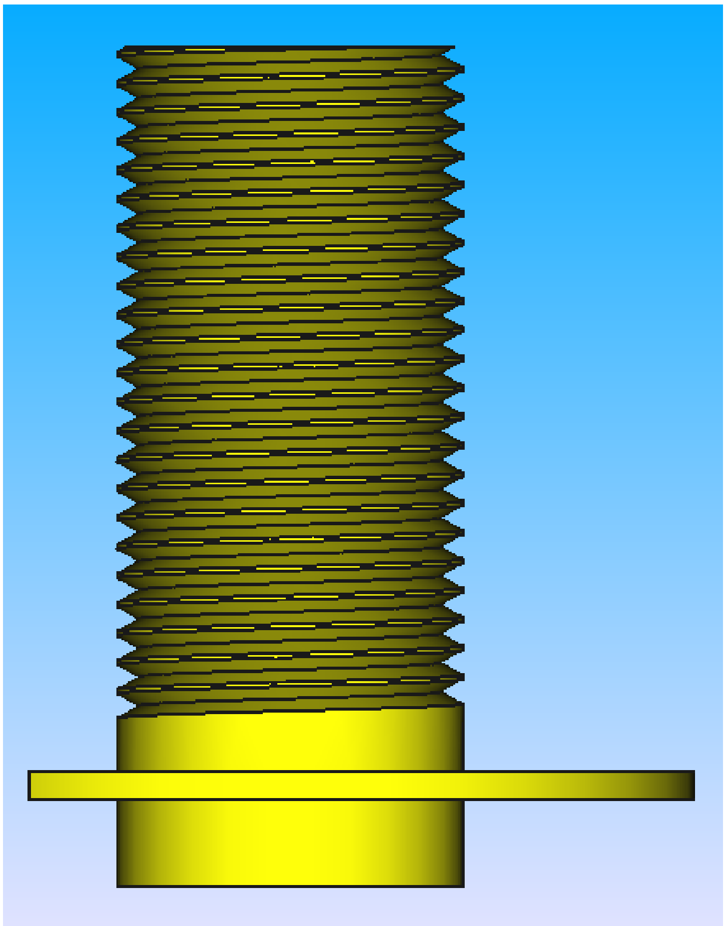


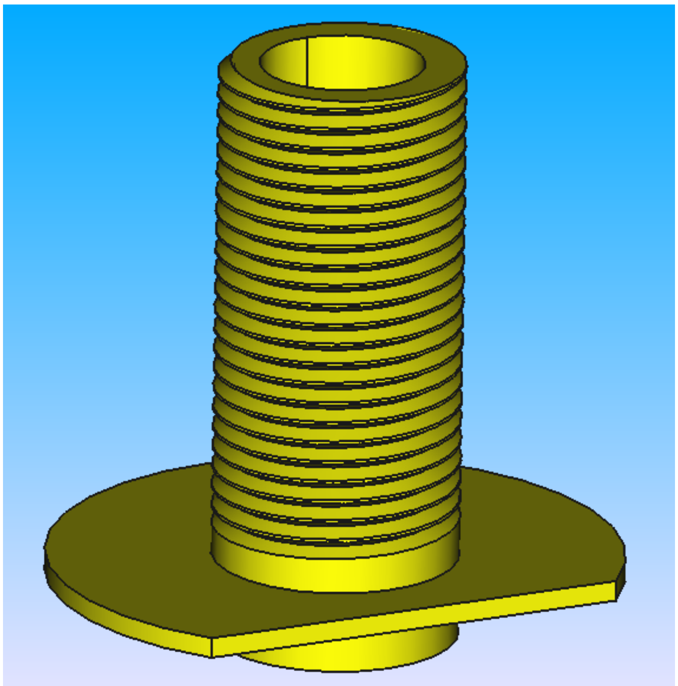
10.4 Concept for Stack Adapter (not realized yet)

10.4.1 Possible Realization Concept with PPR-metals interface

10.4.2 Design for 3D print

10.4.2.1 Part 1

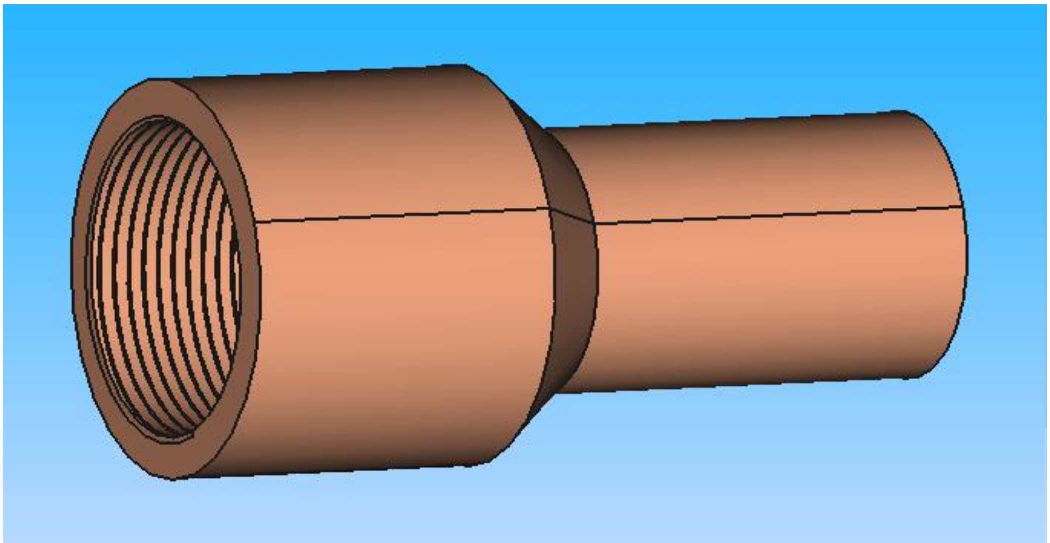


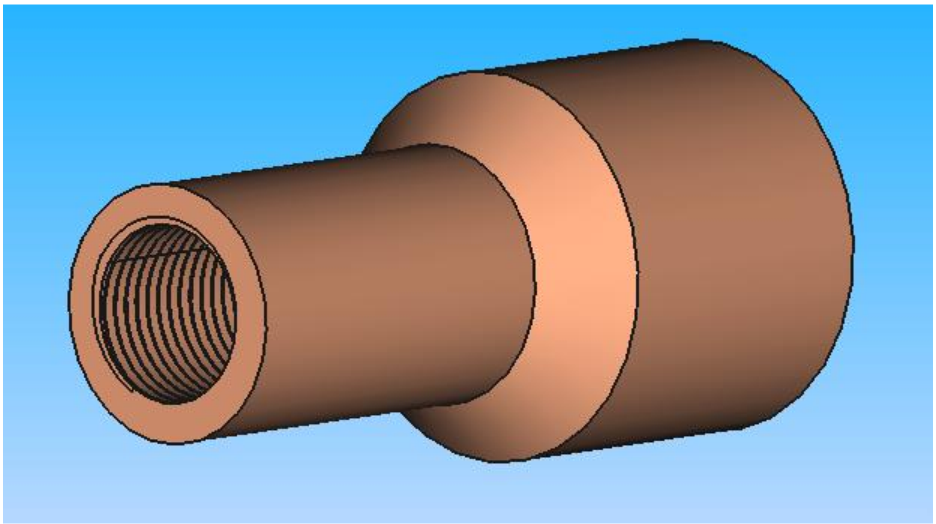


The FreeCAD file :

26122024_Design part 1.FCStd

10.4.2.2 Part 2

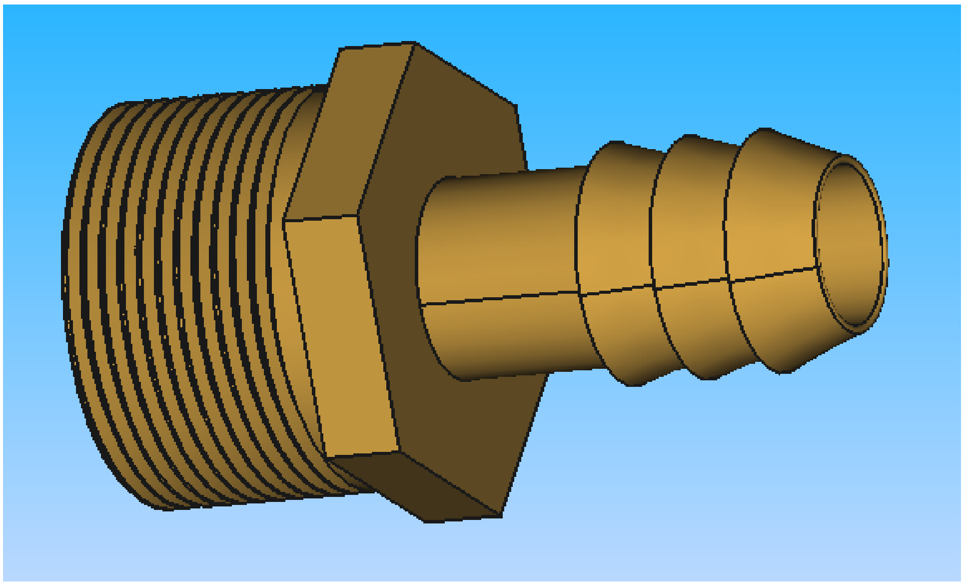




The FreeCAD file :

27122024_design
part 2 _.FCStd

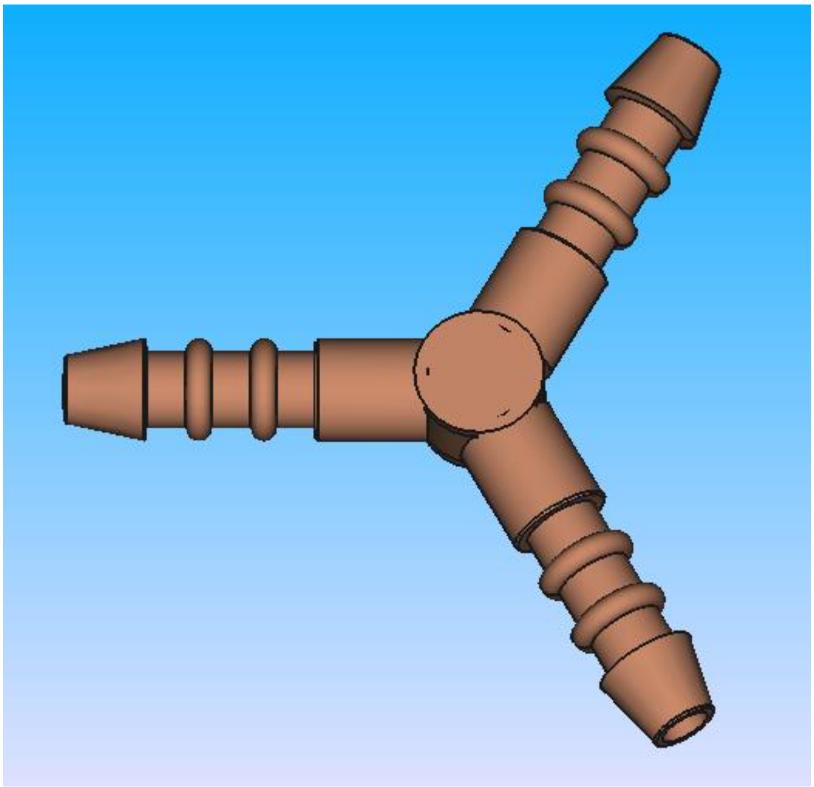
10.4.2.3 Part 3



The FreeCAD file :

27122024_Design
part 3.FCStd

10.4.2.4 Part 4



The FreeCAD file :

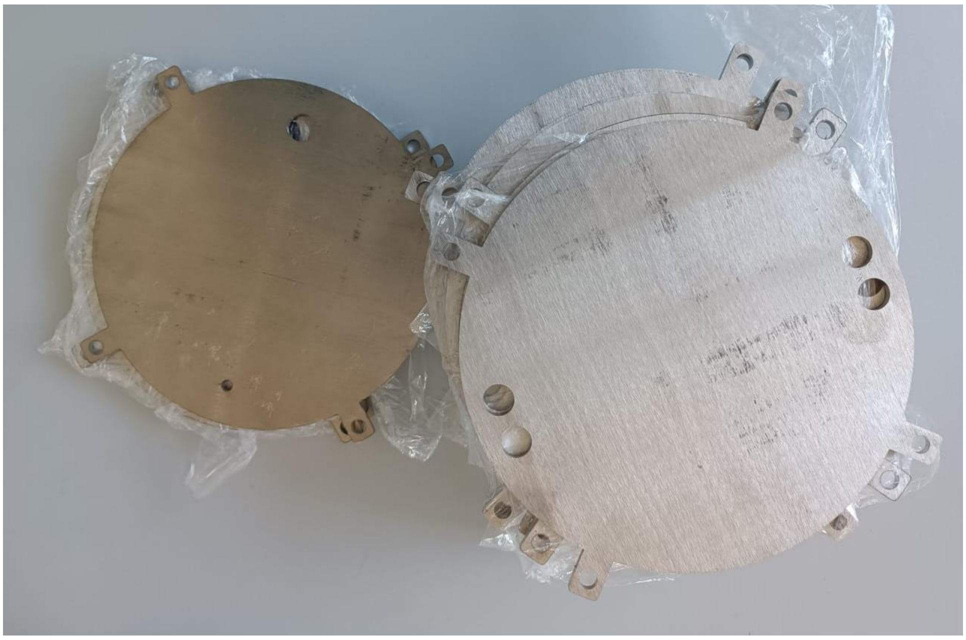
30122024_Design
part 4.FCStd

10.5 Realization of the MSE

10.5.1 Materials of MSE electrolyze stack

10.5.1.1 Stainless for end plates

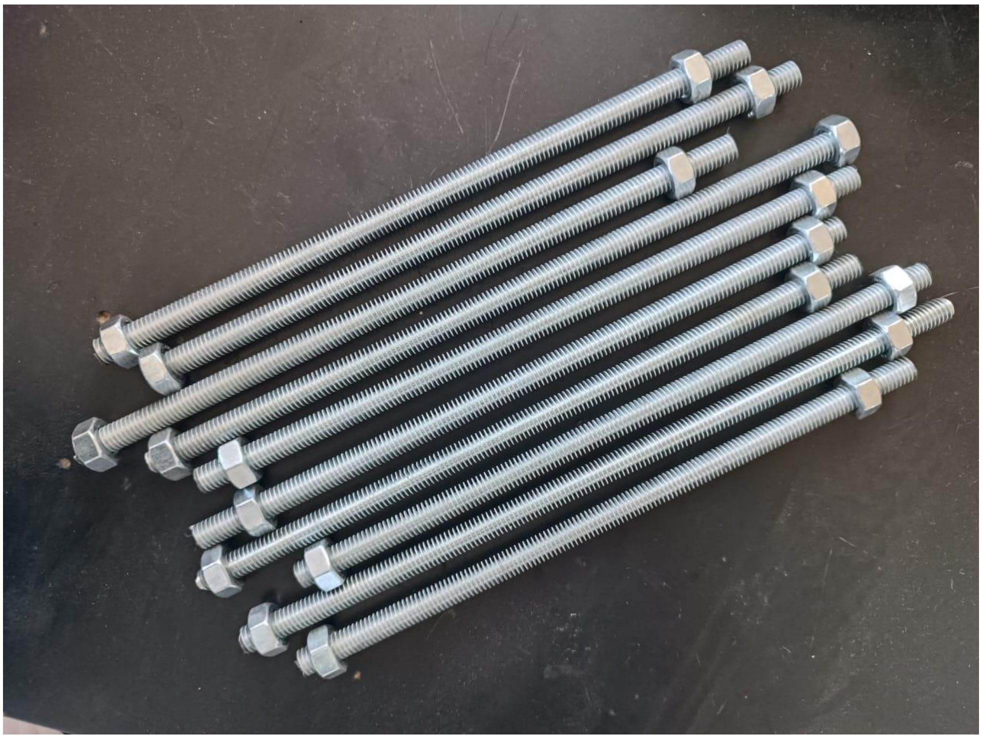
10.5.1.2 Nickel for electrodes



10.5.1.3 AEM for membrane exchange

10.5.1.4 PTFE gasket for gasket between components

10.5.1.5 Bolts & nuts



10.5.2 Material invoices

10.5.2.1 MEA invoice

Quotations

Suzhou Sinero Technology Co., LTD

Date: 17/07/2024 Receipt Num:SIN2024071704

From

Address: No. 337, Binhe Road, High tech Zone, Suzhou, Jiangsu
Zip code: 215000
Phone: 15190163610

NO.	Description	Product model	Unit Price	Quantity	Amount
1	Anion exchange membrane	FAA-3-PK-130 20*20cm	$53.5	28	$1498

Total amount of goods: $1498

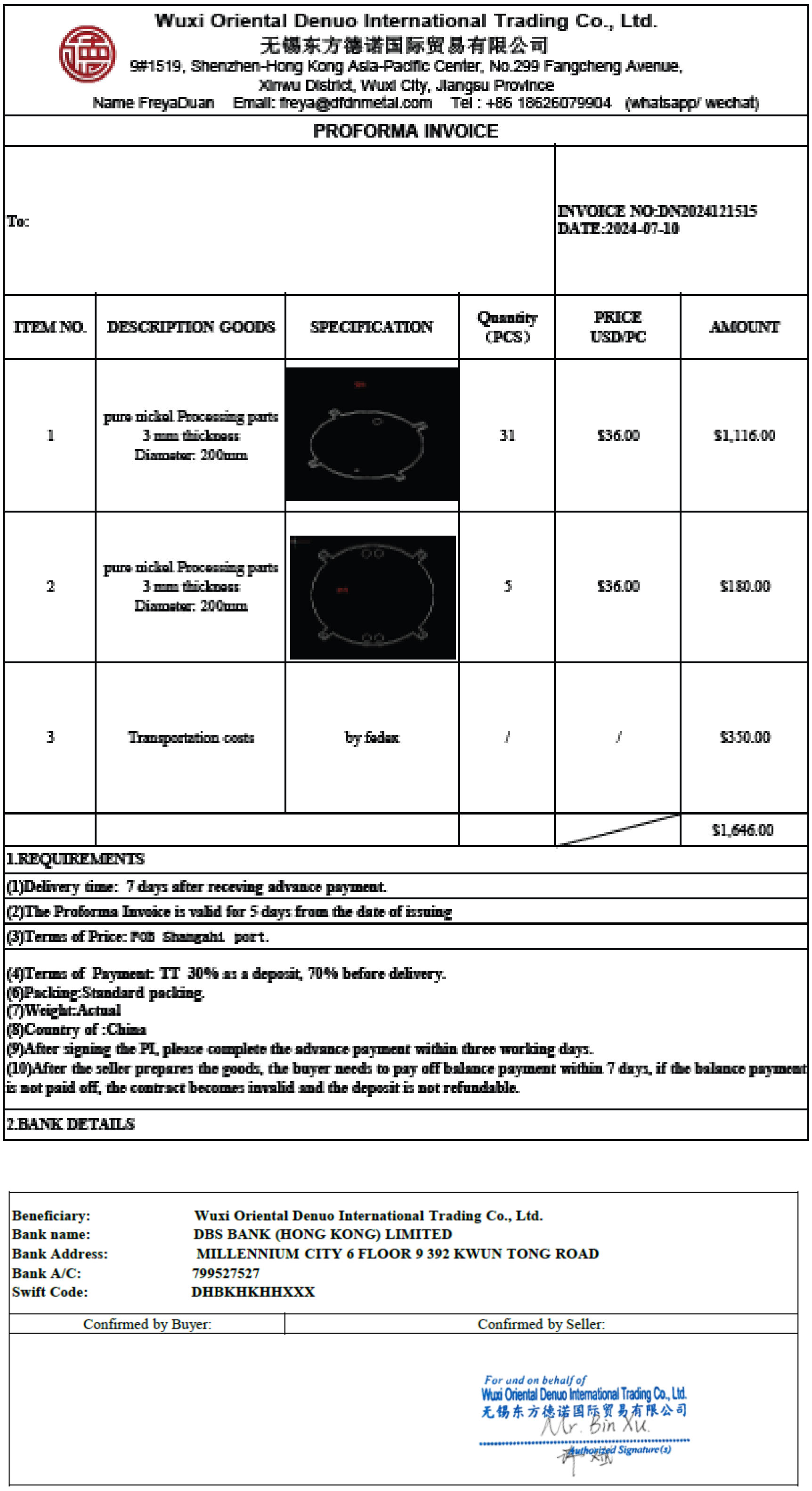
Freight:$48

Total : $1546

Validity of Quotation: 30/7/2024
Bank Reference:
Bank Name: Industrial and Commercial Bank of China Suzhou Oriental Garden sub branch
Bank Address: No. 188, Suchun West Road, Suzhou Industrial Park, Suzhou city, China
Account No: 1102130919000071753

Authorized Signatures: Liu Xiuxiu

10.5.2.2 Nickel plates invoice



Wuxi Oriental Denuo International Trading Co., Ltd.
无锡东方德诺国际贸易有限公司
9#1519, Shenzhen-Hong Kong Asia-Pacific Center, No.299 Fangcheng Avenue,
Xinwu District, Wuxi City, Jiangsu Province
Name FreyaDuan Email: freya@dfdnmetal.com Tel : +86 18626079904 (whatsapp/ wechat)

PROFORMA INVOICE

To:	**INVOICE NO:DN2024121515** **DATE:2024-07-10**

ITEM NO.	DESCRIPTION GOODS	SPECIFICATION	Quantity (PCS)	PRICE USD/PC	AMOUNT
1	pure nickel Processing parts 3 mm thickness Diameter: 200mm		31	$36.00	$1,116.00
2	pure nickel Processing parts 3 mm thickness Diameter: 200mm		5	$36.00	$180.00
3	Transportation costs	by fedex	/	/	$350.00
					$1,646.00

1.REQUIREMENTS

(1)Delivery time: 7 days after receving advance payment.

(2)The Proforma Invoice is valid for 5 days from the date of issuing

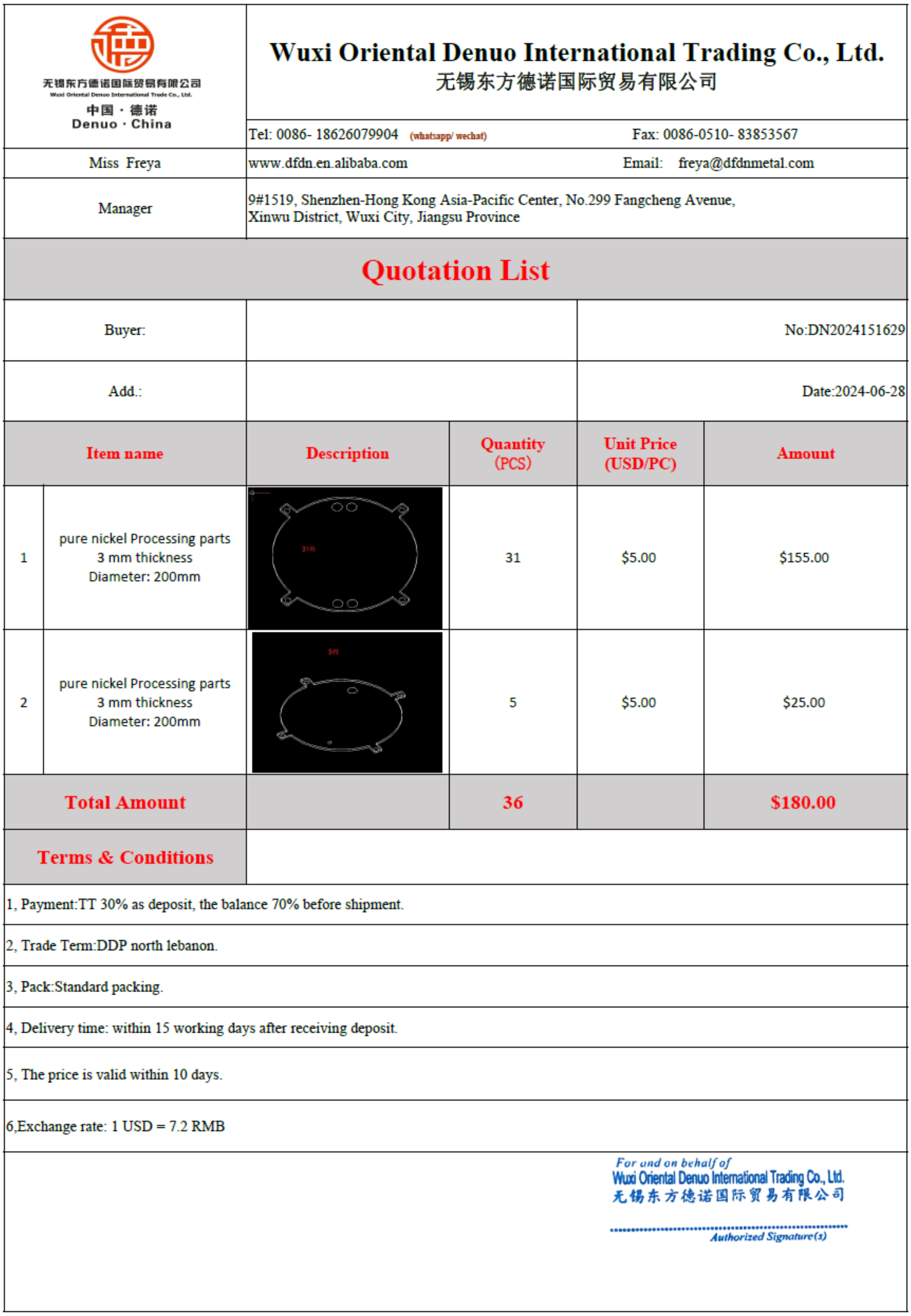
(3)Terms of Price: FOB Shangahi port.

(4)Terms of Payment: TT 30% as a deposit, 70% before delivery.
(6)Packing:Standard packing.
(7)Weight:Actual
(8)Country of :China
(9)After signing the PI, please complete the advance payment within three working days.
(10)After the seller prepares the goods, the buyer needs to pay off balance payment within 7 days, if the balance payment is not paid off, the contract becomes invalid and the deposit is not refundable.

2.BANK DETAILS

Beneficiary:	**Wuxi Oriental Denuo International Trading Co., Ltd.**
Bank name:	**DBS BANK (HONG KONG) LIMITED**
Bank Address:	**MILLENNIUM CITY 6 FLOOR 9 392 KWUN TONG ROAD**
Bank A/C:	**799527527**
Swift Code:	**DHBKHKHHXXX**

Confirmed by Buyer:	Confirmed by Seller:
	For and on behalf of Wuxi Oriental Denuo International Trading Co., Ltd. 无锡东方德诺国际贸易有限公司 Mr. Bin Xu. Authorized Signature(s)



无锡东方德诺国际贸易有限公司
Wuxi Oriental Denuo International Trade Co., Ltd.
中国 · 德诺
Denuo · China

Wuxi Oriental Denuo International Trading Co., Ltd.
无锡东方德诺国际贸易有限公司

	Tel: 0086- 18626079904 (whatsapp/ wechat)	Fax: 0086-0510- 83853567
Miss Freya	www.dfdn.en.alibaba.com	Email: freya@dfdnmetal.com
Manager	9#1519, Shenzhen-Hong Kong Asia-Pacific Center, No.299 Fangcheng Avenue, Xinwu District, Wuxi City, Jiangsu Province	

Quotation List

Buyer:		No:DN2024151629
Add.:		Date:2024-06-28

Item name		**Description**	**Quantity (PCS)**	**Unit Price (USD/PC)**	**Amount**
1	pure nickel Processing parts 3 mm thickness Diameter: 200mm		31	$5.00	$155.00
2	pure nickel Processing parts 3 mm thickness Diameter: 200mm		5	$5.00	$25.00
Total Amount			**36**		**$180.00**

Terms & Conditions

1, Payment:TT 30% as deposit, the balance 70% before shipment.

2, Trade Term:DDP north lebanon.

3, Pack:Standard packing.

4, Delivery time: within 15 working days after receiving deposit.

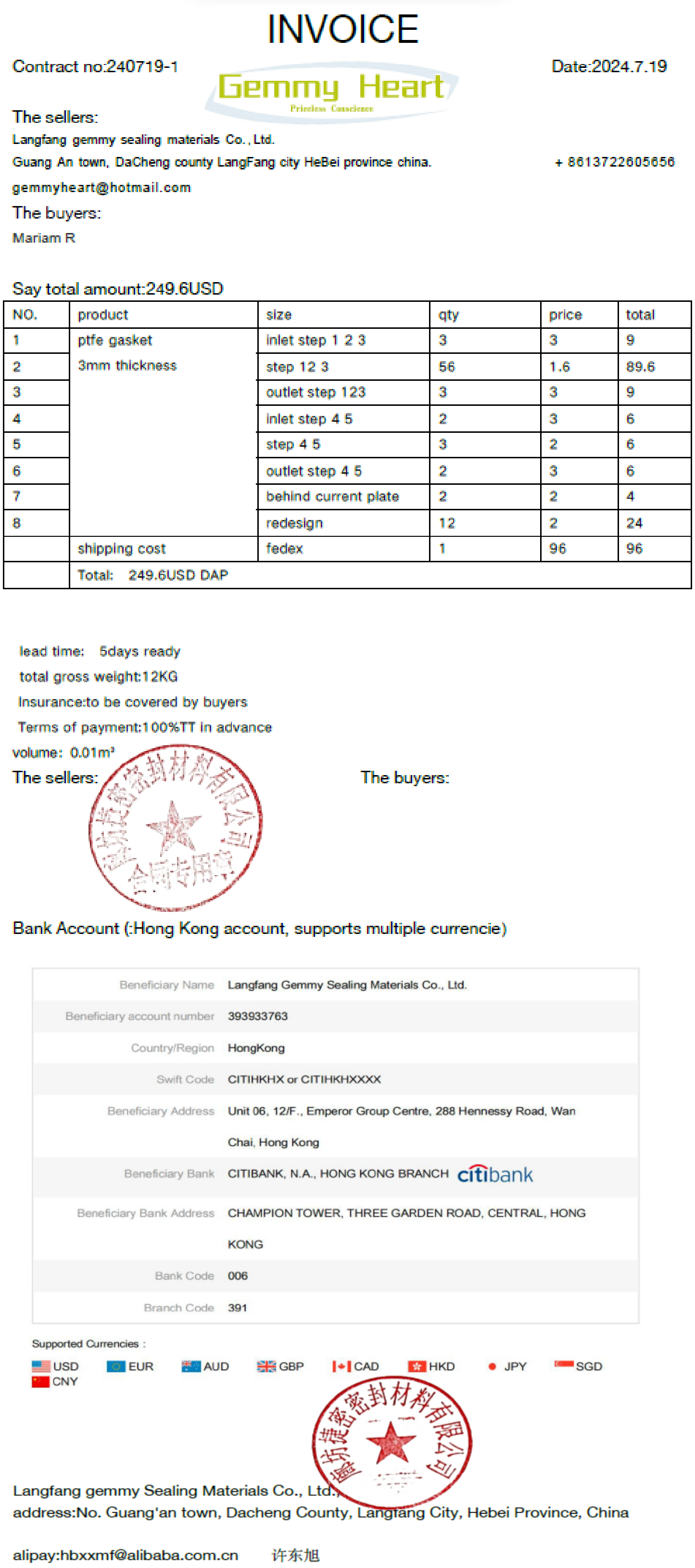
5, The price is valid within 10 days.

6,Exchange rate: 1 USD = 7.2 RMB

For and on behalf of
Wuxi Oriental Denuo International Trading Co., Ltd.
无锡东方德诺国际贸易有限公司

Authorized Signature(s)

10.5.2.3 PTFE invoice



INVOICE

Contract no:240719-1

Gemmy Heart

Priceless Conscience

Date:2024.7.19

The sellers:

Langfang gemmy sealing materials Co., Ltd.
Guang An town, DaCheng county LangFang city HeBei province china. + 8613722605656
gemmyheart@hotmail.com

The buyers:

Mariam R

Say total amount:249.6USD

NO.	product	size	qty	price	total
1	ptfe gasket	inlet step 1 2 3	3	3	9
2	3mm thickness	step 12 3	56	1.6	89.6
3		outlet step 123	3	3	9
4		inlet step 4 5	2	3	6
5		step 4 5	3	2	6
6		outlet step 4 5	2	3	6
7		behind current plate	2	2	4
8		redesign	12	2	24
	shipping cost	fedex	1	96	96
	Total: 249.6USD DAP				

lead time: 5days ready
total gross weight:12KG
Insurance:to be covered by buyers
Terms of payment:100%TT in advance
volume: 0.01m³

The sellers:

The buyers:

Bank Account (:Hong Kong account, supports multiple currencie)

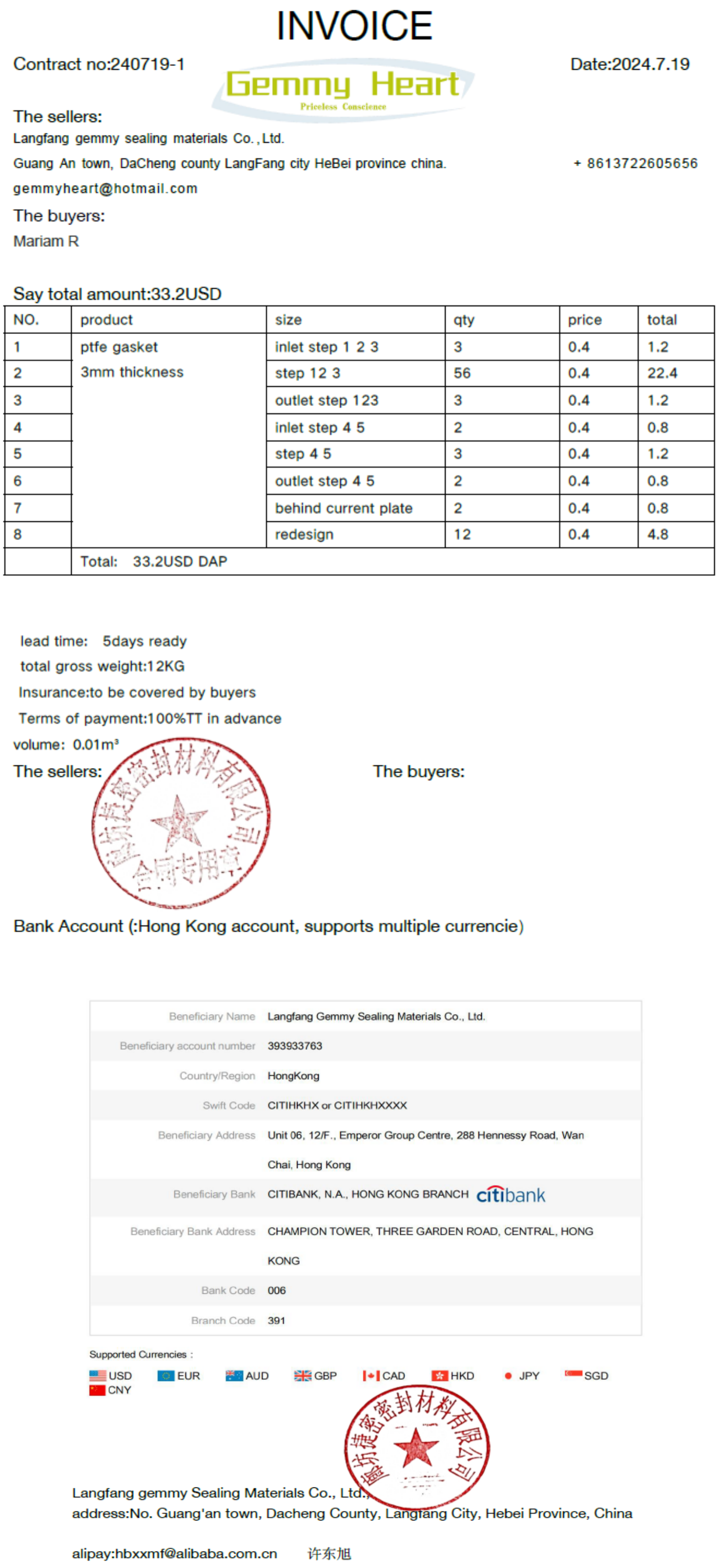
Beneficiary Name	Langfang Gemmy Sealing Materials Co., Ltd.
Beneficiary account number	393933763
Country/Region	HongKong
Swift Code	CITIHKHX or CITIHKHXXXX
Beneficiary Address	Unit 06, 12/F., Emperor Group Centre, 288 Hennessy Road, Wan Chai, Hong Kong
Beneficiary Bank	CITIBANK, N.A., HONG KONG BRANCH citibank
Beneficiary Bank Address	CHAMPION TOWER, THREE GARDEN ROAD, CENTRAL, HONG KONG
Bank Code	006
Branch Code	391

Supported Currencies :

USD EUR AUD GBP CAD HKD JPY SGD
CNY

Langfang gemmy Sealing Materials Co., Ltd.
address:No. Guang'an town, Dacheng County, Langfang City, Hebei Province, China

alipay:hbxxmf@alibaba.com.cn 许东旭



INVOICE

Contract no:240719-1

Date:2024.7.19

Gemmy Heart
Priceless Conscience

The sellers:
Langfang gemmy sealing materials Co.,Ltd.
Guang An town, DaCheng county LangFang city HeBei province china.
+8613722605656
gemmyheart@hotmail.com

The buyers:
Mariam R

Say total amount:33.2USD

NO.	product	size	qty	price	total
1	ptfe gasket	inlet step 1 2 3	3	0.4	1.2
2	3mm thickness	step 12 3	56	0.4	22.4
3		outlet step 123	3	0.4	1.2
4		inlet step 4 5	2	0.4	0.8
5		step 4 5	3	0.4	1.2
6		outlet step 4 5	2	0.4	0.8
7		behind current plate	2	0.4	0.8
8		redesign	12	0.4	4.8
	Total: 33.2USD DAP				

lead time: 5days ready
total gross weight:12KG
Insurance:to be covered by buyers
Terms of payment:100%TT in advance
volume: 0.01m³

The sellers:

The buyers:

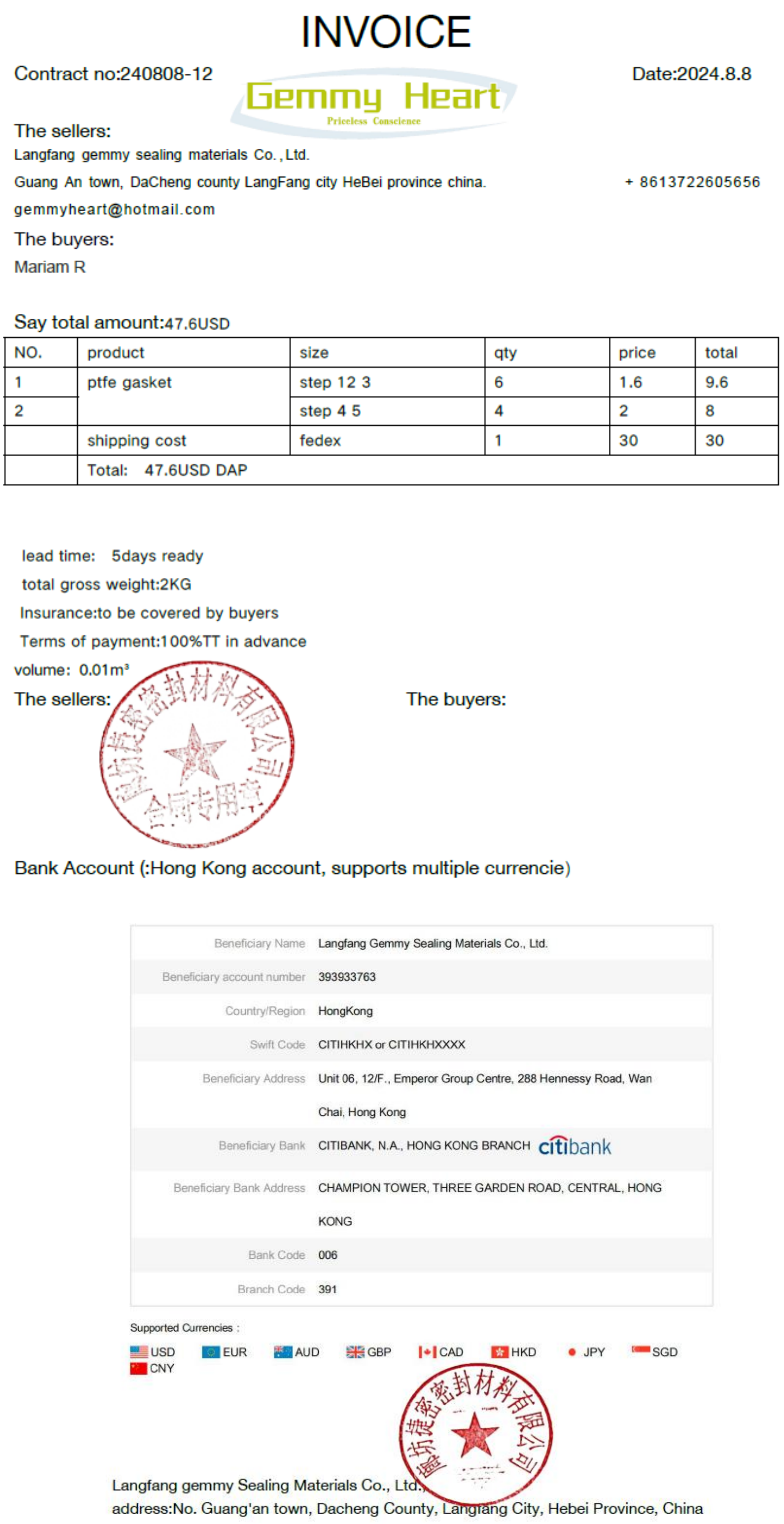
Bank Account (:Hong Kong account, supports multiple currencie)

Beneficiary Name	Langfang Gemmy Sealing Materials Co., Ltd.
Beneficiary account number	393933763
Country/Region	HongKong
Swift Code	CITIHKHX or CITIHKHXXXX
Beneficiary Address	Unit 06, 12/F., Emperor Group Centre, 288 Hennessy Road, Wan Chai, Hong Kong
Beneficiary Bank	CITIBANK, N.A., HONG KONG BRANCH citibank
Beneficiary Bank Address	CHAMPION TOWER, THREE GARDEN ROAD, CENTRAL, HONG KONG
Bank Code	006
Branch Code	391

Supported Currencies :
USD EUR AUD GBP CAD HKD JPY SGD
CNY

Langfang gemmy Sealing Materials Co., Ltd.
address:No. Guang'an town, Dacheng County, Langfang City, Hebei Province, China

alipay:hbxxmf@alibaba.com.cn 许东旭



INVOICE

Contract no:240808-12

Date:2024.8.8

Gemmy Heart
Priceless Conscience

The sellers:
Langfang gemmy sealing materials Co., Ltd.
Guang An town, DaCheng county LangFang city HeBei province china. + 8613722605656
gemmyheart@hotmail.com

The buyers:
Mariam R

Say total amount:47.6USD

NO.	product	size	qty	price	total
1	ptfe gasket	step 12 3	6	1.6	9.6
2		step 4 5	4	2	8
	shipping cost	fedex	1	30	30
	Total: 47.6USD DAP				

lead time: 5days ready
total gross weight:2KG
Insurance:to be covered by buyers
Terms of payment:100%TT in advance
volume: 0.01m³

The sellers:

The buyers:

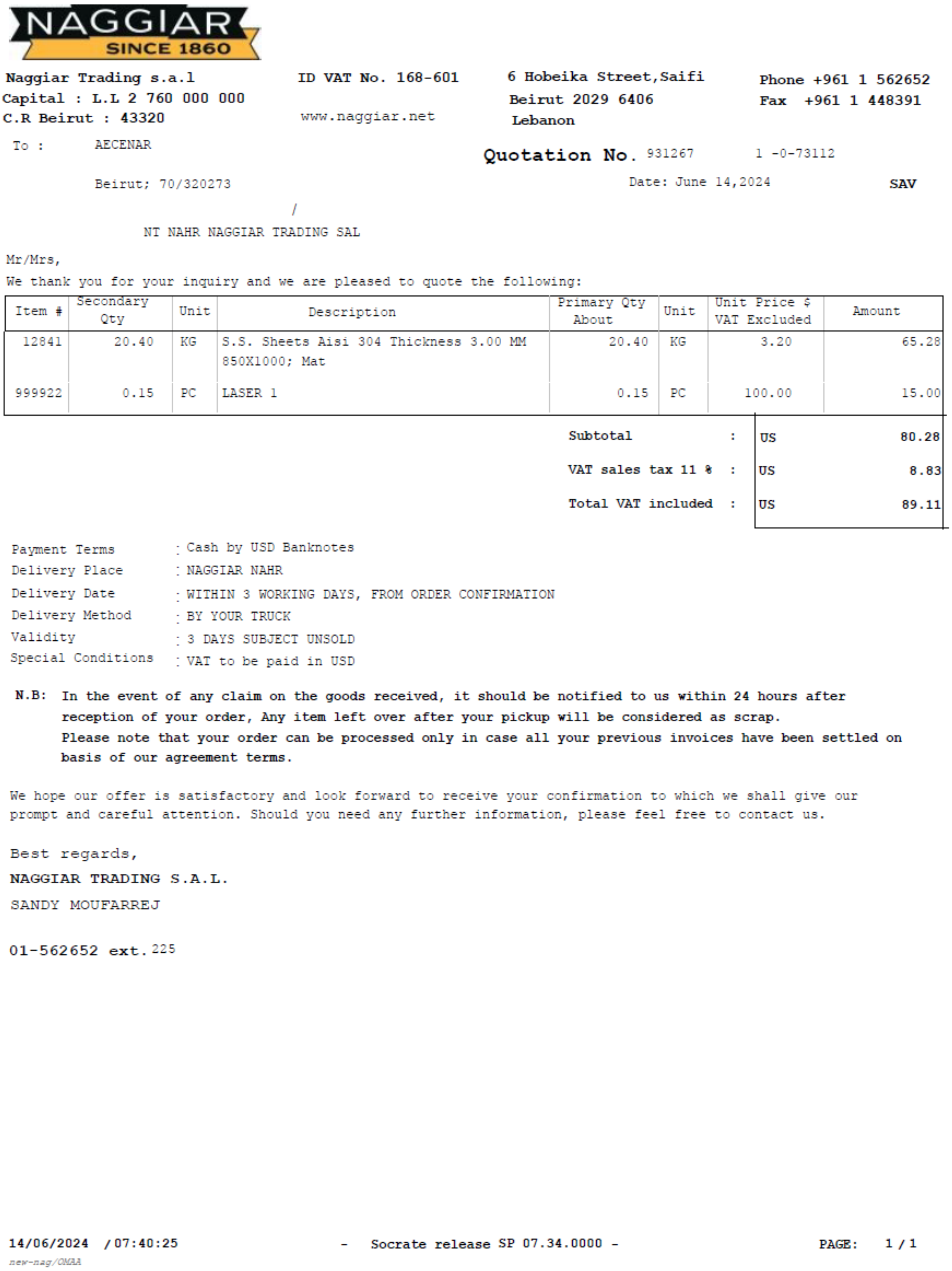
Bank Account (:Hong Kong account, supports multiple currencie)

Beneficiary Name	Langfang Gemmy Sealing Materials Co., Ltd.
Beneficiary account number	393933763
Country/Region	HongKong
Swift Code	CITIHKHX or CITIHKHXXXX
Beneficiary Address	Unit 06, 12/F., Emperor Group Centre, 288 Hennessy Road, Wan Chai, Hong Kong
Beneficiary Bank	CITIBANK, N.A., HONG KONG BRANCH citibank
Beneficiary Bank Address	CHAMPION TOWER, THREE GARDEN ROAD, CENTRAL, HONG KONG
Bank Code	006
Branch Code	391

Supported Currencies :
USD EUR AUD GBP CAD HKD JPY SGD
CNY

Langfang gemmy Sealing Materials Co., Ltd.
address:No. Guang'an town, Dacheng County, Langfang City, Hebei Province, China

10.5.2.4 Stainless invoice



Naggiar Trading s.a.l
Capital : L.L 2 760 000 000
C.R Beirut : 43320

ID VAT No. 168-601
www.naggiar.net

6 Hobeika Street,Saifi
Beirut 2029 6406
Lebanon

Phone +961 1 562652
Fax +961 1 448391

To : AECENAR

Beirut; 70/320273

Quotation No. 931267 1 -0-73112

Date: June 14,2024 **SAV**

/

NT NAHR NAGGIAR TRADING SAL

Mr/Mrs,

We thank you for your inquiry and we are pleased to quote the following:

Item #	Secondary Qty	Unit	Description	Primary Qty About	Unit	Unit Price $ VAT Excluded	Amount
12841	20.40	KG	S.S. Sheets Aisi 304 Thickness 3.00 MM 850X1000; Mat	20.40	KG	3.20	65.28
999922	0.15	PC	LASER 1	0.15	PC	100.00	15.00

Subtotal	:	**US**	**80.28**
VAT sales tax 11 %	:	**US**	**8.83**
Total VAT included	:	**US**	**89.11**

Payment Terms	: Cash by USD Banknotes
Delivery Place	: NAGGIAR NAHR
Delivery Date	: WITHIN 3 WORKING DAYS, FROM ORDER CONFIRMATION
Delivery Method	: BY YOUR TRUCK
Validity	: 3 DAYS SUBJECT UNSOLD
Special Conditions	: VAT to be paid in USD

N.B: In the event of any claim on the goods received, it should be notified to us within 24 hours after reception of your order, Any item left over after your pickup will be considered as scrap.
Please note that your order can be processed only in case all your previous invoices have been settled on basis of our agreement terms.

We hope our offer is satisfactory and look forward to receive your confirmation to which we shall give our prompt and careful attention. Should you need any further information, please feel free to contact us.

Best regards,
NAGGIAR TRADING S.A.L.
SANDY MOUFARREJ

01-562652 ext. 225

14/06/2024 /07:40:25 - **Socrate release SP 07.34.0000** - **PAGE: 1 / 1**

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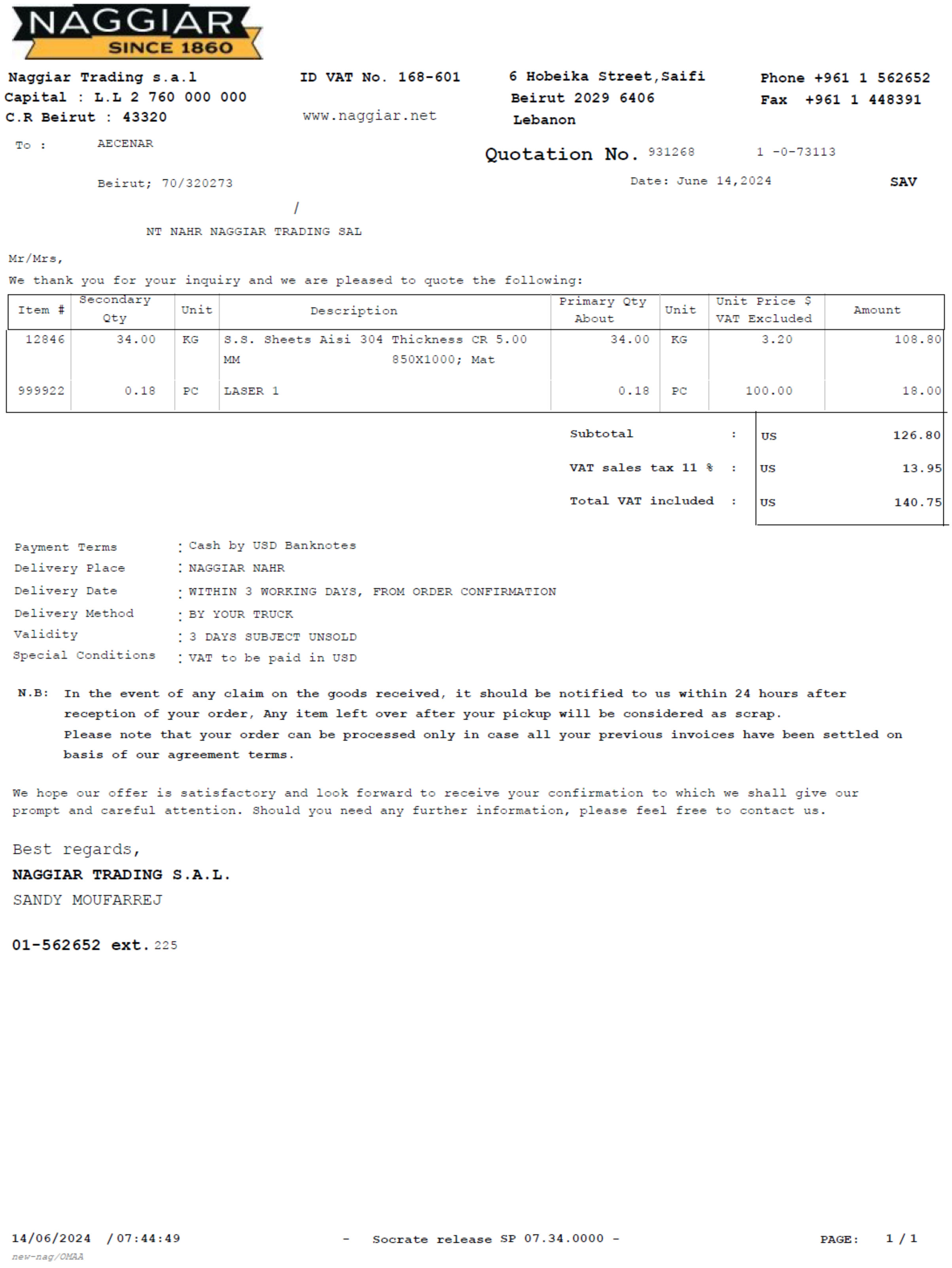


Naggiar Trading s.a.l
Capital : L.L 2 760 000 000
C.R Beirut : 43320

ID VAT No. 168-601
www.naggiar.net

6 Hobeika Street,Saifi
Beirut 2029 6406
Lebanon

Phone +961 1 562652
Fax +961 1 448391

To : AECENAR

Beirut; 70/320273

/

NT NAHR NAGGIAR TRADING SAL

Quotation No. 931268 1 -0-73113

Date: June 14,2024 **SAV**

Mr/Mrs,

We thank you for your inquiry and we are pleased to quote the following:

Item #	Secondary Qty	Unit	Description	Primary Qty About	Unit	Unit Price $ VAT Excluded	Amount
12846	34.00	KG	S.S. Sheets Aisi 304 Thickness CR 5.00 MM 850X1000; Mat	34.00	KG	3.20	108.80
999922	0.18	PC	LASER 1	0.18	PC	100.00	18.00

Subtotal	:	US	126.80
VAT sales tax 11 %	:	US	13.95
Total VAT included	:	US	140.75

Payment Terms : Cash by USD Banknotes
Delivery Place : NAGGIAR NAHR
Delivery Date : WITHIN 3 WORKING DAYS, FROM ORDER CONFIRMATION
Delivery Method : BY YOUR TRUCK
Validity : 3 DAYS SUBJECT UNSOLD
Special Conditions : VAT to be paid in USD

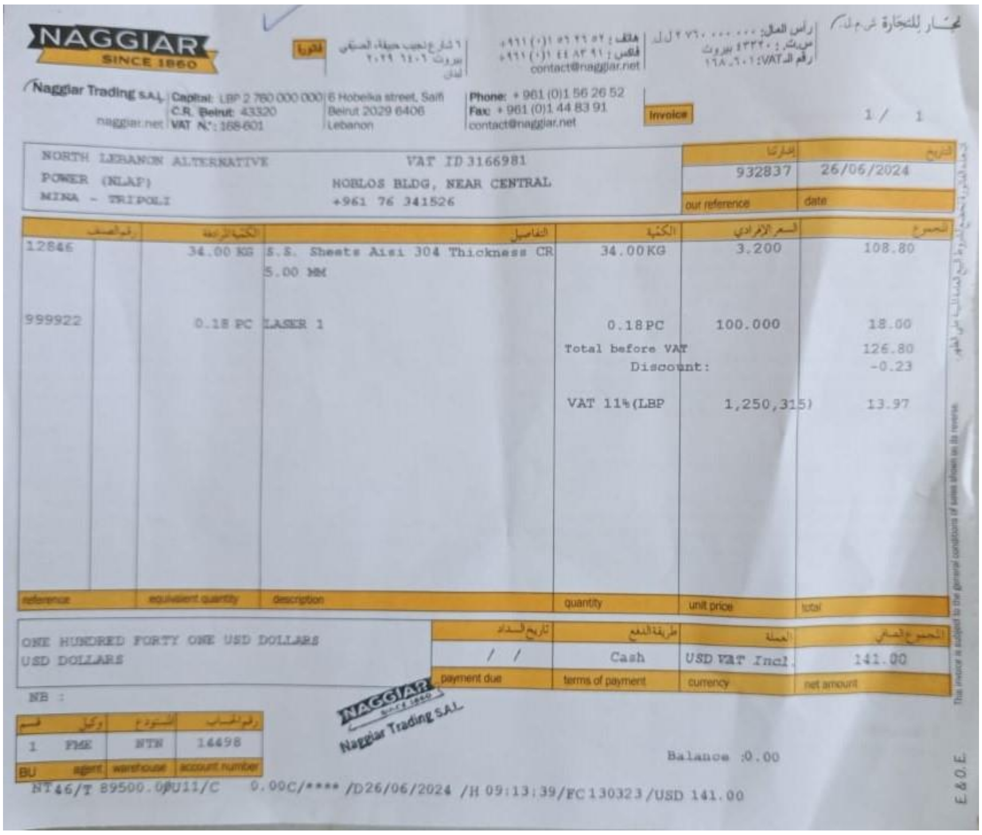
N.B: In the event of any claim on the goods received, it should be notified to us within 24 hours after reception of your order, Any item left over after your pickup will be considered as scrap.
Please note that your order can be processed only in case all your previous invoices have been settled on basis of our agreement terms.

We hope our offer is satisfactory and look forward to receive your confirmation to which we shall give our prompt and careful attention. Should you need any further information, please feel free to contact us.

Best regards,
NAGGIAR TRADING S.A.L.
SANDY MOUFARREJ

01-562652 ext. 225

14/06/2024 / 07:44:49 - Socrate release SP 07.34.0000 - PAGE: 1 / 1
new-nag/OMAA



NAGGIAR
SINCE 1860

Naggiar Trading S.A.L.
naggiar.net
Capital: LBP 2 760 000 000
C.R. Beirut: 43320
VAT N°: 168-601
6 Hobeika street, Saifi
Beirut 2029 6406
Lebanon
Phone: +961 (0)1 56 26 52
Fax: +961 (0)1 44 83 91
contact@naggiar.net

Invoice 1/ 1

NORTH LEBANON ALTERNATIVE
POWER (NLAP)
MINA - TRIPOLI
VAT ID 3166981
HOBLOS BLDG, NEAR CENTRAL
+961 76 341526

our reference	date
932837	26/06/2024

reference	equivalent quantity	description	quantity	unit price	total
12846	34.00 KG	S.S. Sheets Aisi 304 Thickness CR 5.00 MM	34.00KG	3.200	108.80
999922	0.18 PC	LASER 1	0.18PC	100.000	18.00
			Total before VAT		126.80
			Discount:		-0.23
			VAT 11%(LBP	1,250,315)	13.97

ONE HUNDRED FORTY ONE USD DOLLARS
USD DOLLARS

payment due	terms of payment	currency	net amount
/ /	Cash	USD VAT Incl.	141.00

NB :

BU	agent	warehouse	account number
1	FME	NTN	14498

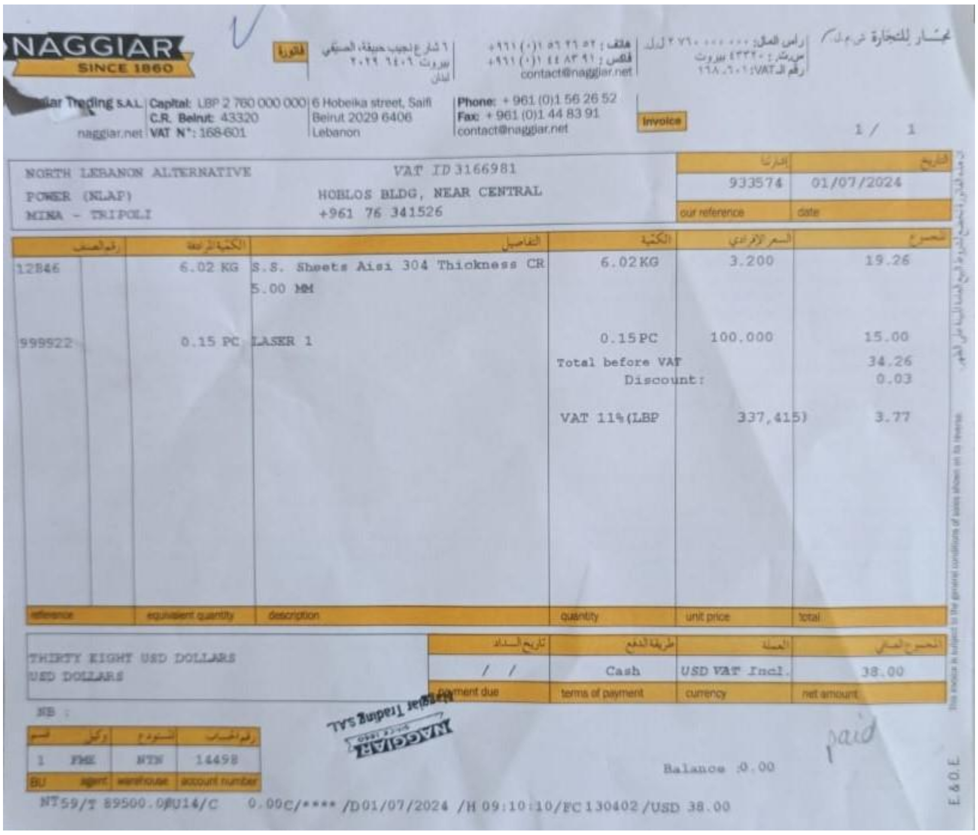
NAGGIAR SINCE 1860 Naggiar Trading S.A.L.

Balance :0.00

NT46/T 89500.0ØU11/C 0.00C/**** /D26/06/2024 /H 09:13:39/FC 130323 /USD 141.00

This invoice is subject to the general conditions of sales shown on its reverse.

E.&O.E.



NAGGIAR
SINCE 1860

Naggiar Trading S.A.L.
naggiar.net
Capital: LBP 2 760 000 000
C.R. Beirut: 43320
VAT N°: 168-601
6 Hobeika street, Saifi
Beirut 2029 6406
Lebanon
Phone: +961 (0)1 56 26 52
Fax: +961 (0)1 44 83 91
contact@naggiar.net

Invoice 1/ 1

NORTH LEBANON ALTERNATIVE
POWER (NLAP)
MINA - TRIPOLI
VAT ID 3166981
HOBLOS BLDG, NEAR CENTRAL
+961 76 341526

our reference	date
933574	01/07/2024

reference	equivalent quantity	description	quantity	unit price	total
12846	6.02 KG	S.S. Sheets Aisi 304 Thickness CR 5.00 MM	6.02KG	3.200	19.26
999922	0.15 PC	LASER 1	0.15PC	100.000	15.00
			Total before VAT		34.26
			Discount:		0.03
			VAT 11%(LBP	337,415)	3.77

THIRTY EIGHT USD DOLLARS
USD DOLLARS

payment due	terms of payment	currency	net amount
/ /	Cash	USD VAT Incl.	38.00

NB :

BU	agent	warehouse	account number
1	FME	NTN	14498

NAGGIAR SINCE 1860 Naggiar Trading S.A.L.

paid

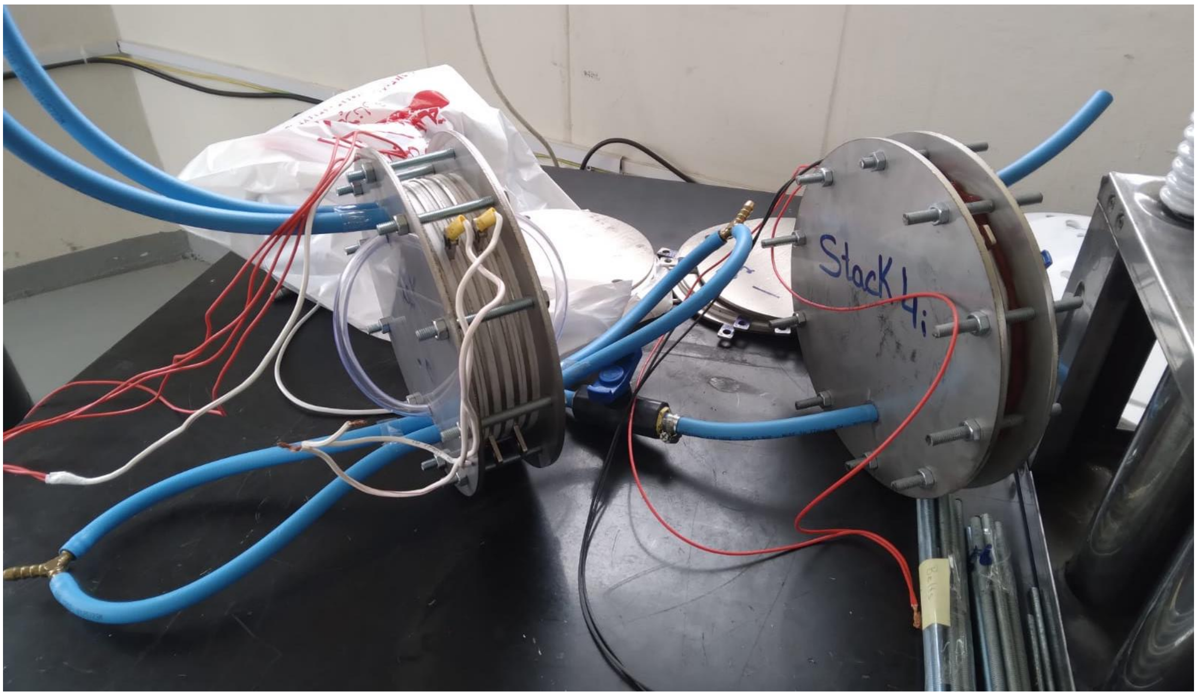
Balance :0.00

NT59/T 89500.0ØU14/C 0.00C/**** /D01/07/2024 /H 09:10:10/FC 130402 /USD 38.00

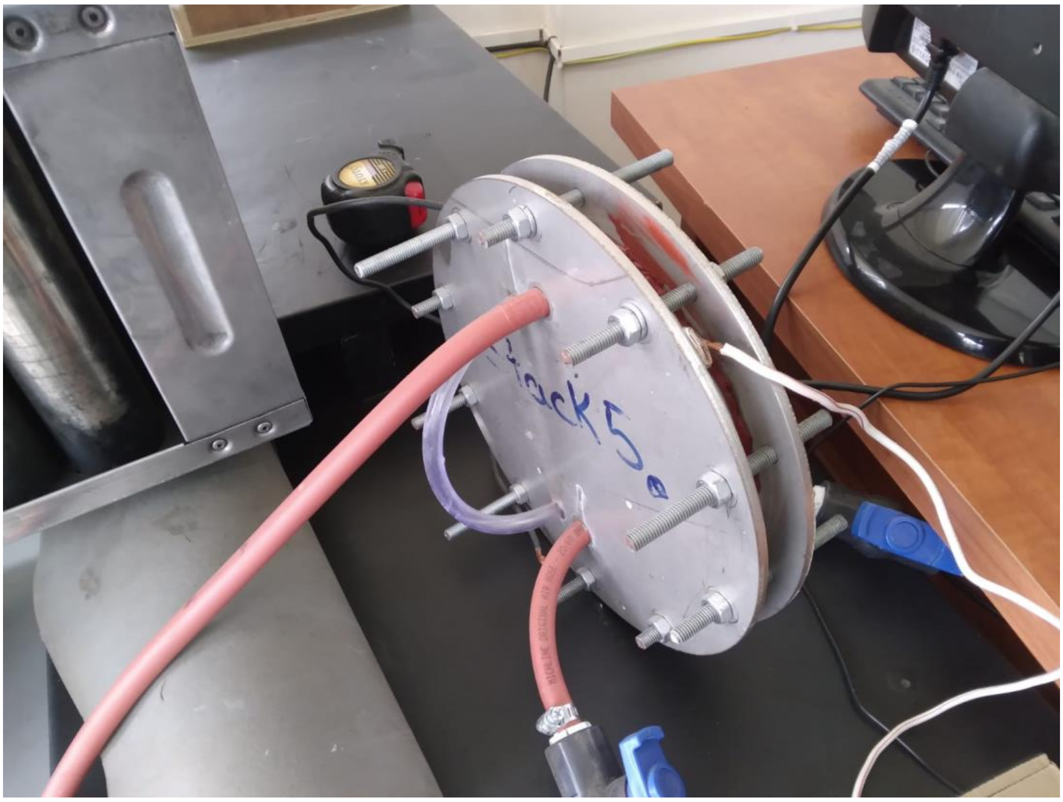
This invoice is subject to the general conditions of sales shown on its reverse.

E.&O.E.

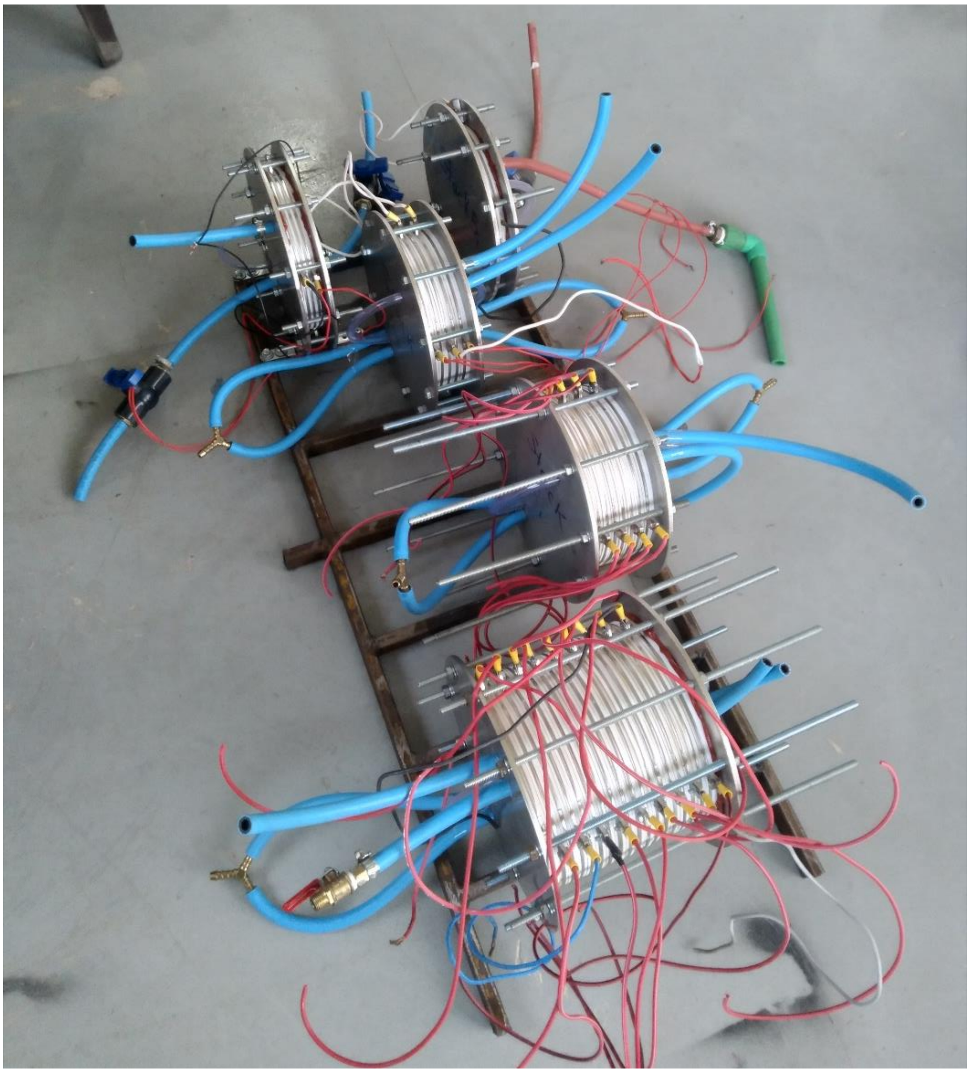
10.5.3 Realization of MSE stacks



Picture above: Stack 3 (left) and Stack 4 (right)



Picture above: Stack 5



Pictures above: Stack 1 to 5

10.6 Operation of the system

10.6.1 Preparation of KOH solution

To prepare this solution we need a:

- 50 L of distilled water

- 4 kg* of KOH crystals

* ⚠ N.B.: The lower the purity of the crystals, the more crystals we need

- Plastic or glass bowl
- Tank 60L of volume
- balance weight per gram
- Stick to mix solution
- pH meter
- Funnel
- Gloves

We weighed 1400 gr of the KOH crystals via a weighing balance. We put 50 L of distilled water in the tank, then added the KOH crystals and mixed the solution well. Based on the value (the pH shall be 13.6), we measured the pH of the solution and added water and/or crystals.

10.6.2 Pre-Operation

1- The Dry ice powder is available

2- The dry ice tank and distillation tank are connected properly

3- The butane gas bottle is full and connected properly to the stove

4- The distilled water tank is in the appropriate place to receive drops of distilled water coming out of the distillation tank

5- All mechanical connections are done

6- Close the ball manual valve of the water tank and fill it with distilled water

7- Close the ball manual valve of the KOH tank and fill it with the KOH solution prepared previously

8- Ensure that the pipes are connected correctly and repair leaks, if any

9- Fill the gas filters with water halfway

10- Ensure that all mechanical valves are working properly, opening and closing

11- Ensure that all electrical equipment (Electrical valves, pumps, sensors, …) is connected to the electrical current

12- Ensure that the system is controlled correctly through the GUI

13- Ensure the DC power is connected correctly to the cells of each stack

14- All breakers ($\mathbf{B_1}$, $\mathbf{B_2}$, $\mathbf{B_3}$, $\mathbf{B_4}$, and $\mathbf{B_5}$) are opened

15- Wash the system with nitrogen gas

1) Open all inlet automatic controller valves of stacks
(Valve **ASI$_1$**, **ASI$_2$**, **ASI$_3$**, **ASI$_4$**, and **ASI$_5$**)

2) Close all outlet automatic controller valves of stacks
(Valve **ASO$_1$**, **ASO$_2$**, **ASO$_3$**, **ASO$_4$**, and **ASO$_5$**)

3) Open the automatic controller valves of hydrogen and oxygen gases
(Valves **AH$_1$**, **AH$_2$**, **AH$_3$**, **AO$_1$**, **AO$_2$**, and **AO$_3$**)

4) Open the ball valve of hydrogen gas **VH** and oxygen gas **VO**

5) Connect the nitrogen tank with the stacks by nitrogen valves
(valve **AN$_1$**, **AN$_2$**, **AN$_3$**, **AN$_4$**, and **AN$_5$**)

6) Open the nitrogen valves (Valve **AN$_1$**, **AN$_2$**, **AN$_3$**, **AN$_4$**, and **AN$_5$**)

7) Open the valve of Nitrogen tank for 5-10 minutes at 3 bars

8) Close the nitrogen tank **VN$_0$**, and nitrogen valves
(Valve **VN$_1$**, **AN$_2$**, **AN$_3$**, **AN$_4$**, and **AN$_5$**)

9) Close the Hydrogen valves (Valve **AH$_1$**, **AH$_2$**, and **AH$_3$**) & Oxygen valves
(Valve **AO$_1$**, **AO$_2$**, and **AO$_3$**)

10) Close the **VH** and **VO** valves

16- Connecting electricity to the fuel cells to withdraw the electricity generated from the fuel cells
17- Reclose all valves

10.6.3 Operation of the MSE system

1- Fill the Condensers with the previously prepared KOH solution using the following steps:

1) Open the KOH tank valve **SV**

2) Open the **AC$_1$**, **AC$_2$**, **AC$_3$** and **AC$_4$** to get solution into the condensers

3) Turn ON the KOH pump (**SP**)

2- Fill the Stack #1 with the previously prepared KOH solution using the following steps:

1) Open the **AH$_1$** and **VH** valve

2) Open the **AO_1** and **VO** valve

3) Open the **ASI_1** valve; to enter the KOH solution into stack #1

4) When the KOH solution reaches the required level in Stack #1, close **ASI_1** while keeping the **AC_1, AC_2, and AC_3** valves opened

3- Turn ON the electricity (DC) on Stack #1 by closing breaker **B_1**

4- Monitoring the solution level in Stack #1, pH, electrical voltage with current, and temperature through sensors

⚠ N.B.: If the temperature of the Stack increases, we disconnect the DC electricity for some time to reduce the temperature of the stack. We can also add more KOH solution to the stack to cool the stack if the solution level decreases.

5- Transfer the remaining solution in Stack #1 to the dry ice tank in the following steps:

1) When the appropriate pH is reached (or the solution level drops to half or less if no solution is added), we disconnect the electrical current from the stack by opening breaker **B_1**

2) Close **AO_1** valve

3) Open the **ASO_1** valve to empty the solution from the stack

4) Open **VMS_1** valve, with keeping the **AD_1** valves closed

6- When the stack is empty, close **VMS_1**

7- Add the right amount of dry ice into the dry ice tank intermittently and in small quantities*

*** ⚠ N.B.: It is important to add dry ice intermittently and in small quantities to avoid boiling and/or freezing and to ensure the effective interaction of materials, as well as for personal safety.**

8- When the reaction of Dry ice with concentrated KOH solution is finished, Open the **AD_1** valve

9- Open the **WV** and the **AW_1** valves and Turn ON the water pump (**WP**)

10- Setting a fire under the distillation tank

11- When the distillation process is finished, open the **ACS_1** valve to add the rest of the KOH solution (5%) to the distilled water tank. Now the KOH solution is ready to be added to Stack #2

12- Turn OFF the water pump (**WP**) if there is no need for other systems, then close the **WV** valve

13- <u>To re-install stack #1</u>, close the **ASO$_1$** valve, and repeat the 2nd step to the 12th of operation steps

14- <u>Add the new KOH solution</u> (Final solution extracted from Stack #1) <u>to Stack #2</u>

1) Open the **AH$_2$** and **VH** valve

2) Open the **AO$_2$** and **VO** valve

3) Open the **ASI$_2$** valve; to enter the KOH solution into stack #2

4) When the KOH solution reaches the required level in Stack #2, close **ASI$_2$** while keeping the **AC$_1$, AC$_2$, and AC$_3$** valves opened

15- Turn ON the electricity (DC) on Stack #2 by closing breaker **B$_2$**

16- Monitoring the solution level in Stack #2, pH, electrical voltage with current, and temperature through sensors

17- <u>Transfer the remaining solution in Stack #2 to the dry ice tank</u> in the following steps:

1) When the appropriate pH is reached (or the solution level drops to half or less if no solution is added), we disconnect the electrical current from the stack by opening breaker **B$_2$**

2) Close **AO$_2$** valve

3) Open the **ASO$_2$** valve to empty the solution from the stack

4) Open **VMS$_2$** valve, with keeping the **AD$_2$** valves closed

18- When the stack is empty, close **VMS$_2$**

19- Add the right amount of dry ice into the dry ice tank intermittently and in small quantities

20- When the reaction of Dry ice with concentrated KOH solution is finished, Open the **AD$_2$** valve

21- Open **AW$_2$** - Open the **WV** valve if it is closed - and Turn ON the water pump (**WP**), if it isn’t running

22- Setting a fire under the distillation tank

23- When the distillation process is finished, open the **ACS$_2$** valve to add the rest of the KOH solution (5%) to the distilled water tank. Now the KOH solution is ready to be added to Stack #3

24- To re-install stack #2, close the **ASO_2** valve, open the **ASI_2**, the **AH_2** valve, and the **AO_2** valve, and repeat the 14th step to 23th of operation steps

25- Add the new KOH solution (Final solution extracted from Stack #2) to Stack #3

1) Open the **AH_3** and **VH** valve

2) Open the **AO_3** and **VO** valve

3) Open the **ASI_3** valve; to enter the KOH solution into stack #3

4) When the KOH solution reaches the required level in Stack #3, close **ASI_3** while keeping the **AC_1, AC_2, and AC_3** valves opened

26- Turn ON the electricity (DC) on Stack #3 by closing breaker **B_3**

27- Monitoring the solution level in Stack #3, pH, electrical voltage with current, and temperature through sensors

28- Transfer the remaining solution in Stack #3 to the dry ice tank in the following steps:

1) When the appropriate pH is reached (or the solution level drops to half or less if no solution is added), we disconnect the electrical current from the stack by opening breaker **B_3**

2) Close **AO_3** valve

3) Open the **ASO_3** valve to empty the solution from the stack

4) Open **VMS_3** valve, with keeping the **AD_3** valves closed

29- When the stack is empty, close **VMS_3**

30- Add the right amount of dry ice into the dry ice tank intermittently and in small quantities

31- When the reaction of Dry ice with concentrated KOH solution is finished, Open the **AD_3** valve

32- Open **AW_3** - Open the **WV** valve if it is closed - and Turn ON the water pump (**WP**), if it isn't running

33- Setting a fire under the distillation tank

34- When the distillation process is finished, open the **ACS_3** valve to add the rest of the KOH solution (5%) to the distilled water tank. Now the KOH solution is ready to be added to Stack #4

35- To re-install stack #3, close the **ASO$_3$** valve, open the **ASI$_3$**, the **AH$_3$** valve, and the **AO$_3$** valve, and repeat the 25th step to 34th of operation steps

36- If Stack #1, Stack #2, and Stack #3 are turned OFF, Turn OFF the KOH solution pump (**SP**) and close the **SV** valve

37- Add the new KOH solution (Final solution extracted from Stack #3) to Stack #4

1) Open the **ASI$_4$** valve; to enter the KOH solution into stack #4

2) Add the newest KOH solution (extracted KOH solution from Stack #3) to Stack #4

3) When the KOH solution reaches the required level in Stack #4, close **ASI$_4$**

38- Turn ON the electricity (DC) on Stack #4 by closing breaker B$_4$

39- Monitoring the solution level in Stack #4, pH, electrical voltage with current, and temperature through sensors

40- Transfer the remaining solution in Stack #4 to the dry ice tank in the following steps:

1) When the appropriate pH is reached (or the solution level drops to half or less if no solution is added), we disconnect the electrical current from the stack by opening breaker **B$_4$**

2) Open the **ASO$_4$** valve to empty the solution from the stack

3) Open **VMS$_4$** valve, with keeping the **AD$_4$** valves closed

41- When the stack is empty, close **VMS$_4$**

42- Add the right amount of dry ice into the dry ice tank intermittently and in small quantities

43- When the reaction of Dry ice with concentrated KOH solution is finished, Open the **AD$_4$** valve

44- Open **AW$_4$** - Open the **WV** valve if it is closed - and Turn ON the water pump (**WP**), if it isn't running

45- Setting a fire under the distillation tank

46- When the distillation process is finished, open the **ACS$_4$** valve to add the rest of the KOH solution (5%) to the distilled water tank. Now the KOH solution is ready to be added to Stack #5

47- When the fuel cell **FC$_1$** is run (when Stack #4 is running), the water coming out of Fuel cell **FC$_1$** must be collected and then added to the product solution from Stack #3 as well.

48- To re-install stack #4, close the **ASO_4** valve, open the **ASI_4** valve, and repeat the 37th step to 48th of operation steps

49- Add the new KOH solution (Final solution extracted from Stack #4) to Stack #5

1) Open the **ASI_5** valve; to enter the KOH solution into stack #5

2) Add the newest KOH solution (extracted KOH solution from Stack #4) to Stack #5

3) When the KOH solution reaches the required level in Stack #4, close **ASI_5**

50. Turn ON the electricity (DC) on Stack #5 by closing breaker **B_5**
51. Monitoring the solution level in Stack #5, pH, electrical voltage with current, and temperature through sensors

52. Transfer the remaining solution in Stack #5 to the dry ice tank in the following steps:

1) When the appropriate pH is reached (or the solution level drops to half or less if no solution is added), we disconnect the electrical current from the stack by opening breaker **B_5**

2) Open the **ASO_5** valve to empty the solution from the stack

3) Keep the **AD_5** valve closed

53- Add the right amount of dry ice into the dry ice tank intermittently and in small quantities

54- When the reaction of Dry ice with concentrated KOH solution is finished, Open the **AD_5** valve

55- Open **AW_5** - Open the **WV** valve if it is closed - and Turn ON the water pump (**WP**), if it isn't running

56- Setting a fire under the distillation tank

57- When pre-starting fuel cell **FC_2**(when Stack #5 is running), the water coming out of Fuel cell **FC_2** must be collected in HW tank

58- When the fuel cell **FC_2** is run (when Stack #5 is running), the water coming out of Fuel cell **FC_2** must be collected and then added to the distilled water produced from Stack #5

59- When the distillation process is finished, the distilled water collected in the distilled water tank should be added to the HW tank. Now the HW is ready to be tested or used.

60- To re-install stack #5, close the **ASO_5** valve, open the **ASI_5** valve, and repeat the 49th step to 59th of operation steps

61- Turn OFF the water pump (**WP**)

10.6.4 Post - Operation

1- All breakers are opened (**B_1**, **B_2**, **B_3**, **B_4**, and **B_5**)

2- Wash the system with nitrogen gas by using the following steps:

1) Open all inlet automatic controller valves of stacks
(Valve **ASI_1**, **ASI_2**, **ASI_3**, **ASI_4**, and **ASI_5**)

2) Close all outlet automatic controller valves of stacks
(Valve **ASO_1**, **ASO_2**, **ASO_3**, **ASO_4**, and **ASO_5**)

3) Open the automatic controller valves of hydrogen and oxygen gases
(Valves **AH_1**, **AH_2**, **AH_3**, **AO_1**, **AO_2**, and **AO_3**)

4) Open the ball valve of hydrogen gas **VH** and oxygen gas **VO**

5) Connect the nitrogen tank with the stacks by nitrogen valves
(valve **AN_1**, **AN_2**, **AN_3**, **AN_4**, and **AN_5**)

6) Open the nitrogen valves (Valve **AN_1**, **AN_2**, **AN_3**, **AN_4**, and **AN_5**)

7) Open the valve of Nitrogen tank for 5-10 minutes at 3 bars

8) Close the nitrogen tank **VN_0**, and nitrogen valves
(Valve **VN_1**, **AN_2**, **AN_3**, **AN_4**, and **AN_5**)

9) Close the Hydrogen valves (Valve **AH_1**, **AH_2**, and **AH_3**) & Oxygen valves
(Valve **AO_1**, **AO_2**, and **AO_3**)

10) Close the **VH** and **VO** valves

3- Wash the condensers with distilled water after operation using the following steps:

1) The **SP** pump is turned OFF

2) Close the KOH tank valve (**SV**)

3) Open the **AC$_1$**, **AC$_2$**, and **AC$_3$** valves

4) Open the **DW$_0$** valve

5) The **ASI$_1$** and **AC$_4$** valves is closed

6) Open the **WI$_1$** valve, Close the **AW$_1$**, **AW$_2$**, **AW$_3$**, **AW$_4$**, **AW$_5$**, **AW$_6$**, and **AW$_7$**

7) Open the **WV** valve and Turn ON the water pump (**WP**)

8) Wait 10-15 minutes and turn OFF the **WP** pump

9) Close the **WI$_1$** valve

4- Wash the Stack#1 used in operation with water by following steps:

1) Close **AC$_1$** and **DW$_0$** valves

2) Open **ASI$_1$** and **ASO$_1$** valves

3) Open **WI$_1$** valve

4) Turn ON the water pump **WP**

5) Check the level sensor to open the **DW$_1$** valve

6) Wait 3 minutes then Turn OFF the **WP** pump and close the **ASI$_1$** valve

7) Wait until the water stops coming out, then close the **ASO$_1$** valve

8) Close the **DW$_1$** valve

5- Wash Stack#2, Stack#3, Stack#4, and Stack#5 used in operation with water by following steps:

1) Open **WI$_x$** valve appropriate to the stack

2) Open the **ASI$_x$** and **ASO$_x$** valves appropriate to the stack

3) Turn ON the water pump **WP**

4) Check the level sensor to open the **DW$_x$** valve appropriate to the stack

5) Turn OFF the **WP** pump

6) Wait until the water stops coming out, then close the **ASI_x** and **ASO_x** valves appropriate to the stack

7) Close the **DW_x** valve appropriate to the stack

6- Wash the Dry ice tank used in the operation with water

7- Wash the lower part of the distillation tank

8- Disconnect All electrical components

⚠ **N.B.:**

- **We can replace cooling water pipes with water hoses.**
- **As for the distillation tank and dry ice tank, we can manufacture (or purchase) them in one piece and use them alternately for all stages of operation, provided that they are cleaned after each use.**
- **We can cool the condensers with water instead of KOH solution, but this requires an adjustment at valves AC_1 and AC_4.**
- **We can replace the Nitrogen pipe with Nitrogen or Gas hoses.**
- **Instead of DW valves, we can separate the dry ice tank from the stack.**
- **We can replace the current fuel cell with a fuel cell based on Hydrogen and Oxygen for higher efficiency**

10.7 System Test Specifications

10.7.1 KOH-Dry ice reaction followed by distillation process

Step	Step description	Expected result
Pre-condition	KOH solution is placed in the distillation tank (bottom part)	
Add Dry ice	- Put the bottom distillation tank in a place well ventilated - Add the dry ice finger to the KOH solution	- Heavy white smoke rising - The formed solution (K_2CO_3) in a liquid state
Distillation process	- Collect the upper part with the lower part of the distillation tank - Put tape where the two parts meet - Add the cooling water to the upper part of the tank - Close the water drain hole	- No leakage of steam - Condensation of water

	- Put the distillation tank on the fire - Put the Erlenmeyer at the outlet of the distilled water - Change the cooling water every 10-15 minutes - When about 950 ml of water is distilled, remove the distillation tank from the fire - Empty the cooling water and wait for the tank to cool - Separate the upper part from the lower part of the distillation tank - Collect the distilled water resulting from the distillation process - Measure the pH of the water using the pH meter	- About 950 mL of distilled water is reclaimed - The bottom of the distillation tank (bottom part) is corroded - The pH of the distilled water is 7

10.7.2 Leakage, followed by installation of the stack (Step 4, and 5)

Step	Step description	Expected result
Pre-condition	KOH solution is placed in the distillation tank (bottom part)	
Add Dry ice	- Put the bottom distillation tank in a place well ventilated - Add the dry ice finger to the KOH solution	- Heavy white smoke rising - The formed solution (K_2CO_3) in a liquid state
Distillation process	- Collect the upper part with the lower part of the distillation tank - Put tape where the two parts meets - Fixed the distillation tank in the water bath - Put the water bath on fire - Add water to the bath - Add the cooling water to the upper part of the tank	- No leakage of steam - Condensation of water - About 950 mL of distilled water is reclaimed - The bottom of the distillation tank (bottom part) is corroded

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	- Close the water drain hole - Put the Erlenmeyer at the outlet of the distilled water - Change the cooling water every 10-15 minutes When about 950 ml of water is distilled, remove the water bath distillation tank from the fire - Remove the distillation tank from the water bath - Empty the cooling water and wait for the tank to cool - Separate the upper part from the lower part of the distillation tank - Collect the distilled water resulting from the distillation process - Measure the pH of the water using the pH meter	- The pH of the distilled water is 7

10.7.3 Leakage, followed by installation of the stack (step 1, 2, and 3)

Step	Step description	Expected result
Pre-condition	- Stack is empty - All equipment (electrical and mechanical) is connected properly	
Fill the stack	- Open the inlet ball valve to fill the stack with KOH solution - Accurately introduce the KOH solution into the stack via the inlet hole, employing a funnel for precise pouring. - When the stack is filled (two-thirds full), close the inlet ball valve.	- The stack is filled by the KOH solution - No leak appears

Verify connections and electrospinning	- Check electrical equipment is connected - Put the multimeter on “Diode mode” - Connect each pole of the multimeter (diode mode) to each end plate - Connect each pole of the multimeter (diode mode) to each electrode - Connect the poles of the multimeter (diode mode) to both the electrode and end plate	- All electrical equipment is connected - The multimeter is functioned in “Diode mode” - The multimeter is beeps - The multimeter beeps - The multimeter does not beep
Install the system	- Turn ON the power supply - Regulate DC voltage and current	- The power is turned ON - Gas bubbles (H_2 & O_2) popping in the gas purification tank
Burn the mixed gases formed	- Close the regulator valve of the torch handle - Wait a few minutes for the gases to compress slightly - Open the regulator valve of the torch handle and bring a spark beside the torch handle with the regulator valve knob	- The mixed gas is burned
Turn OFF the system	- Turn OFF the power supply	- The power supply is turned OFF - After a few minutes, the flame dwindles and disappears
Measurement of pH	- Emptying the KOH solution from the stack - Take a sample from the KOH solution - Use the pH meter to find out the new pH	- The new pH is higher than the old one (initial pH)

10.8 System Tests

10.8.1 KOH/Dry ice rx followed by distillation process test “MSE-T1” (Friday 20.09.2024)

This test is a validation of the application of the distillation process and therefore the correctness of the proposed design

10.8.1.1 Materials

- **Materials for the KOH slt° preparation**

KOH solid (200 gr)

Distilled water (1000 mL)

Spatula

Beaker (V = 1L)

Digital balance

Spatula glass

- **Materials for the KOH-Dry Ice reaction**

  Dry ice (1 Kg finger)

  Spatula glass

- **Materials for the distillation process**

  Distillation tank (Consists of two parts: an upper part (cooling part) and a lower part)

  Water (for cooling)

  Stove (Source of heat)

  Erlenmeyer flask (V = 1L)

  pH-meter

10.8.1.2 Safety precautions

1) Wear appropriate protective equipment:
   - Gloves
   - Goggles
   - Lab coat

2) Perform the reaction KOH/Dry ice in a well-ventilated area
3) Use a suitable reaction vessel
4) Add dry slowly
5) Avoid direct contact with the solution
6) Have a fire extinguisher readily available
7) Use a heat source with a variable temperature control
8) Secure the glassware
9) Avoid direct contact with the hot glassware
10) Be cautious when handling the distillate
11) Properly dispose of waste

10.8.1.3 Pre-test of distillation tank

- **Preparation of KOH solution**
    1) Weigh 200 gr of crystal KOH using a digital scale, spatula, and beaker
    2) Add the KOH crystals in 1 L of the distilled water
    3) Stir until the KOH dissolves completely

- **Add the dry ice finger**
    1) After dissolving the KOH in the water, we put the KOH solution prepared in the bottom of the distillation tank
    2) We put the bottom distillation tank in a ventilated place
    3) Then we add the dry ice finger to the KOH solution
    4) We wait until the reactions between the KOH and the dry ice are complete

⚠ **N.B.: If we add a lot of dry ice, we may have to wait extra time for the ice to melt and the reacted solution to return to its liquid state**

10.8.1.4 Distillation process test

1) When the reaction between the solution and dry ice is complete, we have K_2CO_3 dissolved in water, collect the parts of the distillation tank together (the upper part with the lower)

2) We put tape where the two parts meet, to prevent steam from leaking out of the tank

3) We add the cooling water to the upper part of the tank and close the water drain hole

4) We put the distillation tank on the fire

5) We put the Erlenmeyer at the outlet of the distilled water

6) We change the cooling water every 10-15 minutes; to ensure the condensation of the water

7) When about 950 ml of water is distilled, we remove the distillation tank from the fire

8) After emptying the cooling water and waiting for the tank to cool, we separate the upper part from the lower part of the distillation tank

9) After collecting the distilled water resulting from the distillation process, we measure the pH of the water using the pH meter; to confirm the distillation rate

10.8.1.5 Responsibilities

MSE-T1 : KOH/Dry ice rx followed by distillation process test		
Task	**Responsible**	**Note**
KOH preparation	Maryam R.	
Purchase dry ice	Muhamad K.	
Deliver dry ice	Ali D., Muhamad K.	
Mixed KOH/Dry ice	Maryam R., Muhamad K.	
Fixed Distillation tank	Maryam R., Ali D.	
Heat source for dislillation process	Ali D., Maryam R., Muhamad K.	
Cooling for dislillation process	Ali D., Maryam R., Muhamad K.	
pH measure	Muhamad K., Maryam R.	
Documentation	Maryam R.	
Equipment re-cleaning	Ali D.	

10.8.1.6 Test specification and test results of MSE-T1

Step	**Step description**	**Expected result**	**Results**
Pre-condition	KOH solution is placed in the distillation tank (bottom part)		
Add Dry ice	- Put the bottom distillation tank in a place well ventilated - Add the dry ice finger to the KOH solution	- Heavy white smoke rising - The formed solution (K_2CO_3) in a liquid state	☑ Heavy white smoke rising ☑ The formed solution (K_2CO_3) in a liquid state **after waiting** (because we put an extra amount of the dry ice)
Distillation process	- Collect the upper part with the lower part of the distillation tank	- No leakage of steam - Condensation of water - About 950 mL of distilled	☑ No leakage of steam ☑ Water condenses and

	- Put tape where the two parts meets - Add the cooling water to the upper part of the tank - Close the water drain hole - Put the distillation tank on the fire - Put the Erlenmeyer at the outlet of the distilled water - Change the cooling water every 10-15 minutes - When about 950 ml of water is distilled, remove the distillation tank from the fire - Empty the cooling water and wait for the tank to cool - Separate the upper part from the lower part of the distillation tank - Collect the distilled water resulting from the distillation process - Measure the pH of the water using the pH meter	water is reclaimed - The bottom of the distillation tank (bottom part) is corroded - The pH of the distilled water is 7	collects in the Erlenmeyer ☑ Water collected is about 950 mL ☑ The base of distillation tank (bottom part of tank) is corroded ☒ The pH of distilled water formed is 10.4

Video of MSE-T1 test:

MSE-T1 _
20.09.2024 _ KOH-Dr

10.8.1.7 Test result

1) Adding too much dry ice to the KOH solution causes all the OH^- to react completely, but adding too much causes the solution to freeze, forcing us to wait some time before starting the distillation process

2) Corrosion appears in the bottom part of the distillation tank (when we put the K_2CO_3 solution) due to the increase in temperature and concentration of the K_2CO_3 solution as a result of evaporation

3) The high pH of distilled water formed (10.4) means that the distilled water contains anions, this may be due to the high temperature of the solution during the distillation process

10.8.1.8 What's the next test

In our test, we need to recover the water as pure water free of KCO_3^- ions. To achieve this goal, we must modify the distillation process in terms of reducing the temperature of the solution in the lower section

10.8.2 Distillation process with water bath test "MSE-T2" (Thursday 26.09.2024)

In the previous test (test MSE-T1) we noticed that the pH of the distilled water resulting from evaporating the K_2CO_3 solution was not 7 but 10.4. This test seeks to obtain distilled water with a pH of 7 by adding modifications to the distillation process.

10.8.2.1 Materials

- **<u>Materials for the KOH slt° preparation</u>**

  KOH solid (200 gr)
  Distilled water (1000 mL)
  Spatula
  Beaker (V = 1L)
  Digital balance
  Spatula glass

- **<u>Materials for the KOH-Dry Ice reaction</u>**

  Dry ice (1 Kg finger)
  Spatula glass

- **Materials for the distillation process**

  Distillation tank (Consists of two parts: an upper part (cooling part) and a lower part)

  Water bath for the bottom part of the distillation tank

  Water (for cooling)

  Stove (Source of heat)

  Erlenmeyer flask (V = 1L)

  pH-meter

10.8.2.2 Safety precautions

1) Wear appropriate protective equipment:
    - Gloves
    - Goggles
    - Lab coat

2) Perform the reaction KOH/Dry ice in a well-ventilated area
3) Use a suitable reaction vessel
4) Add dry slowly
5) Avoid direct contact with the solution
6) Have a fire extinguisher readily available
7) Use a heat source with a variable temperature control
8) Secure the glassware
9) Avoid direct contact with the hot glassware
10) Be cautious when handling the distillate
11) Properly dispose of waste

10.8.2.3 Pre-test of distillation tank

- **Preparation of KOH solution**

  1) Weigh 200 gr of crystal KOH using a digital scale, spatula, and beaker
  2) Add the KOH crystals in 1 L of the distilled water
  3) Stir until the KOH dissolves completely

- **Add the dry ice finger**

  1) After dissolving the KOH in the water, we put the KOH solution prepared in the bottom of the distillation tank

  4) We put the bottom distillation tank in a ventilated place
  5) Then we add the dry ice finger to the KOH solution

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6) We wait until the reactions between the KOH and the dry ice are complete

⚠ **N.B.: If we add a lot of dry ice, we may have to wait extra time for the ice to melt and the reacted solution to return to its liquid state**

10.8.2.4 Distillation process test

1) When the reaction between the solution and dry ice is complete, we have K_2CO_3 dissolved in water, collect the parts of the distillation tank together (the upper part with the lower)

2) We put tape where the two parts meet, to prevent steam from leaking out of the tank

3) We fixed the distillation tank in the water bath

4) We put the water bath on fire

5) We add water to the bath

6) We add the cooling water to the upper part of the tank and close the water drain hole

7) We put the Erlenmeyer at the outlet of the distilled water

8) We change the cooling water every 10-15 minutes; to ensure the condensation of the water

9) When about 950 ml of water is distilled, we remove the water bath distillation tank from the fire

10) We remove the distillation tank from the water bath

11) After emptying the cooling water and waiting for the tank to cool, we separate the upper part from the lower part of the distillation tank

12) After collecting the distilled water resulting from the distillation process, we measure the pH of the water using the pH meter; to confirm the distillation rate

10.8.2.5 Responsibilities

MSE-T2 : Distillation process with water bath test		
Task	**Responsible**	**Note**
KOH preparation	Maryam R.	
Purchase dry ice	Muhamad K.	
Deliver dry ice	Ali D., Muhamad K.	
Mixed KOH/Dry ice	Maryam R., Muhamad K.	
Fixed Distillation tank	Maryam R., Ali D.	
Heat source for dislillation process	Ali D., Maryam R., Muhamad K.	
Cooling for dislillation process	Ali D., Maryam R., Muhamad K.	
pH measure	Muhamad K., Maryam R.	
Documentation	Maryam R.	
Equipment re-cleaning	Ali D.	

10.8.2.6 Test specification and test results

Step	**Step description**	**Expected result**	**Results**
Pre-condition	KOH solution is placed in the distillation tank (bottom part)		
Add Dry ice	- Put the bottom distillation tank in a place well ventilated - Add the dry ice finger to the KOH solution	- Heavy white smoke rising - The formed solution (K_2CO_3) in a liquid state	☑ Heavy white smoke rising ☑ The formed solution (K_2CO_3) in a liquid state **after waiting** (because we put an extra amount of the dry ice)
Distillation process	- Collect the upper part with the lower part of the distillation tank - Put tape where the two parts meets - Fixed the distillation tank in the water bath	- No leakage of steam - Condensation of water - About 950 mL of distilled water is reclaimed - The bottom of the distillation tank (bottom	☑ No leakage of steam ☑ Water condenses and collects in the Erlenmeyer ☑ Water collected is about 950 mL

	- Put the water bath on fire - Add water to the bath - Add the cooling water to the upper part of the tank - Close the water drain hole - Put the Erlenmeyer at the outlet of the distilled water - Change the cooling water every 10-15 minutes When about 950 ml of water is distilled, remove the water bath distillation tank from the fire - Remove the distillation tank from the water bath - Empty the cooling water and wait for the tank to cool - Separate the upper part from the lower part of the distillation tank - Collect the distilled water	part) is corroded - The pH of the distilled water is 7	☑ The base of distillation tank (bottom part of tank) is corroded ☑ The pH of distilled water formed is 7.8

	resulting from the distillation process - Measure the pH of the water using the pH meter		

10.8.2.7 Verification test (K_2CO_3 detection test)

One common method to detect the presence of potassium carbonate (K_2CO_3) in a solution is the hydrochloric acid test.

Potassium carbonate (K_2CO_3) is a soluble salt that can be detected using hydrochloric acid (HCl). When HCl is added to a solution containing K_2CO_3, a carbon dioxide (CO_2) gas is produced. This gas can be easily identified by its effervescence (bubbling) when it is released into the solution.

Here's a step-by-step procedure for the test:

1) Prepare a sample: Obtain a sample of the solution you suspect contains K_2CO_3.
2) Add HCl: Add a few drops of dilute hydrochloric acid to the sample.
3) Observe effervescence: If K_2CO_3 is present, you will observe bubbles forming in the solution due to the release of carbon dioxide gas.

Balanced Chemical Equation:

$$K_2CO_3(aq) + 2HCl(aq) \rightarrow 2KCl(aq) + H_2O(l) + CO_2(g)$$

10.8.2.8 Test pictures

Preparation of KOH solution	pH measurement of KOH solution	KOH solution in the lower part of the distillation tank	Solution after adding the dry ice (K_2CO_3 solution

WhatsApp Video
2024-10-01 at 12.16.

WhatsApp Video
2024-10-01 at 12.20.

Adding the dry ice to the KOH solution (formation of K_2CO_3 solution)	Water distillation components	K_2CO_3 detection test

10.8.2.9 Test result

1) Adding a water bath made the distillation process take extra time (slower than normal distillation)

2) Adding a water bath improves the pH of the distilled water produced, improving from 10.4 in the previous test (MSE-T1) to 7.8 in this test

3) The increase in the concentration of the K_2CO_3 solution caused corrosion in the hole in the lower part of the distillation tank, which led to water entering from the water bath into the lower part of the distillation tank

10.8.2.10 What's the next test

The experimental objective was to recover ion-free water through distillation. The distilled water obtained exhibited a pH of 7.8, demonstrating a significant reduction in K_2CO_3. Consequently, multiple distillations will be conducted in the subsequent experiment to obtain distilled water with a neutral pH.

10.8.3 Leakage of Stack #5 test "MSE-T3" (Thursday, 10.10.24)

To ensure the design for stack 5 is leak-free and functions as intended, we've proposed this test.

5.5.1.1. Materials

- KOH solution (pH = 12.39, V=200 mL)
- Beaker
- Funnel
- pH meter
- Stack #5
- Gas purification tank
- Torch handle with a regulator valve knob
- 2 multimeters
- Power supply
- Signal generator

- Resistors
- Wires
- Hoses
- Balls valves
- Lighter

10.8.3.1 Safety precautions

Alkaline Electrolysis Precautions

1) Proper Ventilation: Ensure the area where you're conducting electrolysis is well-ventilated to prevent the buildup of hydrogen gas. this helps to prevent the accumulation of flammable gases and reduce the risk of explosions.
2) Personal Protective Equipment (PPE): Wear safety glasses and gloves to protect your eyes and skin from potential splashes of corrosive alkaline solutions. In addition, wear electrically insulated gloves and shoes.
3) Do not approach: Do not touch or approach while the system is running. If necessary, adhere to all safety standards.
4) Concentrated Alkaline Solutions: Handle concentrated alkaline solutions with extreme caution, as they can cause severe burns. Wear appropriate protective clothing and avoid contact with skin and eyes.

5) Electrical Hazards: Ensure that the electrical connections are secure and properly insulated to prevent electric shock.
6) Electrolyte Disposal: Dispose of used electrolyte solutions responsibly, following local regulations. Do not pour them down the drain or into the environment.

Precautions for Burning Hydrogen-Oxygen Mixed Gases

1) Proper Ventilation: Ensure the area where you're burning gases is well-ventilated to prevent the buildup of hydrogen gas. this helps to prevent the accumulation of flammable gases and reduce the risk of explosions.

2) Personal Protective Equipment (PPE): Wear safety glasses and gloves to protect your eyes and skin from potential splashes of corrosive alkaline solutions.

3) Ignition Source Control: Keep all ignition sources away from the area where the mixture is being handled or burned. This includes open flames, sparks, static electricity, and hot surfaces.

4) Grounding: Ground all equipment that comes into contact with the hydrogen-oxygen mixture to prevent static discharges. This is particularly important when handling high-pressure cylinders or working with metal objects.

5) Pressure Control: Maintain the hydrogen-oxygen mixture at a safe pressure. Avoid exceeding the recommended pressure limits for the equipment and containers being used.

6) Fire Extinguisher: Keep a fire extinguisher readily available in case of a fire.

7) Emergency Preparedness: Have a plan in place for handling emergencies, such as gas leaks or electrical faults.

Additional Considerations:

1) Equipment Inspection: Regularly inspect your electrolysis equipment for signs of wear or damage. Promptly address any leaks to prevent the accumulation of flammable gases.
2) Training: Ensure that anyone involved in the electrolysis process has received proper training understands the associated risks and is knowledgeable about safety procedures.
3) Emergency Procedures: Develop and practice emergency procedures in case of a fire or explosion. Have a clear evacuation plan and know the location of fire extinguishers and other safety equipment.

10.8.3.2 Pre-test (installation of Stack #5)

Components of stack #5:

- Endplate (in/out)
- Gasket (in/out)
- Gasket (inter)
- Electrode plate

Installation of Stack #5

1) Connect the liquid-level gauge hose to the outlet on the endplate of the stack.
2) Connect the solution outlet and gas outlet hoses to the end plate outlet on the stack.
3) Secure the hoses to the end plate using a suitable adhesive, such as super glue.
4) A layer of thermal silicone was applied to the inside of the end plate to seal the gaps between the hoses and prevent leakage.
5) The inlet of the end plate follows the same process.
6) Next, we initiate the stack installation by following these steps:
   1. Mount the endplate firmly to the base, aligning it correctly for a stable and secure installation.
   2. The stack is assembled sequentially, commencing with the gasket plate, followed by the alternating placement of intern gaskets and electrodes, culminating in the gasket plate followed by the end plate.
   3. Bolts and nuts are tightly fastened throughout the stack to ensure a secure seal against gas and solution leakage.
   4. Ball valves are positioned at the stack's inlet and outlet to manage solution flow.
   5. A gas purification tank is attached to the gas outlet to filter impurities and safeguard the system from potential explosion hazards.
   6. The gas purification tank's output is connected to a torch handle with a regulator valve knob for safe gas burning
   7. The electrical equipment (power supply, voltmeter, amperemeter, and resistor(s)) has been successfully connected.

10.8.3.3 Leakage of Stack #5 test steps

- Open the inlet ball valve to fill the stack with KOH solution.
- Accurately introduce the KOH solution into the stack via the inlet hole, employing a funnel for precise pouring.
- When the stack is filled suitable (two-thirds full), close the inlet ball valve
- We check the electrical connections
- Verify connections and electrospinning using a multimeter in diode mode.
- Turn ON the power supply
- After a few minutes, we bring a spark to burn mixed gases
- We monitor the process and collect the data
- When the test is finished, turn OFF the power supply
- The fire fades out gradually

10.8.3.4 Post-test

1) Check the power supply is OFF
2) Disconnect the electrical equipment
3) Open the outlet ball valve to drain the rest of the KOH solution in a beaker
4) Close the outlet ball valve of the solution
5) Wash the stack in Nitrogen gas by introducing nitrogen from the inlet ball valve for a few minutes
6) Open the inlet ball valve and fill the stack with distilled water
7) Drain the distilled water by opening the outlet ball valve
8) Repeat this previous step several times
9) By the pH meter, measure the pH of the rest of the KOH solution

10.8.3.5 Responsibilities

MSE-T3: Leakage of stack #5 test		
Task	**Responsible**	**Note**
KOH preparation	Maryam R., Muhamad K.	
Secure the hoses	Ali D., Maryam R.	
Thermal silicone apply	Ali D., Maryam R.	
Install the stack	Ali D., Maryam R.	
Electrical equipement	Abdallah K.	
Intall the gas purification	Maryam R., Ali D.	
Install the control burner valve	Ali D.	
Electrical control	Abdallah K.	
pH measure	Maryam R., Muhamad K.	
Collect data	Maryam R.	
Documentation	Maryam R.	
Equipment re-cleaning	Ali D.	

10.8.3.6 Test results

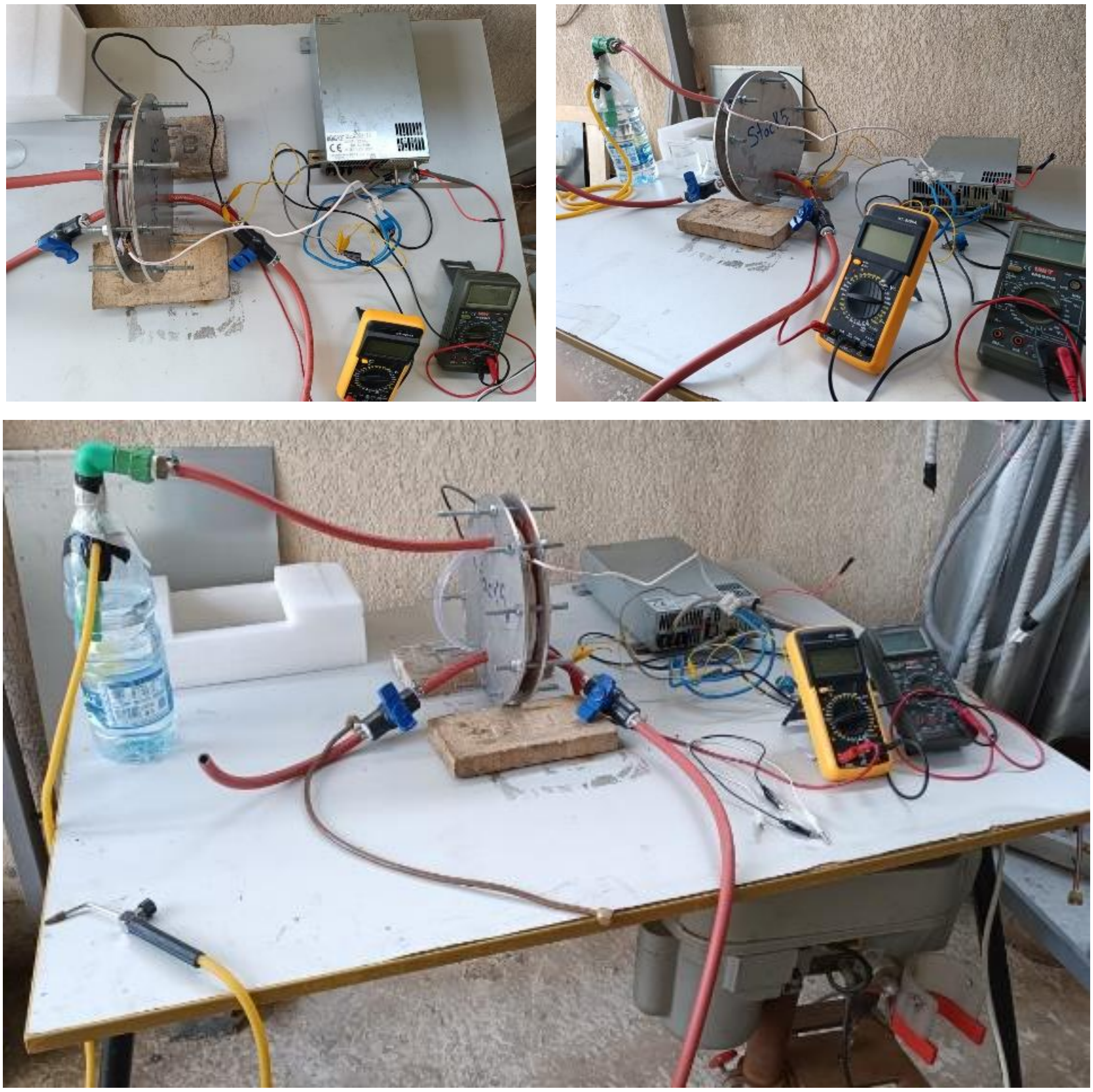
Step	**Step description**	**Expected result**	**Results**
Pre-condition	- Stack is empty - All equipment (electrical and mechanical) is connected properly		
Fill the stack	- Open the inlet ball valve to fill the stack with KOH solution - Accurately introduce the KOH solution into the stack via the inlet hole, employing a funnel for precise pouring. - When the stack is filled (two-thirds full), close	- The stack is filled by the KOH solution - No leak appears	☑ The stack is filled with the KOH solution ☑ No leak

	the inlet ball valve.		
Verify connections and electrospinning	- Check electrical equipment is connected - Put the multimeter on “Diode mode” - Connect each pole of the multimeter (diode mode) to each end plate - Connect each pole of the multimeter (diode mode) to each electrode - Connect the poles of the multimeter (diode mode) to both the electrode and end plate	- All electrical equipment is connected - The multimeter is functioned in “Diode mode” - The multimeter is beeps - The multimeter beeps - The multimeter does not beep	☑ All electrical equipment is connected ☑ The multimeter is on “Diode mode” ☑ The multimeter beeps; this means that two endplates are electrically connected from each other ☑ The multimeter beeps; this means that two electrodes are electrically connected from each other ☑ The multimeter does not beep; this means that the end plate and electrodes are electrically isolated from each other

Install the system	- Turn ON the power supply - Regulate DC voltage and current	- The power is turned ON - Gas bubbles (H_2 & O_2) popping in the gas purification tank	☑ The power is turned ON ☑ The bubbles of gases popping in the gas purification tank
Burn the mixed gases formed	- Close the regulator valve of the torch handle - Wait a few minutes for the gases to compress slightly - Open the regulator valve of the torch handle and bring a spark beside the torch handle with the regulator valve knob	- The mixed gas is burned	☒ The mixed gas exploded
Turn OFF the system	- Turn OFF the power supply	- The power supply is turned OFF - After a few minutes, the flame dwindles and disappears	☑The power supply is turned OFF ☑The flame flickers and dies
Measurement of pH	- Emptying the KOH solution from the stack - Take a sample from the KOH solution	- The new pH is higher than the old one (initial pH)	☑ The new pH ($pH_{(n)}$=12.54) is higher than the old one ($pH_{(i)}$= 12.39)

	- Use the pH meter to find out the new pH		

5.5.1.2. Test pictures



Overview of the System Components

Test resumed in this video:

WhatsApp Video
2024-10-14 at 10.30.

10.8.3.7 Test result analysis

- The super glue and the thermal silicone are suitable for fixing and electrically insulating the endplates.
- Unscrewing the regulator valve knob on the torch handle triggered a sudden ignition of the gas, resulting in an explosion.

10.8.3.8 What's the next test

The experimental objective was to verify the effectiveness of the materials used as electrical insulators and the absence of leakage. The usage of the super glue with the thermal silicone demonstrates electrical insulation without reaction with the KOH solution.

Consequently, the other stacks will be insulated in the same method with the same materials.

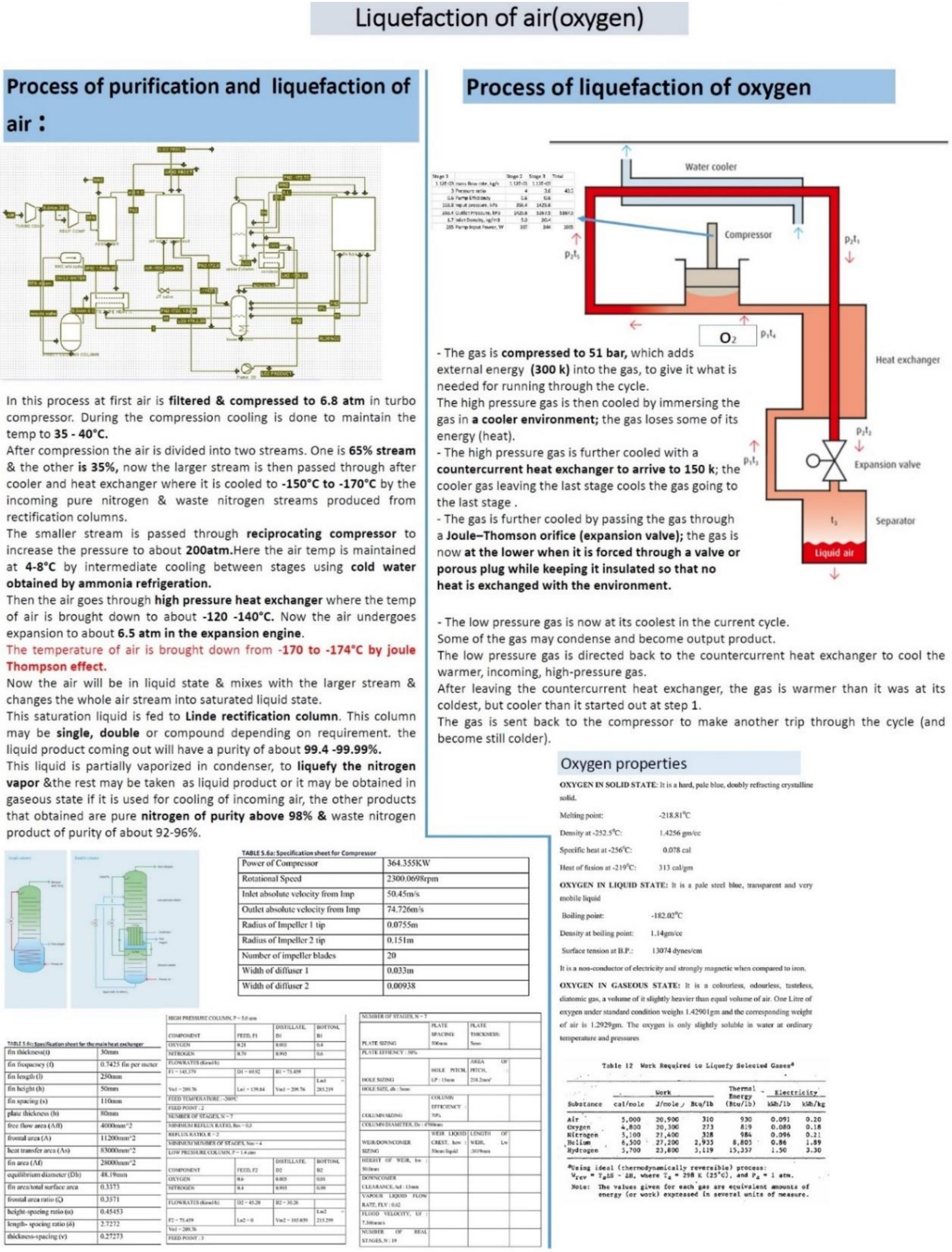
10.9 What's next

After completing the design and installation part of the stacks, the stacks must be tested and then the system must be assembled for testing.

11 Project D and G in 21: Air Separation, Liquefaction, Cryogenics, Distillation – Part I: Basics

Air Liquefaction and Cryogenics – Report 1 (2021), *Part I : Basics*, Last update: 30.07.2021, Author: Mariam El Rez, Editor: Dr. Samir Mourad

11.1 Starting point December 2020 (Work of Maysaa Kamareddine 2019)



Liquefaction of air(oxygen)

Process of purification and liquefaction of air :

In this process at first air is **filtered & compressed to 6.8 atm** in turbo compressor. During the compression cooling is done to maintain the temp to **35 - 40°C.**

After compression the air is divided into two streams. One is **65% stream** & the other **is 35%,** now the larger stream is then passed through after cooler and heat exchanger where it is cooled to **-150°C to -170°C** by the incoming pure nitrogen & waste nitrogen streams produced from rectification columns.

The smaller stream is passed through **reciprocating compressor** to increase the pressure to about **200atm.**Here the air temp is maintained at **4-8°C** by intermediate cooling between stages using **cold water obtained by ammonia refrigeration.**

Then the air goes through **high pressure heat exchanger** where the temp of air is brought down to about **-120 -140°C.** Now the air undergoes expansion to about **6.5 atm in the expansion engine.**

The temperature of air is brought down from -170 to -174°C by joule Thompson effect.

Now the air will be in liquid state & mixes with the larger stream & changes the whole air stream into saturated liquid state.

This saturation liquid is fed to **Linde rectification column**. This column may be **single, double** or compound depending on requirement. the liquid product coming out will have a purity of **99.4 -99.99%.**

This liquid is partially vaporized in condenser, to **liquefy the nitrogen vapor** &the rest may be taken as liquid product or it may be obtained in gaseous state if it is used for cooling of incoming air, the other products that obtained are pure **nitrogen of purity above 98% &** waste nitrogen product of purity of about 92-96%.

Process of liquefaction of oxygen

- The gas is **compressed to 51 bar,** which adds external energy **(300 k)** into the gas, to give it what is needed for running through the cycle.

The high pressure gas is then cooled by immersing the gas in **a cooler environment;** the gas loses some of its energy (heat).

- The high pressure gas is further cooled with a **countercurrent heat exchanger to arrive to 150 k;** the cooler gas leaving the last stage cools the gas going to the last stage .

- The gas is further cooled by passing the gas through a **Joule–Thomson orifice (expansion valve);** the gas is now **at the lower when it is forced through a valve or porous plug while keeping it insulated so that no heat is exchanged with the environment.**

- The low pressure gas is now at its coolest in the current cycle.

Some of the gas may condense and become output product.

The low pressure gas is directed back to the countercurrent heat exchanger to cool the warmer, incoming, high-pressure gas.

After leaving the countercurrent heat exchanger, the gas is warmer than it was at its coldest, but cooler than it started out at step 1.

The gas is sent back to the compressor to make another trip through the cycle (and become still colder).

Oxygen properties

OXYGEN IN SOLID STATE: It is a hard, pale blue, doubly refracting crystalline solid.

Melting point:	-218.81°C
Density at -252.5°C:	1.4256 gm/cc
Specific heat at -256°C:	0.078 cal
Heat of fusion at -219°C:	313 cal/gm

OXYGEN IN LIQUID STATE: It is a pale steel blue, transparent and very mobile liquid

Boiling point:	-182.02°C
Density at boiling point:	1.14gm/cc
Surface tension at B.P.:	13074 dynes/cm

It is a non-conductor of electricity and strongly magnetic when compared to iron.

OXYGEN IN GASEOUS STATE: It is a colourless, odourless, tasteless, diatomic gas, a volume of it slightly heavier than equal volume of air. One Litre of oxygen under standard condition weighs 1.42901gm and the corresponding weight of air is 1.2929gm. The oxygen is only slightly soluble in water at ordinary temperature and pressures

TABLE 5.6a: Specification sheet for Compressor

Power of Compressor	364.355KW
Rotational Speed	2300.0698rpm
Inlet absolute velocity from Imp	50.45m/s
Outlet absolute velocity from Imp	74.726m/s
Radius of Impeller 1 tip	0.0755m
Radius of Impeller 2 tip	0.151m
Number of impeller blades	20
Width of diffuser 1	0.033m
Width of diffuser 2	0.00938

TABLE 5.6c: Specification sheet for the main heat exchanger

fin thickness(t)	30mm
fin frequency (f)	0.7425 fin per meter
fin length (l)	250mm
fin height (h)	50mm
fin spacing (s)	110mm
plate thickness (b)	80mm
free flow area (Aff)	4000mm^2
frontal area (A)	11200mm^2
heat transfer area (As)	83000mm^2
fin area (Af)	28000mm^2
equilibrium diameter (Dh)	48.19mm
fin area/total surface area	0.3373
frontal area ratio (ζ)	0.3571
height-spacing ratio (α)	0.45453
length- spacing ratio (δ)	2.7272
thickness-spacing (v)	0.27273

HIGH PRESSURE COLUMN, P = 5.0 atm			
COMPONENT	FEED, F1	DISTILLATE, D1	BOTTOM, B1
OXYGEN	0.21	0.005	0.4
NITROGEN	0.79	0.995	0.6
FLOWRATES (Kmol/h)			
F1 = 145.379	D1 = 69.92	B1 = 75.459	
Vn1 = 209.76	Ln1 = 139.84	Vm1 = 209.76	Lm1 = 285.219
FEED TEMPERATURE : -200°C			
FEED POINT : 2			
NUMBER OF STAGES, N = 7			
MINIMUM REFLUX RATIO, Rm = 0.5			
REFLUX RATIO, R = 2			
MINIMUM NUMBER OF STAGES, Nm = 4			
LOW PRESSURE COLUMN, P = 1.4 atm			
COMPONENT	FEED, F2	DISTILLATE, D2	BOTTOM, B2
OXYGEN	0.6	0.005	0.01
NITROGEN	0.4	0.995	0.99
FLOWRATES (Kmol/h)	D2 = 45.28	B2 = 30.26	
F2 = 75.459	Ln2 = 0	Vm2 = 181.039	Lm2 = 215.299
Vn1 = 209.76			
FEED POINT : 3			

NUMBER OF STAGES, N = 7			
PLATE SIZING	PLATE SPACING: 500mm	PLATE THICKNESS: 5mm	
PLATE EFFIENCY : 50%			
HOLE SIZING	HOLE PITCH, LP : 15mm	AREA OF PITCH, : 218.2mm²	
HOLE SIZE, dh : 5mm			
COLUMN SIZING	COLUMN EFFICIENCY : 70%		
COLUMN DIAMETER, Dc : 4700mm			
WEIR/DOWNCOMER SIZING	WEIR LIQUID CREST, how : 50mm liquid	LENGTH OF WEIR, Lw :3619mm	
HEIGHT OF WEIR, hw : 50.0mm			
DOWNCOMER CLEARANCE, hd : 13mm			
VAPOUR LIQUID FLOW RATE, FLV : 0.62			
FLOOD VELOCITY, Uf : 7.300m/s			
NUMBER OF REAL STAGES, N : 19			

Table 12 Work Required to Liquefy Selected Gases[a]

Substance	Work cal/mole	Work J/mole	Work Btu/lb	Thermal Energy (Btu/lb)	Electricity kWh/lb	Electricity kWh/kg
Air	5,000	20,900	310	930	0.091	0.20
Oxygen	4,800	20,300	273	819	0.080	0.18
Nitrogen	5,100	21,400	328	984	0.096	0.21
Helium	6,500	27,200	2,935	8,805	0.86	1.89
Hydrogen	5,700	23,800	3,119	15,357	1.50	3.30

[a] Using ideal (thermodynamically reversible) process: $W_{rev} = T_a\Delta S - \Delta H$, where $T_a = 298$ K (25°C), and $P_a = 1$ atm.

Note: The values given for each gas are equivalent amounts of energy (or work) expressed in several units of measure.

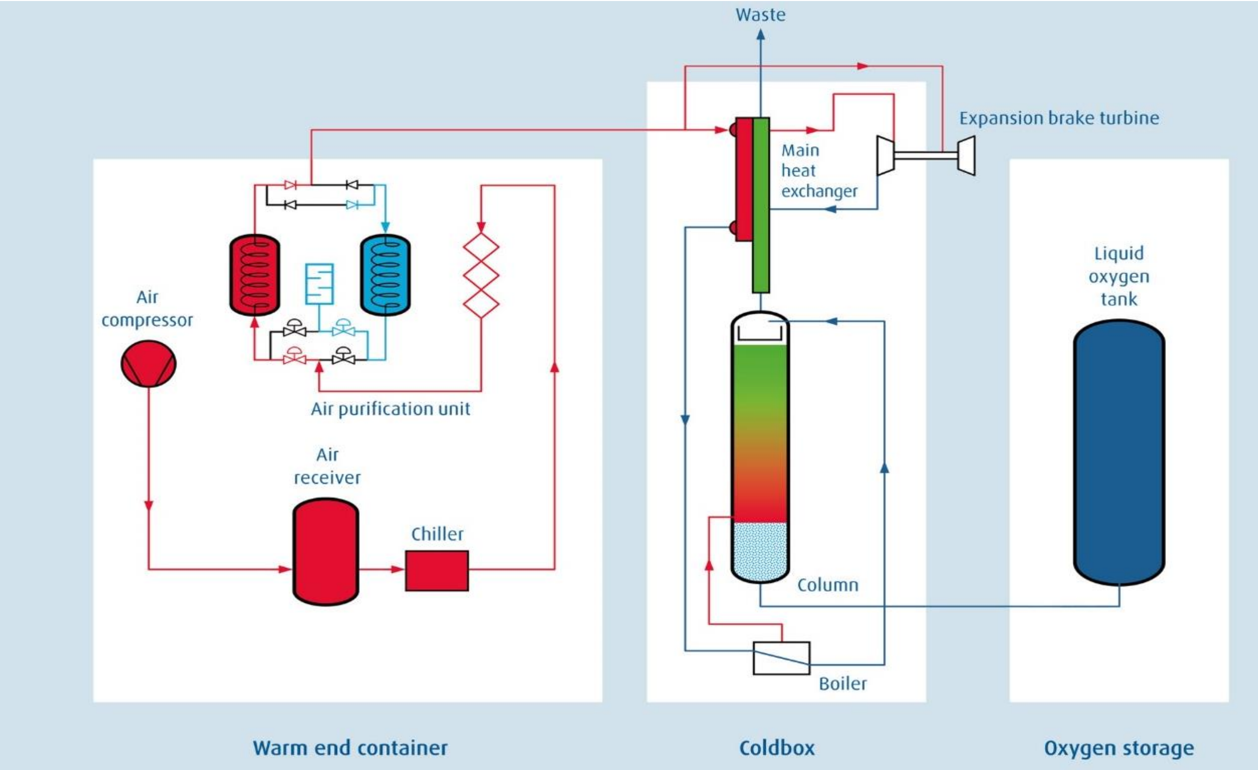
11.2 Cryogenic air plant principle

A cryogenic air plant is an industrial facility that creates molecular oxygen at relatively high purity. Air is the most common element in the earth's crust and the second largest industrial gas.

11.2.1 Purpose

The cryogenic air separation achieves high purity oxygen of more than 99.5%. The resulting high purity product can be stored as a liquid and/or filled into cylinders. These cylinders can even be distributed to customer in the medical sector, welding or mixed with other gases and used as breathing gas for diving. Typical production ranges from 50 normal m^3/hour up to 860,000 Nm^3/hour

11.2.2 Plant modules

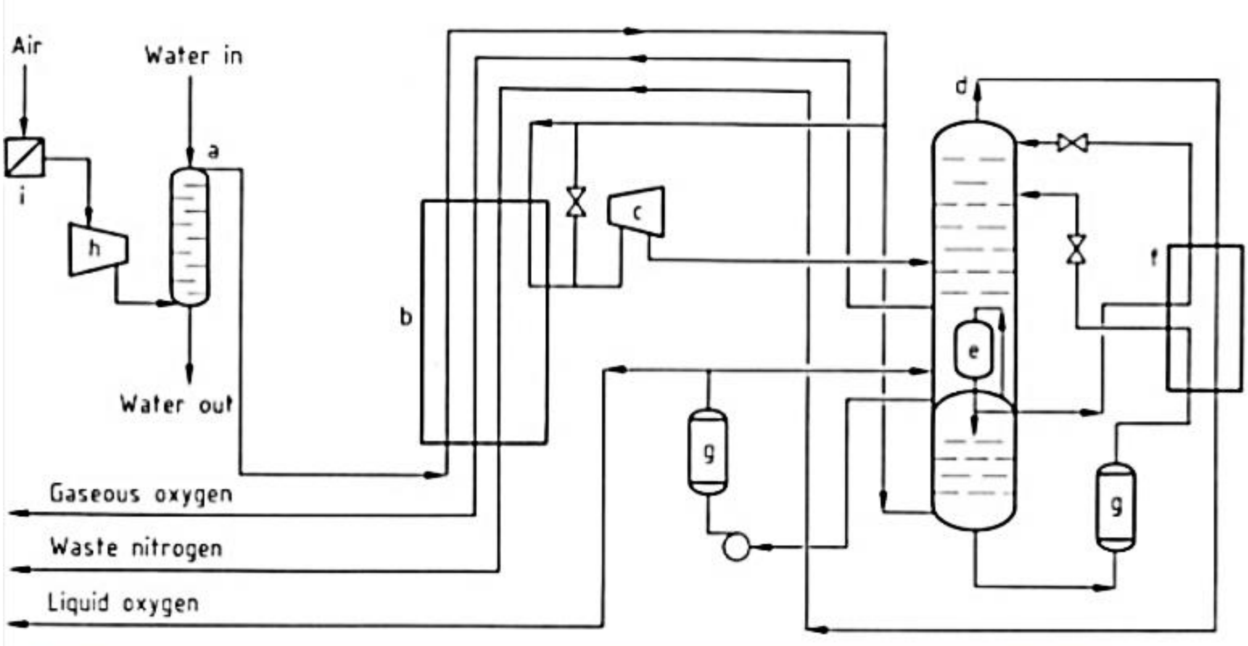


A cryogenic air plant comprises:

- Warm end (W/E) container
    - Compressor
    - Air receiver
    - Chiller (Heat exchanger)
    - Pre-filter
    - Air purification unit (APU)
- Coldbox
    - Main heat exchanger
    - Boiler
    - Distillation column
    - Expansion brake turbine
- Storage

  - Liquid oxygen tank
  - Vaporizer
  - Filling station

11.2.2.1 Annotated diagram



a) Water wash cooler; b) Reversing heat exchanger; c) Expansion turbine; d) Double column rectifier; e) Condenser; f) Subcooler; g) Adsorber; h) Compressor; i) Filter

- **Raw materials**
  - Basis: 1000kg Oxygen (95%)
  - Air = 3600Nm^3
  - Steam = 1750kg
  - Cooling water = 5000kg
  - Electricity = 450-480kWH

11.2.3 Linde's Method of liquefaction of gases.[5]

The Hampson-Linde cycle or the Linde's liquefaction process is used by coupled with regenerative cooling and the Joule Thomson effect.

By this method, we can easily liquefy air, and many other gases too.

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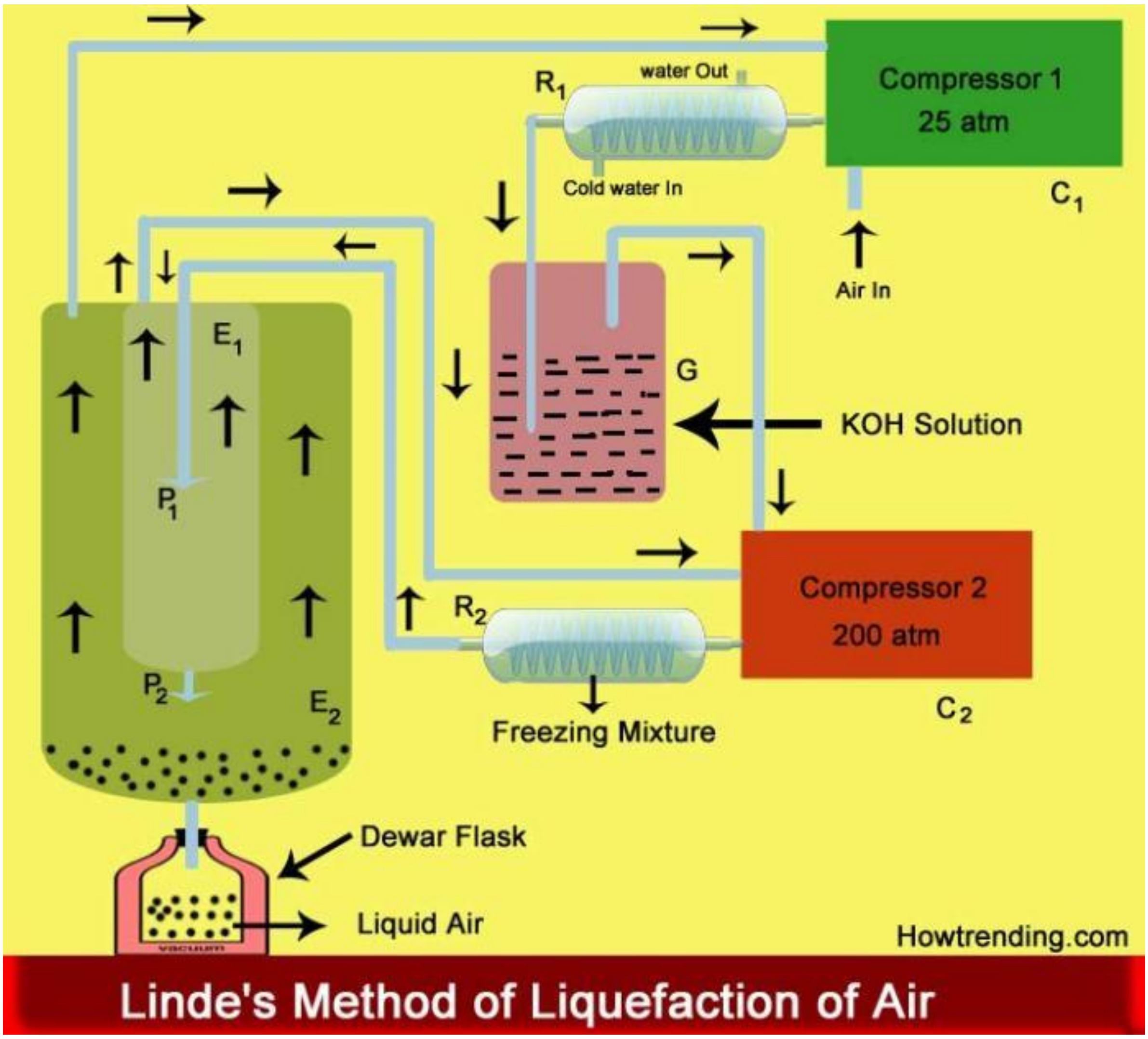
[5] https://www.howtrending.com/liquefaction-of-gases/



Linde's Method of Liquefaction of Gases – Howtrending.com

The above figure is Linde's method for Liquefaction of Air and some other gases too.

By this figure, you can understand that liquefaction of air or those gases that have a low value of critical temperatures is hard, as compared to those that have high critical temperature values.

11.2.3.1 About this apparatus

1. In this method, two compressors C_1 at (25 atm pressure) and C_2 (200 atm pressure) are used.
2. Heat exchangers R_1 and R_2 are used into which cold water and a freezing mixture is used as a refrigerant.
3. A Liquid solution of KOH (Potassium Hydroxide), that is required to get pure air.
4. Two chambers E_1 and E_2, and P_1 and P_2 are the two small nozzles.
5. At last, the liquid air is collected into a Dewar flask.

11.2.3.2 Principle

Linde's process of liquefaction is work on the principle of the **Joule Thomson effect** coupled with **regenerative cooling**.

11.2.3.3 Linde's process Working

This method is quite different as we compared to the previous one, the Cascade method.

First, the air is pumped at a pressure of 25 atm into the spiral tube. The air gets cooled after passing through the R_1 heat exchangers. Here the gas becomes cool because of cool water inside the R1 heat exchangers. This cooled air then passes through a liquid solution of Potassium hydroxide (KOH).

The reason for the use of the KOH solution is that air contains many gases and water vapors too. To separate air from water vapors this solution is used, and also this solution absorbs CO_2 gas from the air (The **Critical temperature of water = 374°C**). After this, the air further moves in the second compressor C_2.

In the C_2 compressor, the air is pumped at a pressure of 200 atm into the next spiral tube. Now the gas becomes cool again, after passing through the second heat exchangers R_2. Here the gas-cooled because of the Freezing mixture inside the R_2 heat exchangers.

Now the temperature of this air decreases to around −20°C. Then this pre-cooled air is allowed to expand through nozzle P_1 in a chamber E_1 and suffers the Joule Thomson effect. Due to this effect, more cooling is produced into the chamber E_1, and pressure reduces to about 50 atm.

This cooled air then returns back to the compressor C_2 and where it again pumped at a pressure of 200 atm into the spiral tube. This air again suffers Joule Thomson effect, and more cooling produced in chamber E_1.

Repeating some cycles of this process, more and more cooling is produced in chamber E_1. After getting sufficient temperature, the cooled air is allowed to expand through nozzle P_2 in chamber E_2 and again suffers the Joule Thomson effect, and pressure reduces to about 1 atm.

Now the temperature decreases to around −188°C in chamber E_2 and the air gets liquefied. This liquefied air is collected into the Dewar flask.

Also, in chamber E_2 the un-liquefied air is returned back to the compressor C_1, this further cooled the air, and where it again pumped at a pressure of 25 atm into the spiral tube.

This is the overall Linde's process for liquefaction of air.

11.2.4 Claude's method of liquefaction of gases

Claude's process works on the same principle as Linde's process. Hence cooling of the air, or if we say liquefaction of gases is carried out by the help of the Joule Thomson effect.

But, the only difference between Linde Claude's process of liquefaction of air, or other gases is that in Claude's process there is an isentropic expansion.

That's why Claude's process is more efficient than Linde's process.

The principle used in Claude’s Process

Claude’s method works on two principles.

First, the Joule Thomson effect.

Second is a mechanical expansion (By, the use of an expansion turbine).

What is an expansion turbine or the turboexpander?

“The expansion turbine or the turboexpander is an axial-flow or centrifugal turbine, through which a high pressurized gas is allowed to expand to produce work. This work is used to rotate a shaft, which is often connected with a compressor or generator.

Due to the turbo-expander, the outcoming gas has a very low temperature as compared to the temperature of input gas. This is because, in this process, the work is done by the gas, and due to this the gas loses its kinetic energy and resulting in a decrease in temperature of the gas“.

Working of Claude’s process

As you know Claude’s process is modified Linde’s process, Therefore, like Linde’s process, the gas which is at 200 atm pressure is pumped into the spiral tube, the gas then moved further. In Claude’s process, this gas is divided into two sections. In the first section, the gas is allowed to expand through the expansion turbine (turbo-expander). In the second section, the gas is allowed to suffers the Joule Thomson effect.

Therefore, more cooling is produced inside the chamber. One is by turbo-expander, and the second is by the Joule Thomson effect. The overall process is repeated until the gas gets liquefied completely, and during each cycle of repetition, the un-liquefied gas is returned back to the Compressors.

The very low critical temperature of H_2, and He

Now I will discuss the very low values of critical temperatures for gases like Neon, Hydrogen, and the Helium gas.

The Critical temperature (T_C) values of these gases are

Neon (Ne) = −228.7°C

Hydrogen (H_2) = −240°C

Helium (He) = −267.8°C

For liquefying these, we need a very low-temperature range. The hydrogen and helium must be kept below their inversion temperature while suffers the Joule Thomson effect.

The principle used in Hydrogen and Helium’s liquefaction.

Liquefaction of Hydrogen and helium works on the principle of the Joule-Thomson effect coupled with regenerative cooling.

In the liquefaction of Hydrogen, liquid air is used as a refrigerant, and in the liquefaction of Helium, Liquid hydrogen is used as a refrigerant.

By the use of previous processes, we can get liquefied Hydrogen and helium too.

https://www.sciencedirect.com/science/article/abs/pii/S0140700701000032

11.3 Large Scale Factory study

11.3.1 Overview

Factory					
	Equipment	**Details**	**Price per unit**	**Total Price**	
Warm End Container	Filter per year	unit per week	~10$	~ 520 $	
	Air Compressor (364.5 KW)		~ 2 500 $	~ 2 500 $	
	Air Receiver (Pre-Cooler)	unit (300 L, 0.8 Mpa)	200 $		قابل للتصنيع
	Chiller				
	Air Purification Unit (13x Zeolite)	Stainless stell (710 Kg)	710 $	1 707.4 $	
		Brazed Aluminum fins (1(	10 $		
		Aluminun (195 kg)	390 $		
		Lagging (2.45$/m2)	29.4 $		
		Bed packed with 13x Zeo	520 $		
		Column (4 columns)	48 $		
ColdBox	Main Heat Exchanger		3 869 406.9 $	3 869 406.9 $	**مذكور بpdf دراسة المشروع**
			1 000 $ - 5 500 $	1 000 $ - 5 500 $	**alibaba.com حسب موقع**
	Expansion Brake Turbine	Absorber Column (stains	180 $	196 $	
		Adsorption (Aluminum)	16 $		
		turbine (40 KW)	19 300 $		
	Cryogenic Distillation column		386 562.4 $	386 562.4 $	قابل للتصنيع
		HP Tower	499 000 $	2 653 000 $	**ref: Study_Dynamic Design of a Cryogenic Air Separation Unit**
		LP Tower	1 250 000 $		
		Crude Argon Tower	904 000 $		
	Boiler				
Storage	Cylinder 50L (50 $ /piece)	Liquid Oxygen Tank			
		Liquid Nitrogen Tank			
		Liquid Argon Tank			

11.3.2 Dynamic design of a cryogenic air separation unit (Source?)

	ASU will produce (per day)	
***Study_Dynamic Design of a* Cryogenic Air Separation Unit**	Oxygen (99.5%)	1 500 metric tons
	Nitrogen (99.5%)	5 000 metric tons
	Argon	58 metric tons
	Total Annual Cost	
	Compressor capital cost	16 500 000 $
	Venture guidance appraisal	118 500 000 $
	Worth of products (Sell)	113 900 000 $
	Annual cost for equipment and utilities	39 000 000 $
	Yield yearly profit	73 400 000 $

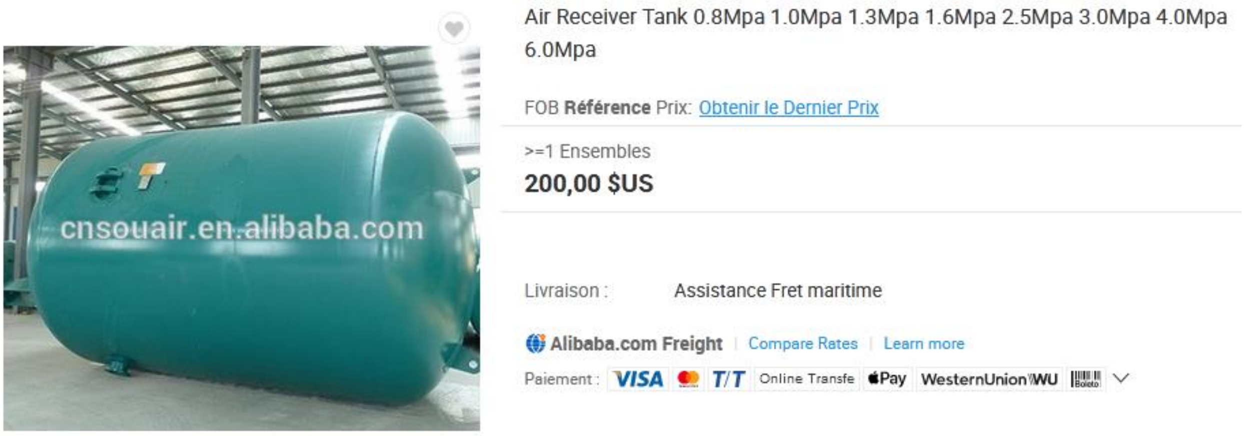
** ASU: Air Seperation Unit*

11.3.3 Total annual cost of plant equipment

Total annual cost of Plant Equipment			
Equipment	**Capital Cost ($)**	**Utility Costs ($)**	
Air receiver			
Air Compressor	~ 2 500 $	~ 850 $	
Chiller		0 $	
Air purification unit			
Main heat exchanger	1 000 $ - 5 500 $		
Distillation column			
Reboiler/condenser	1 041 000 $	0 $	ref: Study_Dynamic Design of a Cryogenic Air Separation Unit
Turbine			
Pumps			
Controls			

11.3.4 Costs of modules

11.3.4.1 Air receiver tank

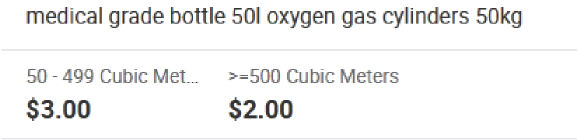

Air Receiver Tank 0.8Mpa 1.0Mpa 1.3Mpa 1.6Mpa 2.5Mpa 3.0Mpa 4.0Mpa 6.0Mpa

FOB **Référence** Prix: Obtenir le Dernier Prix

>=1 Ensembles

200,00 $US

Livraison : Assistance Fret maritime


medical grade bottle 50l oxygen gas cylinders 50kg

50 - 499 Cubic Met...	>=500 Cubic Meters
$3.00	**$2.00**

- Filter


Prix pas cher De Chine Approvisionnement Commercial Et Industriel De Qualité Alimentaire Mini Haute .

Produits de commerce électronique

10,00 $US-50,00 $US/ Unité

1 Unité (Commande minimum)

Guangzhou Jielv Environment Technology Co., Ltd.

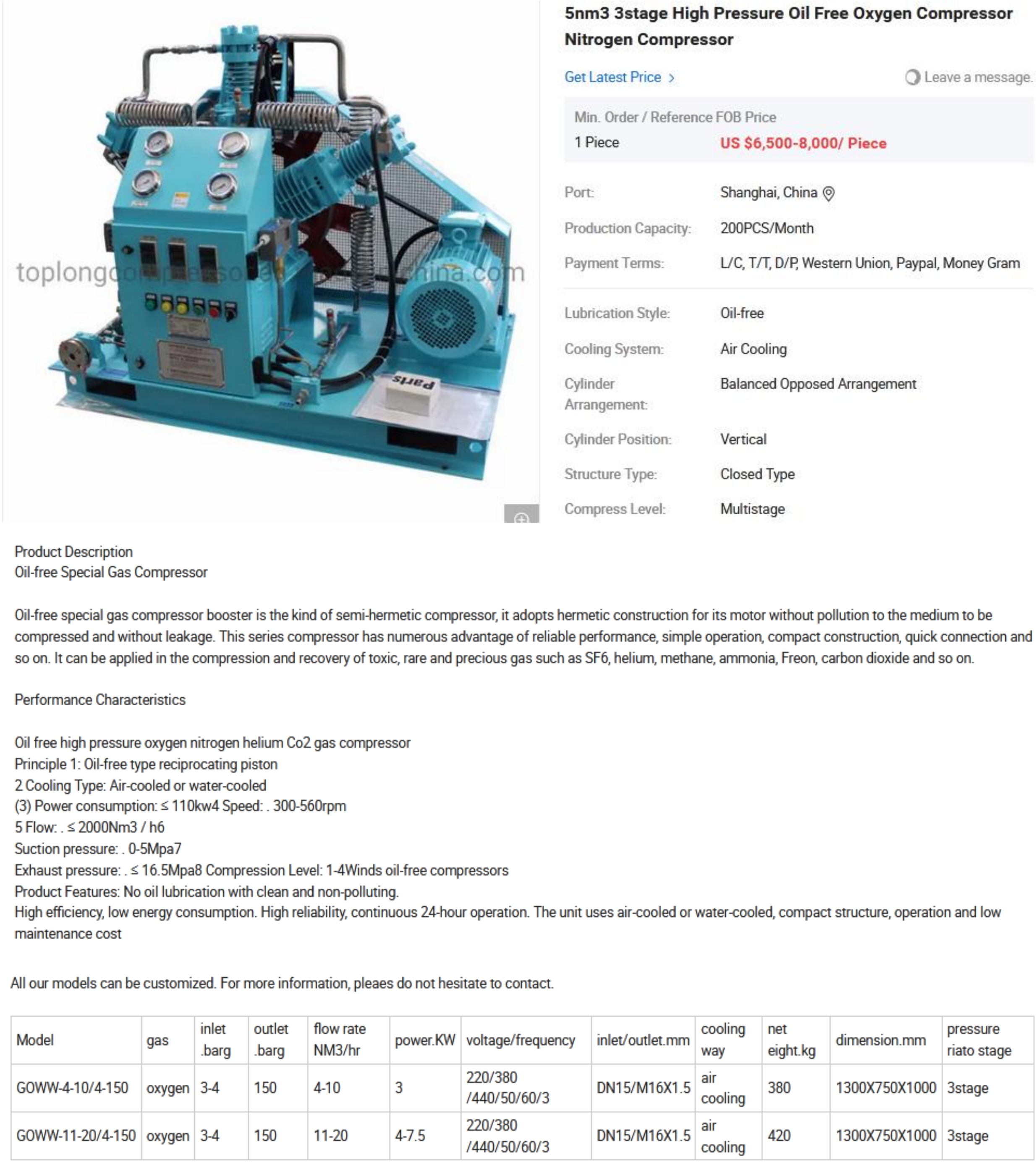
93.9% Taux de réponse

US $440,000+ in 81 Transaction (s)

11.3.4.2 Air/Oxygene Compressor

Choice 1:

https://toplongcompressor.en.made-in-china.com/product/IvVmtGBbhyhA/China-5nm3-3stage-High-Pressure-Oil-Free-Oxygen-Compressor-Nitrogen-Compressor.html



5nm3 3stage High Pressure Oil Free Oxygen Compressor Nitrogen Compressor

Get Latest Price › ◯ Leave a message.

Min. Order / Reference FOB Price	
1 Piece	US $6,500-8,000/ Piece

Port:	Shanghai, China
Production Capacity:	200PCS/Month
Payment Terms:	L/C, T/T, D/P, Western Union, Paypal, Money Gram
Lubrication Style:	Oil-free
Cooling System:	Air Cooling
Cylinder Arrangement:	Balanced Opposed Arrangement
Cylinder Position:	Vertical
Structure Type:	Closed Type
Compress Level:	Multistage

Product Description
Oil-free Special Gas Compressor

Oil-free special gas compressor booster is the kind of semi-hermetic compressor, it adopts hermetic construction for its motor without pollution to the medium to be compressed and without leakage. This series compressor has numerous advantage of reliable performance, simple operation, compact construction, quick connection and so on. It can be applied in the compression and recovery of toxic, rare and precious gas such as SF6, helium, methane, ammonia, Freon, carbon dioxide and so on.

Performance Characteristics

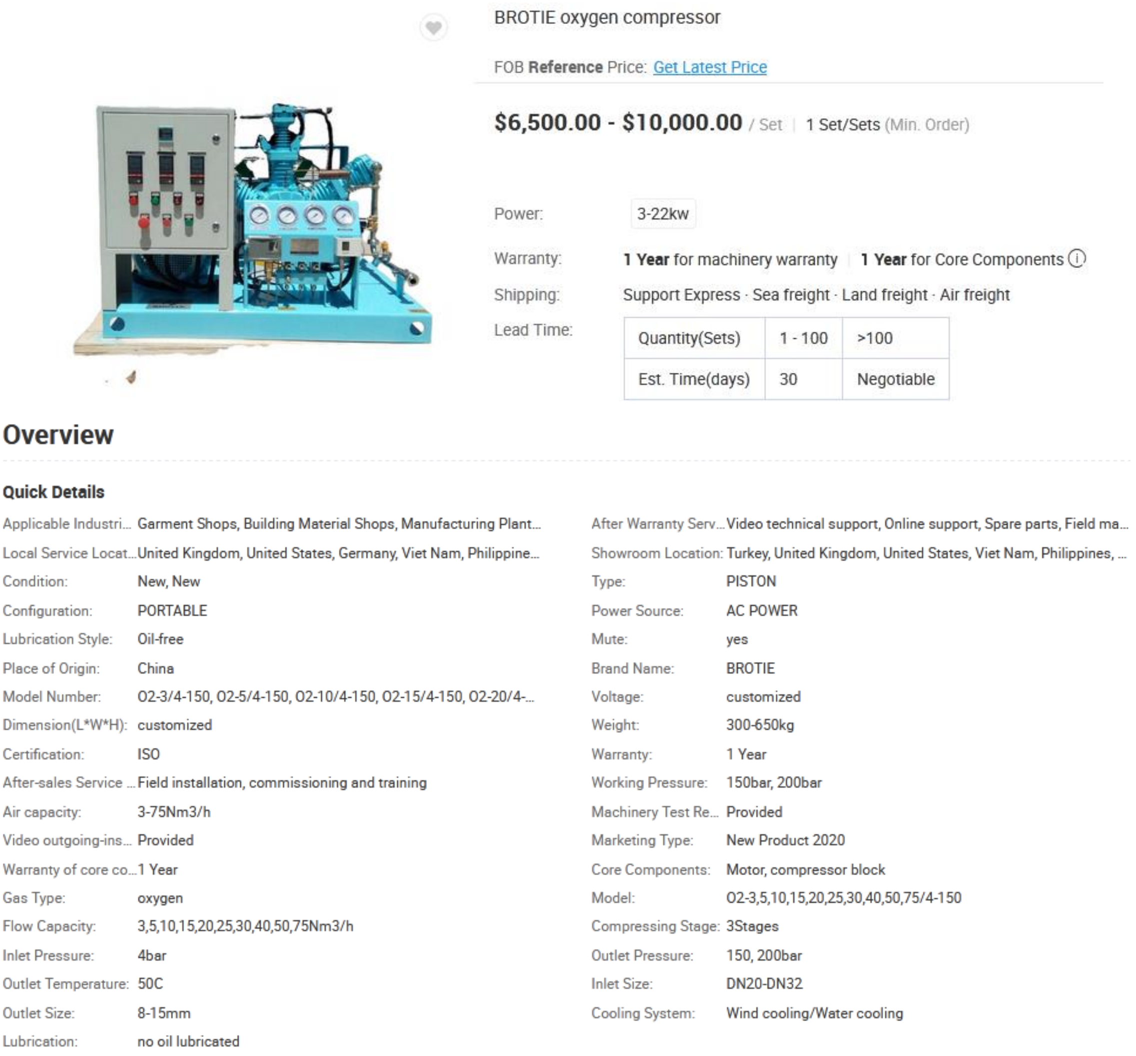
Oil free high pressure oxygen nitrogen helium Co2 gas compressor
Principle 1: Oil-free type reciprocating piston
2 Cooling Type: Air-cooled or water-cooled
(3) Power consumption: ≤ 110kw4 Speed: . 300-560rpm
5 Flow: . ≤ 2000Nm3 / h6
Suction pressure: . 0-5Mpa7
Exhaust pressure: . ≤ 16.5Mpa8 Compression Level: 1-4Winds oil-free compressors
Product Features: No oil lubrication with clean and non-polluting.
High efficiency, low energy consumption. High reliability, continuous 24-hour operation. The unit uses air-cooled or water-cooled, compact structure, operation and low maintenance cost

All our models can be customized. For more information, pleaes do not hesitate to contact.

Model	gas	inlet .barg	outlet .barg	flow rate NM3/hr	power.KW	voltage/frequency	inlet/outlet.mm	cooling way	net eight.kg	dimension.mm	pressure riato stage
GOWW-4-10/4-150	oxygen	3-4	150	4-10	3	220/380 /440/50/60/3	DN15/M16X1.5	air cooling	380	1300X750X1000	3stage
GOWW-11-20/4-150	oxygen	3-4	150	11-20	4-7.5	220/380 /440/50/60/3	DN15/M16X1.5	air cooling	420	1300X750X1000	3stage

Choice 2:

https://www.alibaba.com/product-detail/BROTIE-oxygen-compressor_1600122723363.html?spm=a2700.galleryofferlist.topad_classic.d_image.35d821fd7VGM2u



BROTIE oxygen compressor

FOB **Reference** Price: Get Latest Price

$6,500.00 - $10,000.00 / Set | 1 Set/Sets (Min. Order)

Power: 3-22kw

Warranty: **1 Year** for machinery warranty | **1 Year** for Core Components

Shipping: Support Express · Sea freight · Land freight · Air freight

Lead Time:

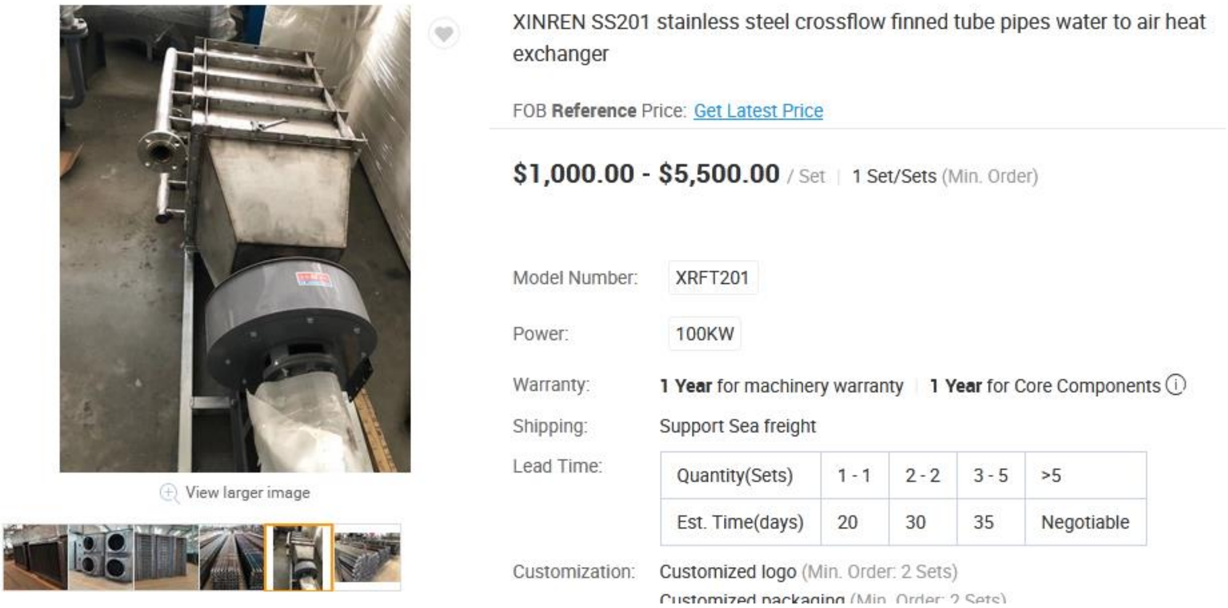
Quantity(Sets)	1 - 100	>100
Est. Time(days)	30	Negotiable

Overview

Quick Details

Applicable Industri...	Garment Shops, Building Material Shops, Manufacturing Plant...	After Warranty Serv...	Video technical support, Online support, Spare parts, Field ma...
Local Service Locat...	United Kingdom, United States, Germany, Viet Nam, Philippine...	Showroom Location:	Turkey, United Kingdom, United States, Viet Nam, Philippines, ...
Condition:	New, New	Type:	PISTON
Configuration:	PORTABLE	Power Source:	AC POWER
Lubrication Style:	Oil-free	Mute:	yes
Place of Origin:	China	Brand Name:	BROTIE
Model Number:	O2-3/4-150, O2-5/4-150, O2-10/4-150, O2-15/4-150, O2-20/4-...	Voltage:	customized
Dimension(L*W*H):	customized	Weight:	300-650kg
Certification:	ISO	Warranty:	1 Year
After-sales Service ...	Field installation, commissioning and training	Working Pressure:	150bar, 200bar
Air capacity:	3-75Nm3/h	Machinery Test Re...	Provided
Video outgoing-ins...	Provided	Marketing Type:	New Product 2020
Warranty of core co...	1 Year	Core Components:	Motor, compressor block
Gas Type:	oxygen	Model:	O2-3,5,10,15,20,25,30,40,50,75/4-150
Flow Capacity:	3,5,10,15,20,25,30,40,50,75Nm3/h	Compressing Stage:	3Stages
Inlet Pressure:	4bar	Outlet Pressure:	150, 200bar
Outlet Temperature:	50C	Inlet Size:	DN20-DN32
Outlet Size:	8-15mm	Cooling System:	Wind cooling/Water cooling
Lubrication:	no oil lubricated		

11.3.4.3 Main Heat exchanger



XINREN SS201 stainless steel crossflow finned tube pipes water to air heat exchanger

FOB **Reference** Price: Get Latest Price

$1,000.00 - $5,500.00 / Set | 1 Set/Sets (Min. Order)

Model Number: XRFT201

Power: 100KW

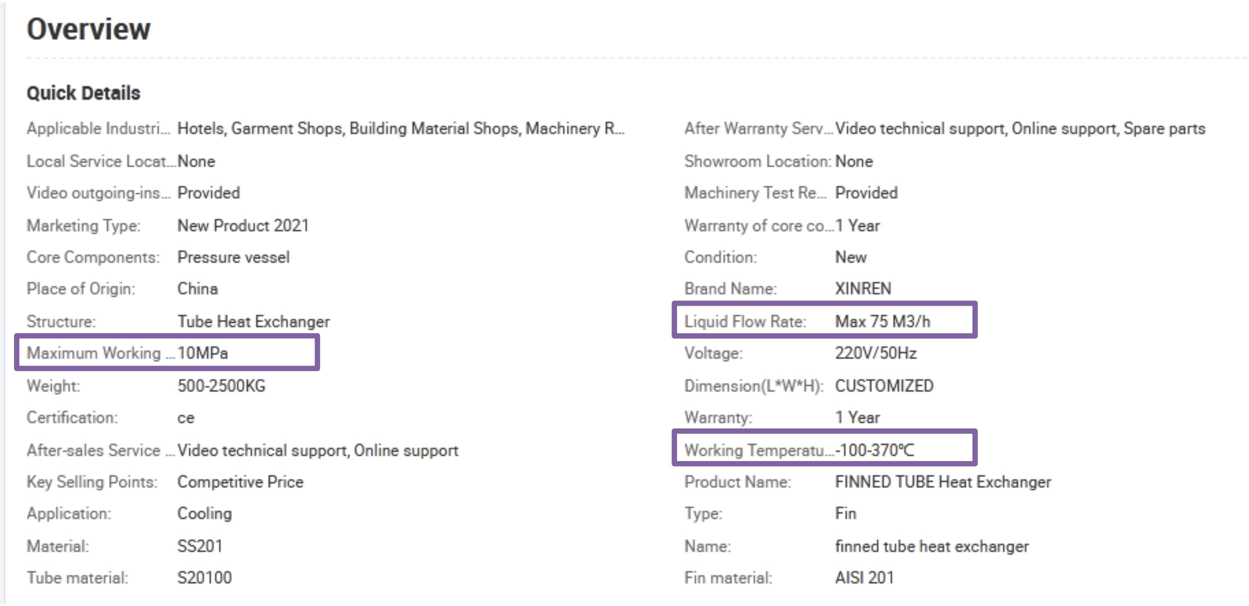
Warranty: **1 Year** for machinery warranty | **1 Year** for Core Components

Shipping: Support Sea freight

Lead Time:

Quantity(Sets)	1 - 1	2 - 2	3 - 5	>5
Est. Time(days)	20	30	35	Negotiable

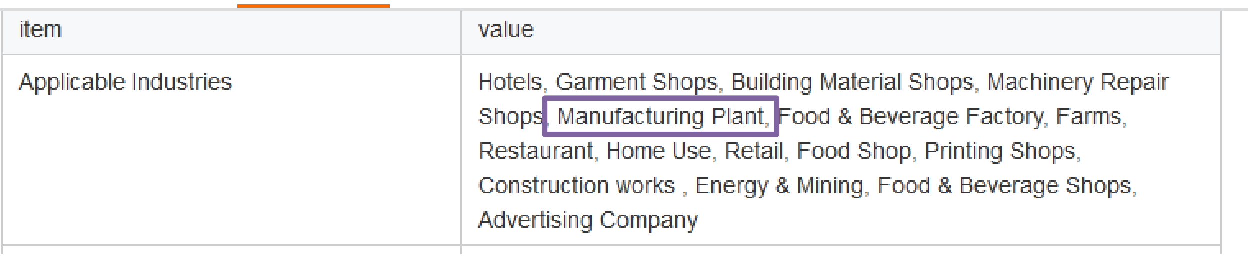
Customization: Customized logo (Min. Order: 2 Sets)
Customized packaging (Min. Order: 2 Sets)



Overview

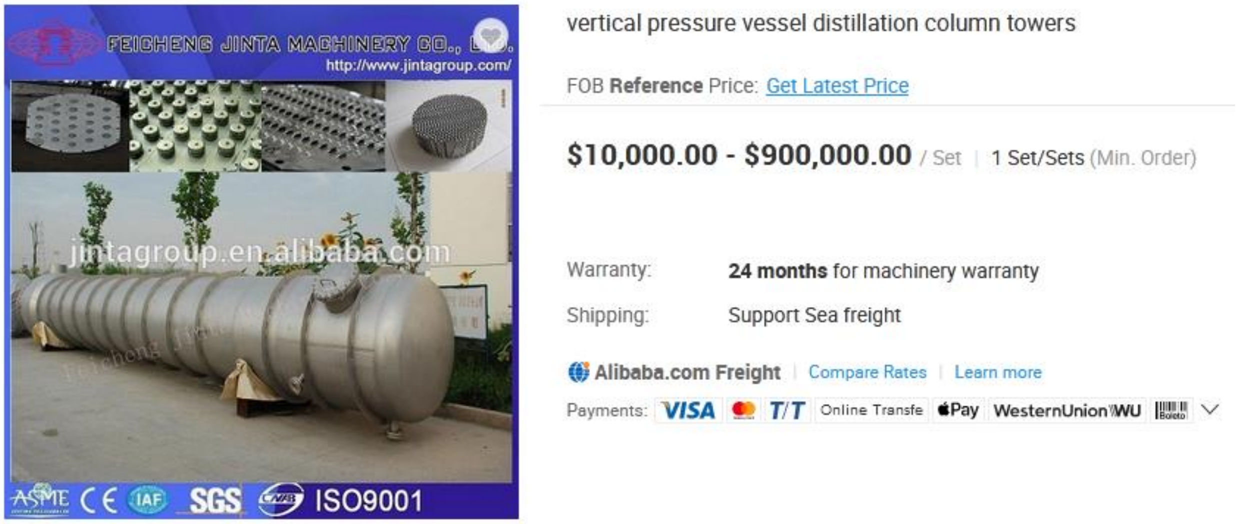
Quick Details

Applicable Industri...	Hotels, Garment Shops, Building Material Shops, Machinery R...	After Warranty Serv...	Video technical support, Online support, Spare parts
Local Service Locat...	None	Showroom Location:	None
Video outgoing-ins...	Provided	Machinery Test Re...	Provided
Marketing Type:	New Product 2021	Warranty of core co...	1 Year
Core Components:	Pressure vessel	Condition:	New
Place of Origin:	China	Brand Name:	XINREN
Structure:	Tube Heat Exchanger	Liquid Flow Rate:	Max 75 M3/h
Maximum Working ...	10MPa	Voltage:	220V/50Hz
Weight:	500-2500KG	Dimension(L*W*H):	CUSTOMIZED
Certification:	ce	Warranty:	1 Year
After-sales Service ...	Video technical support, Online support	Working Temperatu...	-100-370℃
Key Selling Points:	Competitive Price	Product Name:	FINNED TUBE Heat Exchanger
Application:	Cooling	Type:	Fin
Material:	SS201	Name:	finned tube heat exchanger
Tube material:	S20100	Fin material:	AISI 201



item	value
Applicable Industries	Hotels, Garment Shops, Building Material Shops, Machinery Repair Shops, Manufacturing Plant, Food & Beverage Factory, Farms, Restaurant, Home Use, Retail, Food Shop, Printing Shops, Construction works , Energy & Mining, Food & Beverage Shops, Advertising Company

11.3.4.4 Distillation column tower



vertical pressure vessel distillation column towers

FOB **Reference** Price: Get Latest Price

$10,000.00 - $900,000.00 / Set | 1 Set/Sets (Min. Order)

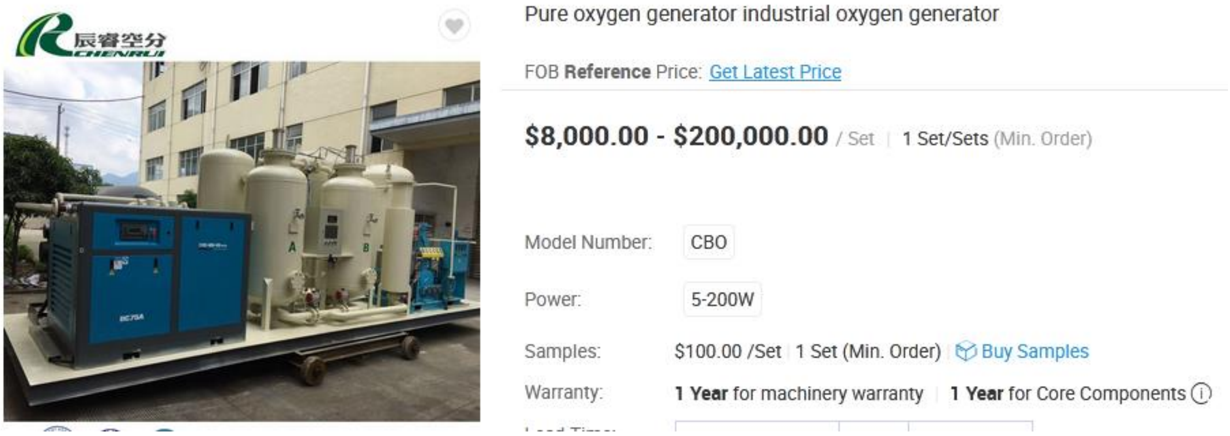
Warranty: **24 months** for machinery warranty

Shipping: Support Sea freight

Alibaba.com Freight | Compare Rates | Learn more

Payments: VISA T/T Online Transfe Pay WesternUnion WU

11.3.4.5 Industrial oxygen generator (whole system)



Pure oxygen generator industrial oxygen generator

FOB **Reference** Price: Get Latest Price

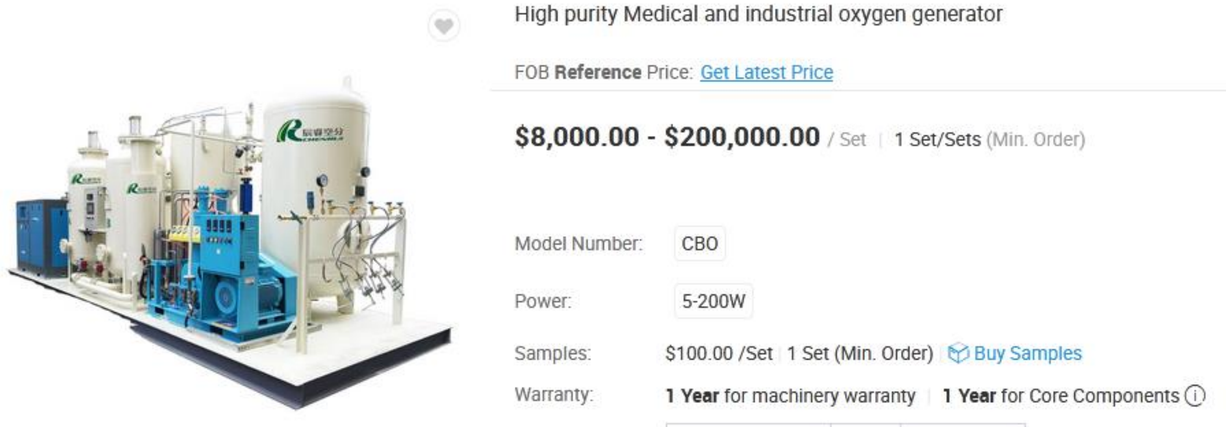
$8,000.00 - $200,000.00 / Set | 1 Set/Sets (Min. Order)

Model Number: CBO

Power: 5-200W

Samples: $100.00 /Set | 1 Set (Min. Order) | Buy Samples

Warranty: **1 Year** for machinery warranty | **1 Year** for Core Components



High purity Medical and industrial oxygen generator

FOB **Reference** Price: Get Latest Price

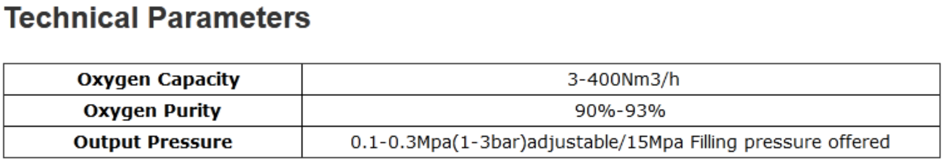
$8,000.00 - $200,000.00 / Set | 1 Set/Sets (Min. Order)

Model Number: CBO

Power: 5-200W

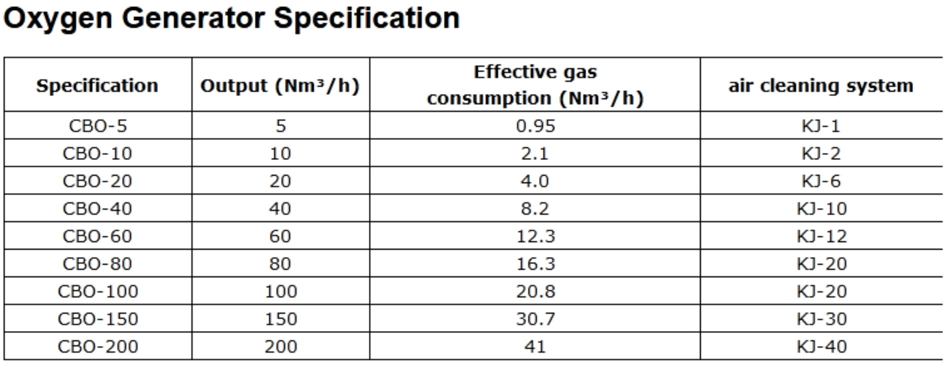
Samples: $100.00 /Set | 1 Set (Min. Order) | Buy Samples

Warranty: **1 Year** for machinery warranty | **1 Year** for Core Components



Technical Parameters

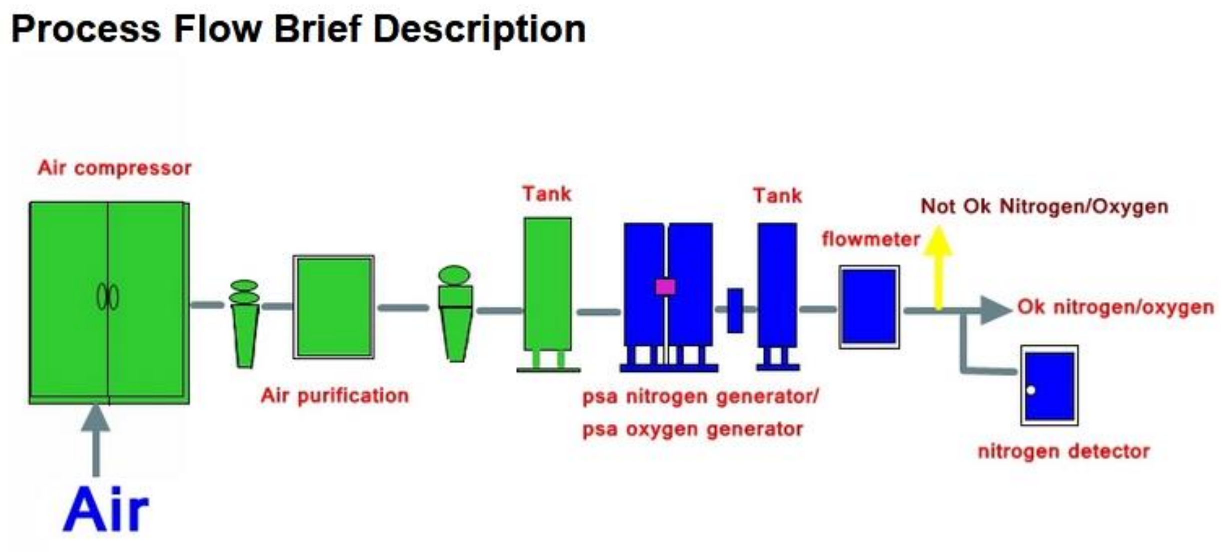
Oxygen Capacity	3-400Nm3/h
Oxygen Purity	90%-93%
Output Pressure	0.1-0.3Mpa(1-3bar)adjustable/15Mpa Filling pressure offered



Oxygen Generator Specification

Specification	**Output (Nm³/h)**	**Effective gas consumption (Nm³/h)**	**air cleaning system**
CBO-5	5	0.95	KJ-1
CBO-10	10	2.1	KJ-2
CBO-20	20	4.0	KJ-6
CBO-40	40	8.2	KJ-10
CBO-60	60	12.3	KJ-12
CBO-80	80	16.3	KJ-20
CBO-100	100	20.8	KJ-20
CBO-150	150	30.7	KJ-30
CBO-200	200	41	KJ-40

11.4 Process Flow Brief Description



11.4.1 ملخص_الهواء في حالة سائلة

11.4.2 نظرة عامة

محرك دورة الهواء السائل (LACE) هو نوع من محركات دفع المركبات الفضائية التي تحاول زيادة كفاءتها من خلال جمع جزء من مؤكسده من الجو. يستخدم محرك دورة الهواء السائل وقود الهيدروجين السائل (LH2) لتسييل الهواء . في صاروخ الأكسجين السائل / الهيدروجين السائل ، يكون الأكسجين السائل (LOX) اللازم للاحتراق هو الجزء الأكبر من وزن المركبة الفضائية عند الإقلاع ، لذلك إذا كان من الممكن جمع بعض هذا من الهواء في الطريق ، فقد يحدث ذلك بشكل كبير خفض وزن الاقلاع للمركبة الفضائية .
تمت دراسة LACE إلى حد ما في الولايات المتحدة الأمريكية خلال أواخر الخمسينيات وأوائل الستينيات ، وفي أواخر عام 1960 ، كان لدى ماركوارت نظام اختبار يعمل. ومع ذلك ، عندما انتقلت ناسا إلى كبسولات بالستية خلال مشروع ميركوري ، اختفى تمويل البحث عن المركبات المجنحة ببطء ، ويعمل LACE معها .

السائل الذي تم الحصول عليه عن طريق خفض درجة حرارة الهواء. ويسمى الهواء المسال في القانون. 1895 يقوم CPGRvon Linde بالضغط على الهواء وتوسيعه ، مما تسبب في انخفاض درجة حرارة الهواء تأثير جول طومسون باستخدام الهواء تمييع بالإضافة إلى ذلك ، جعل G. Claude الإنتاج الضخم الصناعي ممكنًا. في الآونة الأخيرة ، تم طرح سوائل نيتروجين الهواء في السوق التي تضغط غاز الهيليوم ثم تقوم بتوسيعه لإنشاء درجة حرارة منخفضة واستخدامه لتسييل الهواء. الجهاز صغير ومفيد مع القليل من القوى العاملة. الهواء السائل عبارة عن سائل أزرق فاتح ، وهو مزيج من النيتروجين السائل) نقطة الغليان 77.3 كيلو ، الثقل النوعي 0.810) والأكسجين السائل (نقطة الغليان 90.17 K، الثقل النوعي 1.144) ، الثقل النوعي حوالي 1 ، نقطة الغليان حوالي −190 °C. إذا تم السماح للهواء السائل بالوقوف ، فإن النيتروجين السائل ذو نقطة الغليان المنخفضة والضغط الجزئي العالي يتم تبخيره أولاً ، ويزداد تركيز

الأكسجين السائل في الهواء السائل. الاستفادة من هذه الخاصية ، يتم إرفاق برج تجزئة بوحدة تسييل النيتروجين في الهواء لفصل واستخدام النيتروجين السائل. من الناحية الصناعية ، يتم استخدام كمية كبيرة من الهواء السائل لفصل الأكسجين المستخدم في صناعة الصلب والنيتروجين المستخدم في تخليق الأمونيا . الأرجون ، النيون ، الخ الغاز النبيل يستخدم أيضا بشكل منفصل عن الهواء السائل. لا ينبغي أن يكون الهواء السائل على اتصال مباشر مع المواد القابلة للاشتعال ، وخاصة المذيبات العضوية القابلة للاشتعال مثل الكحول والإيثر وثاني أكسيد الكربون والأسيتون والمساحيق العضوية القابلة للاشتعال مثل السكر والنافثالين والكافور. وذلك لأن هذه المواد العضوية تتأكسد مرة واحدة وخطر الانفجار كبير. كان الهواء السائل عبارة عن مادة تجميد نموذجية في المختبر ، ولكن الآن يتم استخدام النيتروجين السائل الذي لا ينفجر ، ونادراً ما يستخدم الهواء السائل والأكسجين السائل. ومع ذلك ، فإن الأكسجين السائل)الحرارة الكامنة 6820 (J / mol والهواء السائل الذي يحتوي على الكثير منه أقل عرضة للتبخر من النيتروجين السائل (الحرارة الكامنة 5577 (J / mol ، لذلك فهو مناسب للاستخدام كمبرد طويل الأمد [6] .

يتم سائله عن طريق ضغط الهواء عند درجة حرارة منخفضة −140 درجة مئوية أو أقل. السائل السائل مع طفيف مزرق. درجة الغليان عند حوالي 1.1 الضغط الجوي حوالي −190 درجة مئوية. تستخدم في تجارب درجات الحرارة المنخفضة للحصول على الأكسجين والنيتروجين باستخدام الفرق في نقاط الغليان[7] .

11.5 توليد النيتروجين (N2) باستخدام تقنية الامتزاز بالضغط المتأرجح (PSA)

https://www.atlascopco.com/ar-eg/compressors/wiki/compressed-air-articles/what-is-nitrogen

11.5.1 توليد النيتروجين باستخدام تقنية الأغشية

https://www.atlascopco.com/ar-eg/compressors/wiki/compressed-air-articles/generating-nitrogen-membrane

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[6] World Encyclopedia

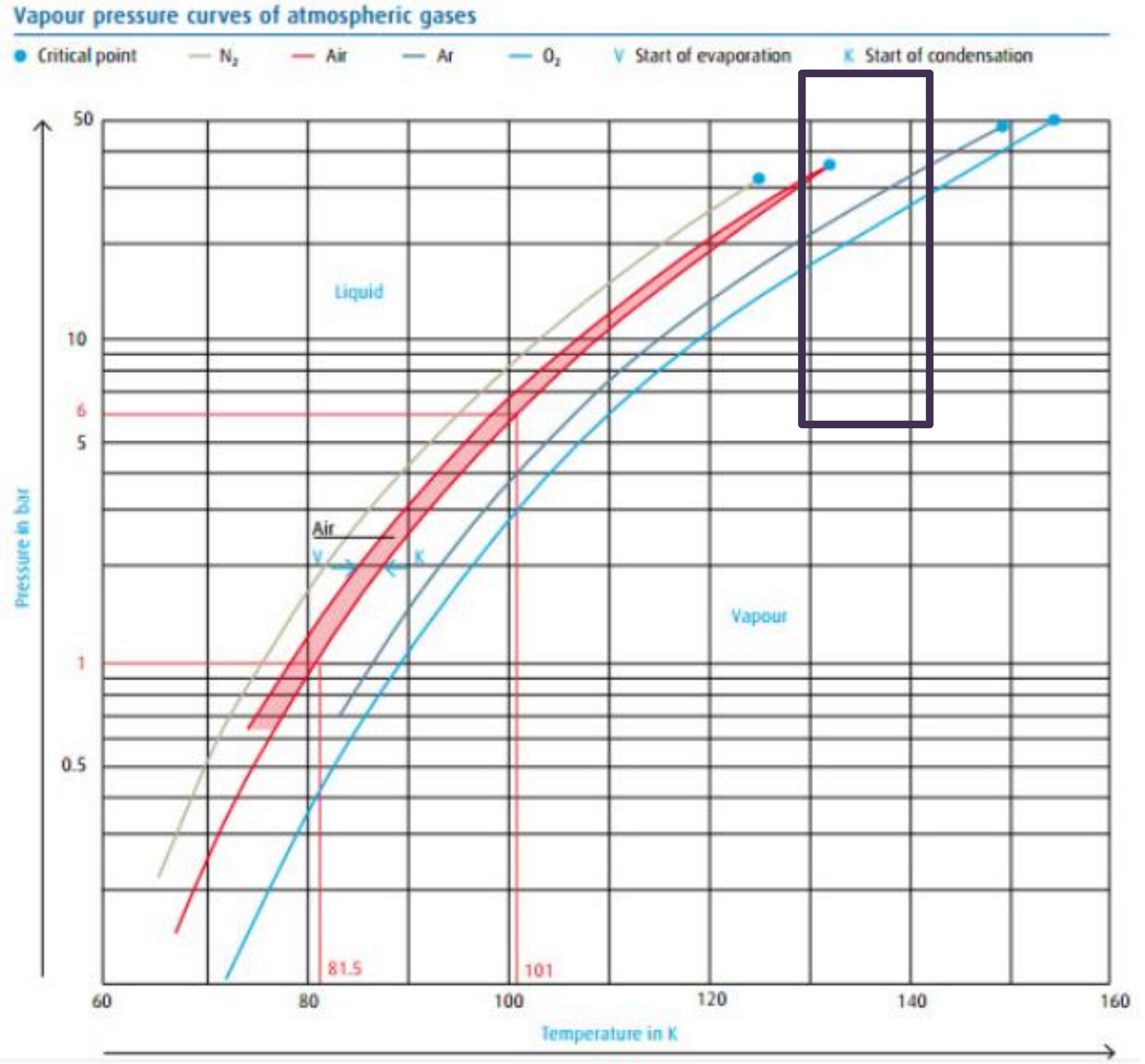
[7] Encyclopedia Mypedia

	غشائي	الامتزاز بالضغط المتأرجح (PSA)
النقاء الذي يمكن تحقيقه	كفاءة تصل إلى 99.9%	كفاءة تصل إلى 99.999%
الكفاءة	عالية	أعلى
الأداء مقابل درجة الحرارة	أعلى عند درجة الحرارة المرتفعة*	أقل عند درجة الحرارة المرتفعة
تعقيد النظام	منخفض	متوسط
كثافة الصيانة	منخفضة للغاية	منخفض
استقرار الضغط	ثابت	دخل/خرج متقلب
استقرار التدفق	ثابت	دخل/خرج متقلب
سرعة بدء التشغيل	توانٍ	دقائق/ ساعات**
حساسية الماء (البخار)	لا يوجد ماء سائل	ارتفاع حرارة مرشحات PDP عند 8 درجات مئوية كحد أقصى (بشكل عام)
حساسية الزيت	غير مسموح (< 0,01 مجم/م٣)	غير مسموح (< 0,01 مجم/م٣)
مستوى الضوضاء	منخفضة للغاية	مرتفع (ذروات التصريف)
الوزن	منخفض	متوسط

جدول المقارنة: مولدات النيتروجين الغشائية وتلك التي تعمل بتقنية الامتزاز بالضغط المتأرجح (PSA). *اعتمادًا على نوع الغشاء المستخدم **اعتمادًا على النقاء ووقت الإعداد المطلوبين

11.6 Parameters of Liquefaction of Oxygen

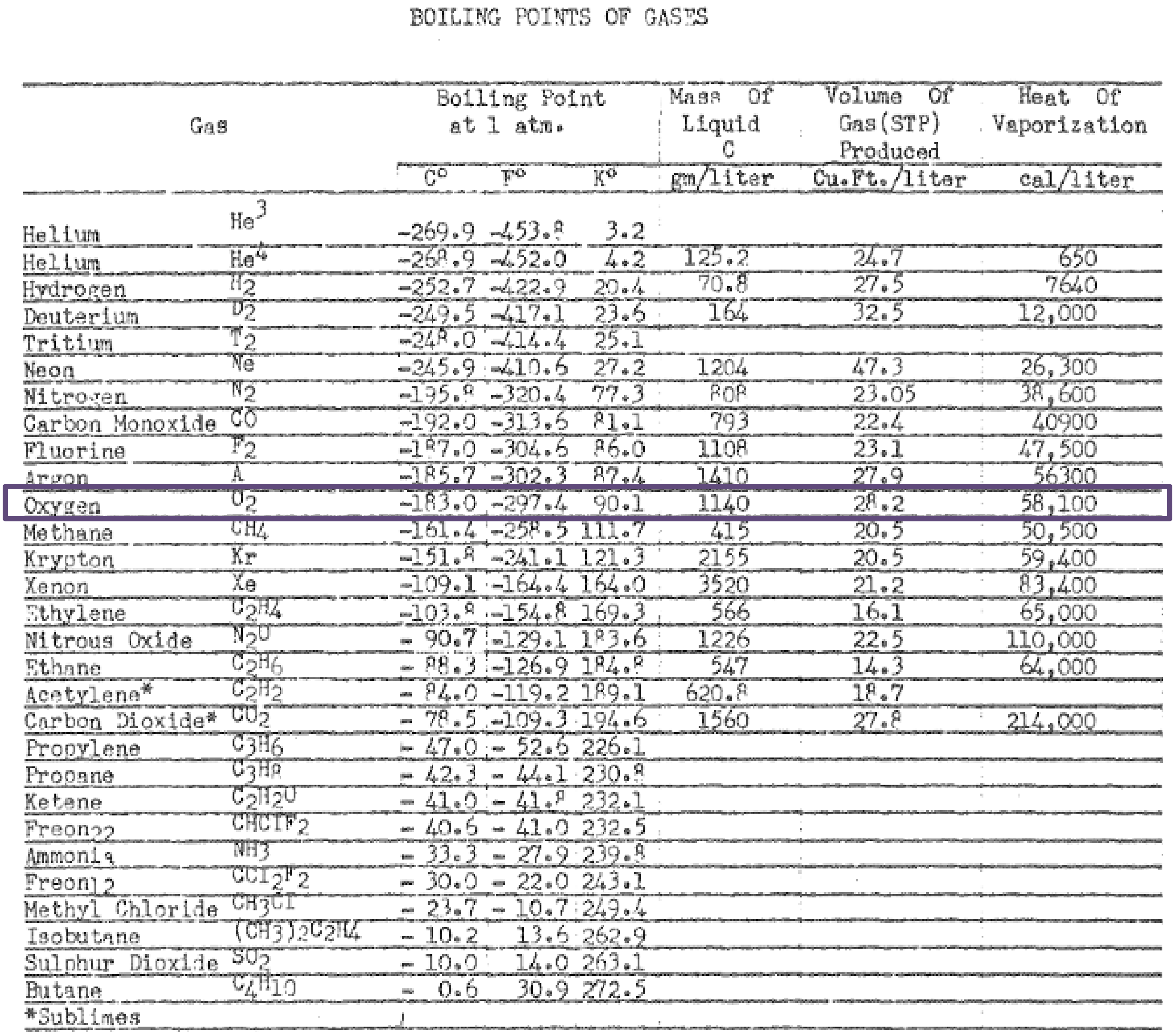
11.6.1 Properties of Oxygen



FLUID PROPERTIES

REF: NBS TM No. 36, p. 41

Properties	Liquid Hydrogen	Liquid Nitrogen	Water	Oxygen	Freon-11	Freon-22
Heat of Vaporization (cal./gr.)	106.5	47.6	586	50.8	43.5	55.9
Vapor Pressure (mm Hg)	760	760	18.8	760	760	760
Molecular Weight (gr./gr.mole)	2	28	18	32	137.4	86.5
Specific Volume (cc/gr.)	14.1	1.24	1.00	0.871	0.673	0.706
Temperature (°K)	20	77	294 (70°F)	90.13	297	232
C_p - Specific Heat (cal./gr.°K)	2.3	0.49	1.00	0.405	0.210	0.255
Viscosity (centipoises)	0.0130	0.158	0.98	0.190	0.429	———



BOILING POINTS OF GASES

Gas		Boiling Point at 1 atm.			Mass Of Liquid C	Volume Of Gas (STP) Produced	Heat Of Vaporization
		C°	F°	K°	gm/liter	Cu.Ft./liter	cal/liter
Helium	He^3	-269.9	-453.8	3.2			
Helium	He^4	-268.9	-452.0	4.2	125.2	24.7	650
Hydrogen	H_2	-252.7	-422.9	20.4	70.8	27.5	7640
Deuterium	D_2	-249.5	-417.1	23.6	164	32.5	12,000
Tritium	T_2	-248.0	-414.4	25.1			
Neon	Ne	-245.9	-410.6	27.2	1204	47.3	26,300
Nitrogen	N_2	-195.8	-320.4	77.3	808	23.05	38,600
Carbon Monoxide	CO	-192.0	-313.6	81.1	793	22.4	40900
Fluorine	F_2	-187.0	-304.6	86.0	1108	23.1	47,500
Argon	A	-185.7	-302.3	87.4	1410	27.9	56300
Oxygen	O_2	-183.0	-297.4	90.1	1140	28.2	58,100
Methane	CH_4	-161.4	-258.5	111.7	415	20.5	50,500
Krypton	Kr	-151.8	-241.1	121.3	2155	20.5	59,400
Xenon	Xe	-109.1	-164.4	164.0	3520	21.2	83,400
Ethylene	C_2H_4	-103.8	-154.8	169.3	566	16.1	65,000
Nitrous Oxide	N_2O	- 90.7	-129.1	183.6	1226	22.5	110,000
Ethane	C_2H_6	- 88.3	-126.9	184.8	547	14.3	64,000
Acetylene*	C_2H_2	- 84.0	-119.2	189.1	620.8	18.7	
Carbon Dioxide*	CO_2	- 78.5	-109.3	194.6	1560	27.8	214,000
Propylene	C_3H_6	- 47.0	- 52.6	226.1			
Propane	C_3H_8	- 42.3	- 44.1	230.8			
Ketene	C_2H_2O	- 41.0	- 41.8	232.1			
Freon22	$CHClF_2$	- 40.6	- 41.0	232.5			
Ammonia	NH_3	- 33.3	- 27.9	239.8			
Freon12	CCl_2F_2	- 30.0	- 22.0	243.1			
Methyl Chloride	CH_3Cl	- 23.7	- 10.7	249.4			
Isobutane	$(CH_3)_2C_2H_4$	- 10.2	13.6	262.9			
Sulphur Dioxide	SO_2	- 10.0	14.0	263.1			
Butane	C_4H_{10}	- 0.6	30.9	272.5			
*Sublimes							

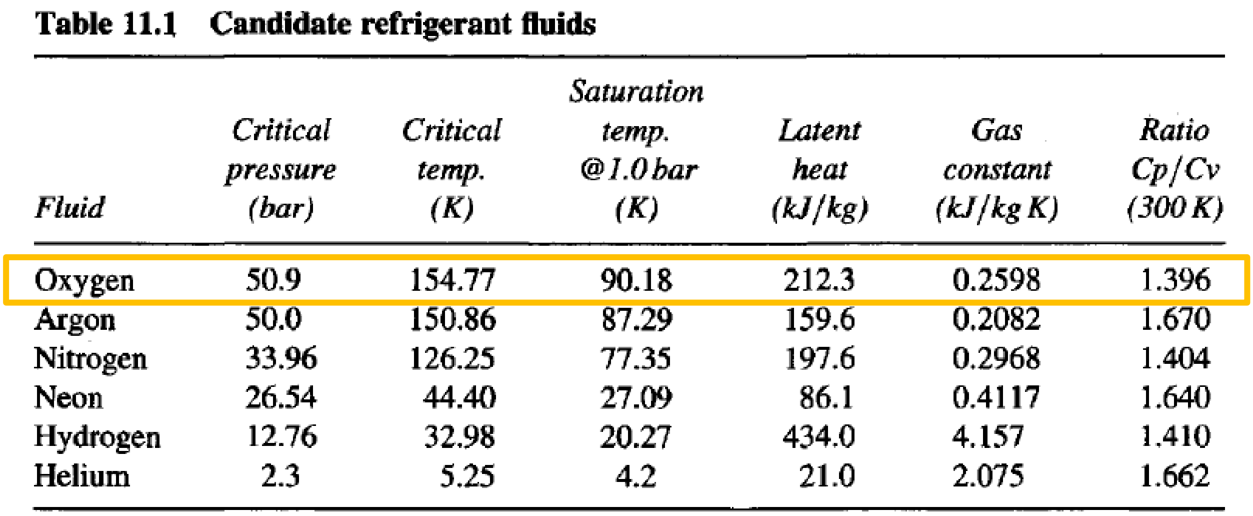


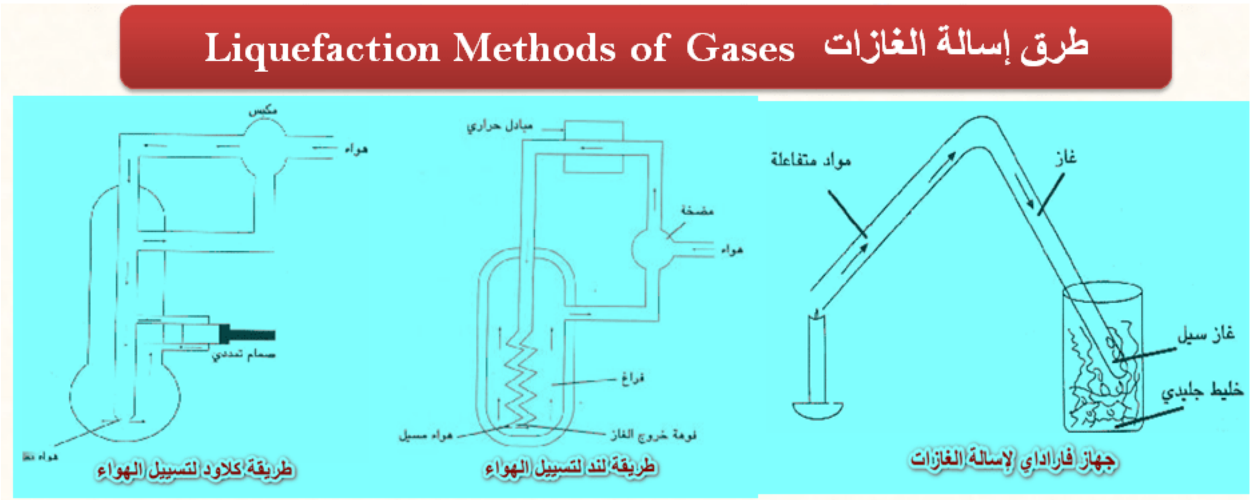
Table 11.1 Candidate refrigerant fluids

Fluid	*Critical pressure (bar)*	*Critical temp. (K)*	*Saturation temp. @1.0 bar (K)*	*Latent heat (kJ/kg)*	*Gas constant (kJ/kg K)*	*Ratio Cp/Cv (300 K)*
Oxygen	50.9	154.77	90.18	212.3	0.2598	1.396
Argon	50.0	150.86	87.29	159.6	0.2082	1.670
Nitrogen	33.96	126.25	77.35	197.6	0.2968	1.404
Neon	26.54	44.40	27.09	86.1	0.4117	1.640
Hydrogen	12.76	32.98	20.27	434.0	4.157	1.410
Helium	2.3	5.25	4.2	21.0	2.075	1.662

Table 1 Properties of Principal Cryogens

	Normal Boiling Point			Critical Point		Triple Point		
Name	T (K)	Liquid Density (kg/m^3)	Latent Heat (J/kg·mole)	T (K)	P (kPa)	T (K)	P (kPa)	Reference
Helium	4.22	123.9	91,860	5.28	227			1
Hydrogen	20.39	70.40	902,300	33.28	1296	14.00	7.20	2, 3
Deuterium	23.56	170.0	1,253,000	38.28	1648	18.72	17.10	4
Neon	27.22	1188.7	1,737,000	44.44	2723	26.28	43.23	5
Nitrogen	77.33	800.9	5,579,000	126.17	3385	63.22	12.55	6
Air	78.78	867.7	5,929,000					7, 8
Carbon monoxide	82.11	783.5	6,024,000	132.9	3502	68.11	15.38	9
Fluorine	85.06	1490.6	6,530,000	144.2	5571			10
Argon	87.28	1390.5	6,504,000	151.2	4861	83.78		11, 12, 13
Oxygen	90.22	1131.5	6,801,000	154.8	5081	54.39	0.14	6
Methane	111.72	421.1	8,163,000	190.61	4619	90.67	11.65	14
Krypton	119.83	2145.4	9,009,000	209.4	5488	116.00	73.22	15
Nitric oxide	121.50	1260.2	13,809,000	179.2	6516	108.94		
Nitrogen trifluoride	144.72	1525.6	11,561,000	233.9	4530			
Refrigerant-14	145.11	1945.1	11,969,000	227.7	3737	89.17	0.12	16
Ozone	161.28	1617.8	14,321,000	261.1	5454			
Xenon	164.83	3035.3	12,609,000	289.8	5840	161.39	81.50	17
Ethylene	169.39	559.4	13,514,000	282.7	5068	104.00	0.12	18

11.6.2 Liquefaction Methods of gases



عملية الإسالة عكس عملية التبخير

– إن عملية التسييل معاكسة لعملية التبخير.

– تعتمد عملية الإسالة على طبيعة الغاز فأبخرة المواد التي تكون سائلة في أو قرب درجة حرارة الغرفة والضغط الجوي تتكثف بسهولة بالتبريد.

– وأما المواد التي تكون سائلة في درجات حرارة منخفضة فإنها تتكثف إما بواسطة الضغط أو بالضغط والتبريد.

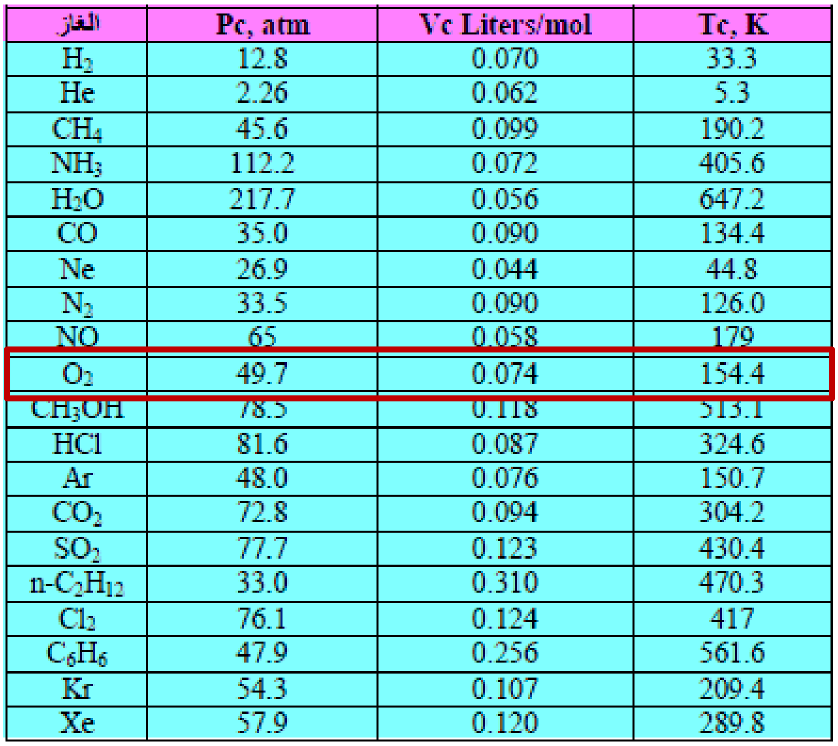
القيم الحرجة لإسالة الغازات

– قد وجد أن الضغط وحده لا يكفي لتسييل غازات معينة مثل ما يعرف بالغازات الدائمة كالأكسجين (O_2)والهيدروجين (H_2) والهيليوم (He) والنيتروجين (N_2) والتي لها درجات حرارة حرجة منخفضة جداً، ولكن بالضغط العالي وتبريدها الى درجات حرارة أدنى من درجات حرارتها الحرجة أمكن تسييل هذه الغازات.

– يوجد لكل غاز درجة حرارة لا يمكن إسالته فوقها مهما زاد الضغط وتعرف هذا الدرجة بدرجة الحرارة الحرجة critical temperature والضغط الحرج critical pressure هو الضغط اللازم لإسالة الغاز عند درجة الحرارة الحرجة للغاز.

–الجدول التالي يمثل درجات الحرارة الحرجة والضغط الحرج لبعض الغازات:

قيم (P, V, and T) عند النقطة الحرجة. الغازات مرتبة حسب الكتل الجزيئية



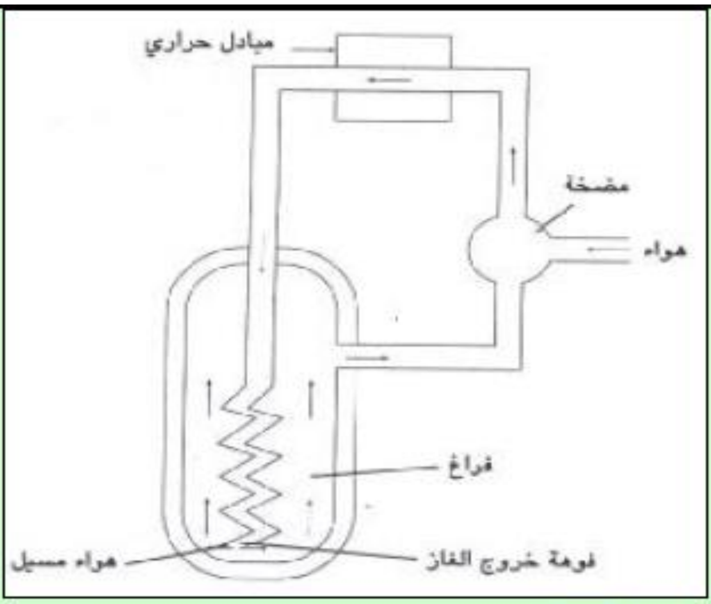
الغاز	Pc, atm	Vc Liters/mol	Tc, K
H_2	12.8	0.070	33.3
He	2.26	0.062	5.3
CH_4	45.6	0.099	190.2
NH_3	112.2	0.072	405.6
H_2O	217.7	0.056	647.2
CO	35.0	0.090	134.4
Ne	26.9	0.044	44.8
N_2	33.5	0.090	126.0
NO	65	0.058	179
O_2	49.7	0.074	154.4
CH_3OH	78.5	0.118	513.1
HCl	81.6	0.087	324.6
Ar	48.0	0.076	150.7
CO_2	72.8	0.094	304.2
SO_2	77.7	0.123	430.4
$n\text{-}C_2H_{12}$	33.0	0.310	470.3
Cl_2	76.1	0.124	417
C_6H_6	47.9	0.256	561.6
Kr	54.3	0.107	209.4
Xe	57.9	0.120	289.8

الطريقة الأولى لتسييل الغازات: طريقة ليند و هامبسون Lind-Hampson’s Method

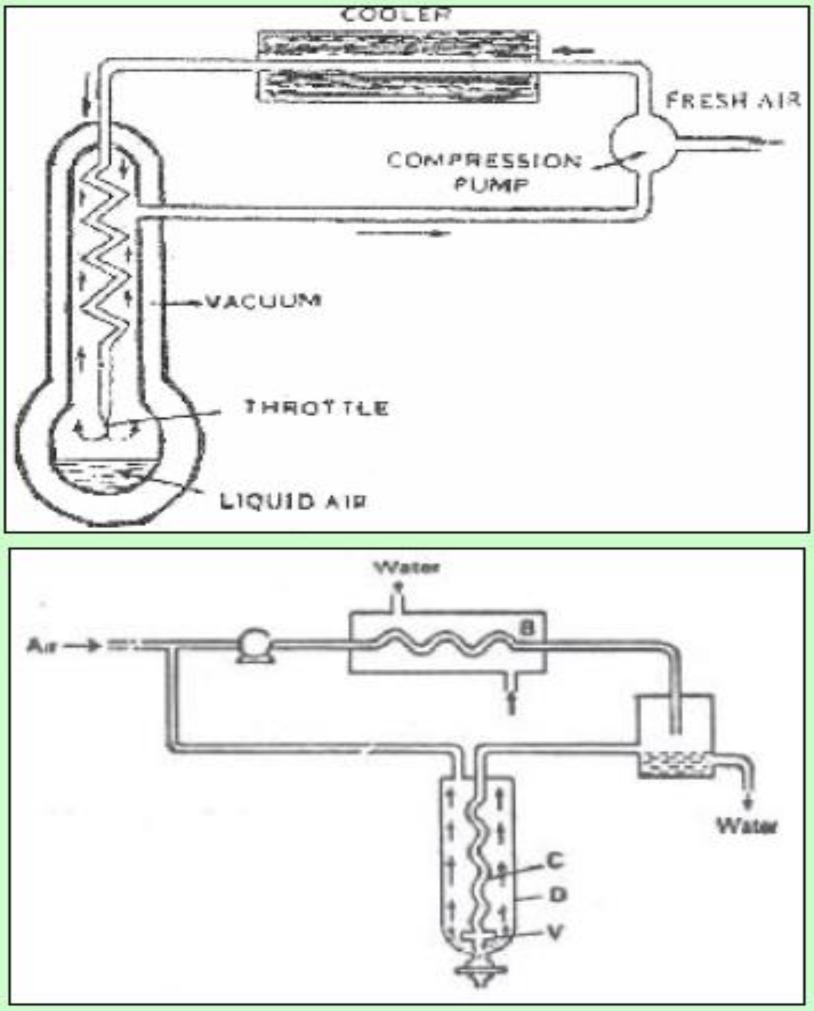
-تعتمد طريقة ليند وهامبسون على تأثير جول- طومسون والذي ينص على أنه:

عندما يسمح لأي غاز موجود تحت ضغط عال بالتمدد المفاجيء في منطقة ذات ضغط منخفض، فإن درجة حرارته سوف تنخفض. ويبرد الغاز بسبب حقيقة أنه أثناء التمدد سوف تستغل الطاقة الحركية للغاز المتمدد في التغلب على قوى التجاذب بين الجزيئات حيث أن الغاز يقوم بشغل داخلي .

-الأشكال التالية توضح الجهاز الذي استخدمه ليند في إسالة الهواء :



طريقة لند لتسييل الهواء



جهاز ليند لإسالة الهواء.

لذا نستطيع تسييل الأكسجين وذلك بالتمدد المفاجئ للغاز المضغوط تحت ضغوط عالية مما ينتج عنه انخفاضاً في درجة حرارة ذلك الغاز .

11.6.3 خطوات العمل 8

(1) ينقى الأكسجين المراد تبريده من ثاني أكسيد الكربون CO_2 والمواد العضوية والرطوبة.

(2) يضخ الأكسجين في أنبوبة حلزونية (جهاز ضغط Compressor)حيث يضغط إلى ضغط حوالي (50 bar)[حسب الجدول المذكور أعلاه]

ونتيجة لارتفاع الضغط فإن درجة حرارة الأكسجين تزداد (تتولد حرارة أثناء الضغط).

(3) ولما كان الغرض من هذه العملية تخفيض درجة الحرارة وليس زيادتها فإن هذا الأكسجين الذي ارتفعت درجة حرارته يتم التخلص من حرارته حيث يمرر في مبادل حراري (heat exchanger أنابيب نحاسية حلزونية مبردة) لتخفيض درجة الحرارة. حيث تصل درجة تبريده إلى حوالي $(< -123^oC)$ $[< 150\ K]$

(4) حيث يمرر هذا الأكسجين في أنبوب حلزوني (c) ينتهى بفوهة صغيرة جداً لينتهي بالمحيط ذي الضغط المنخفض (الغرفة D) ليصل ضغطها إلى حوالى (1 atm) وذلك بضبط الصمام (V) [العملية هنا هي عملية تمدد مفاجئ]. ونتيجة للتمدد سوف تهبط درجة حرارة غاز الأكسجين الى حوالي (-183^oC) أو أدنى [حالة الأكسجين السائل].

(5) يمرر الأكسجين الذي تم تبريده بهذه الطريقة مرة ثانية فوق الحلزونات النحاسية (c) وبهذه الطريقة سوف يؤدي الى تبريد الغاز الداخل الى درجة أقل حتى قبيل تمدده.

(6) بعد إتمام الدورة عدة مرات (يعود الى الضاغطة compressor) تعاد العملية مرة ثانية وثالثة ...الخ حتى الوصول الى الضغط ودرجة الحرارة الحرجين حيث يتحول الى سائل)، فإن درجة حرارة الغاز المتمدد سوف تصبح منخفضة للغاية لدرجة أن الأكسجين السائل سوف يتدفق عبر الصمام (V) أما الأكسجين الذي لم يتكثف بعد، فإنه يعاد مرة ثانية الى جهاز الضغط حيث تكتمل الدورة .

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[8] https://learnchemistry12.com/2019/02/liquefaction-methods-of-gases.html

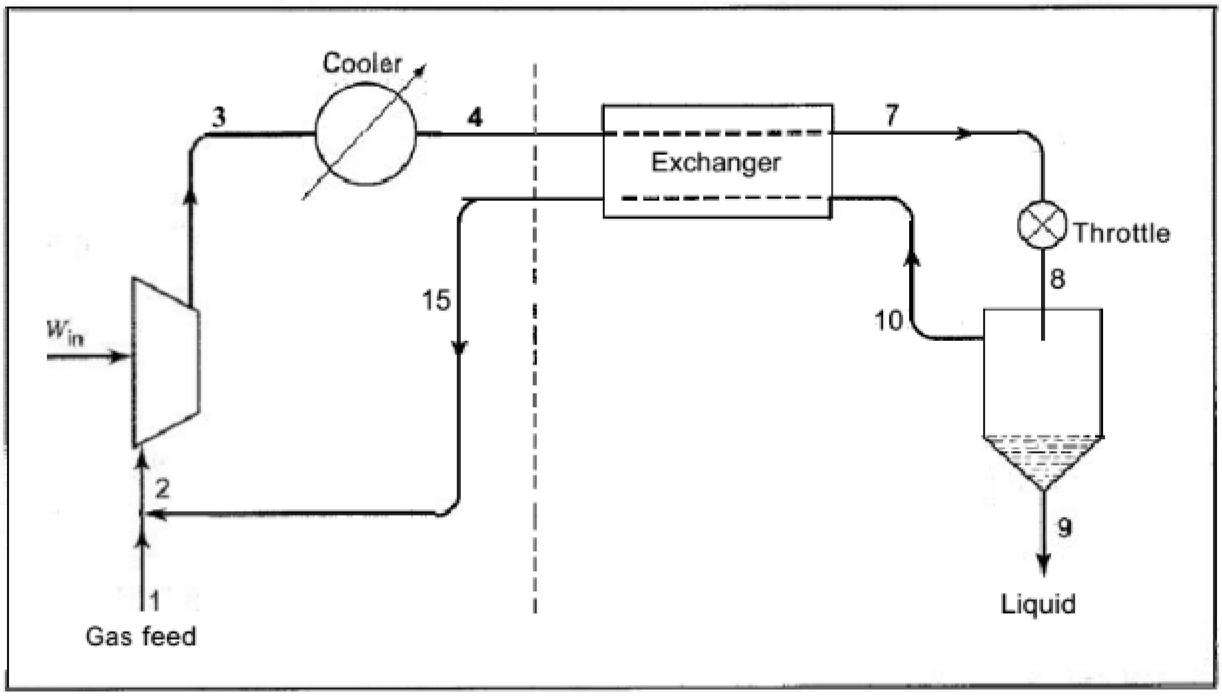


Figure 9.6 Linde liquefaction process

11.7 Static Analysis

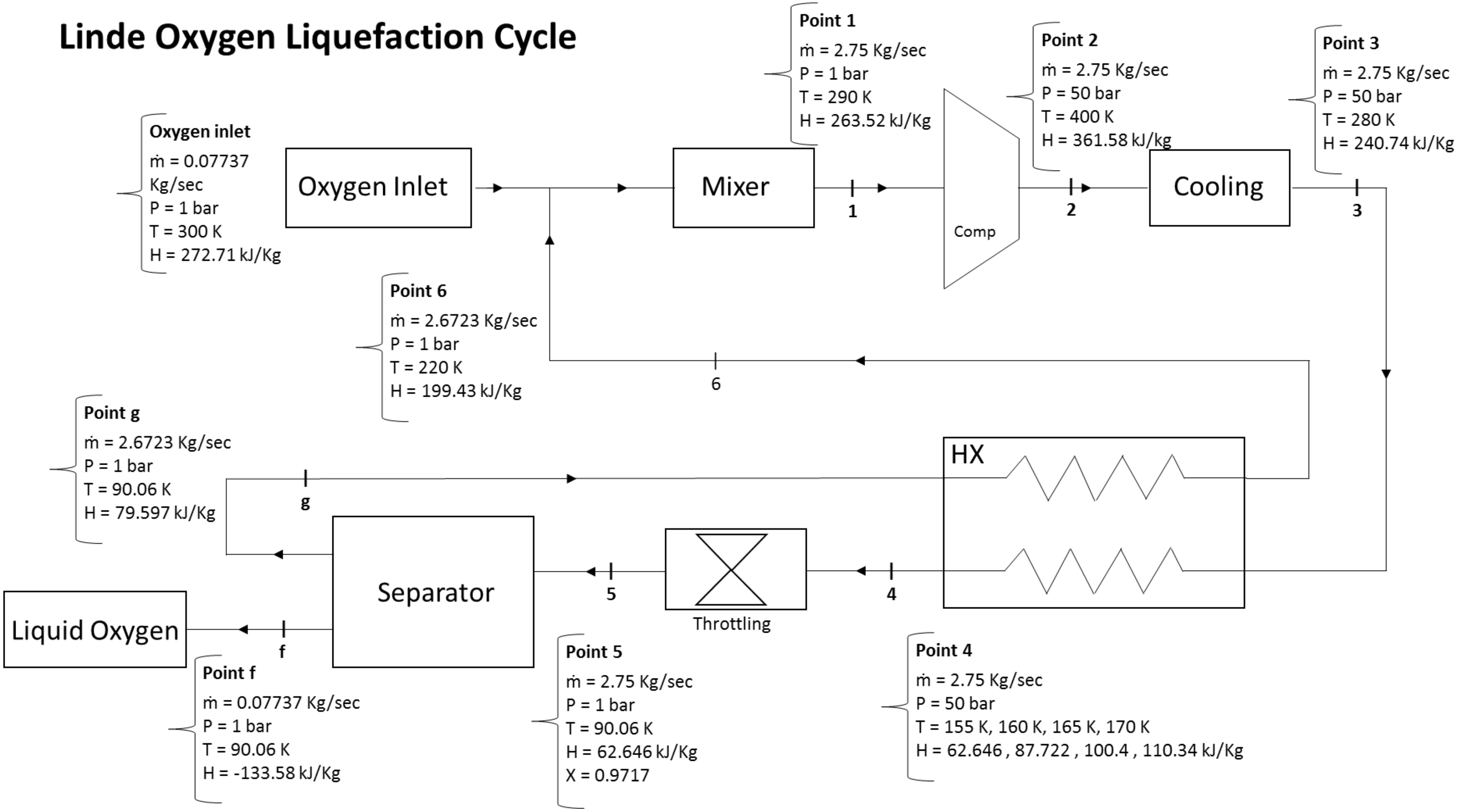
At the start of the first cycle, the oxygen gas passes from the oxygen inlet towards the compressor at the ambient temperature (300 K, 1 bar), through the mixer. It is at this stage that the mixer plays the role of the tank. The oxygen gas comes out hot from the compressor (400 K, 50 bar) in the direction of cooling in order to reduce the temperature of the compressed oxygen gas (280 K, 50 bar). Then the chilled oxygen gas goes to the heat exchanger, and here and in the first gas cycle the gas is not cooled through the heat exchanger due to the vacuum of the heat exchanger from the cold refrigerant gas. The compressed gas exits the heat exchanger with the cooling temperature (280 K, 50 bar) towards the throttle. In the throttle, the compressed gas (280 K, 50 bar) passes through a small aperture, allowing the gas to expand and expand suddenly and expand causing a sudden drop in pressure (from 50 bar to 1 bar) accompanied by a sudden drop in the temperature of the oxygen gas. The table below shows the temperature change before and after the throttle (at the outlet of the heat exchanger).

# of cycle	Heat exchanger			Throttling	ΔT (K)
	T inlet (K)	T outlet (K)	H outlet (kJ/Kg)	T outlet (K)	
1	280	280	240.71	265	15
2	280	~ 270	230.55	255	15
3	280	~ 260	220.23	245	15
4	280	~ 250	209.78	231	19
5	280	~ 237.5	196.5	216.8	20.7
6	280	~ 227.5	185.55	204	23.5
7	280	~ 210	165.67	183	27
8	280	~ 190	140.79	156	34
9	280	~ 165	100.4	107.5	57.5
10	280	~ 155	62.646	90.062	64.94

Note: The temperature change at the outlet of the heat exchanger (throttle inlet) occurs due to the temperature change of the cold oxygen gas entering the heat exchanger.

When oxygen is out of the throttle, it goes directly to the separator. At 90 K, oxygen is in a mixture of a gas and a liquid. And oxygen is in a gas state with a temperature higher than 90 K, while it is in a liquid state with a temperature below 90 K. The separator has two outlets, one for liquid oxygen and the second for gas oxygen. Liquid oxygen exits from the outlet of the first separator to the tank, while the oxygen gas exits, at a temperature of approximately 90 K, from the outlet of the second separator towards the mixer, passing through the heat exchanger. The cold oxygen gas coming out from the separator plays an important role in cooling the hot gas entering the heat exchanger (leaving the coolant) towards the throttle. After the cold gas passes through the heat exchanger, its temperature is heated up (about 220 K) and then it reaches the mixer where it is mixed with the oxygen gas coming from the oxygen inlet.

11.7.1 Schema of Linde-Hampson liquefaction cycle of Oxgene with example values



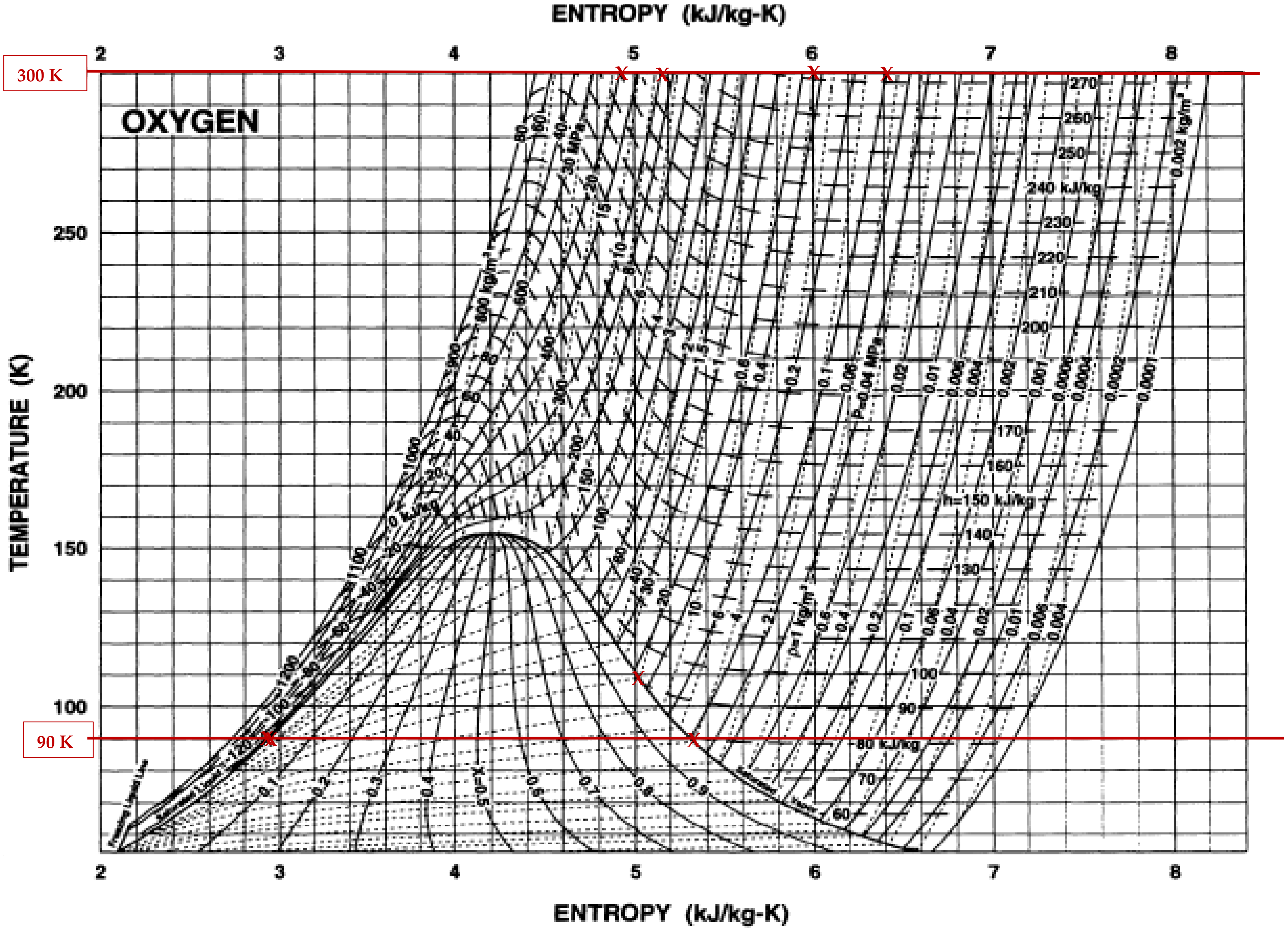
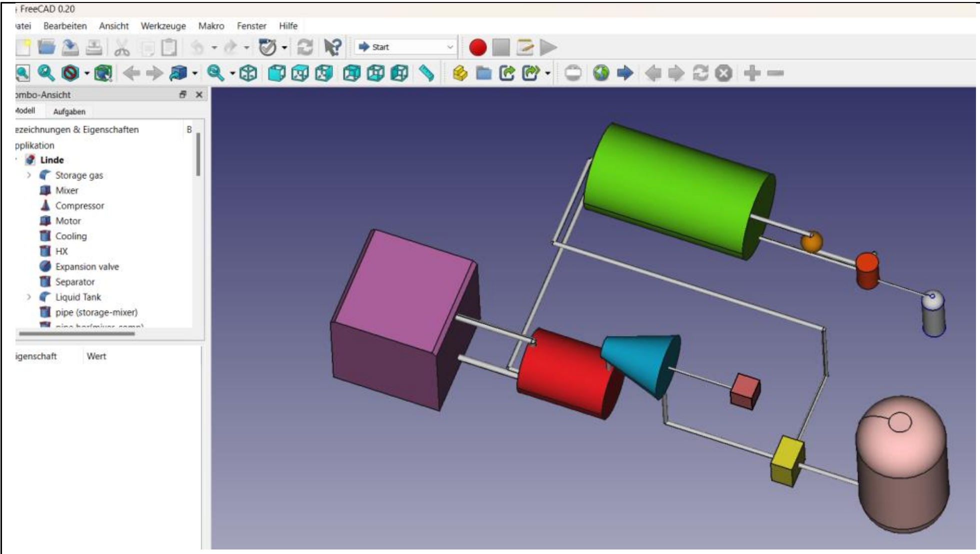


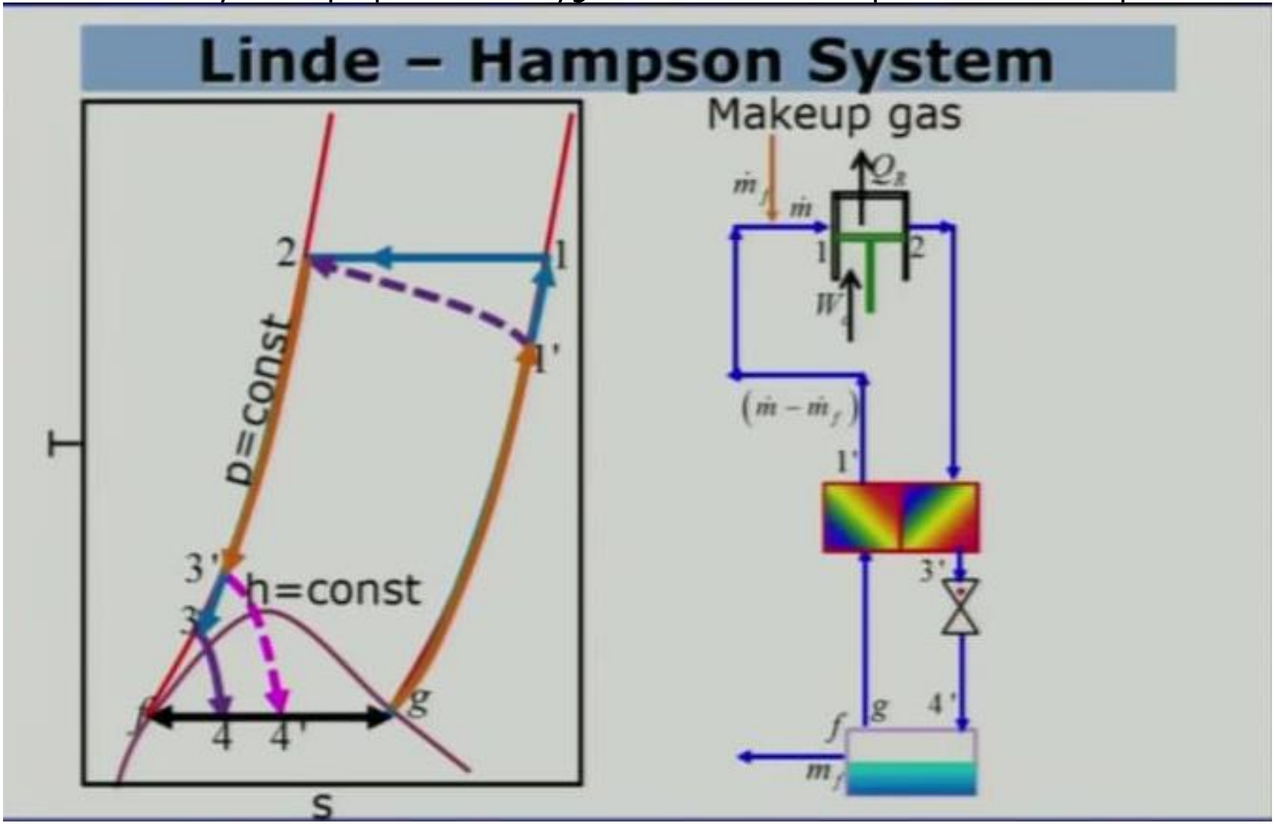
Fig. 5.30. T–S diagram for oxygen (T = 50–300 K)

11.7.2 Drawing by FreeCad

	Linde.FCStd

11.7.3 Detailes of calculation

- Thermodynamic properties of Oxygen with variation of pressure and temperature



1→2 isothermal compressor
3→4 Isenthalpic expansion
2→3’ , g→1 isobaric heat exchange
2→3’ , g→1’ heat exchange (actual)

We choose 90 K as temperature of boiling point (see table above)

Thermodynamic Properties of Oxygen	Unit	**P= 1 bar = 0.1 Mpa**		**P= 50 bar = 5 Mpa**		**P= 100 bar = 10 Mpa**		**P= 200 bar = 20 Mpa**	
		T= 90 K	**T= 300 K**	**T= 90 K**	**T= 300 K**	**T= 90 K**	**T= 300 K**	**T= 90 K**	**T= 300 K**
Enthalpy	**kJ/Kg**	**-133.69**	**272.71**	**-131.04**	**260.88**	**-128.28**	**249.39**	**-122.61**	**229.99**
Entropy	**kJ/Kg.K**	**2.9383**	**6.4163**	**2.9202**	**5.3679**	**2.9029**	**5.1561**	**2.8712**	**4.9208**

Note: The mass flow ṁ=2.75 Kg/s is an approximated value, a change in this value will affect Q-dot as well as ṁf and thus yield Y.

- In steady state conditions, the first Law around the compressor gives:
  $\dot{\mathbf{W}}c - (Q\text{-dot})r + \dot{m}(h1 - h2) = 0$

The second Law around the compressor gives:

$$(Q\text{-dot})r = \dot{m}\ T1\ (S1 - S2)$$

Combining, we have:

$$\dot{\mathbf{W}}c = \dot{m}\ [T1\ (S1 - S2) - (h1 - h2)]$$

$$= (Q\text{-dot})r - \dot{m}\ (h1 - h2)$$

Or $(Q\text{-dot})c = \dot{m}\ (h1 - h2)$

- Applying the 1st Law around everything except the compressor gives:
  $\dot{m}\ (h1 - h2) = \dot{m}f\ (h1 - hf)$

$$\rightarrow \dot{m}f = \frac{\dot{m}\ (h1 - h2)}{h1 - hf}$$

- Defining yield, $y = \frac{\dot{m}f}{\dot{m}} = \frac{h1 - h2}{h1 - hf}$

- $\text{FOM} = \frac{(h1 - h2)(T1 - Tc)}{[T1\ (S1 - S2) - (h1 - h2)]\ Tc}$

Thus, the table below contains the results of calculation with variation of pressure

Pesure P	Unit	**1 bar → 50 bar**	**1 bar → 100 bar**	**1 bar → 200 bar**
Gas mass flow rate ṁ	**Kg/sec**	**2.75**	**2.75**	**2.75**
Heat transfer of compressor Qr	kJ/sec	864.93	1039.665	1233.7875
Heat transfert of evaporator Qc	kJ/sec	32.5325	64.13	115.995
Work transfert compressor W-dot	kJ/sec	832.3975	975.535	1117.7925
Liquid mass flow rate ṁf	**Kg/sec**	**0.08005**	**0.1578**	**0.28542**
Yield Y		0.02911	0.0573	0.10379
FOM		**0.09111**	**0.15324**	**0.241903**

11.7.4 Heat exchanger

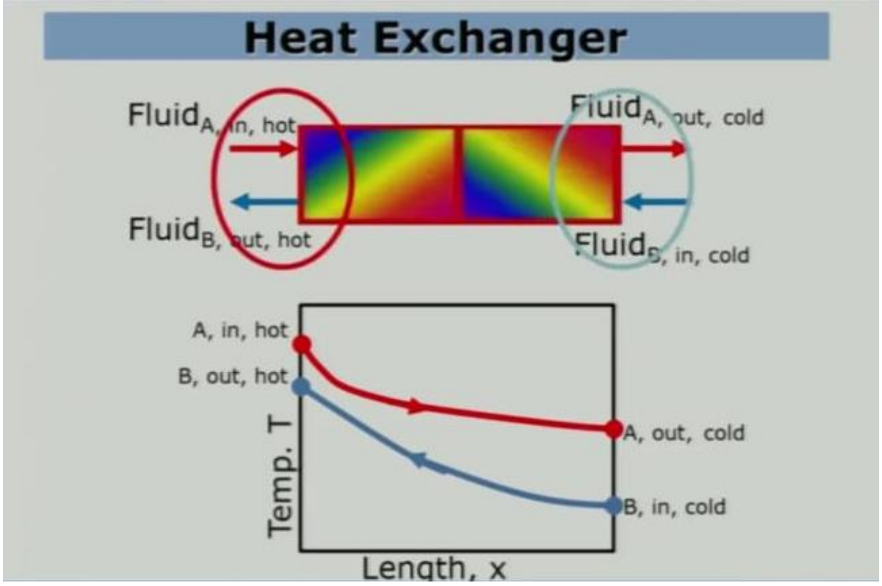
- **Heat Exchanger Design Process**
  1. Identify application – Temperature, heat loads, mass flow rates,etc.
  2. Decide on construction type.
  3. Evaluate LMTD, q and F
  4. Determine dimensions.
  5. Evaluate heat transfert coefficient on hot side
  6. Evaluate heat transfer coefficient on cold side
  7. Determine overall heat transfer coefficient.
  8. Determine dimensions – iterate
  9. Check power consumpltion

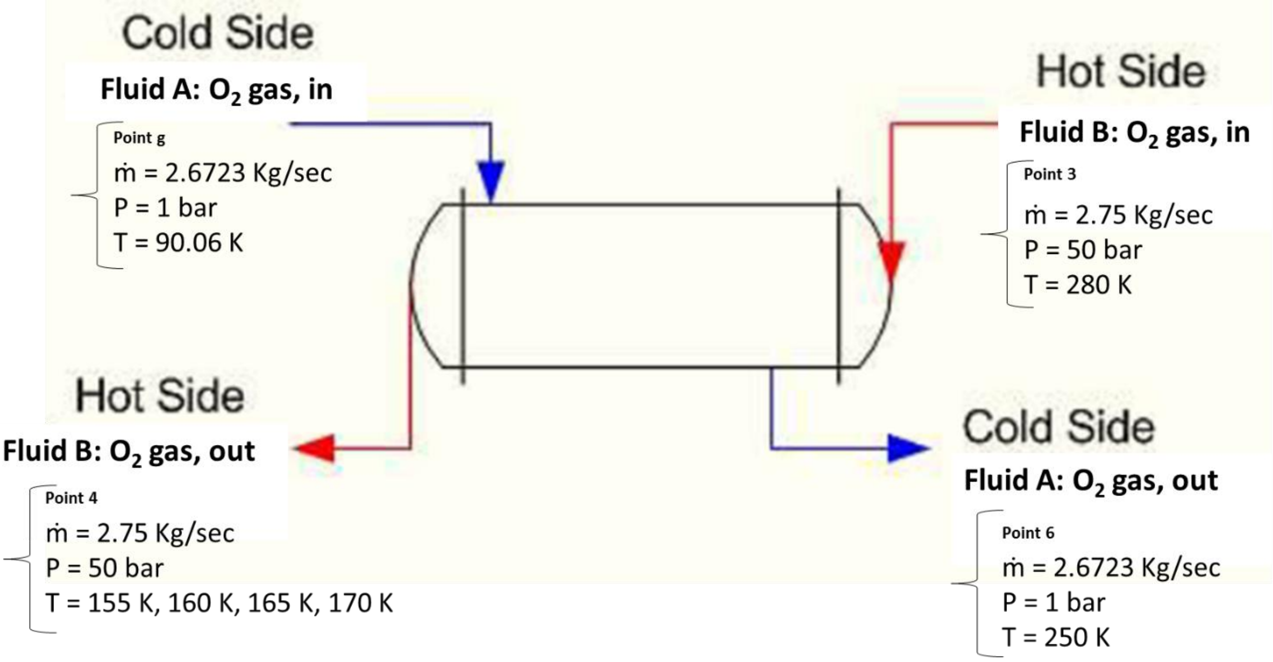
11.7.4.1 Calculation of heat exchanger [9]

✍ **Notes :**

1- U value is taken approximate (40 W/m^2.K)

2- A base of inlet and outlet temperature (hot & cold), the appropriate type of heat exchanger is 2 shells and 4 tubes





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[9] https://checalc.com/solved/LMTD_Chart.html & https://checalc.com/calc/ShortExch.html

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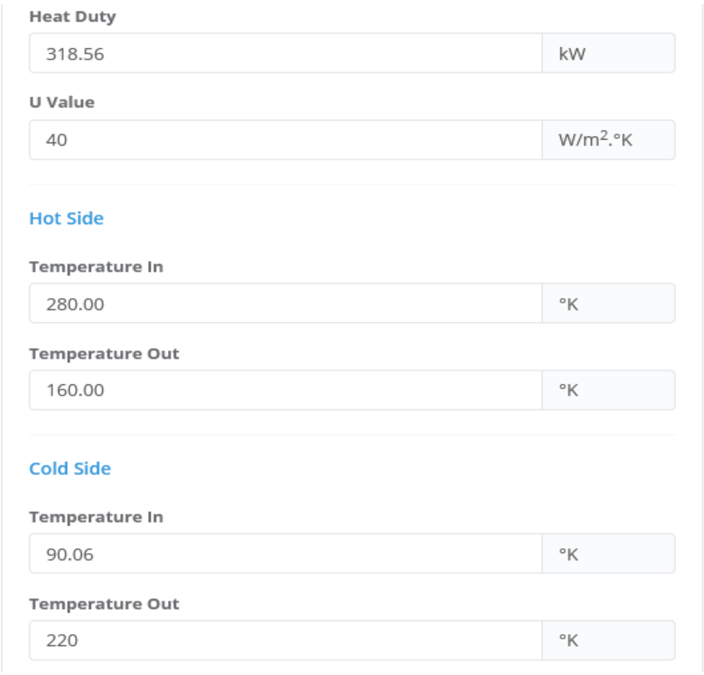


Heat Duty
318.56 kW

U Value
40 W/m².°K

Hot Side

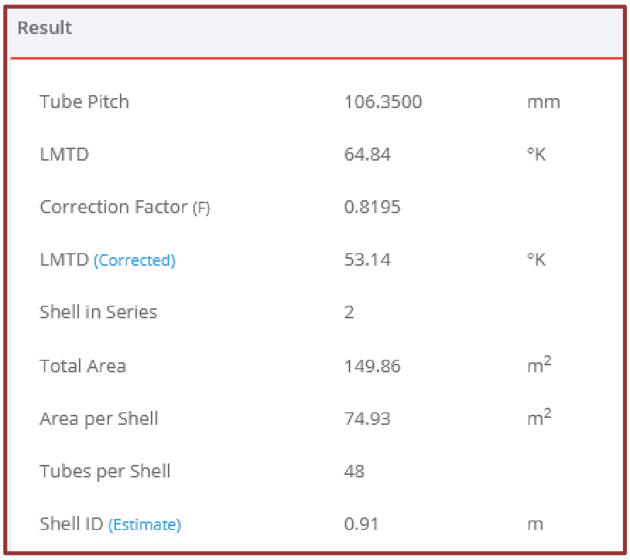
Temperature In
280.00 °K

Temperature Out
160.00 °K

Cold Side

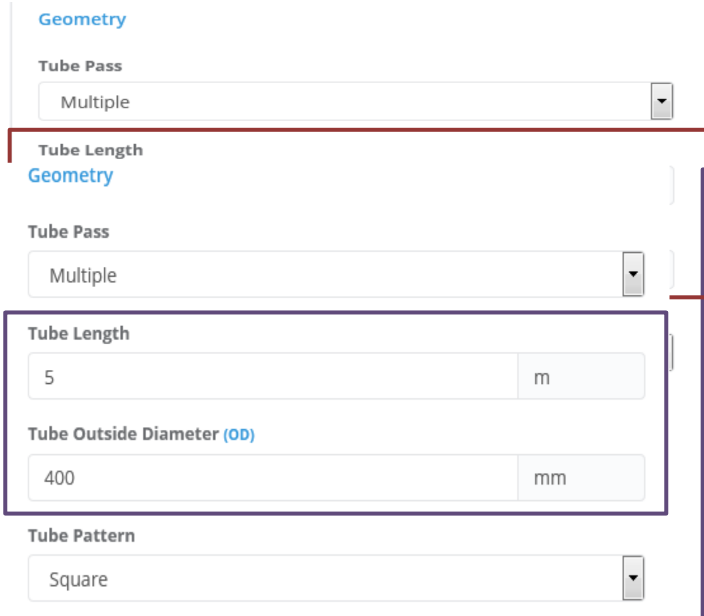
Temperature In
90.06 °K

Temperature Out
220 °K



Result

Tube Pitch	106.3500	mm
LMTD	64.84	°K
Correction Factor (F)	0.8195	
LMTD (Corrected)	53.14	°K
Shell in Series	2	
Total Area	149.86	m²
Area per Shell	74.93	m²
Tubes per Shell	48	
Shell ID (Estimate)	0.91	m



Geometry

Tube Pass
Multiple

Tube Length

Geometry

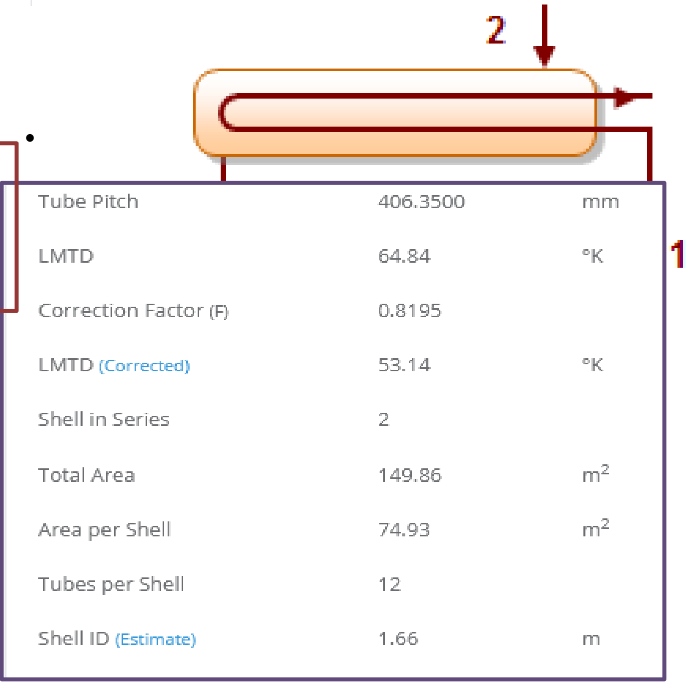
Tube Pass
Multiple

Tube Length
5 m

Tube Outside Diameter (OD)
400 mm

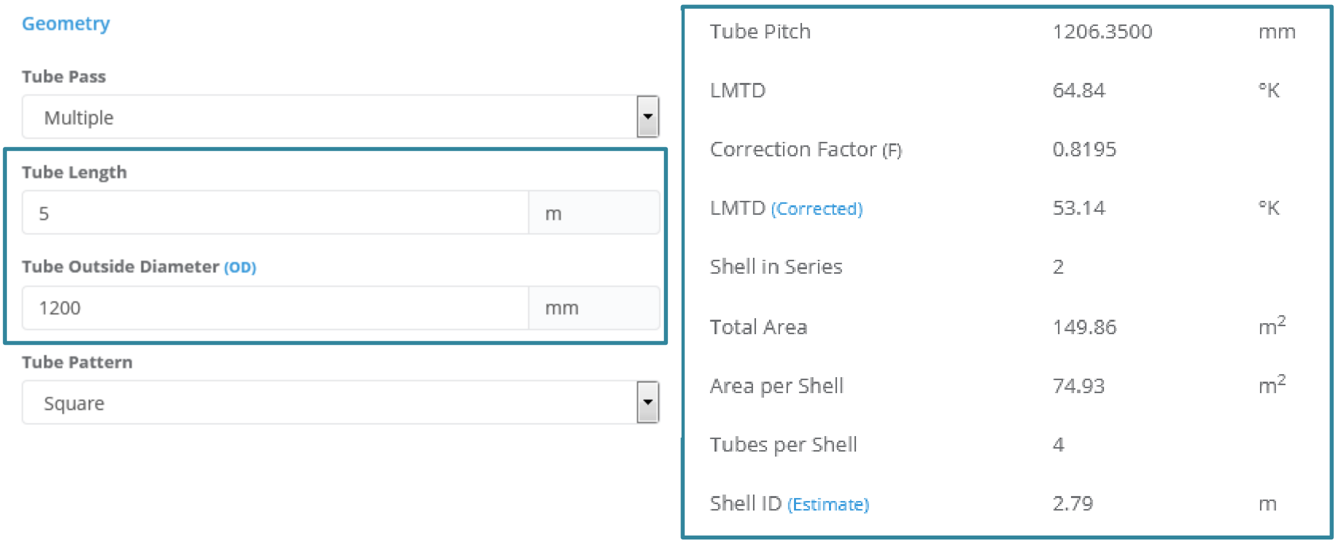
Tube Pattern
Square

-



Tube Pitch	406.3500	mm
LMTD	64.84	°K
Correction Factor (F)	0.8195	
LMTD (Corrected)	53.14	°K
Shell in Series	2	
Total Area	149.86	m²
Area per Shell	74.93	m²
Tubes per Shell	12	
Shell ID (Estimate)	1.66	m

-



Geometry

Tube Pass: Multiple

Tube Length: 5 m

Tube Outside Diameter (OD): 1200 mm

Tube Pattern: Square

Tube Pitch	1206.3500	mm
LMTD	64.84	°K
Correction Factor (F)	0.8195	
LMTD (Corrected)	53.14	°K
Shell in Series	2	
Total Area	149.86	m^2
Area per Shell	74.93	m^2
Tubes per Shell	4	
Shell ID (Estimate)	2.79	m

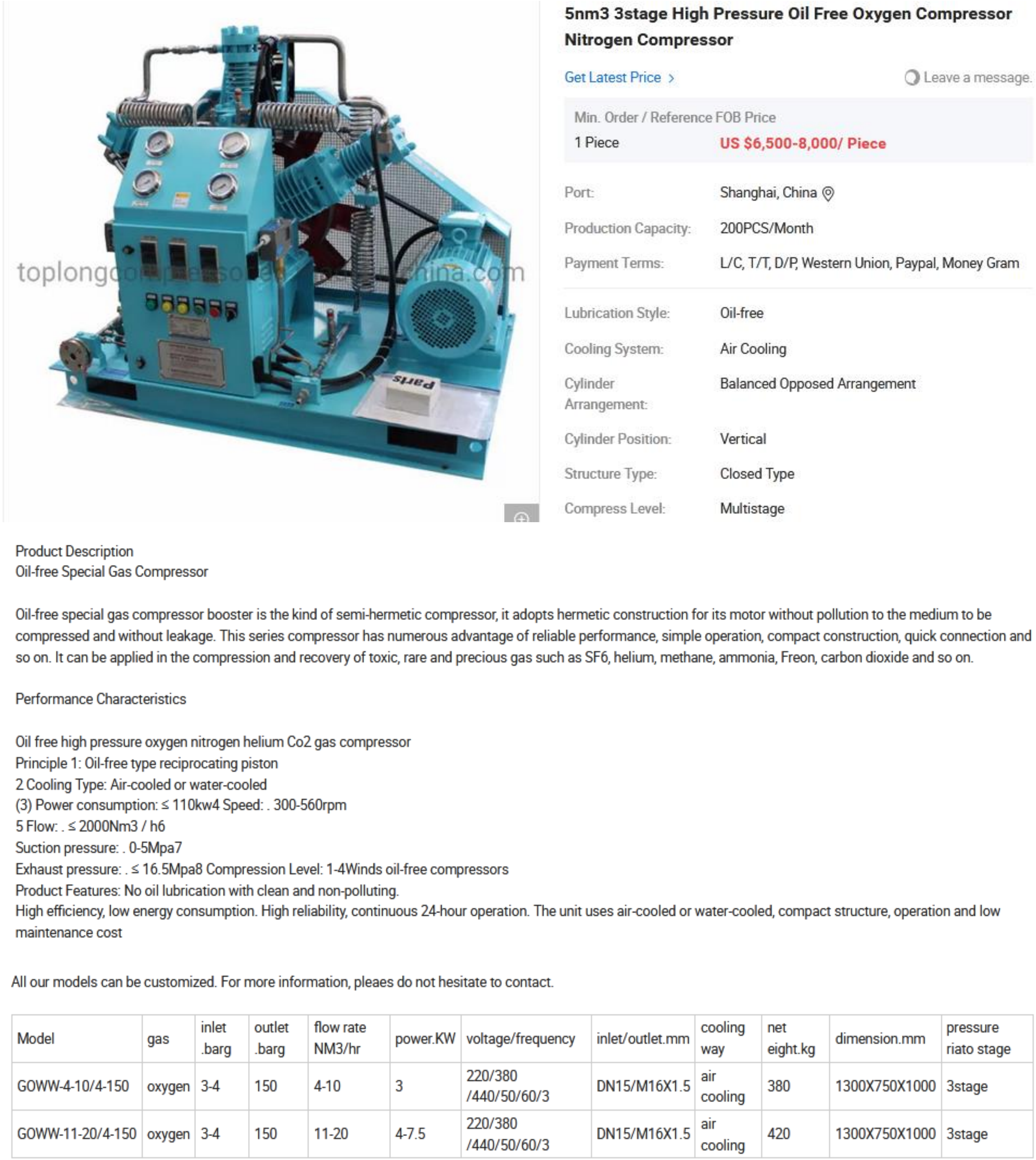
11.7.5 Calculation of compressor

	Stage 1	**Stage 2**	**Stage 3**	**Total**
Mass flow rate (Kg/s)	1.12E-03	1.12E-03	1.12E-03	
Pessure ratio	3	4	3.6	43.5
Pump efficiency	0.6	0.6	0.6	
Input pressure (bar)	1.18	3.56	14.25	
Outlet pressure (bar)	3.56	14.25	51.67	51.67
Intel density (Kg/m3)	1.7	5.0	20.4	
Pump input power (W)	265	397	344	1005

- **Compressor choice :**

Choice 1:

https://toplongcompressor.en.made-in-china.com/product/IvVmtGBbhyhA/China-5nm3-3stage-High-Pressure-Oil-Free-Oxygen-Compressor-Nitrogen-Compressor.html



5nm3 3stage High Pressure Oil Free Oxygen Compressor Nitrogen Compressor

Min. Order / Reference FOB Price	
1 Piece	US $6,500-8,000/ Piece
Port:	Shanghai, China
Production Capacity:	200PCS/Month
Payment Terms:	L/C, T/T, D/P, Western Union, Paypal, Money Gram
Lubrication Style:	Oil-free
Cooling System:	Air Cooling
Cylinder Arrangement:	Balanced Opposed Arrangement
Cylinder Position:	Vertical
Structure Type:	Closed Type
Compress Level:	Multistage

Product Description
Oil-free Special Gas Compressor

Oil-free special gas compressor booster is the kind of semi-hermetic compressor, it adopts hermetic construction for its motor without pollution to the medium to be compressed and without leakage. This series compressor has numerous advantage of reliable performance, simple operation, compact construction, quick connection and so on. It can be applied in the compression and recovery of toxic, rare and precious gas such as SF6, helium, methane, ammonia, Freon, carbon dioxide and so on.

Performance Characteristics

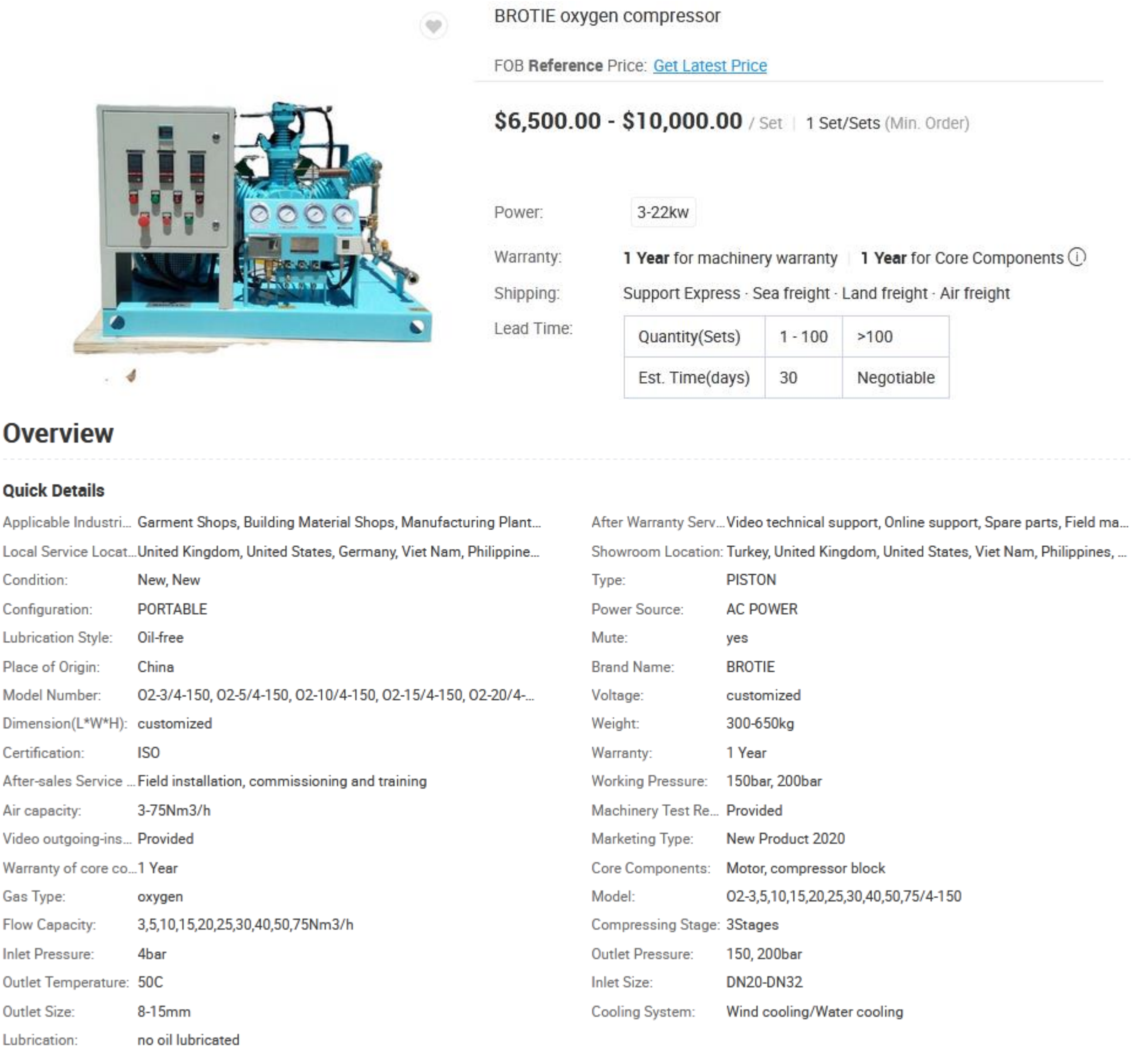
Oil free high pressure oxygen nitrogen helium Co2 gas compressor
Principle 1: Oil-free type reciprocating piston
2 Cooling Type: Air-cooled or water-cooled
(3) Power consumption: ≤ 110kw4 Speed: . 300-560rpm
5 Flow: . ≤ 2000Nm3 / h6
Suction pressure: . 0-5Mpa7
Exhaust pressure: . ≤ 16.5Mpa8 Compression Level: 1-4Winds oil-free compressors
Product Features: No oil lubrication with clean and non-polluting.
High efficiency, low energy consumption. High reliability, continuous 24-hour operation. The unit uses air-cooled or water-cooled, compact structure, operation and low maintenance cost

All our models can be customized. For more information, pleaes do not hesitate to contact.

Model	gas	inlet .barg	outlet .barg	flow rate NM3/hr	power.KW	voltage/frequency	inlet/outlet.mm	cooling way	net eight.kg	dimension.mm	pressure riato stage
GOWW-4-10/4-150	oxygen	3-4	150	4-10	3	220/380 /440/50/60/3	DN15/M16X1.5	air cooling	380	1300X750X1000	3stage
GOWW-11-20/4-150	oxygen	3-4	150	11-20	4-7.5	220/380 /440/50/60/3	DN15/M16X1.5	air cooling	420	1300X750X1000	3stage

Choice 2:

https://www.alibaba.com/product-detail/BROTIE-oxygen-compressor_1600122723363.html?spm=a2700.galleryofferlist.topad_classic.d_image.35d821fd7VGM2u



BROTIE oxygen compressor

FOB **Reference** Price: Get Latest Price

$6,500.00 - $10,000.00 / Set | 1 Set/Sets (Min. Order)

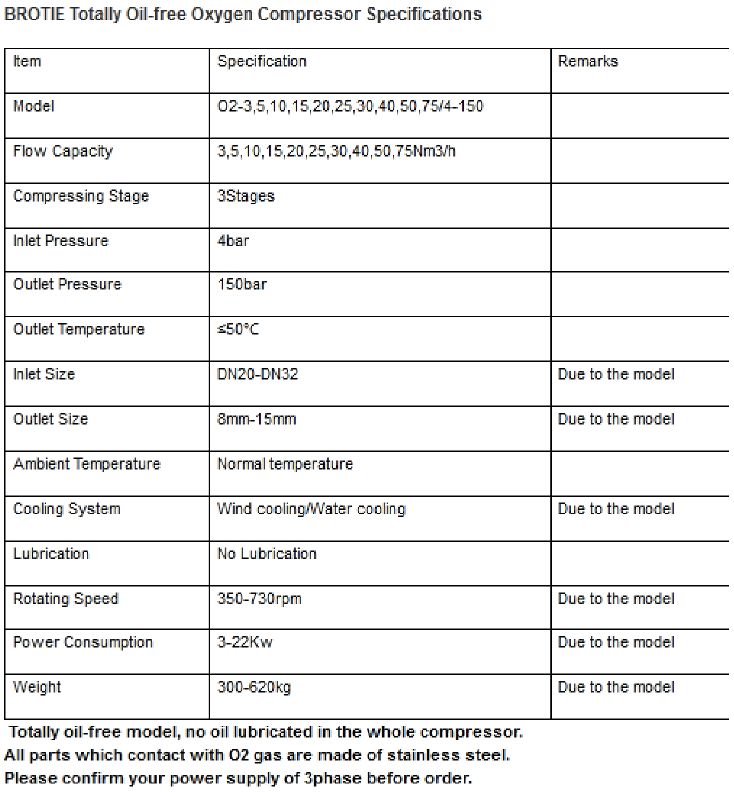
Power:	3-22kw
Warranty:	**1 Year** for machinery warranty | **1 Year** for Core Components
Shipping:	Support Express · Sea freight · Land freight · Air freight
Lead Time:	

Quantity(Sets)	1 - 100	>100
Est. Time(days)	30	Negotiable

Overview

Quick Details

Applicable Industri...	Garment Shops, Building Material Shops, Manufacturing Plant...	After Warranty Serv...	Video technical support, Online support, Spare parts, Field ma...
Local Service Locat...	United Kingdom, United States, Germany, Viet Nam, Philippine...	Showroom Location:	Turkey, United Kingdom, United States, Viet Nam, Philippines, ...
Condition:	New, New	Type:	PISTON
Configuration:	PORTABLE	Power Source:	AC POWER
Lubrication Style:	Oil-free	Mute:	yes
Place of Origin:	China	Brand Name:	BROTIE
Model Number:	O2-3/4-150, O2-5/4-150, O2-10/4-150, O2-15/4-150, O2-20/4-...	Voltage:	customized
Dimension(L*W*H):	customized	Weight:	300-650kg
Certification:	ISO	Warranty:	1 Year
After-sales Service ...	Field installation, commissioning and training	Working Pressure:	150bar, 200bar
Air capacity:	3-75Nm3/h	Machinery Test Re...	Provided
Video outgoing-ins...	Provided	Marketing Type:	New Product 2020
Warranty of core co...	1 Year	Core Components:	Motor, compressor block
Gas Type:	oxygen	Model:	O2-3,5,10,15,20,25,30,40,50,75/4-150
Flow Capacity:	3,5,10,15,20,25,30,40,50,75Nm3/h	Compressing Stage:	3Stages
Inlet Pressure:	4bar	Outlet Pressure:	150, 200bar
Outlet Temperature:	50C	Inlet Size:	DN20-DN32
Outlet Size:	8-15mm	Cooling System:	Wind cooling/Water cooling
Lubrication:	no oil lubricated		



BROTIE Totally Oil-free Oxygen Compressor Specifications

Item	Specification	Remarks
Model	O2-3,5,10,15,20,25,30,40,50,75/4-150	
Flow Capacity	3,5,10,15,20,25,30,40,50,75Nm3/h	
Compressing Stage	3Stages	
Inlet Pressure	4bar	
Outlet Pressure	150bar	
Outlet Temperature	≤50°C	
Inlet Size	DN20-DN32	Due to the model
Outlet Size	8mm-15mm	Due to the model
Ambient Temperature	Normal temperature	
Cooling System	Wind cooling/Water cooling	Due to the model
Lubrication	No Lubrication	
Rotating Speed	350-730rpm	Due to the model
Power Consumption	3-22Kw	Due to the model
Weight	300-620kg	Due to the model

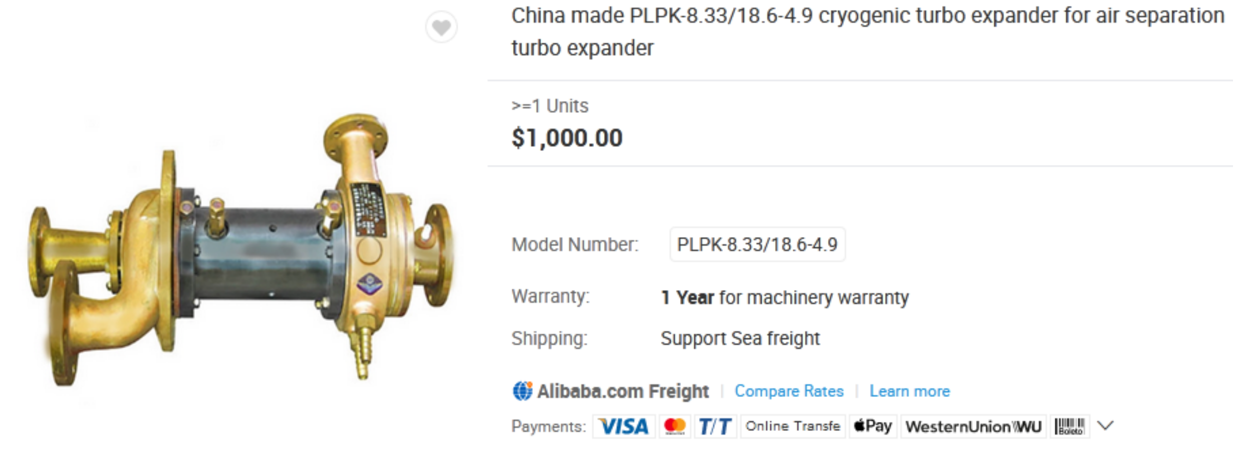
Totally oil-free model, no oil lubricated in the whole compressor.
All parts which contact with O2 gas are made of stainless steel.
Please confirm your power supply of 3phase before order.

11.7.6 Expansion valve :

Catalogue : https://www.parker.com/literature/Instrumentation%20Products%20Division/Catalogs/Cryogenic%20Valves%20for%20Industrial%20Gas%20Applications.pdf

Choice 1 :

https://www.alibaba.com/product-detail/Cryogenic-Turbo-Expander-China-Made-PLPK_60832517222.html?spm=a2700.7735675.normal_offer.d_title.1e6742e1VyAiHQ&s=p



China made PLPK-8.33/18.6-4.9 cryogenic turbo expander for air separation turbo expander

>=1 Units

$1,000.00

Model Number: PLPK-8.33/18.6-4.9

Warranty: **1 Year** for machinery warranty

Shipping: Support Sea freight

Alibaba.com Freight | Compare Rates | Learn more

Payments: VISA T/T Online Transfe Pay WesternUnion WU

Parameters of turbo expander for air separation

Models	technical parameter					matching air separation	remark
	output (Nm³/h)	intake pressure (MPa，G)	discharge pressure (MPa，G)	intake temperature (K)	efficiency (%)		
PLPK-6/6-0.42	360	0.6	0.042	130	76	180m³/h oxygen generating	
PLPK-8.33/18.6-4.9	500	1.86	0.49	173	76	medium-pressure 150 m³/h oxygen generating	
PLPK-7.1/3.6-0.3	425	0.36	0.03	118.3	77	oxygen producing truck	military
PLPK-10/8-0.47	600	0.8	0.047	150	76	350~750 m³ /h oxygen generating	booster turbine
PLPK-18.33/7.7-0.38	1100	0.77	0.038	147	78	oxygen generating plant	booster turbine
PLPK-25/6.25-0.45	1500	0.625	0.045	153	78	1500m³/h oxygen generating	booster turbine
PLPK-30/5.5-0.4	1800	0.55	0.04	150	80	1600 m³/h oxygen generating	adjustable nozzle
PLPK-40/13.7-0.2	2400	1.37	0.02	150	78	pure nitrogen plants	booster turbine
PLPK-46.17/13.4-0.19	2770	1.34	0.019	148	78	pure nitrogen plants	booster turbine
PLPK-43.3/4.6-0.4	2600	0.46	0.04	110	81	pure nitrogen plants	adjustable nozzle
PLPK-80/9.5-5.2	4800	0.95	0.52	112	81	pure nitrogen plants	adjustable nozzle
PLPK-83.67/3.2-0.3	5020	0.32	0.03	116	81	pure nitrogen plants	

11.7.7 Materials suitable for cryogenic heat exchanger

Material link: [10]

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[10] https://www.gasparini.com/en/blog/metals-and-materials-for-low-temperatures/

11.7.7.1 Materials suitable down to -45 °C

This first threshold is important because, besides being typically the lower limit of the temperatures naturally reached on the planet, it is also the temperature at which some industrial operations and some chemical processes are carried out.

Unfortunately, common construction steels are no longer usable at this level, either because of their intrinsic characteristics or because they are not usually tested for hardness and resistance to low temperatures. Some steelworks, however, have special carbon steels for these applications. These are mainly quenched and tempered low alloy steels.

Almost all aluminium alloys can be used at temperatures down to -45 °C, except series such as 7075-T6 and 7178-T6, and titanium alloys 13V-11Cr-3Al or 8Mn. Copper and nickel alloys can generally all be used at these temperatures. PH stainless steels, i.e. precipitation hardening stainless steels, are not suitable for temperatures below -20 °C because of embrittlement and cracks.

11.7.7.2 Materials suitable down to -75 °C

Some steels can be used at these temperatures, such as low alloy, quenched and tempered steels or ferritic nickel steels. Most low carbon (0.20-0.35%) martensitic steels can be used with sufficient reliability. Many of these alloys contain manganese, nickel, chromium, molybdenum and vanadium, and some zirconium and boron.

11.7.7.3 Materials suitable down to -100 °C

Low carbon, 3.5%-nickel steels are often used in liquid gas storage tanks at temperatures down to -100°C. Many aluminium, nickel, and titanium alloys are also suitable for these temperatures. Aluminium 7076-T6 can also be used up to -128 °C, but not for critical applications.

11.7.7.4 Materials suitable down to -196 °C

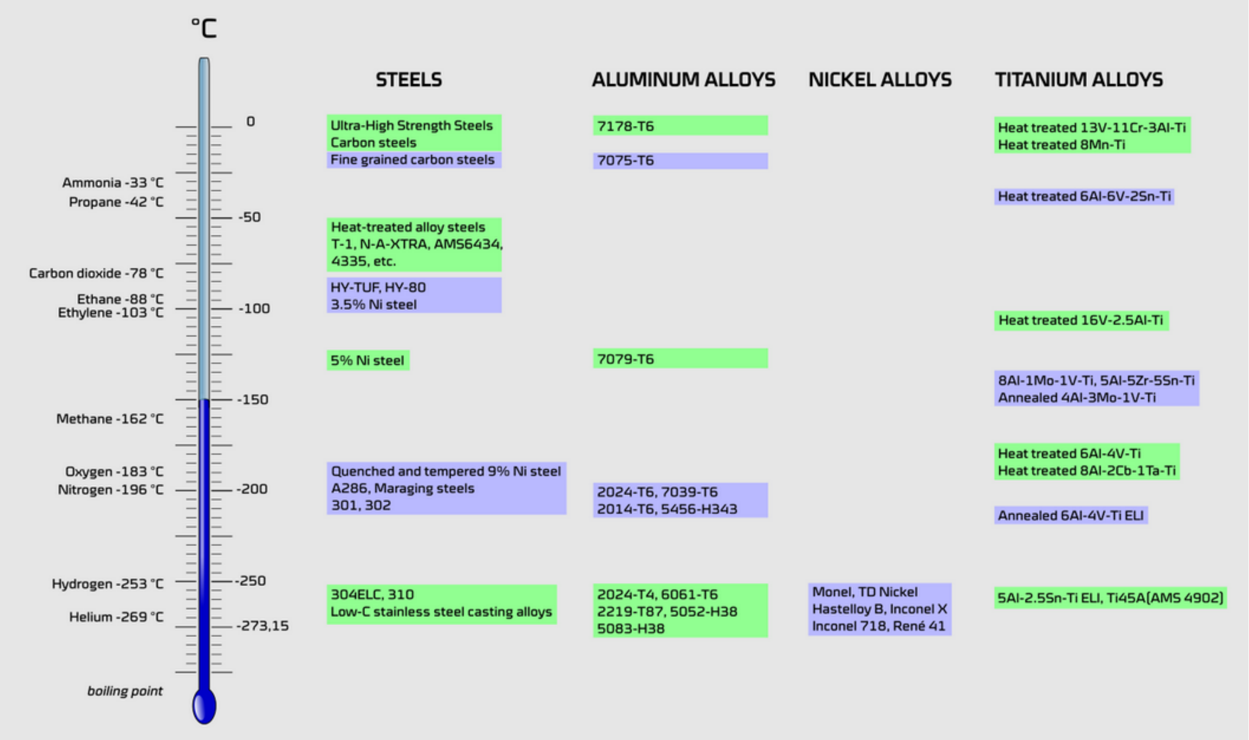
The austenitic stainless steels of the 300 series are all suitable for working in this temperature range. Maraging steels with nickel content between 20% and 25% and the addition of cobalt, molybdenum, titanium, aluminium, and niobium are also suitable. Maraging steels have excellent malleability, toughness and hardness characteristics, and must be hardened at a temperature of just 400 °C.

Many aluminium alloys, such as 2024-T6, 7039-T6 and 5456-H343 have excellent fracture resistance at -196 °C; also 2014-T6 but with the exception of welds. Other alloys resistant to even lower temperatures are the 5000 series aluminium-magnesium alloys, the 2219-T87 and the 6061-T6.

The nickel-based materials are almost all resistant to -196 °C. Titanium alloys such as 5Al-2.5Sn-Ti, 6A1-4V-Ti and 8Al-2Cb-1Ta-TiY are also suitable, but should be kept free of impurities such as oxygen, nitrogen, carbon and iron as they cause embrittlement.

The aluminium alloys that can be used at the temperatures involved are typically in the 2000 and 5000 series, or the 6061-T6 alloy. In particular, welds on 2219-T87 have demonstrated excellent fracture resistance, while 5052-H38 and 5083-1138 have high crack resistance. The same applies to Monel, K-Monel, electroformed nickel, hardened nickel for thorium dispersion, and nickel alloys such as Inconel X, Inconel 718, René 41, and Hastelloy B. At these temperatures, only Ti45A and 5Al-2.5Sn-Ti titanium alloys can be used, both as base metal and welded.

Copper alloys are generally also used in contact with liquid hydrogen and helium, such as 70-30 brass, copper-beryllium, iron-silicon and aluminium bronzes. Magnesium alloys, on the other hand, tend to become brittle but can be used in low stress applications with careful design.



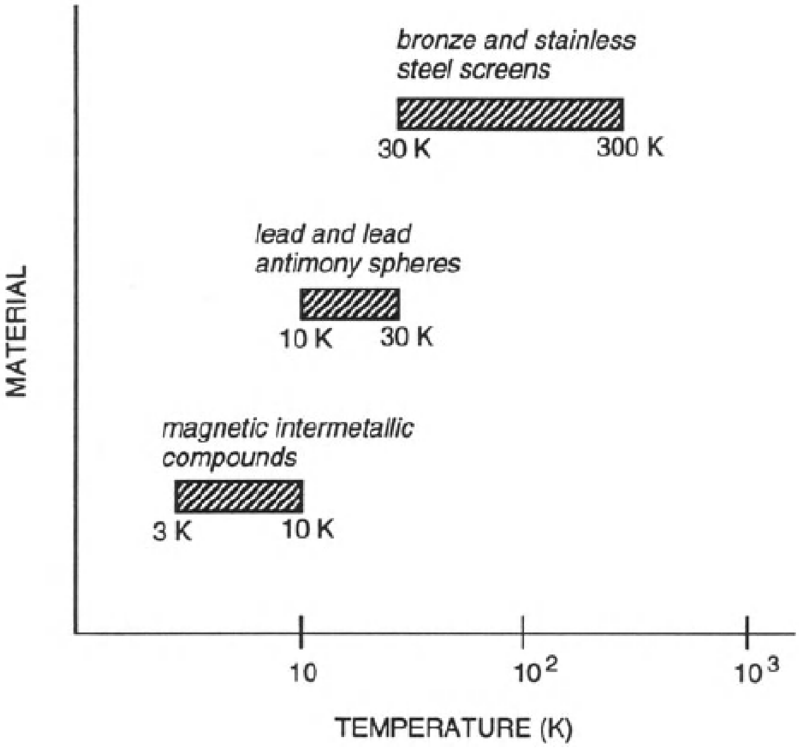


Fig. 2.16. Temperature range for commonly used regenerator materials in cryogenic refrigerators. [11]

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[11] https://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.468.3966&rep=rep1&type=pdf

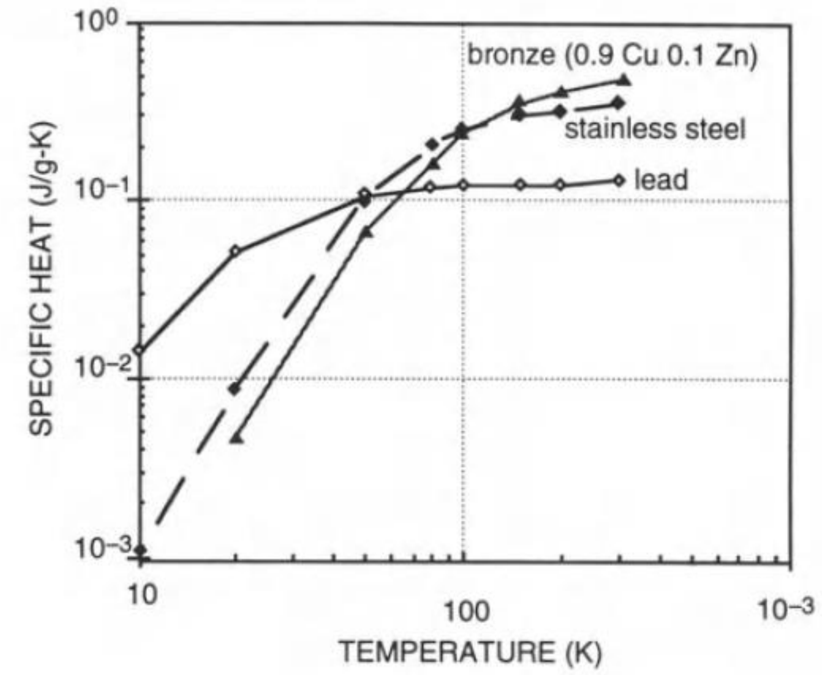

Fig. 2.17. Comparison of the specific heats for three commonly used regenerator materials. 6

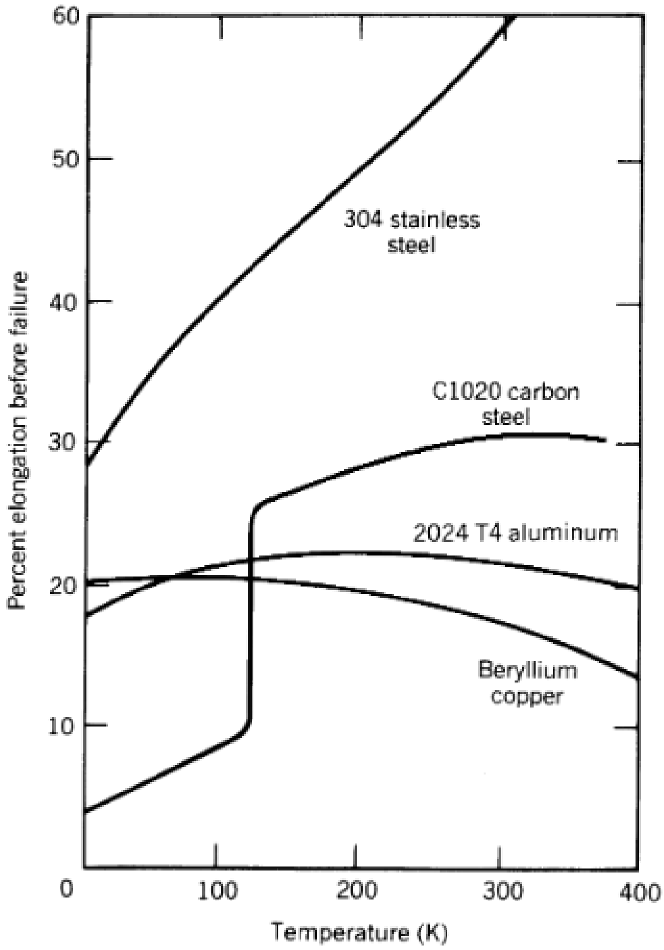

Figure 33 Percent elongation before rupture of some materials used in cryogenic service. 6

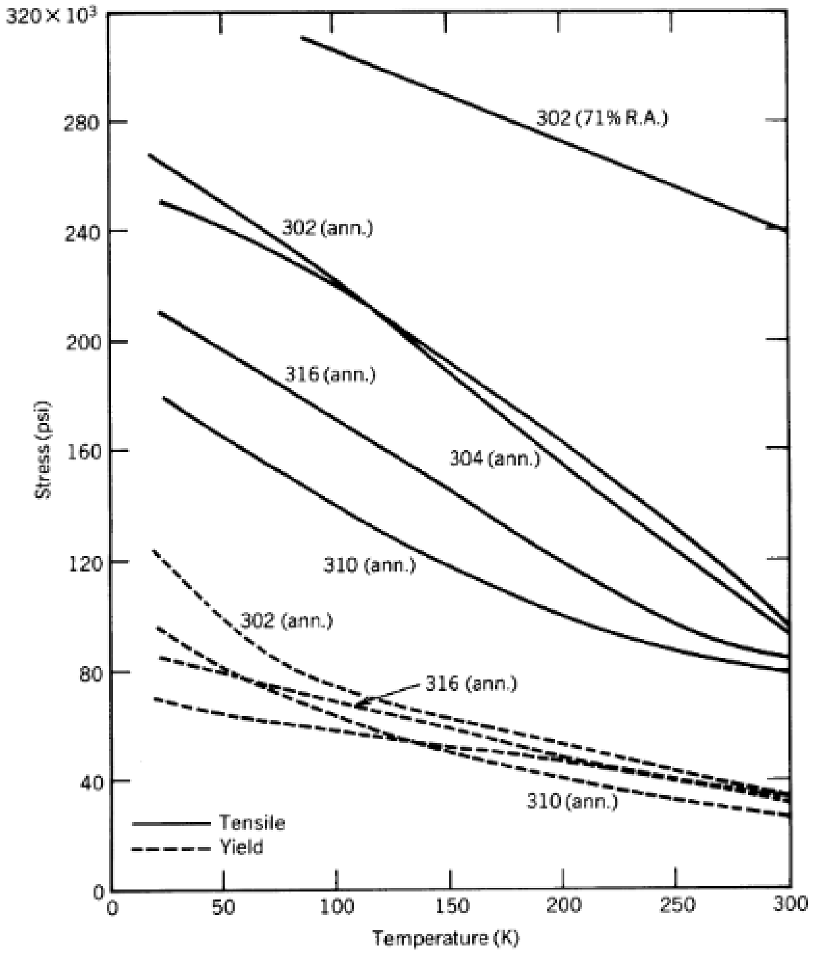

Figure 34 Yield and tensile strength of several AISI 300 series stainless steels.[33] (Courtesy American Iron and Steel Institute.)

6

Table 6 Properties of Various Multilayer Insulations (Warm Wall at 300 K)

Sample Thickness (cm)	Shields per Centimeter	Density (g/cm³)	Cold Wall T (K)	Conductivity (μW/cm·K)	Material[a]
3.7	26	0.12	76	0.7	1
3.7	26	0.12	20	0.5	1
2.5	24	0.09	76	2.3	2
1.5	76	0.76	76	5.2	3
4.5	6	0.03	76	3.9	4
2.2	6	0.03	76	3.0	5
3.2	24	0.045	76	0.85	5
1.3	47	0.09	76	1.8	5

[a] 1, Al foil with glass fiber mat separator; 2, Al foil with nylon net spacer; 3, Al foil with glass fabric spacer; 4, Al foil with glass fiber, unbonded spacer; 5, aluminized Mylar, no spacer.

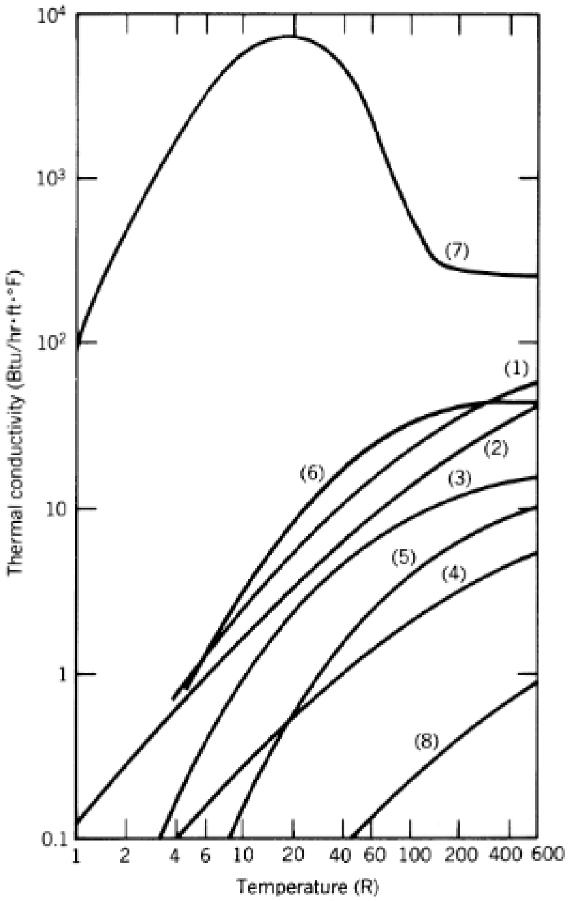

Figure 36 Thermal conductivity of materials useful in low-temperature service. (1) 2024TA aluminum; (2) beryllium copper; (3) K-Monel; (4) titanium; (5) 304 stainless steel; (6) C1020 carbon steel; (7) pure copper; (8) Teflon.[35] [6]

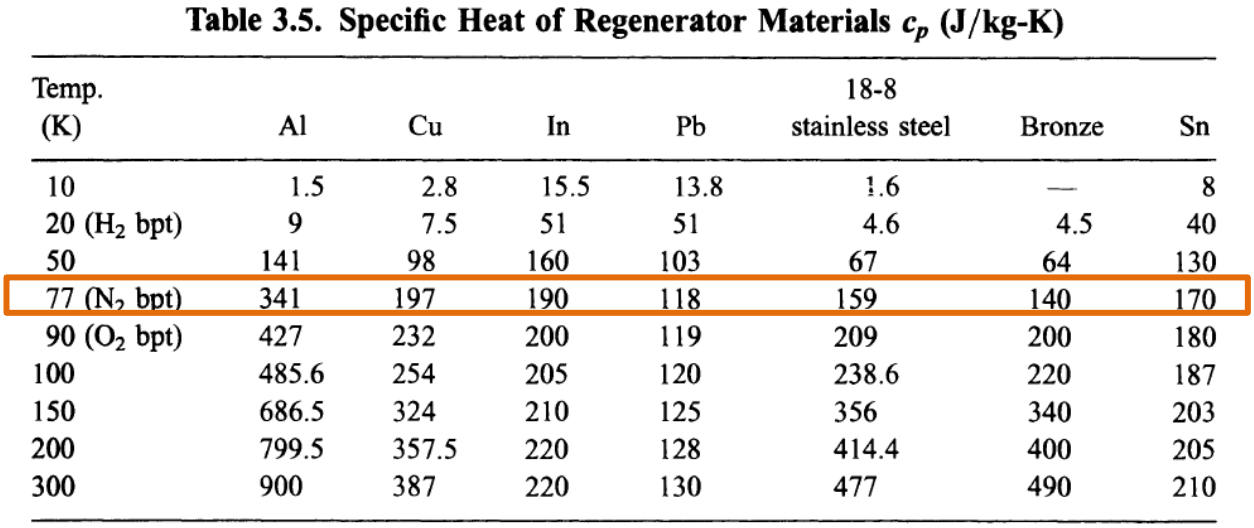

Table 3.5. Specific Heat of Regenerator Materials c_p (J/kg-K)

Temp. (K)	Al	Cu	In	Pb	18-8 stainless steel	Bronze	Sn
10	1.5	2.8	15.5	13.8	1.6	—	8
20 (H_2 bpt)	9	7.5	51	51	4.6	4.5	40
50	141	98	160	103	67	64	130
77 (N_2 bpt)	341	197	190	118	159	140	170
90 (O_2 bpt)	427	232	200	119	209	200	180
100	485.6	254	205	120	238.6	220	187
150	686.5	324	210	125	356	340	203
200	799.5	357.5	220	128	414.4	400	205
300	900	387	220	130	477	490	210

11.7.8 Liquid oxygen tank

The liquid oxygen tank is an insulated vertical tank with double layer cover for storing liquid oxygen. The material used for inner tank is s30408 stainless steel.

The liquid oxygen tank is an insulated vertical tank with double layer cover for storing liquid oxygen. The material used for inner tank is S30408 stainless steel; The outer container materials are chosen as Q235-B, Q245R or 345R according to the national regulations according to the user's area. The inner and outer container sandwiches are filled with sand pearl thermal insulation materials, insulated and broomed.

The liquid oxygen tank has the features of high air tightness, low thermal conductivity, good thermal insulation performance, small evaporation loss and long service life, it is widely used in the pharmaceutical, chemical, manufacturing and other industries.

The structure of the liquid oxygen tank[12]

Liquid oxygen tank (LO2 tank) consists of tank body, tools, tubes, valves, etc.

1. Relief device
2. Inner container
3. Insulation layer (sand pearl)
4. Shell
5. Instrument (Differential pressure gauge, oxygen pressure gauge, combination valve)
6. Pump port and vacuum valve
7. Pipeline valve

Describe:

(1) The liquid oxygen tank drive system is mostly centered on the bottom of the tank, and the instrument system and the built-in valve are arranged on the tank wall for easy monitoring and operation.

(2) Cryogenic storage tank contains booster and boost regulator to increase the tank pressure to the pressure required by the user.

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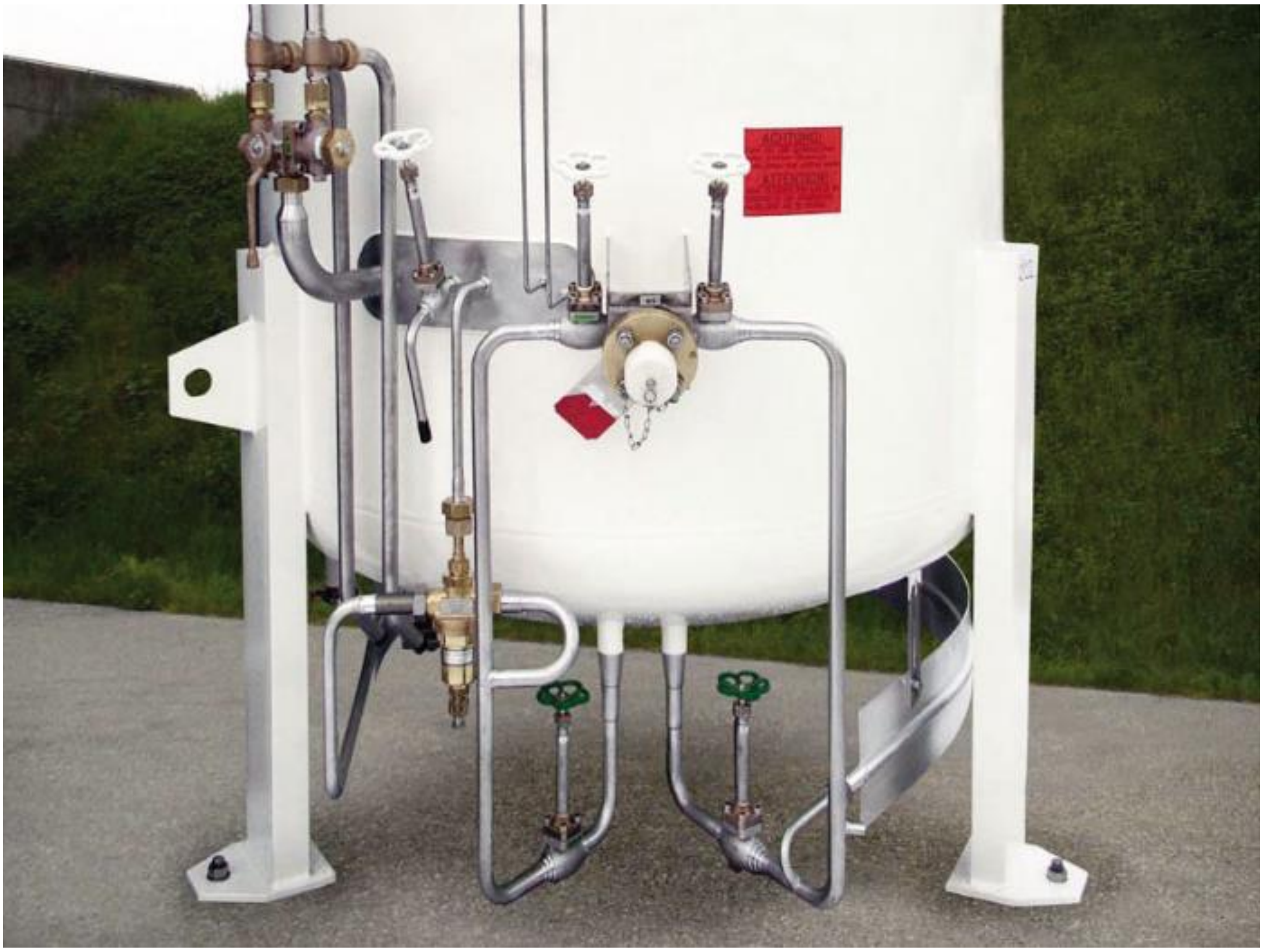
[12] http://m.zhongjie-se.com/cryogenic-tank/cryogenic-storage-tank/liquid-oxygen-tank.html

(3) The inner container for liquid oxygen storage tanks is equipped with two safety valves, two rupture discs, a tube safety valve, an intermediate pressure relief device.



LOX tanks are stationary, vacuum-insulated pressure vessels and consist of an inner and an outer pressure vessel. The inner vessel, designed for the storage of low-temperature, liquefied gas, is manufactured out of cold-stretched material (stainless steel 1.4311 or 1.4301). The outer vessel is manufactured out of carbon steel. The space between the inner and outer vessel is filled with perlite, a grained insulation material and is evacuated up to a pressure of below 50 microns in a warm state (20°C). In addition, a molecular sieve ensures, by means of absorption, the long-term stability of the vacuum during the operation of the tank. An automatic regulation system helps maintain the working pressure and minimizes losses in case of lower

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withdrawal rates. The quality of the welded seams is checked by a leak test with helium, which also ensures long-term durability of the vacuum.13

To improve the efficiency of the cold converter, the tank is equipped with an additional pressure reducing system. This system works with a pressure reducing regulator which is installed in a connecting line between the gas phase and the highest point of the product withdrawal line. If, due to a prolonged standstill, the pressure in the tank is above the adjusted opening pressure of the regulator, and if valve is open, the economizer will open and opens the connection between gas phase and liquid phase. In case of product withdrawal through valve, it will now be taken out of the gas reserve of thetank and this measure will result in a rapid reduction of pressure. If the tank pressure is now below the opening pressure of the regulator, the economizer will close andwithdrawal will be done out of the liquid phase, consequently with a smaller pressure drop. The standard opening pressure is set 1 bar above the closing pressure of the pressure reducing regulator.

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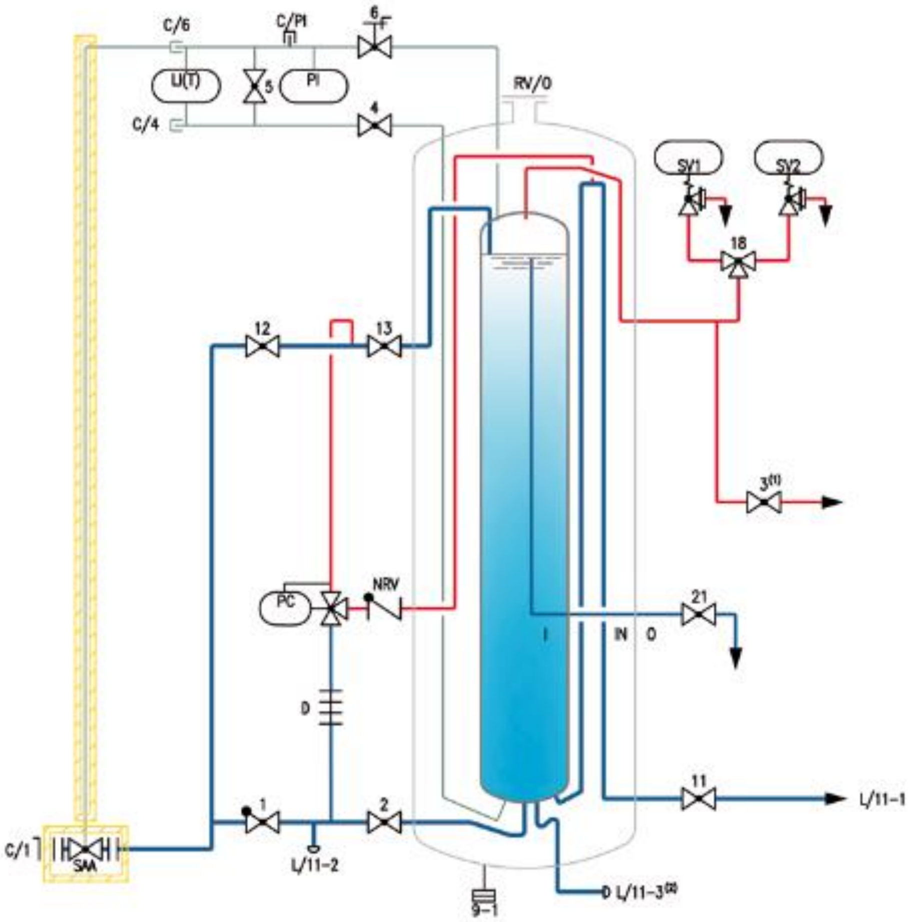
13 https://acprodbponlinebcc5.blob.core.windows.net/bp-public-files/bp_editor_div_mgs/TechnicalInformation/PMGS_LOX_Storage_Tanks_HTM_Instruction_Book_EN_8102341086.pdf



[14]

Flow diagram - tanks for nitrogen, oxygen, argon.

Instrumentation and equipment, standard

C/1	Fill coupling
C/4, C/6	Connection add. transmitter
C/PI	Test connection pressure indicator
D	Pressure building coil
I	Inner vessel
IN	Insulation
LI	Level indicator
L/11-1	Pipeline discharge
L/11-2	Pipeline discharge (plugged)
L/11-3	Pipeline discharge (plugged)
NRV	Non return valve
O	Outer vessel
PC	Pressure controller
PI	Pressure indicator
RV/O	Relief valve-outer vessel
SV1, SV2	Safety valve
(1)	only T ... V110 - T ... V800
(2)	only T18 V200 - T18 V800

Valves, standard

1	Filling
2	Pressure building valve
3	Vent valve
4	Bottom gauge (+)
5	Gauge bypass
6	Top gauge (-)
9-1	Evacuation connection
11	Discharge
12	Top filling
13	Gas shut-off
18	Change over
21	Trycock

Options

SAA	Safety shut-off valve, control line for SAA
LI(T)	Level indicator Samson Media 6 incl. instrument panel and standard programming, extra programming of Samson Media 6 acc. to customer requirements
LI(T)	Level indicator WIKA with transmitter output 4 - 20 mA

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[14] https://www.linde-engineering.com/en/images/P_3_3_e_12_150dpi_tcm19-5774.pdf

Patents - 6,782,339 • 6,944,570

Interchangeable gauge systems with digital telemetry capable gauge and flexible stainless steel interconnection lines.

Combination pressure building/economizer regulator for easy in-field adjustments.

Long-life extended stem packing pressure builder and economizer isolating valves are standard on the VS-01 series.

Liquefied gases are store at ultra-cold temperatures in a vacuum insulated tank. Controls on the tank keep the pressure at optimum levels to assure proper liquid delivery to the application.Vacuum insulated pipe connects the tank's liquid withdrawal to the application equipment. The pipe is the foundation for the system's heat-loss efficiency and long-term integrity. It must be engineered to work with the associated controls and accessories.

Modular Piping Design Advantages 15

- Reduces your life-cycle costs by reducing the number of external piping joints, minimizing the risk of external piping leaks and the cost to repair.
- Simple by design yet robust and able to support a broad range of customer applications.
- Combination pressure building/economizer regulator for easy pressure adjustment and extended bonnet bronze control valves for ease of operation.

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15 Bulk Storage Product Catalog

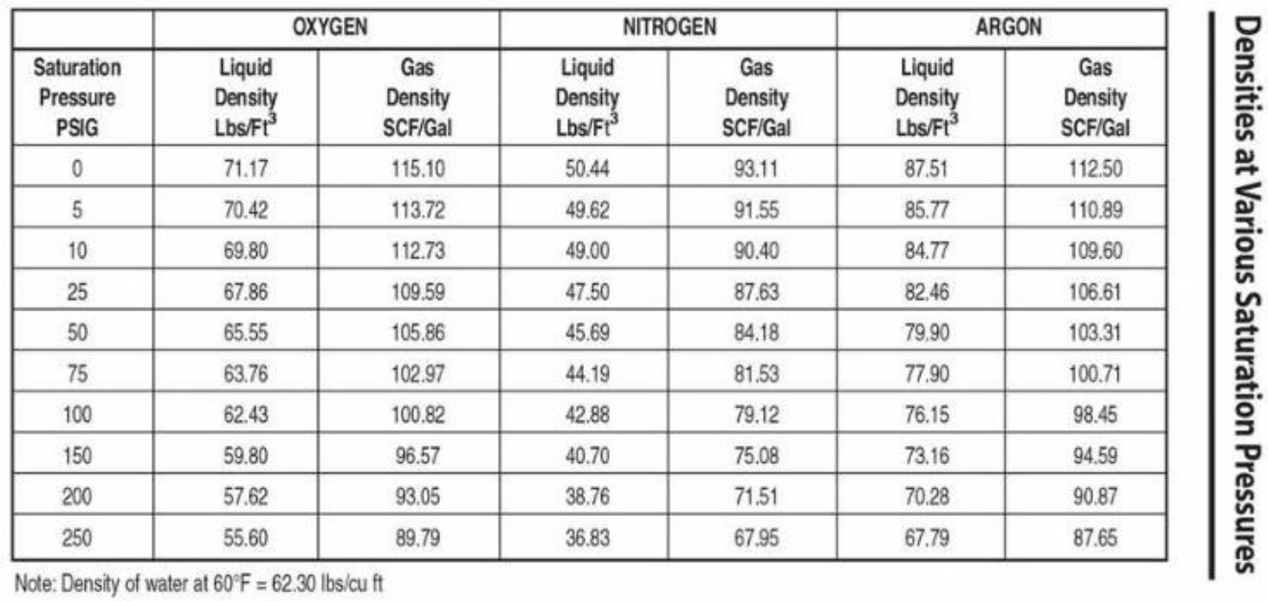
- Piping modules designed for ease-of-access to all operational control valves with stainless steel inter- connecting piping for improved durability.

High performance safety system with dual relief valves and rupture disks supplied as standard

New, innovative vertical fin pressure building system improves performance, while reducing frost and ice build up to further reduce your maintenance costs

Dual regulator economizer and pressure builder supplied as standard.

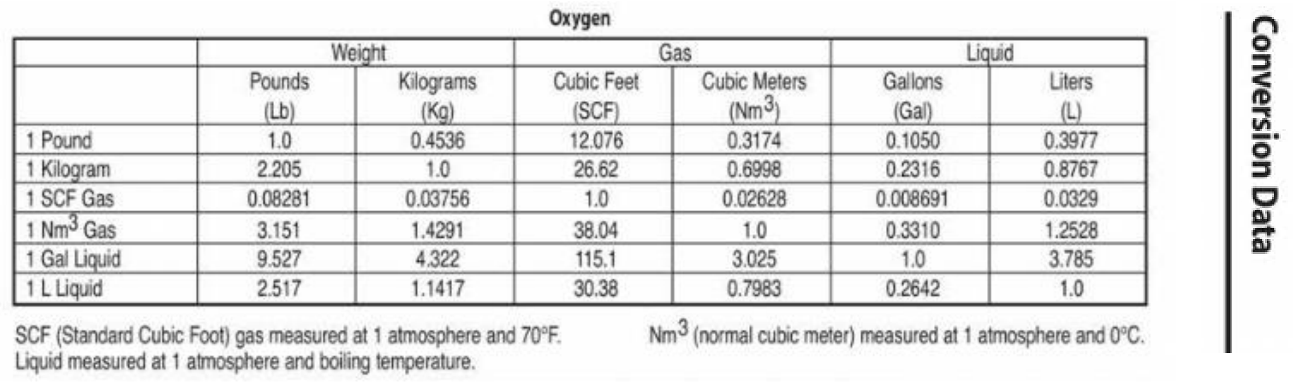
Full-trycock and economizer valves come standard with non-extended packing



Densities at Various Saturation Pressures

	OXYGEN		NITROGEN		ARGON	
Saturation Pressure PSIG	Liquid Density Lbs/Ft^3	Gas Density SCF/Gal	Liquid Density Lbs/Ft^3	Gas Density SCF/Gal	Liquid Density Lbs/Ft^3	Gas Density SCF/Gal
0	71.17	115.10	50.44	93.11	87.51	112.50
5	70.42	113.72	49.62	91.55	85.77	110.89
10	69.80	112.73	49.00	90.40	84.77	109.60
25	67.86	109.59	47.50	87.63	82.46	106.61
50	65.55	105.86	45.69	84.18	79.90	103.31
75	63.76	102.97	44.19	81.53	77.90	100.71
100	62.43	100.82	42.88	79.12	76.15	98.45
150	59.80	96.57	40.70	75.08	73.16	94.59
200	57.62	93.05	38.76	71.51	70.28	90.87
250	55.60	89.79	36.83	67.95	67.79	87.65

Note: Density of water at 60°F = 62.30 lbs/cu ft



Conversion Data

Oxygen

	Weight		Gas		Liquid	
	Pounds (Lb)	Kilograms (Kg)	Cubic Feet (SCF)	Cubic Meters (Nm^3)	Gallons (Gal)	Liters (L)
1 Pound	1.0	0.4536	12.076	0.3174	0.1050	0.3977
1 Kilogram	2.205	1.0	26.62	0.6998	0.2316	0.8767
1 SCF Gas	0.08281	0.03756	1.0	0.02628	0.008691	0.0329
1 Nm^3 Gas	3.151	1.4291	38.04	1.0	0.3310	1.2528
1 Gal Liquid	9.527	4.322	115.1	3.025	1.0	3.785
1 L Liquid	2.517	1.1417	30.38	0.7983	0.2642	1.0

SCF (Standard Cubic Foot) gas measured at 1 atmosphere and 70°F.
Liquid measured at 1 atmosphere and boiling temperature.

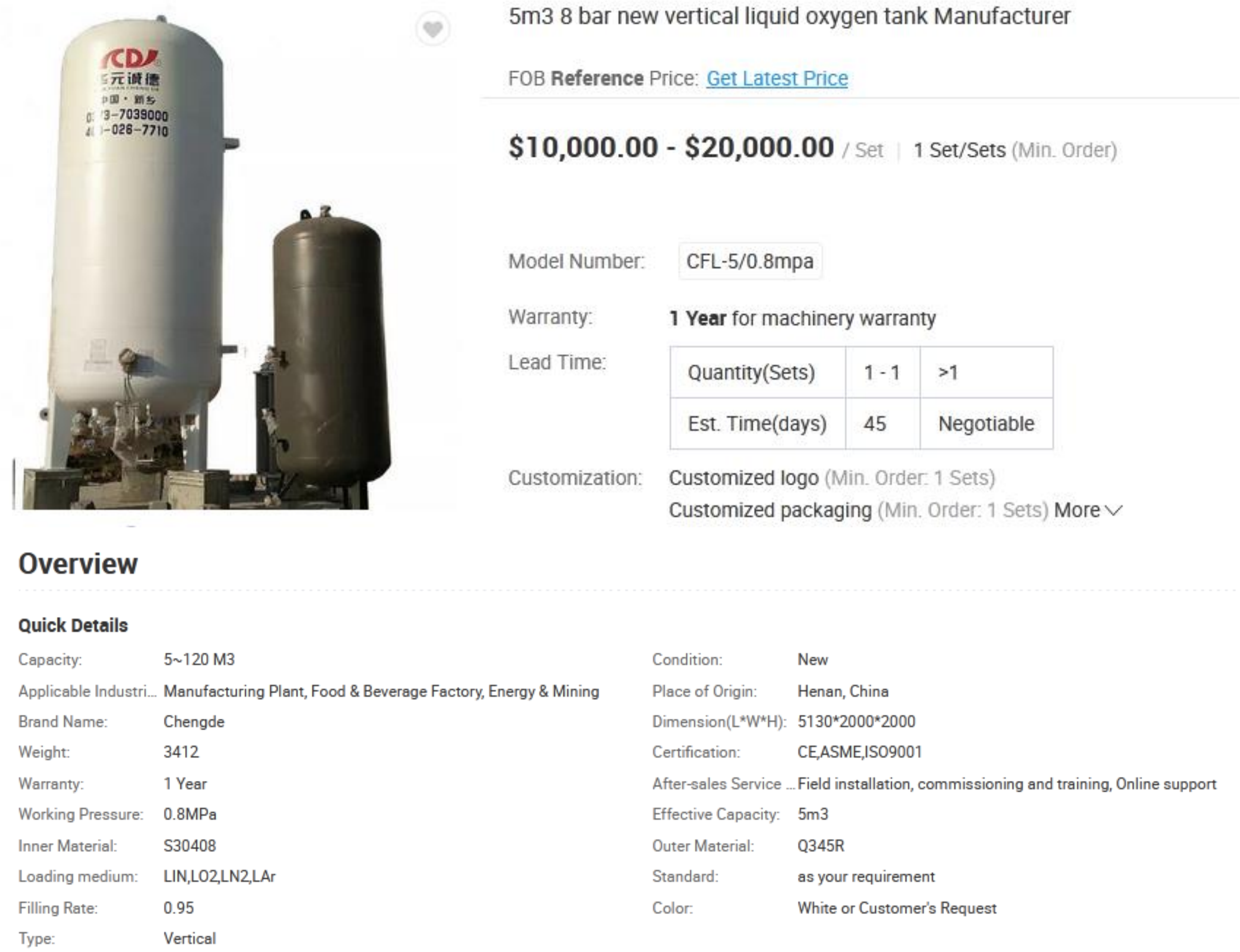
Nm^3 (normal cubic meter) measured at 1 atmosphere and 0°C.

مواصفات خزان الأوكسجين السائل كما يلي:

لا.	نموذج	متوسط	البعد (مم)	الوزن (كلغ)
1	CFL-5 / 0.8	LO2	Φ1916 * 5262	3940
2	CFL-10 / 0.8	LO2	Φ2316 * 5981	5970
3	CFL-15 / 0.8	LO2	Φ2316 * 8035	8045
4	CFL 20 / 0.8	LO2	Φ2716 * 7377	9855
5	CFL-30 / 0.8	LO2	Φ2920 * 8904	14025
6	CFL-50 / 0.8	LO2	Φ3220 * 11204	21570
7	CFL-100 / 0.8	LO2	Φ3424 * 18466	38300
8	CFL-150 / 0.8	LO2	Φ3728 * 22128	54700

- Choice 1:

https://www.alibaba.com/product-detail/5m3-8-bar-new-vertical-liquid_62150227966.html?spm=a2700.galleryofferlist.normal_offer.d_title.7011710cmDfcd2



5m3 8 bar new vertical liquid oxygen tank Manufacturer

FOB **Reference** Price: Get Latest Price

$10,000.00 - $20,000.00 / Set | 1 Set/Sets (Min. Order)

Model Number: CFL-5/0.8mpa

Warranty: **1 Year** for machinery warranty

Lead Time:

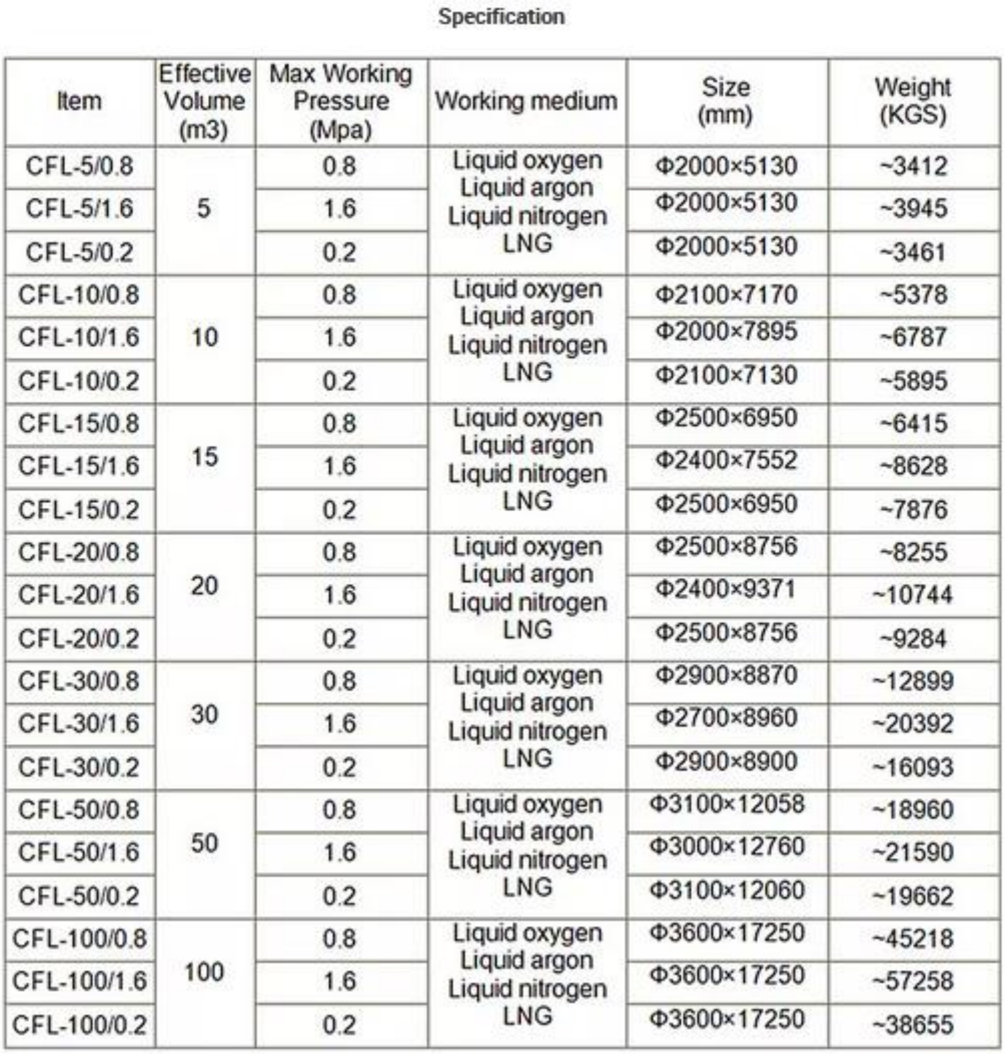
Quantity(Sets)	1 - 1	>1
Est. Time(days)	45	Negotiable

Customization: Customized logo (Min. Order: 1 Sets)
Customized packaging (Min. Order: 1 Sets) More

Overview

Quick Details

Capacity:	5~120 M3	Condition:	New
Applicable Industri...	Manufacturing Plant, Food & Beverage Factory, Energy & Mining	Place of Origin:	Henan, China
Brand Name:	Chengde	Dimension(L*W*H):	5130*2000*2000
Weight:	3412	Certification:	CE,ASME,ISO9001
Warranty:	1 Year	After-sales Service ...	Field installation, commissioning and training, Online support
Working Pressure:	0.8MPa	Effective Capacity:	5m3
Inner Material:	S30408	Outer Material:	Q345R
Loading medium:	LIN,LO2,LN2,LAr	Standard:	as your requirement
Filling Rate:	0.95	Color:	White or Customer's Request
Type:	Vertical		



Specification

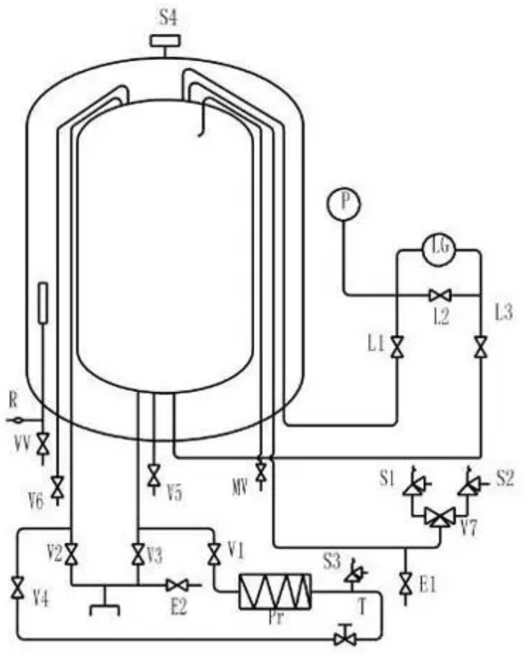
Item	Effective Volume (m3)	Max Working Pressure (Mpa)	Working medium	Size (mm)	Weight (KGS)
CFL-5/0.8	5	0.8	Liquid oxygen Liquid argon Liquid nitrogen LNG	Φ2000×5130	~3412
CFL-5/1.6		1.6		Φ2000×5130	~3945
CFL-5/0.2		0.2		Φ2000×5130	~3461
CFL-10/0.8	10	0.8	Liquid oxygen Liquid argon Liquid nitrogen LNG	Φ2100×7170	~5378
CFL-10/1.6		1.6		Φ2000×7895	~6787
CFL-10/0.2		0.2		Φ2100×7130	~5895
CFL-15/0.8	15	0.8	Liquid oxygen Liquid argon Liquid nitrogen LNG	Φ2500×6950	~6415
CFL-15/1.6		1.6		Φ2400×7552	~8628
CFL-15/0.2		0.2		Φ2500×6950	~7876
CFL-20/0.8	20	0.8	Liquid oxygen Liquid argon Liquid nitrogen LNG	Φ2500×8756	~8255
CFL-20/1.6		1.6		Φ2400×9371	~10744
CFL-20/0.2		0.2		Φ2500×8756	~9284
CFL-30/0.8	30	0.8	Liquid oxygen Liquid argon Liquid nitrogen LNG	Φ2900×8870	~12899
CFL-30/1.6		1.6		Φ2700×8960	~20392
CFL-30/0.2		0.2		Φ2900×8900	~16093
CFL-50/0.8	50	0.8	Liquid oxygen Liquid argon Liquid nitrogen LNG	Φ3100×12058	~18960
CFL-50/1.6		1.6		Φ3000×12760	~21590
CFL-50/0.2		0.2		Φ3100×12060	~19662
CFL-100/0.8	100	0.8	Liquid oxygen Liquid argon Liquid nitrogen LNG	Φ3600×17250	~45218
CFL-100/1.6		1.6		Φ3600×17250	~57258
CFL-100/0.2		0.2		Φ3600×17250	~38655

المسافات الآمنة لتعرض صهاريج الأكسجين المُسال لإحتمالات التسريب أو الإنسكاب	**حتى 20 طن (متر)**	**أكبر من 20 طن (متر)**
عن الأماكن المسموح فيها بالتدخين أو إشعال النيران	5	8
عن أماكن التجمعات العامة	10	15
عن المكاتب، و المقاصف، و الأماكن المشغولة بالأشخاص	5	8
عن الحفر، و القنوات، و مصارف المياه السطحية (غير المستغلة)	5	8
عن الفتحات المؤدية إلى الأنظمة الموجودة تحت الأرض	5	8
عن حدود الملكية	5	8
عن الطريق العام	5	8

عن السكك الحديدية	10	15
عن أماكن إنتظار السيارات (غير المُرَخَّصَة)	5	8
عن الإنشاءات الخشبية الضخمة	15	15
عن المخزونات الصغيرة من المواد القابلة للإشتعال، و كرافانات المواقع، و ما إلى ذلك	5	8
عن معدات التشغيل (التي ليست جزء من منظومة شبكة الغازات الطبية)	5	8
عن خطوط الغازات القابلة للإشتعال	3	3
عن فلانشات خطوط الغازات القابلة للإشتعال (المقاسات التي تتعدى 50 mm)	15	15
عن مواسير تنفيس الوقود الغازي	5	8
عن مآخذ هواء الكباسات و أجهزة التنفس الصناعي	5	8

عن إسطوانات الوقود الغازي (التي تصل إلى 70 m^3)	5	5
عن صهاريج تخزين وقود الغاز المُسال (التي تصل إلى 4 أطنان)	7.5	7.5
عن صهاريج تخزين وقود الغاز المُسال (التي تصل إلى 60 طن)	15	15
عن صهاريج تخزين الوقود السائل (التي تصل إلى 7.8 m^3)	7.5	7.5
عن صهاريج تخزين الوقود السائل (التي تصل إلى 117 m^3)	15	15
عن محطات الجهد العالي HV و الجهد المتوسط MV الفرعية	5	8

Cryogenic Liquid Storage Tank Flow Chart (B)



V1	Pressure building valve	V2	Upper inlet valve	V3	Lower inlet valve	V4	Gas passing valve
V5	Liquid Outlet valve	V6	Gas return valve	V7	3-way switch valve	R	Vacuum tube
VV	Vacuum Valve	MV	Full measuring valve	E1	Vent valve	E2	Raffinate vent valve
Pr	Turbo charger	T	Pressure regulating valve	S1	Inner tank safety valve	S2	Inner tank safety valve
S3	Inner tank safety valve	S4	Outer tank safety device	L1	Liquid gauge upper valve	L2	Balancing valve
L3	Liquid gauge lower valve	P	Pressure Gauge	LG	Liquid Level Gauge		

Xinxiang Chengde Energy Technology Equipment Co., Ltd

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新乡市诚德能源科技装备有限公司
Xinxiang Chengde Energy Technology Equipment Co.,Ltd.

1. Loading medium: LN2, LO2, LAr, LNG, LPG, etc.
2. Effective Volume: 20m3
3. Working pressure: 0.8 MPa
4. Overall dimension: Φ3000*6100mm
5. Cylinder design temperature: -196℃
6. Shell material:Outer jacket: Q245-R; Inner: S30408.
7. Insulation: Vacuum powder insulation
8. Filling rate: 0.95
9. Relief Valve: All valves are high grade Chinese valves.
10. Delivery date: Within 60 days after received pre-payment,or more shorter time.
11. Payment model: We can negotiate,we suggest TT,LC.
12. Documents: Bill of Loading, Invoice, Packing list, Contract (3 originals).

الطرف أ: معلمات المنتجات

15CBM 0.8Mpaعموديخزان مبرد

1.وسيط التحميل: LAr ، Ln2 ، Lo2

2.إجمالي الحجم: 15.789 م^{3}الحجم الفعال: 15.0 م^3

3. ضغط التصميم: 0.8 ميجا باسكالضغط العمل: 0.8 ميجا باسكال

4. البعد الكلي: 002500 × 6912 مم

5.درجة حرارة تصميم الاسطوانة الخارجية: 60 °Cدرجة حرارة تصميم الاسطوانة الداخلية: -196 °C

6. قذيفة المواد: سترة الخارجي: Q245-R ، الداخلية: S30408.

7.عزل: فراغ مسحوق العزل

8.الوزن الفارغ: حوالي 6415 كجم

9. معدل التعبئة: 0.95

10.صمام الإغاثة: جميع الصمامات عبارة عن صمامات صينية عالية الجودة.[16]

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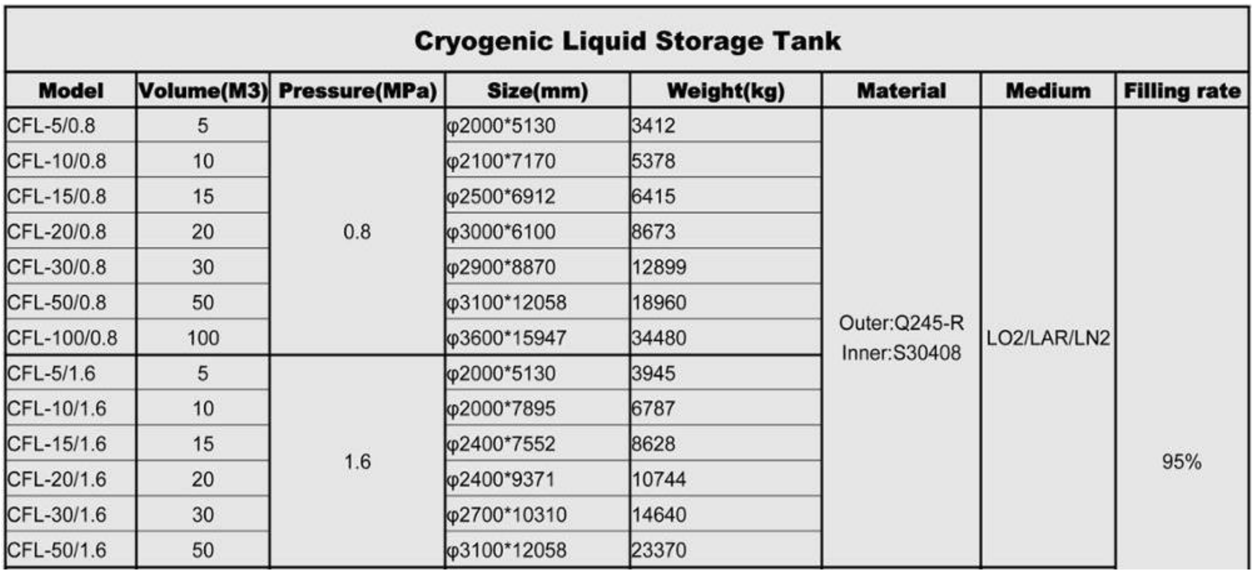
[16] http://ar.cncdtank.com/cryogenic-tank/5000l-oxygen-liquid-tank.html



Cryogenic Liquid Storage Tank

Model	Volume(M3)	Pressure(MPa)	Size(mm)	Weight(kg)	Material	Medium	Filling rate
CFL-5/0.8	5	0.8	φ2000*5130	3412	Outer:Q245-R Inner:S30408	LO2/LAR/LN2	95%
CFL-10/0.8	10		φ2100*7170	5378			
CFL-15/0.8	15		φ2500*6912	6415			
CFL-20/0.8	20		φ3000*6100	8673			
CFL-30/0.8	30		φ2900*8870	12899			
CFL-50/0.8	50		φ3100*12058	18960			
CFL-100/0.8	100		φ3600*15947	34480			
CFL-5/1.6	5	1.6	φ2000*5130	3945			
CFL-10/1.6	10		φ2000*7895	6787			
CFL-15/1.6	15		φ2400*7552	8628			
CFL-20/1.6	20		φ2400*9371	10744			
CFL-30/1.6	30		φ2700*10310	14640			
CFL-50/1.6	50		φ3100*12058	23370			

[17]

- Another method of Oxygen liquefaction

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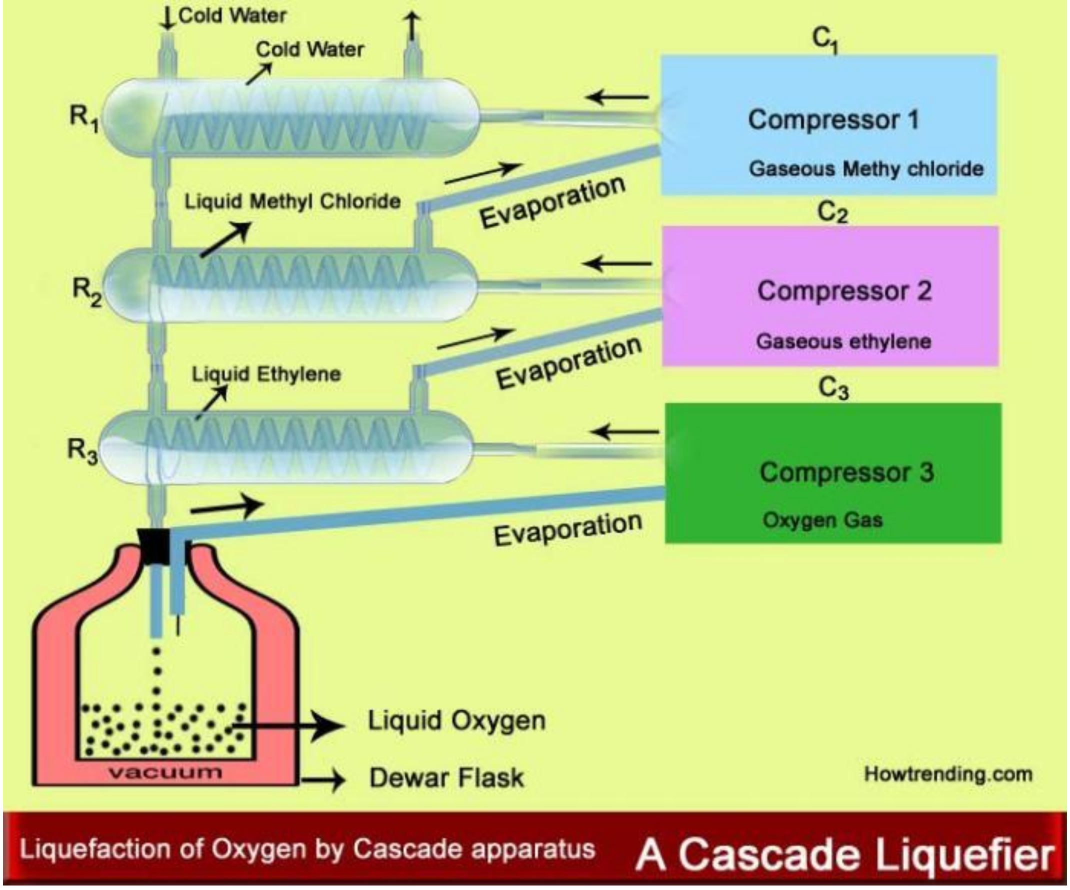
17 http://ar.cncdtank.com/news/safety-use-standards-that-liquid-oxygen-storag-26472706.html

Cascade system for Liquefaction of Oxygen Gas or Cascade Liquefier or Apparatus for Liquefaction of Oxygen Gas.[18]



As you can see in the above figure that, before getting liquid oxygen many stages of liquefaction are used. That's why we called it a cascade system or a Cascade liquefier, which is used to liquefy Oxygen or air.

As you know this process is first used by **Pictet** after sometime **K Onnes (Kamerlingh Onnes**) used this apparatus.

11.7.8.1 About the Apparatus

1. In this apparatus, three compressors C_1, C_2, C_3 are used to fulfill the requirement of sufficient pressure. Also, the C_1, C_2, and C_3 have a suction side which is used during the process.
2. Three condensers R_1, R_2, R_3 are used, into which three refrigerants cold water, Methyl chloride, and ethylene are used to get the desired result.
3. The Liquid oxygen is collected in the last, into a Dewar flask.

11.7.8.2 Principles

This apparatus work on two principles.

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[18] https://www.howtrending.com/liquefaction-of-gases/

1. The first, Principle, compression of gases below its critical temperature resulting in a change to liquid.
2. Second is, producing cooling by the principle of evaporation of liquids.

11.7.8.3 How does it work?

First, the gaseous methyl chloride (CH_3Cl) is pumped by the compressor C_1 into the spiral tube. The refrigerant in condenser R_1 surrounding this tube starts liquefying the methyl chloride.

This is because the critical temperature of methyl chloride is 143°C, which is more than room temperature as well.

Now the liquid methyl chloride comes in Condensor R_2 through the tube. Here one portion of condenser R_2 is connected with the suction side of compressor C_1.

Here due to the evaporation of liquid methyl chloride in reduced pressure, more cooling as a result produced, and the temperature of condenser R_2 decreases more.

The evaporated methyl chloride return back to the compressor C_1 through the suction side of the compressor.

Now the gaseous ethylene (C_2H_4) pumped by the compressor C_2 into the next spiral tube.

Here the refrigerant, liquid methyl chloride which is achieved in the previous stage, surrounding the tube which contains gaseous ethylene, starts to convert this gas into liquid ethylene.

This is because the critical temperature of ethylene is around 9.2°C.

Now, this liquid ethylene comes in Condensor R_3, and one portion of R_3 condenser connected with the suction side of compressor C_2.

Here evaporation of liquid ethylene takes place in reduced pressure like in the previous stage, and the evaporated ethylene return back to the compressor C_2 through the suction side of the compressor.

Therefore, due to the evaporation process more cooling produced into the condenser R_3, which is more than the cooling that we achieved in Condenser R_2.

This cooling has a temperature of around −160°C.

Now, the oxygen (which is in gaseous form) is pumped by the compressor C_3 into the next spiral tube.

Here, due to the very low temperature inside the Condenser R_3 the oxygen gas into the spiral tube starts converting into liquid and later collected into a Dewar flask.

This is because the critical temperature of oxygen gas is around −118°C.

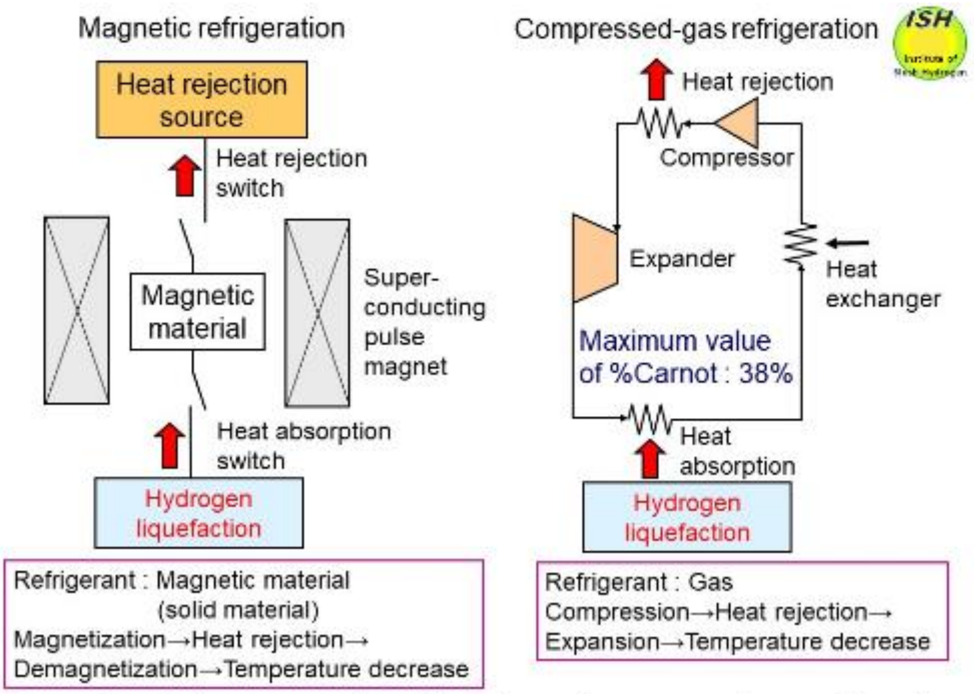
Here, likewise the previous stages, the evaporated oxygen return back to the compressor C_3 through the suction side of the compressor.

If we continue this cascade system, we can liquefy air and other gases like Nitrogen, etc.

Note: But by this system, we cannot liquefy the gases that have very low critical temperatures, such as Hydrogen (T_c around −240 °C) and Helium (T_c around −267.8 °C).

11.7.9 Liquefaction of hydrogen

The principles of magnetic refrigeration and compressed-gas refrigeration are presented in the below figure. The temperature-entropy diagrams of magnetic material and gas as a refrigerant in liquefaction cycle are respectively shown in the below figure. The magnetic refrigeration for hydrogen liquefaction uses an external magnetic field to magnetize and demagnetize a magnetic material in repeated cycles, thus producing low temperatures through the magnetocaloric effect.



Comparison between magnetic refrigeration and compressed-gas refrigeration. [19]

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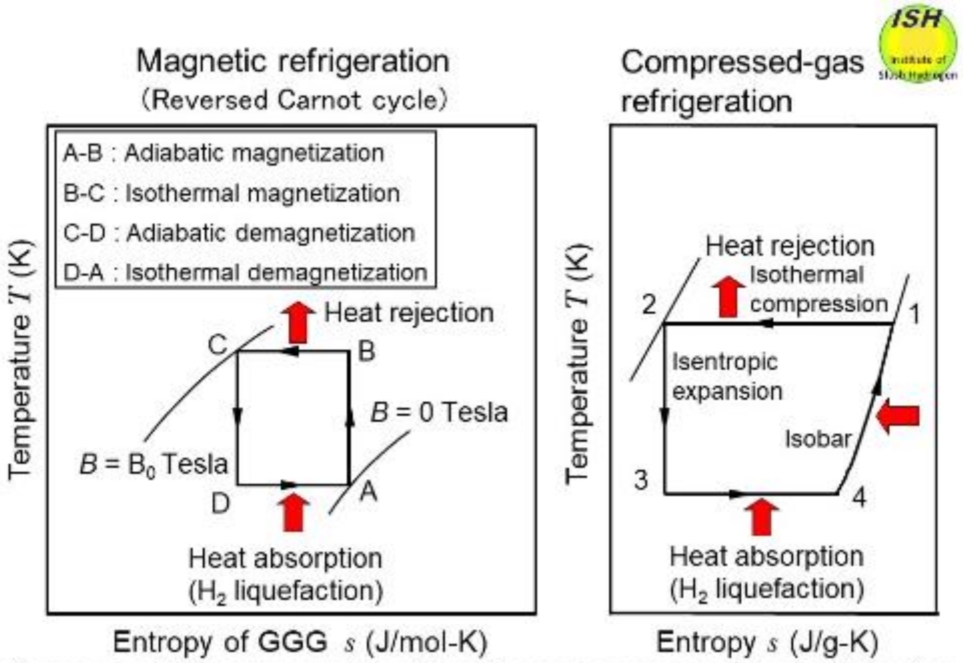
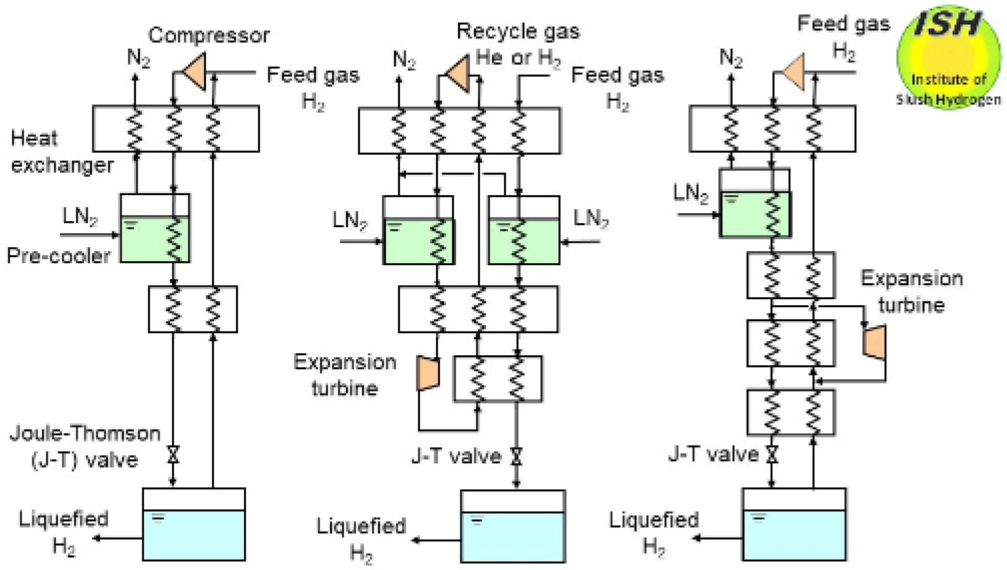
[19] https://slush-ish-mag-english.com/technology2.html



Comparison between magnetic refrigeration and compressed-gas refrigeration (temperature-entropy diagram).



Precooled Linde system

Because the inversion temp. of helium is 40 K, helium cannot be liquefied by this system.

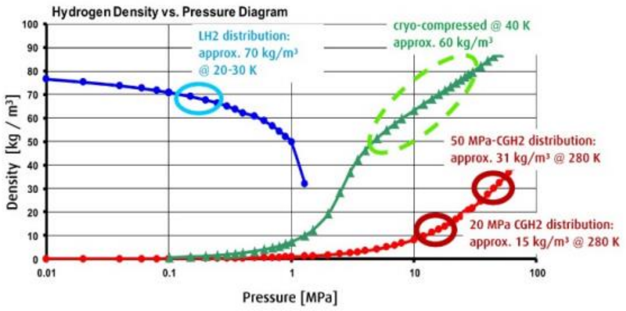
Brayton system

A refrigeration cycle using He gas or H$_2$ gas is used to cool and liquefy hydrogen.

Claude system

A part of compressed H$_2$ gas is expanded in the expansion turbine to generate colder gas.

Simplified typical hydrogen liquefaction systems.

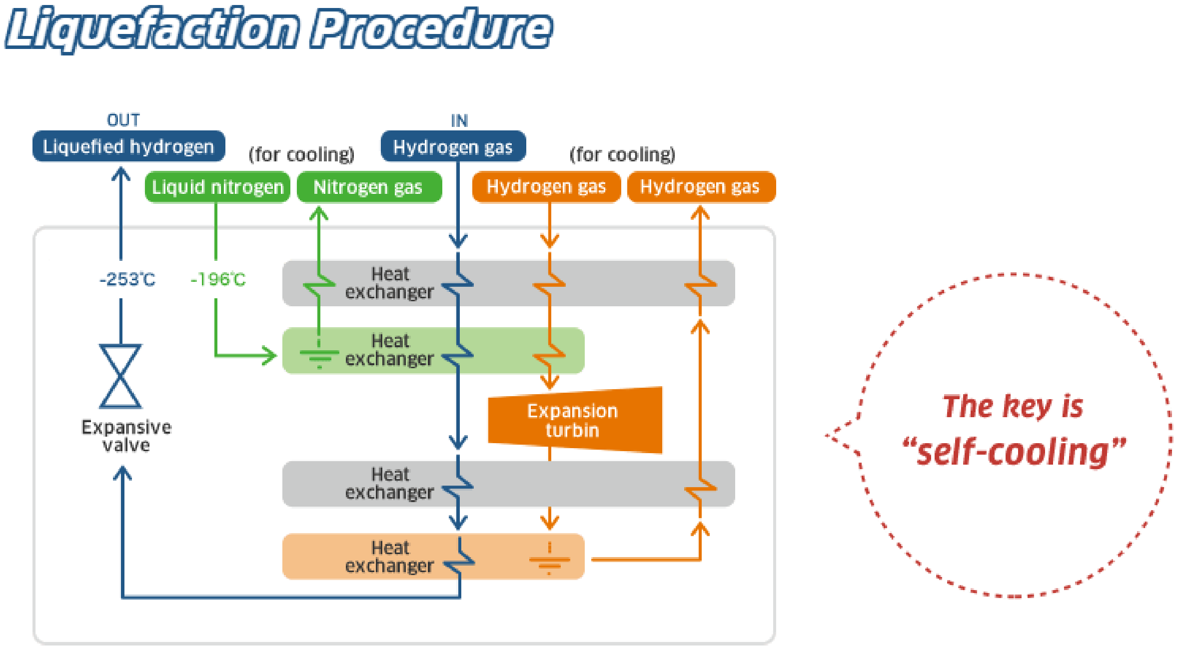


Comparison of hydrogen density in storage form of hydrogen [20]

11.7.9.1 Liquefaction of hydrogen by compressed-gas

http://sadanaresearch.com/liquid-helium-generator-overview/ !

https://vorbuchner.com/en/helium-liquefaction/



[21]

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[20] https://www.jstra.jp/seminar/PDF/English_Report%20of%20The%202nd%20International%20Workshop%20on%20Liquefied%20Hydrogen%20Technology.pdf

[21] https://global.kawasaki.com/en/stories/articles/vol57/

Compounds	T_c , K	P_c, atm	Z_c	Compounds	T_c , K	P_c, atm	Z_c
Methane ميثان	191	45.8	0.290	Methyl Alcohol الكحول الميثيلي	513	78.5	0.220
Ethane إيثان	306	48.2	0.284	Methyl Chloride كلوريد الميثيل	416	65.9	0.276
Propane بروبان	370	42.0	0.276	Methyl Ethyl Ketone	533	39.5	0.26
n-Butane بيوتان	425	37.5	0.274	Toluene التولوين	594	41.6	0.270
Iso-butane أيزوبيوتان	408	36.0	0.282	Tri-Chloro Fluoro Methane (فريون 11)	471	43.2	0.277
Pentane بنتان	470	33.3	0.268	Tri-Chloro Trifluoro Ethane (فريون 13)	487	33.7	0.274
Iso-pentane أيزوبنتان	461	32.9	0.268	Bromine (Br_2) بروم	584	102	0.307
Neo-pentane	434	31.6	0.260	Chlorine, Cl_2 كلور	417	76.1	0.276
Hexane هكسان	508	29.9	0.264	Helium (He) هيليوم	5.3	2.26	0.300
Heptane هبتان	540	27.0	0.260	Hydrogen (H_2) هيدروجين	33.3	12.8	0.304
Octane أوكتان	569	24.6	0.258	Neon (Ne) نيون	44.5	26.9	0.307
Ethylene إيثيلين	282	50.0	0.268	Nitrogen (N_2) نيتروجين	126.0	33.5	0.291
Propylene بروبيلين	365	45.6	0.276	Oxygen (O_2) أكسجين	155	50.1	0.29
1- Butene بيوتين	420	39.7	0.276	Ammonia (NH_3) نشادر (أمونيا)	406	111	0.242
1-Pentene ١- بنتين	474	40.0	-	Carbon Dioxide (CO_2) ثاني أكسيد الكربون	304	72.9	0.276
Acetic Acid حامض الخليك	595	57.1	0.200	Carbon Monoxide (CO) أول أكسيد الكربون	133	34.5	0.294
Acetone أسيتون	509	46.6	0.237	Hydrazine هيدرازين	653	145	-
Acetylene أسيتيلين	309	61.6	0.274	Hydrogen Chloride (HCl) كلوريد الهيدروجين	325	81.5	0.266
Benzene بنزين	562	48.6	0.274	Hydrogen Sulfide (H_2S) كبريتيد الهيدروجين	374	88.9	0.284
1,3-Butadiene	425	42.7	0.270	Nitric Oxide (NO) أكسيد النيتريك	180.0	64	0.25
Cyclohexane هكسان حلقي	553	40.0	0.271	Nitrous Oxide (N_2O) أكسيد النيتروز	310	71.7	0.271
Dichloro-difluoro methane	385	39.6	0.273	Sulfur (S) كبريت	1313	116	-
Ethylene إيثيلين	282	50.0	0.268	Sulfur Dioxide (SO_2) ثاني أكسيد الكبريت	431	77.8	0.268
Diethyle Ether ثنائي إيثيل إيثر	467	35.6	0.261	Sulfur Trioxide (SO_3) ثالث أكسيد الكبريت	491	83.8	0.262
Ethyl Alcohol كحول إيثيلي	516	63.0	0.249	Water (H_2O) ماء	647	218	0.320
Ethylene Oxide أكسيد الإيثيلين	468	71.0	0.25				

11.7.10 Methane liquefaction

11.7.10.1 Characteristics of Methane

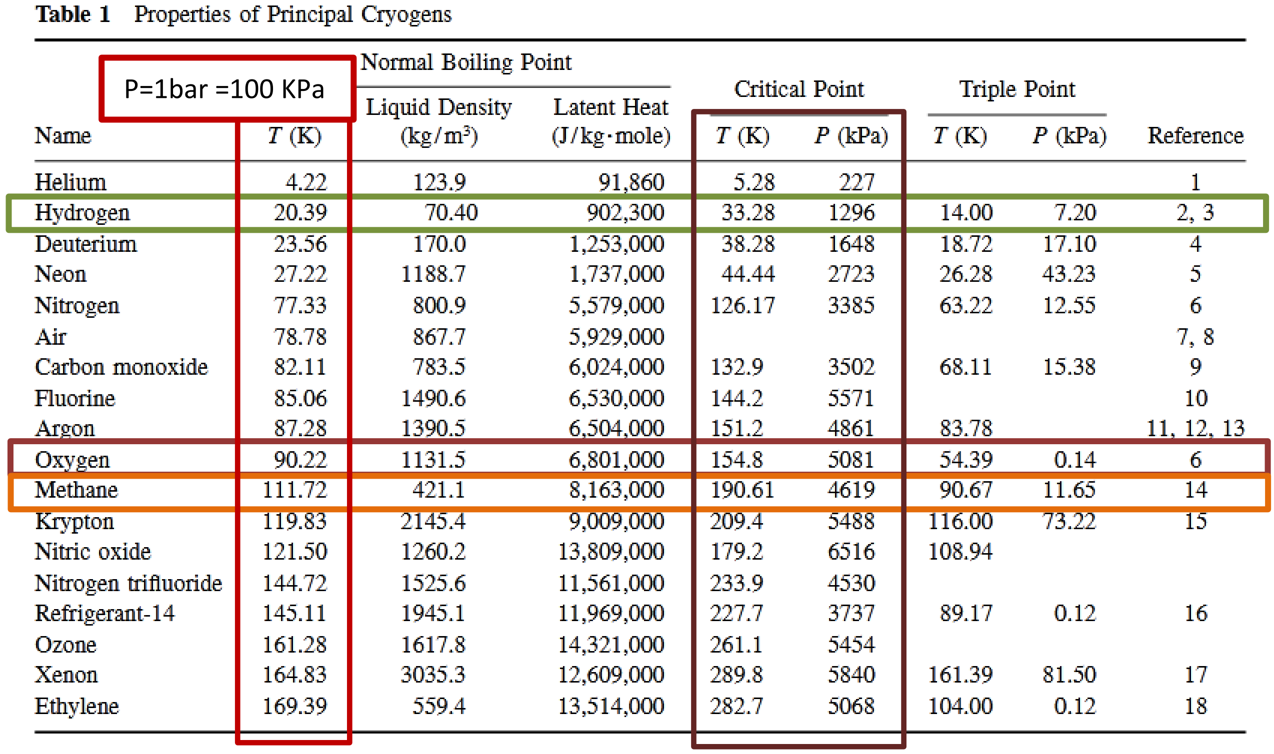

Table 1 Properties of Principal Cryogens

P=1bar =100 KPa

Name	Normal Boiling Point T (K)	Liquid Density (kg/m³)	Latent Heat (J/kg·mole)	Critical Point T (K)	Critical Point P (kPa)	Triple Point T (K)	Triple Point P (kPa)	Reference
Helium	4.22	123.9	91,860	5.28	227			1
Hydrogen	20.39	70.40	902,300	33.28	1296	14.00	7.20	2, 3
Deuterium	23.56	170.0	1,253,000	38.28	1648	18.72	17.10	4
Neon	27.22	1188.7	1,737,000	44.44	2723	26.28	43.23	5
Nitrogen	77.33	800.9	5,579,000	126.17	3385	63.22	12.55	6
Air	78.78	867.7	5,929,000					7, 8
Carbon monoxide	82.11	783.5	6,024,000	132.9	3502	68.11	15.38	9
Fluorine	85.06	1490.6	6,530,000	144.2	5571			10
Argon	87.28	1390.5	6,504,000	151.2	4861	83.78		11, 12, 13
Oxygen	90.22	1131.5	6,801,000	154.8	5081	54.39	0.14	6
Methane	111.72	421.1	8,163,000	190.61	4619	90.67	11.65	14
Krypton	119.83	2145.4	9,009,000	209.4	5488	116.00	73.22	15
Nitric oxide	121.50	1260.2	13,809,000	179.2	6516	108.94		
Nitrogen trifluoride	144.72	1525.6	11,561,000	233.9	4530			
Refrigerant-14	145.11	1945.1	11,969,000	227.7	3737	89.17	0.12	16
Ozone	161.28	1617.8	14,321,000	261.1	5454			
Xenon	164.83	3035.3	12,609,000	289.8	5840	161.39	81.50	17
Ethylene	169.39	559.4	13,514,000	282.7	5068	104.00	0.12	18

11.7.11 Methane liquefaction basic cycle22

To liquefy natural gas methane taken at 1 bar and 280 K is compressed to 100 bar and then cooled to 210 K (it is assumed in this example that a refrigeration cycle is available for that).

Isentropic compression is assumed, but the very high compression ratio requires the use of several compressors (3 in this example) with intermediate cooling at 280 K. Intermediate pressures are equal to 5 and 25 bar.

The gas cooled at 210 K is isenthalpically expanded from 100 bar to 1 bar, and gas and liquid phases separated. As shown in the diagram in Figure below, the methane enters in the upper left, and liquid and gaseous fractions exit in the bottom right.

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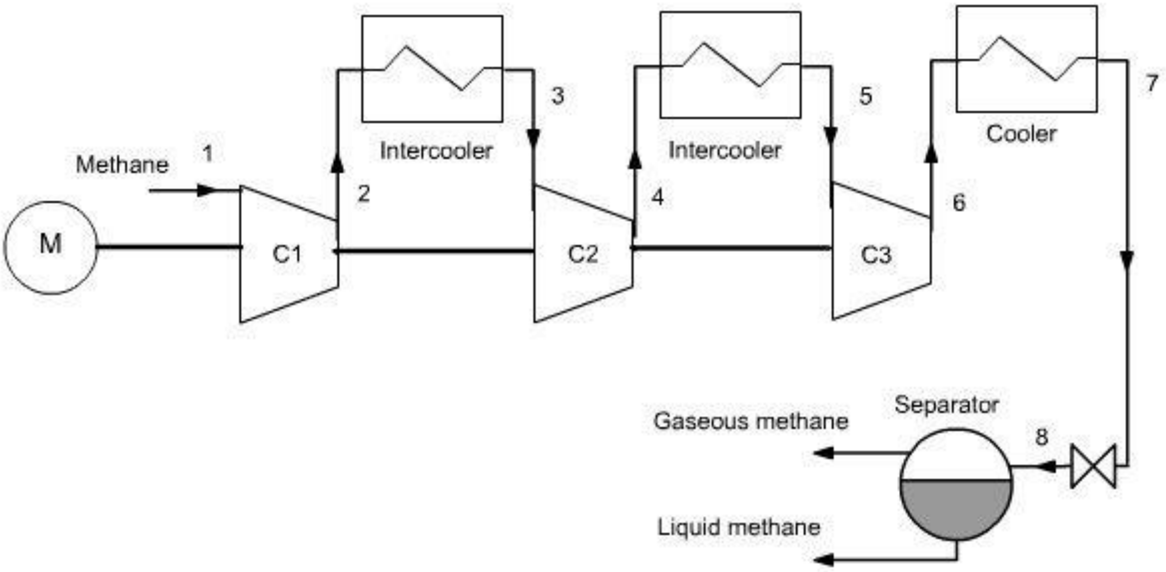
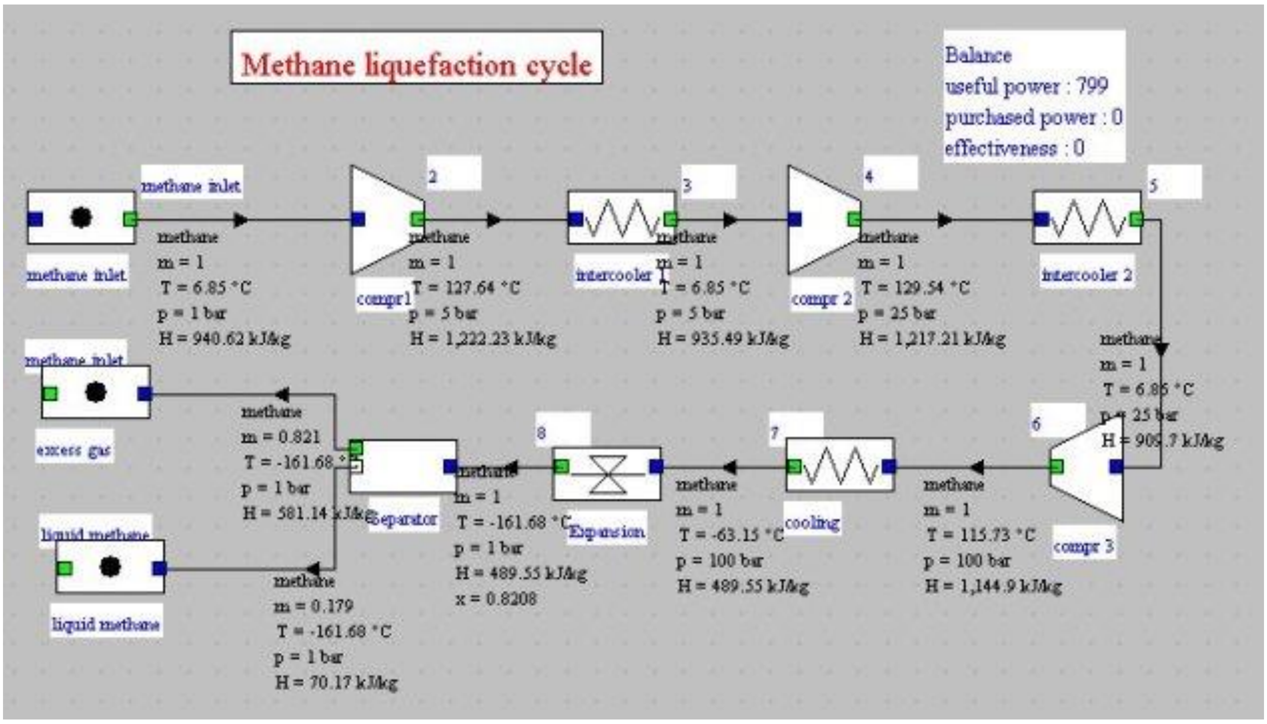
[22] https://direns.mines-paristech.fr/Sites/Thopt/en/co/cryogenie.html





Balance
useful power : 799
purchased power : 0
effectiveness : 0

methane
m = 1
T = 6.85 °C
p = 1 bar
H = 940.62 kJ/kg

methane
m = 1
T = 127.64 °C
p = 5 bar
H = 1,222.23 kJ/kg

methane
m = 1
T = 6.85 °C
p = 5 bar
H = 935.49 kJ/kg

methane
m = 1
T = 129.54 °C
p = 25 bar
H = 1,217.21 kJ/kg

methane
m = 1
T = 6.85 °C
p = 25 bar
H = 909.7 kJ/kg

methane
m = 1
T = 115.73 °C
p = 100 bar
H = 1,144.9 kJ/kg

methane
m = 1
T = -63.15 °C
p = 100 bar
H = 489.55 kJ/kg

methane
m = 1
T = -161.68 °C
p = 1 bar
H = 489.55 kJ/kg
x = 0.8208

methane
m = 0.821
T = -161.68 °C
p = 1 bar
H = 581.14 kJ/kg

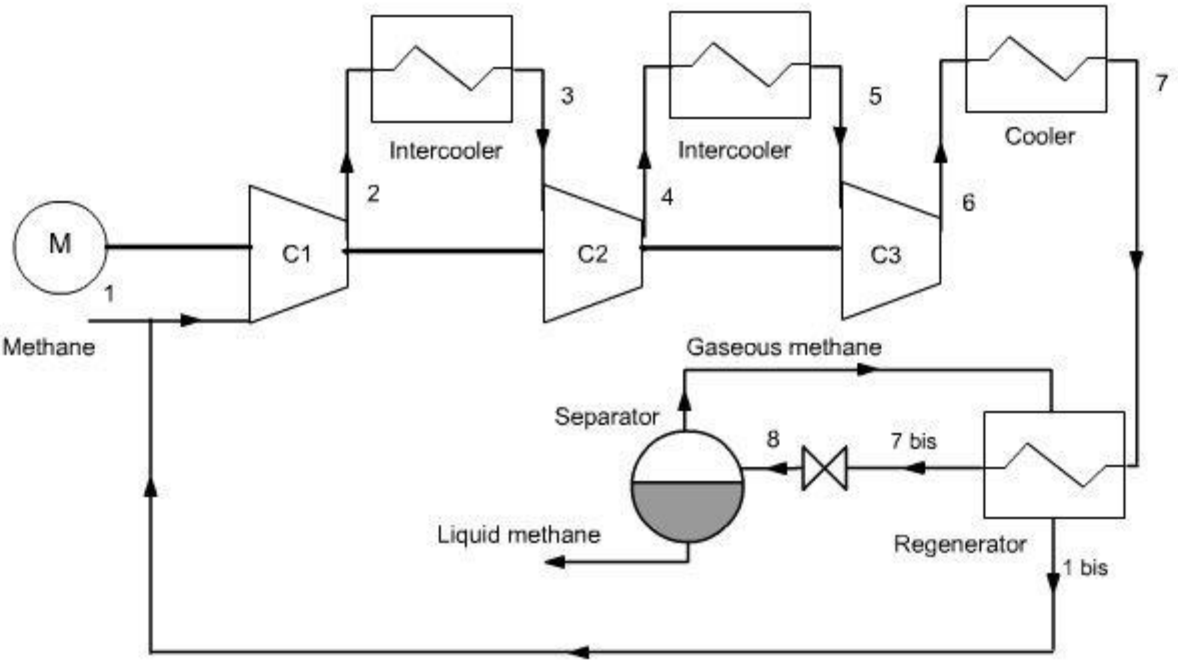
methane
m = 0.179
T = -161.68 °C
p = 1 bar
H = 70.17 kJ/kg

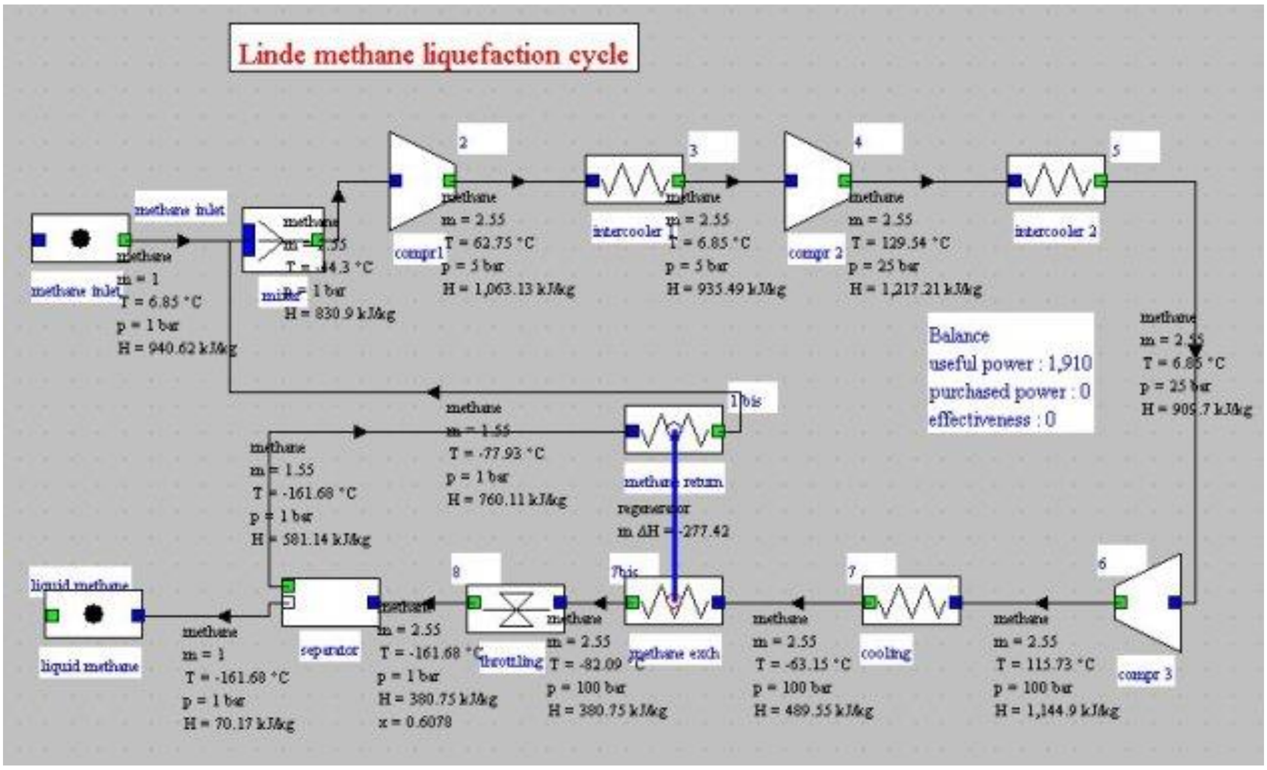
The compression work required per kilogram of methane sucked is 798.5 kJ, and 0.179 kg of liquid methane is produced, which corresponds to a work of 4.46 MJ per kilogram of liquefied methane.

11.7.12 Linde cycle

The Linde cycle (Figure below) improves the previous on two points:

- gaseous methane is recycled after isenthalpic expansion;
- we introduce a heat exchanger between the gaseous methane and methane out of the cooler in order to cool the compressed gas not at 210 K but at 191 K.





11.7.13 Conclusion related to methane liquefaction

Each gas has a temperature it cannot be flushed over whatever the pressure. This temperature is known as critical temperature, and critical pressure is the pressure needed to liquefy the gas at the critical temperature of the gas.

Linde cycle can be applied to hydrogen gas, methane as well as oxygen, with consideration given to the critical point of each. Oxygen gas needs a temperature of 90 K (1 bar) to be in the liquid state, or it needs a pressure higher than 51 bar and a temperature of 154 K.

As for hydrogen gas, it needs a temperature of 20 K (atm pressure 1 bar) to become in the liquid state, or it needs a pressure higher than 13 bar and a temperature of 33 K.

Finally, for gas, methane needs 110 K (1 bar air pressure) to become in the liquid state, or it needs a pressure higher than 46.2 bar and a temperature of 190 K.

12 Project E: Compressors - Basics

Various types of compressors are used in the oil and gas industry and the same can be said about the medical, dental and pharmaceutical industries.

Their variety ensures that each is specifically tailored to serve a particular purpose and to the best of its ability.

That being the case, the review of main types of compressors and their applications will give you a good knowledge of the best out there whose level of performance is on par with what you're out to get.23

12.1 WHAT IS A COMPRESSOR?

A compressor is also known as a Heating, Ventilation & Air-Conditioning (HVACR) machine.

It is a mechanical device that reduces the volume of a fluid such as gas or liquid while at the same time increasing its temperature and pressure.

A compressor features two major components and these are the power source and a compressing mechanism (for example piston and vanes).

What's more, these machines are similar to gas pumps because they transport compressed gas through pipes.

The latter has aided in the compression of natural gas in the oil and gas industry where the gas is pressurized in order to meet with the standards of certain jurisdictions that require at least 95 percent of the gas in petroleum to be compressed.

It is also worthy to note that certain factors influence a compressor's performance and these are:

- Speed of rotation
- Pressure at suction
- Pressure at discharge
- Type of refrigerant used

12.2 THE BASIC TYPES OF COMPRESSORS

A list of the major types of compressors by mechanical design has been outlined below and the feature of each, aids in its functionality.

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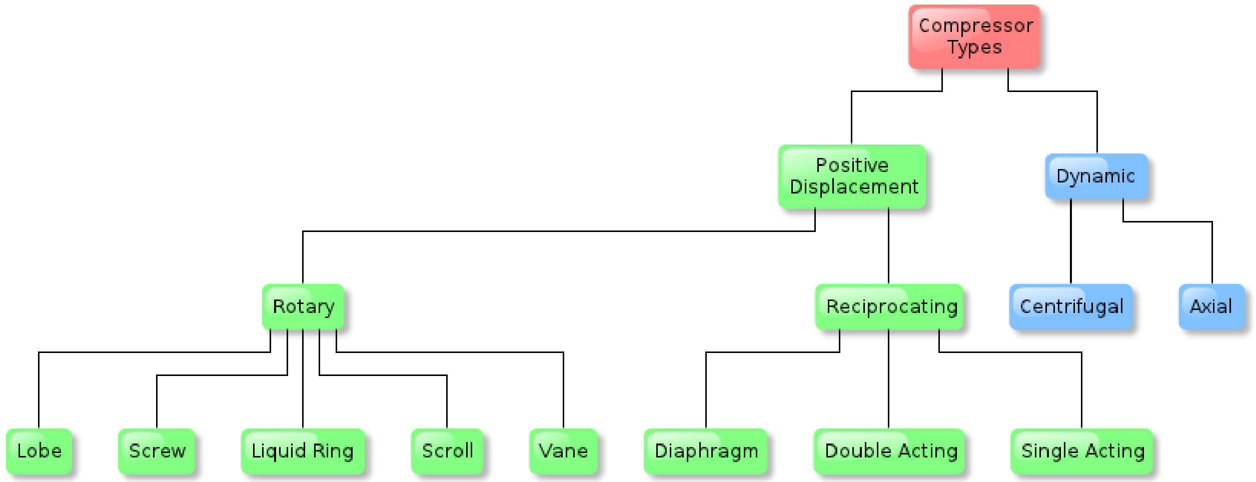
23 https://kbdelta.com/blog/main-types-of-compressors.html



Now, the best way to get a good idea of these devices is to compare them side by side and as such, a comparison between different types of compressors, how they work, and when to use them has also been given in this section.

Therefore, the two basic types of compressors are:

1. Positive displacement compressors
2. Dynamic compressors

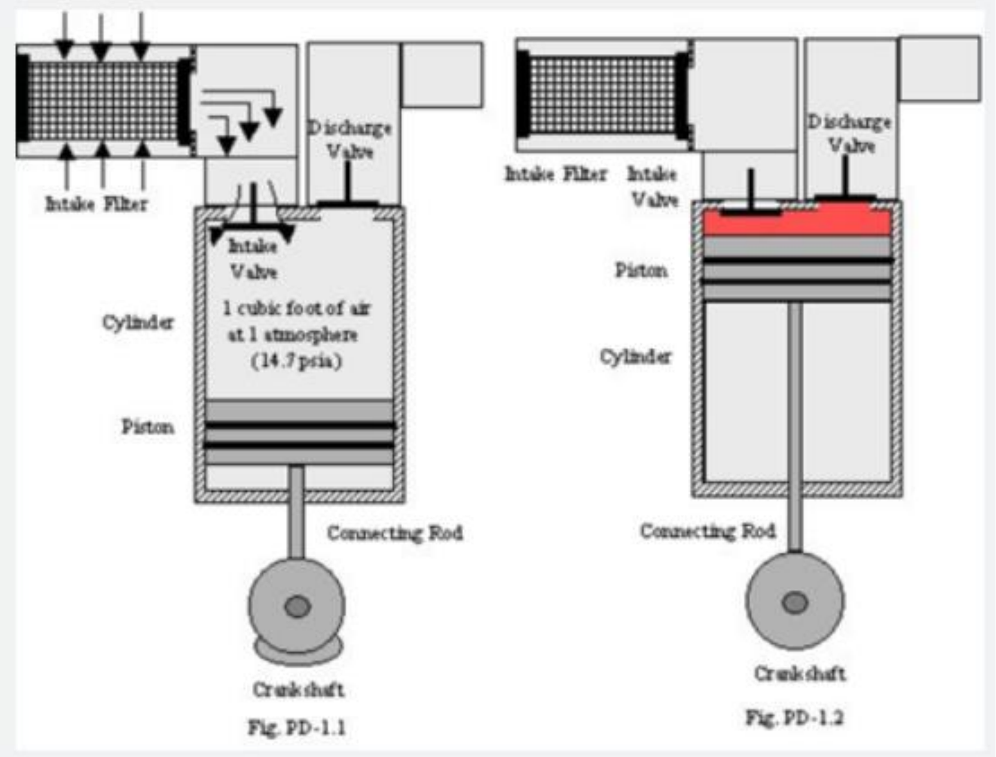
12.2.1 POSITIVE DISPLACEMENT COMPRESSORS

In positive displacement compressors, gases are compressed due to the displacement of a mechanical linkage which reduces its volume.

First off, a certain amount of gas is passed into a confined space and the volume or space is subsequently reduced which helps to boost the gas' pressure levels.

The gas is then released into a discharge piping or vessel system once the pressure has been raised.

If you're wondering why this displacement is called positive in the first place, then reference can be made to thermodynamics where a displacement caused by the movement of a piston (as is the case of a reciprocating compressor) is known to be positive.



[24]

The movement can also be caused by rotation as is the case of a twin helical screw-rotating machine.

Consequently, the types of positive displacement compressors are:

A) Reciprocating compressors
B) Rotary compressors

8.2.1.A) RECIPROCATING COMPRESSORS

Reciprocating compressors or piston compressors feature one or more pistons which are driven by a crankshaft; a component that also drives the piston rod, and connecting rod.

As the piston within the cylinder moves back and forth, the pressure of the gas is increased. This, in turn, helps in its compression. The compressed gas is then discharged into high pressure receiving tanks.

On the other hand, this positive displacement compressor can also be driven by electric motors or internal combustion engines.

They can be fixed to a particular location or portable enough to be moved around.

In terms of their horsepower, small compressors operate within the range of 5 to 30 horsepower (hp) and they are mostly used in the automobile sector of the economy.

Large compressors, on the contrary, have a horsepower above 1,000 hp (750 kW). They are available in the oil and gas industry and generally in large industrial applications.

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[24] https://cascousa.com/compressed-air-101/types-of-compressors/positive-displacement-compressors/

12.2.2 TYPES OF RECIPROCATING COMPRESSORS

12.2.2.1 The various types of Reciprocating compressors are:

- Single-cylinder: A single cylinder reciprocating compressor features a suction, discharge area and compression. A double cylinder comes with dual suction, discharge areas, and compression, and it helps to achieve higher gas pressures.
- Multi-cylinder: While double cylinders are prevalent, there are instances where compressors are designed with as many as six cylinders.
- Multi-stage design: As the name implies, more stages are incorporated to arrive at the final processed gas. Here, the gas is compressed multiple times in several compression cylinders to increase pressure levels.
- Diaphragm compressor: This differs from the conventional reciprocating compressor since the compression of gas is brought about by the to and fro movement of a flexible membrane. The movement is facilitated by a rod and the crankshaft.

12.2.3 ROTARY COMPRESSORS

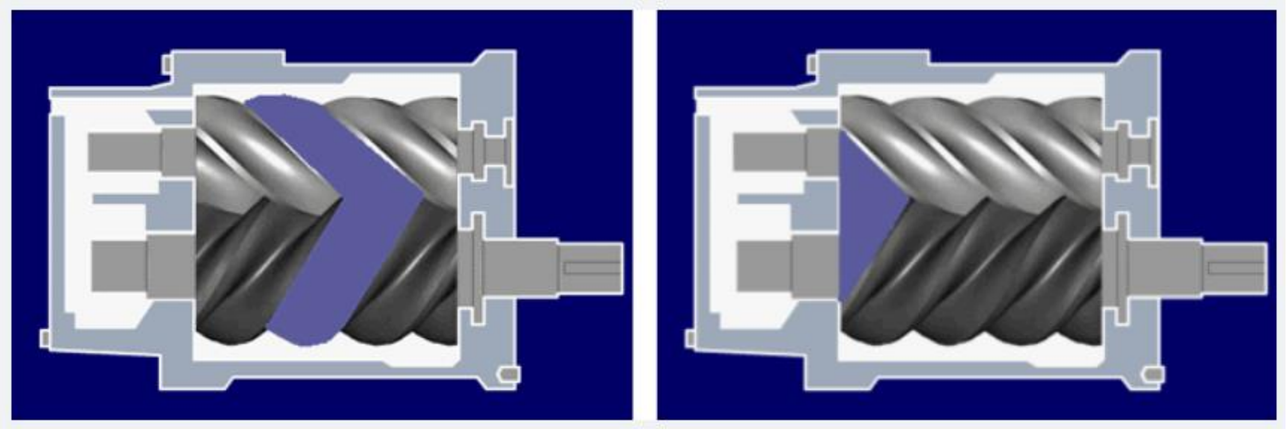
Rotary compressors also have a positive displacement. These low capacity types of equipment have applications in home freezers and refrigerators.

They can either have a single vane that is located within the cylinder and kept away from the rotor, or multiple vanes located in the rotor.

The various types of rotary compressors include:

12.2.4 – ROTARY SCREW COMPRESSORS

It uses two meshed helical screws in rotation to force the gas into a smaller space.

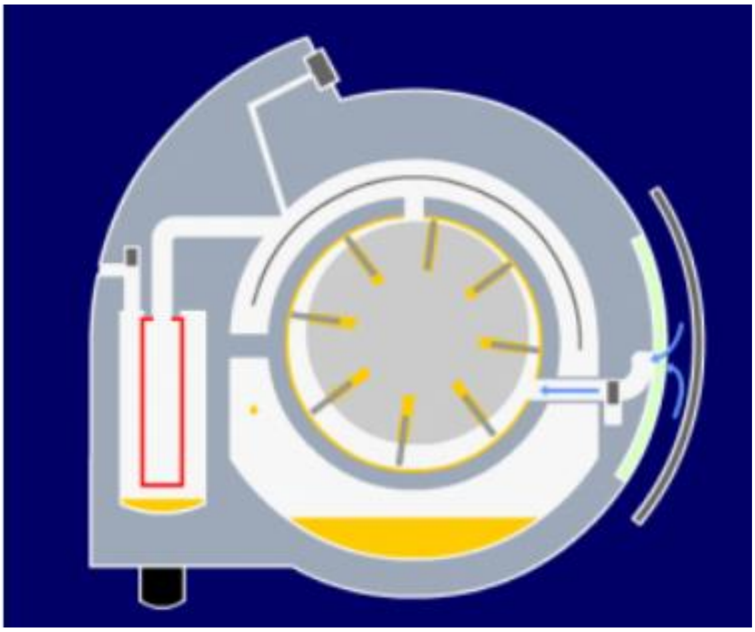


They can be employed in industrial and commercial purposes and their application can range between 3 horsepower (2.2 kW) to about 1,200 horsepower (890 kW).

Likewise, the discharge pressure can range between low to moderately high pressure (>1,200 psi or 8.3 MPa).

12.2.5 ROTARY VANE COMPRESSORS

These machines feature a rotor that is mounted in a larger housing which has either a circular or complex shape.



The rotor also has several blades which are inserted in radial slots within the rotor.

As the rotor moves, the blades move in and out of the slots. This increases and decreases the volume of the gas.

In comparison with a piston compressor, a rotary vane compressor operates more quietly and is best suited to the electric motor drive.

Like piston compressors, they can also be single or multi-staged, as well as stationary or portable.

Their discharge range can be between 29 psi as is the case of dry vane machines and 190 psi for oil-injected machines.

12.2.6 - SCROLL COMPRESSORS

These are also known as scroll pump or scroll vacuum pump and they feature two spiral vanes that are interwoven.

While one of the vanes is fixed, the other moves around it which help in compressing the gas.

Scroll compressors also operate even more quietly and smoothly than other types of compressors in the lower volume range.

12.2.7 DYNAMIC COMPRESSORS

Dynamic compressors are also known as turbo compressors and they depend on a fluid’s inertia and momentum to bring about its increased pressure levels.

In their mode of operation, velocity energy is impacted to a stream of gas and this energy is then converted to pressure energy.

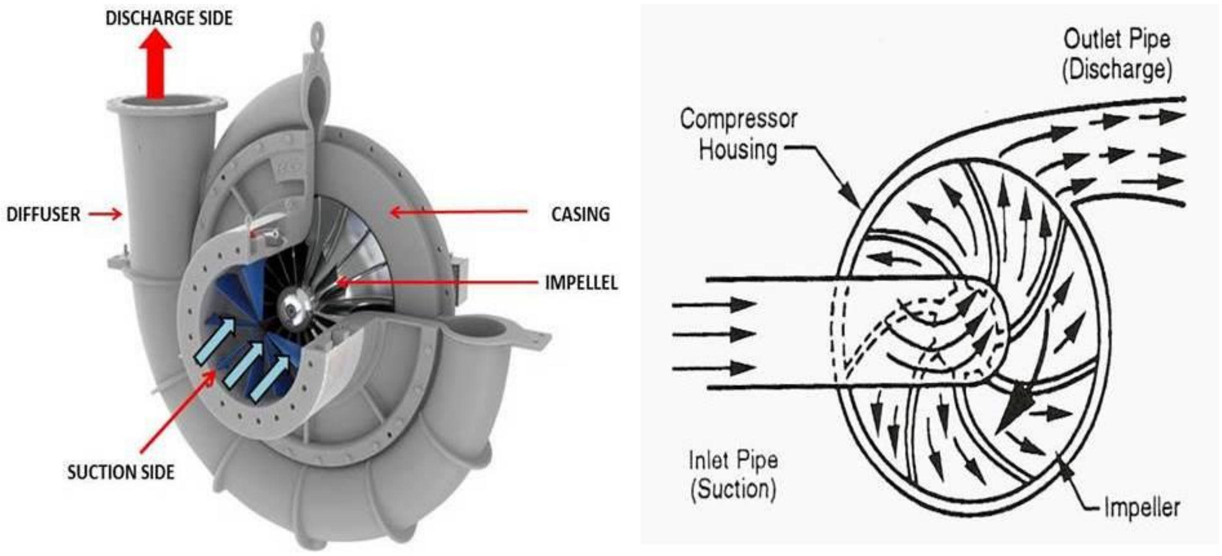
There are two basic types of dynamic compressors and these are:

A. Centrifugal compressors
B. Axial compressors

12.2.8 CENTRIFUGAL COMPRESSORS

Centrifugal compressors make up about 80 percent of the entire dynamic processors, therefore, leaving 20 percent to axial compressors.

That being the case, they are widely used in oil refineries, natural gas processing plants, chemical and petrochemical plants.



CENTRIFUGAL COMPRESSOR

[25]

Due to their high output pressures of over 1,000 psi (6.9 MPa) and horsepower range of a 100 to 1000, these machines can be used in:

- Snowmaking operations
- Refrigeration
- Air conditioning systems

For their mode of operation, compression is made possible by exerting inertial force on the gas with the use of high-speed rotating impellers

The gas is forced to the rim of the impeller which helps to increase its velocity. This velocity is then converted to pressure energy by a diffuser.

The process can also be carried out in a single stage or multi-stage where each stage takes advantage of an impeller (a rotating disk) and diffuser (a stationary element).

Both single and multistage machines are generally made up of standardized components. However, the multistage helps in improving the compression ratio since centrifugal compressors generally have lower compression ratios in comparison to displacement compressors.

Centrifugal compressor also features two casing designs and these are:

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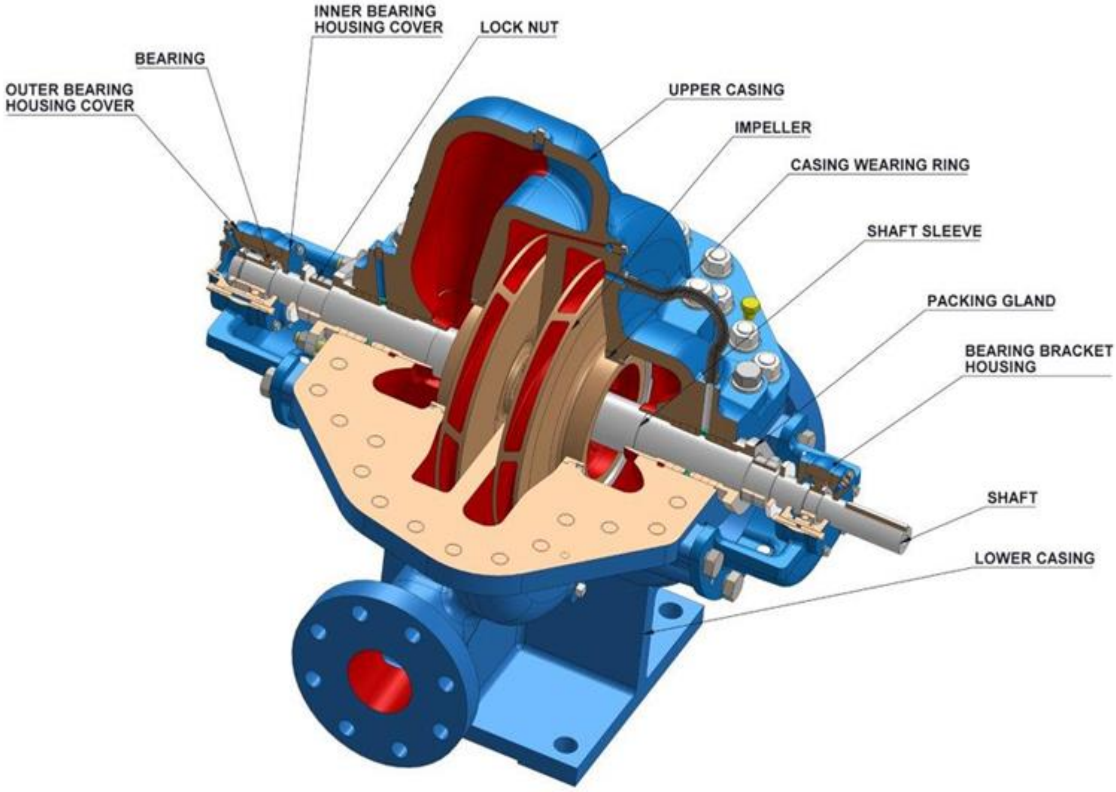
[25] https://www.mech4study.com/2017/11/centrifugal-compressor.html

12.2.9 - HORIZONTALLY SPLIT CASING DESIGN

This compressor has an outer casing which can be split horizontally to aid in the maintenance of its internal component.

Within the compressor, the rotating disk or impellers are connected to one rotating shaft to form a multi-stage structure.

As the gas passes through the intake nozzle, a centrifugal force created by the high-speed movement of the impellers causes it to be compressed and pressurized before it is sent out to an ejection nozzle.



[26]

12.2.10 - VERTICALLY SPLIT CASING DESIGN

While the internal components of this machine have a similar design to that of the horizontal split type casing, its outer design differs.

Here, the rotor bundle and the diaphragm seals are axially arranged in a steel barrel casing.

Generally, this design depends on the working pressure and the type of gas that is to be compressed.

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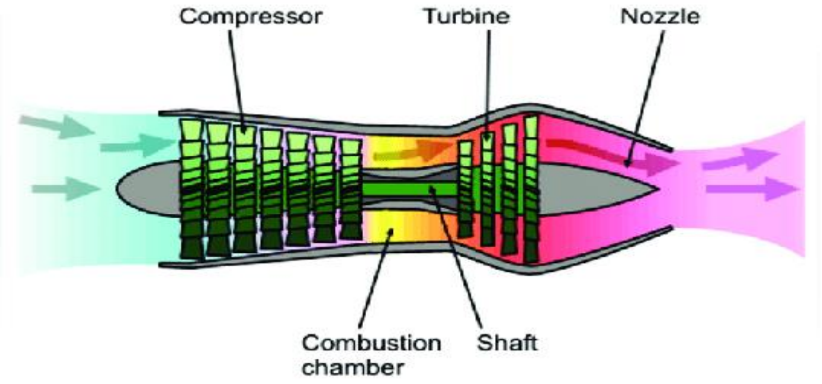
[26] https://www.flowmorepumps.com/product/horizontal-split-casing-pumps.html

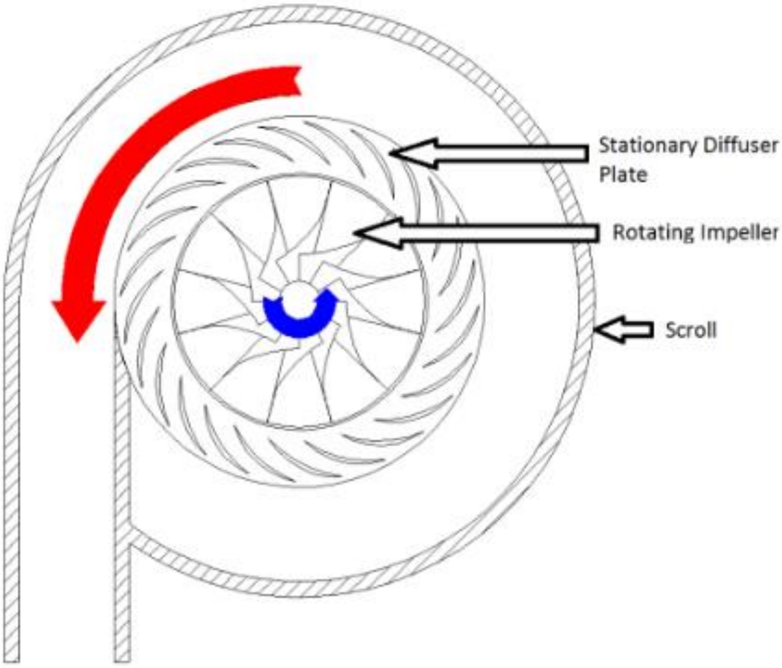
12.2.11 AXIAL-FLOW COMPRESSORS

Another type of dynamic rotating compressors is the axial-flow compressor. They are mostly employed where compact design or high flow rates (large flow volumes) is desired.

These compressors have a pressure range between low to medium and you'll find their application in jet engines, natural gas pumping stations, chemical plants, and large gas turbine engines.



[27]



Axial Compressors-Centrifugal Compressors[28]

When it comes to how this compressor works, gas is compressed with the use of an array of airfoils which are arranged in rows.

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[27] https://www.researchgate.net/figure/Axial-flow-compressor-engine_fig4_261477455

[28] https://cascousa.com/compressed-air-101/types-of-compressors/dynamic-displacement-compressors/

The airfoils can exist as pairs, where one of the set is a rotating airfoil known as the blade or rotor and the other is a stationary airfoil also known as stators or vanes.

While the rotating airfoil accelerates the fluid; the stationary airfoil decelerates and also redirects its direction in preparation for the rotor blades of the next stage.

12.2.12 Pros and Contras

What this means is that the velocity of the gas is first increased before it is slowed down and passed through the blades which help to increase the gas pressure.

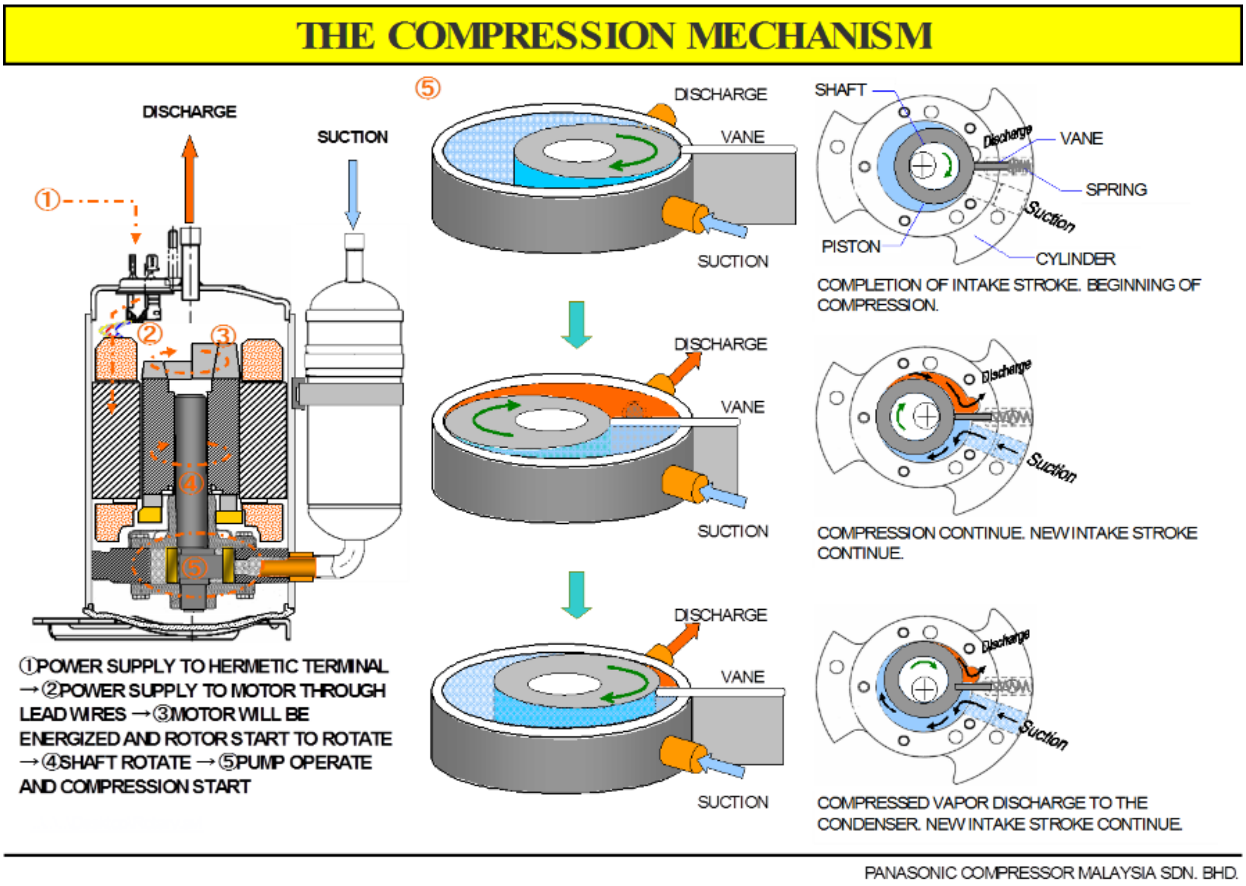
In comparison with other compressors, axial machines are relatively expensive since they require more parts and materials of high quality.

They, however, have high efficiencies and employ multi-stages where the cross-sectional area of the gas passing along the compressor diminishes to give an optimum axial Mach number.

12.2.13 HERMETICALLY SEALED, OPEN, OR SEMI-HERMETIC

There are also compressors that are specifically designed for refrigerators. These types can either be classified as hermetically open, sealed, or semi-hectic.

Each description refers to the way the motor drive is positioned in relation to the gas that is being compressed.


THE COMPRESSION MECHANISM

①POWER SUPPLY TO HERMETIC TERMINAL →②POWER SUPPLY TO MOTOR THROUGH LEAD WIRES →③MOTOR WILL BE ENERGIZED AND ROTOR START TO ROTATE →④SHAFT ROTATE →⑤PUMP OPERATE AND COMPRESSION START

COMPLETION OF INTAKE STROKE. BEGINNING OF COMPRESSION.

COMPRESSION CONTINUE. NEW INTAKE STROKE CONTINUE.

COMPRESSED VAPOR DISCHARGE TO THE CONDENSER. NEW INTAKE STROKE CONTINUE.

PANASONIC COMPRESSOR MALAYSIA SDN. BHD.

[29]

Design of Oil-Less Compressors and Vacuum Pumps (pdf)

https://docs.lib.purdue.edu/cgi/viewcontent.cgi?article=1017&context=icec

https://oaktrust.library.tamu.edu/bitstream/handle/1969.1/188625/TT02.pdf?sequence=1

Denair compressor to inquire about:

http://www.denair.net/Gas_Compressor/Gas_Compressor.html (#8)

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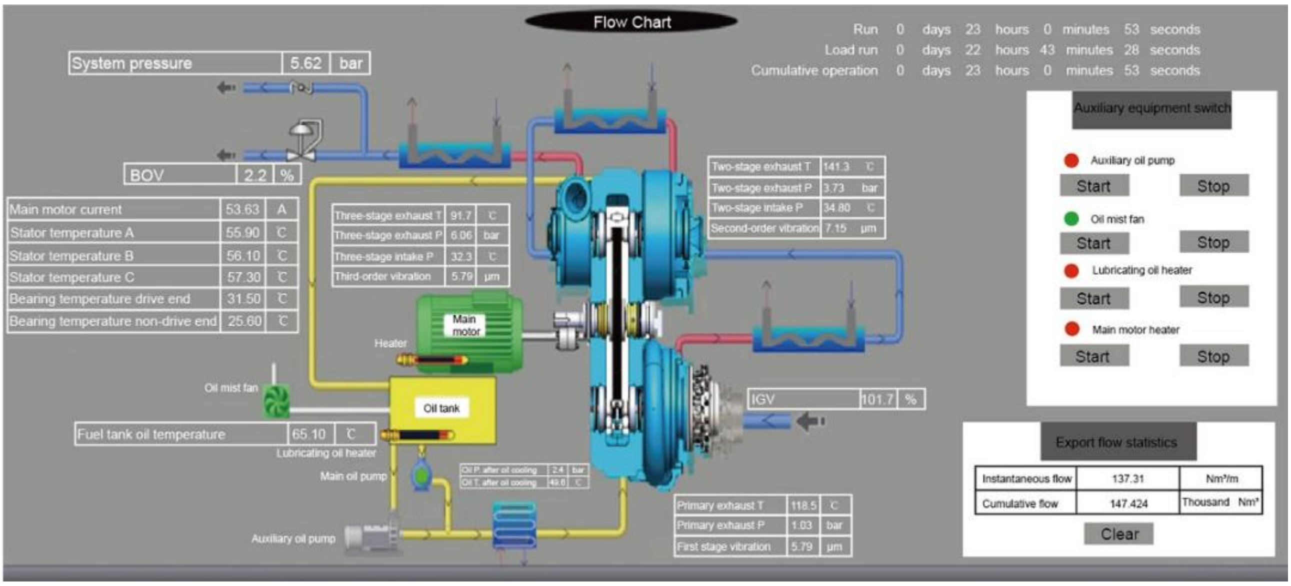
[29] https://na.industrial.panasonic.com/complete-guide-rotary-compressors



Run 0 days 23 hours 0 minutes 53 seconds
Load run 0 days 22 hours 43 minutes 28 seconds
Cumulative operation 0 days 23 hours 0 minutes 53 seconds

System pressure 5.62 bar

BOV 2.2 %

Main motor current	53.63	A
Stator temperature A	55.90	℃
Stator temperature B	56.10	℃
Stator temperature C	57.30	℃
Bearing temperature drive end	31.50	℃
Bearing temperature non-drive end	25.60	℃

Three-stage exhaust T	91.7	℃
Three-stage exhaust P	6.06	bar
Three-stage intake P	32.3	℃
Third-order vibration	5.79	μm

Two-stage exhaust T	141.3	℃
Two-stage exhaust P	3.73	bar
Two-stage intake P	34.80	℃
Second-order vibration	7.15	μm

Fuel tank oil temperature 65.10 ℃

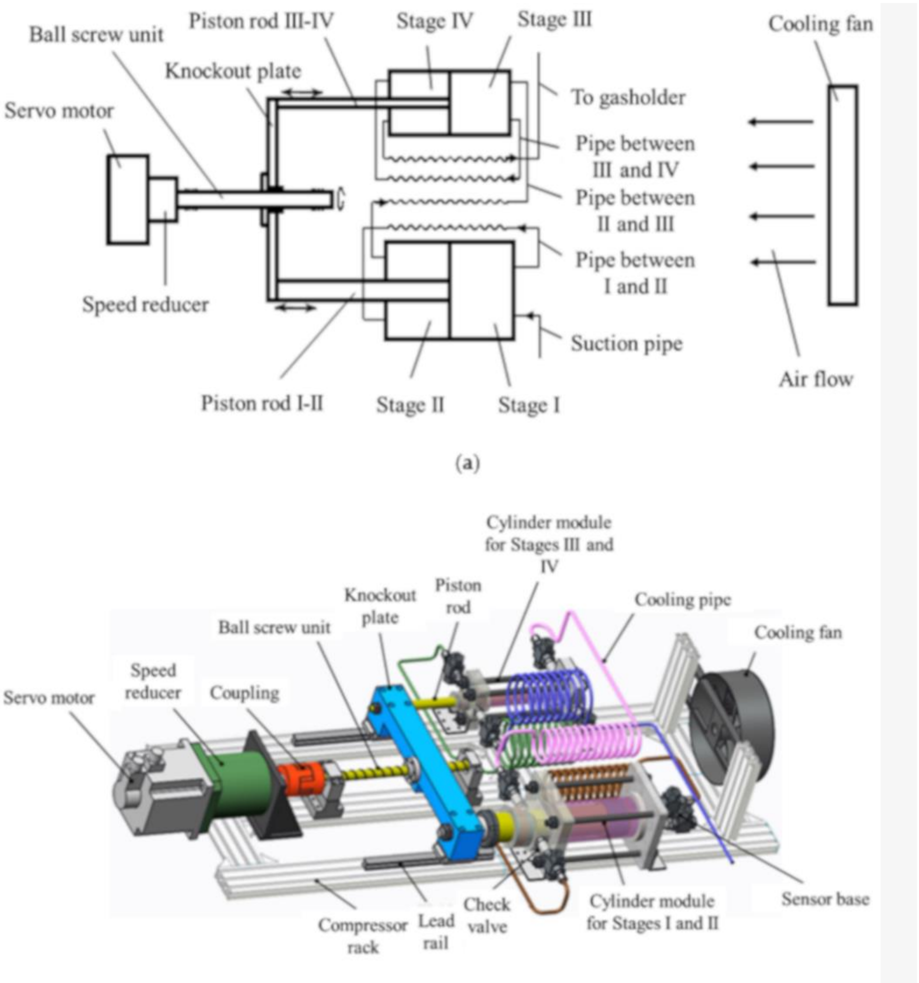
Oil P. after oil cooling	2.4	bar
Oil T. after oil cooling	49.6	℃

IGV 101.7 %

Primary exhaust T	118.5	℃
Primary exhaust P	1.03	bar
First stage vibration	5.79	μm

● Auxiliary oil pump
● Oil mist fan
● Lubricating oil heater
● Main motor heater

Instantaneous flow	137.31	Nm³/m
Cumulative flow	147.424	Thousand Nm³



(a)

(b)

[30]

(**a**) Structural diagram and (**b**) 3D model of the multistage compressor unit.

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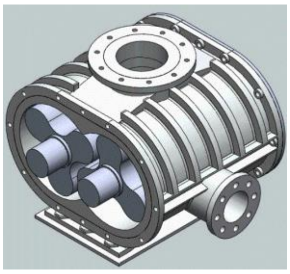
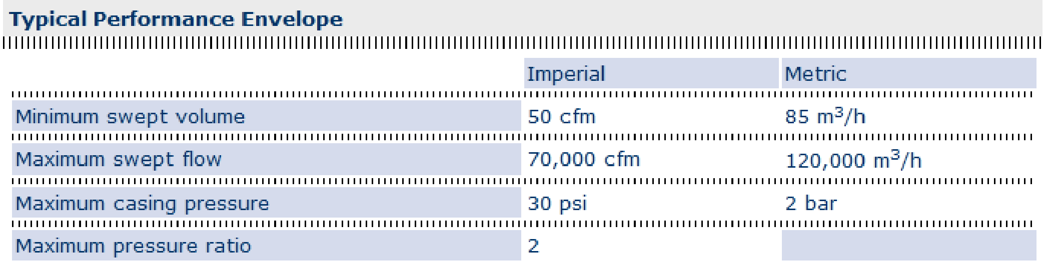
[30] https://www.mdpi.com/1996-1073/13/1/112/htm

12.3 Gas compressors [31]

12.3.1 Positive displacement rotary blower



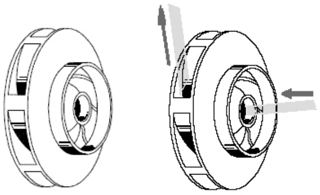
Two profiled rotors turn in a figure of eight shaped housing. They are geared together so that they run very close to each other, but cannot touch. There is no compression within the machine, it simply pushes gas into the system to which it is connected. Machines with semi-screw profile rotors are also available, which reduces noise and vibration.



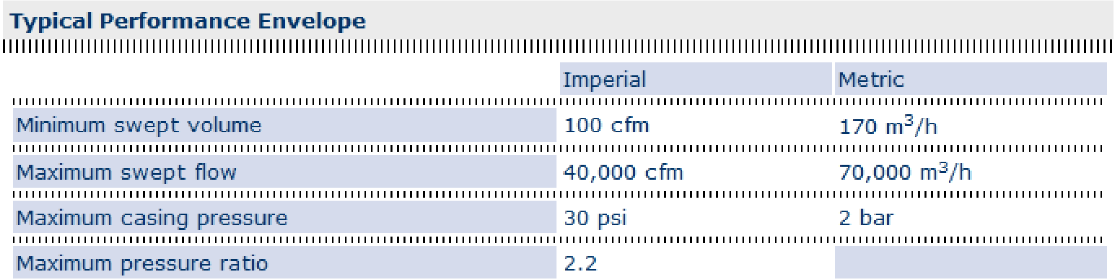
Typical Performance Envelope

	Imperial	Metric
Minimum swept volume	50 cfm	85 m^3/h
Maximum swept flow	70,000 cfm	120,000 m^3/h
Maximum casing pressure	30 psi	2 bar
Maximum pressure ratio	2	

12.3.2 Centrifugal blower



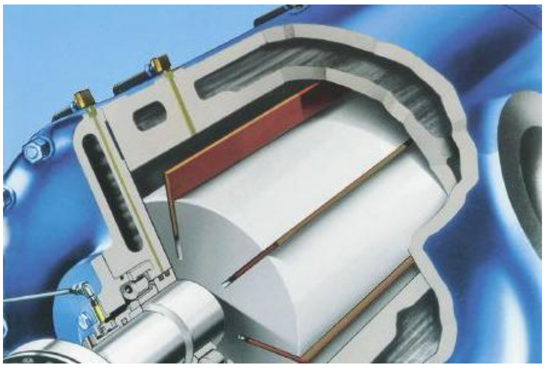
An impeller is attached to a rotating shaft within a cylindrical housing. Gas drawn into the housing near the centre, is then thrown towards the perimeter. The imparted velocity of the gas causes a pressure rise and flow. Multi-stage machines direct the gas back to the centre of the next stage.



Typical Performance Envelope

	Imperial	Metric
Minimum swept volume	100 cfm	170 m^3/h
Maximum swept flow	40,000 cfm	70,000 m^3/h
Maximum casing pressure	30 psi	2 bar
Maximum pressure ratio	2.2	

12.3.3 Rotary vane compressor



A single rotor is mounted offset in a cylindrical housing. Slots in the rotor contain vanes, which are thrown against the wall of the housing as it rotates. Oil is injected into the compression space to lubricate the bearings and vanes. As the rotor is offset, the segments that are created by the vanes vary in size through the cycle, causing the trapped gas to be compressed. Ports in the housing wall are positioned to let the gas in and out at the points of minimum and maximum pressure. Fully oil flooded versions are also available, with no oil loss to process.

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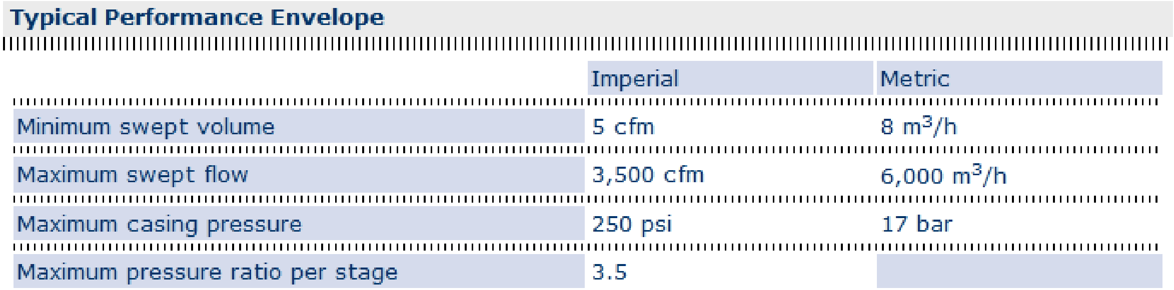
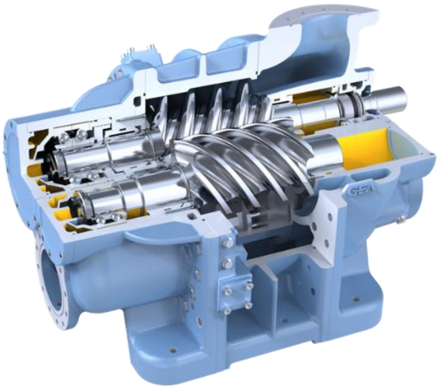
[31] http://www.gascompressors.co.uk/tech-osc.php



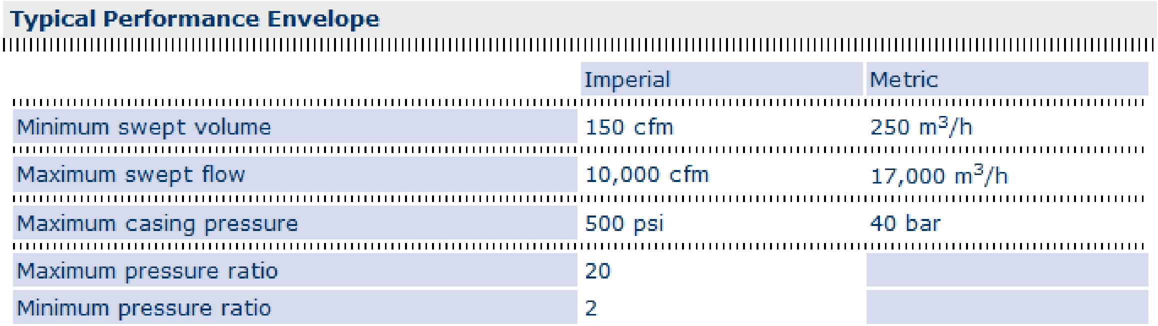
Typical Performance Envelope

	Imperial	Metric
Minimum swept volume	5 cfm	8 m^3/h
Maximum swept flow	3,500 cfm	6,000 m^3/h
Maximum casing pressure	250 psi	17 bar
Maximum pressure ratio per stage	3.5	

12.3.4 Oil flooded screw compressor



Twin screw shaped meshing rotors are mounted in a figure of eight shaped housing, which has suction and discharge ports at either end. As the rotors turn they form a space that traps gas, the space travels down the length of the housing, and because of the profile of the screws, is compressed as it goes. Oil is flood injected into the compression space to lubricate the bearings and screws, and to absorb the heat of compression. The oil and compressed gas mixture subsequently passes into a de-oiling vessel. The oil is then cooled and filtered and goes back round the cycle once again.

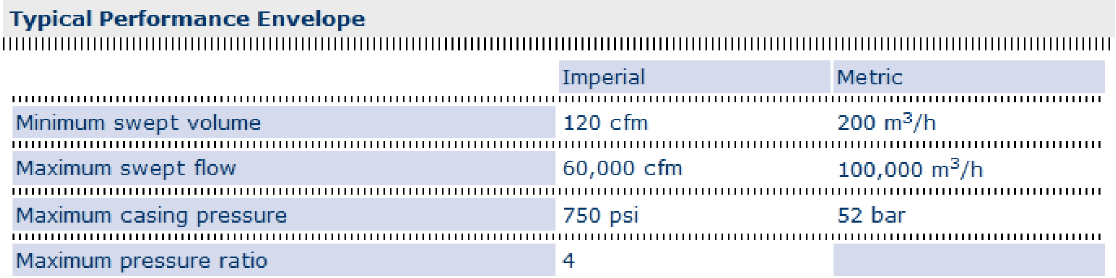


Typical Performance Envelope

	Imperial	Metric
Minimum swept volume	150 cfm	250 m^3/h
Maximum swept flow	10,000 cfm	17,000 m^3/h
Maximum casing pressure	500 psi	40 bar
Maximum pressure ratio	20	
Minimum pressure ratio	2	

12.3.5 Oil free screw compressor

Twin screw shaped meshing rotors are mounted in a figure of eight shaped housing, which has suction and discharge ports at either end. As the rotors turn they form a space that traps gas, the space travels down the length of the housing, and because of the profile of the screws, is compressed as it goes. Due to no lubricant in the compression space, timing gears are employed to ensure that the two rotors do not touch.



Typical Performance Envelope

	Imperial	Metric
Minimum swept volume	120 cfm	200 m^3/h
Maximum swept flow	60,000 cfm	100,000 m^3/h
Maximum casing pressure	750 psi	52 bar
Maximum pressure ratio	4	

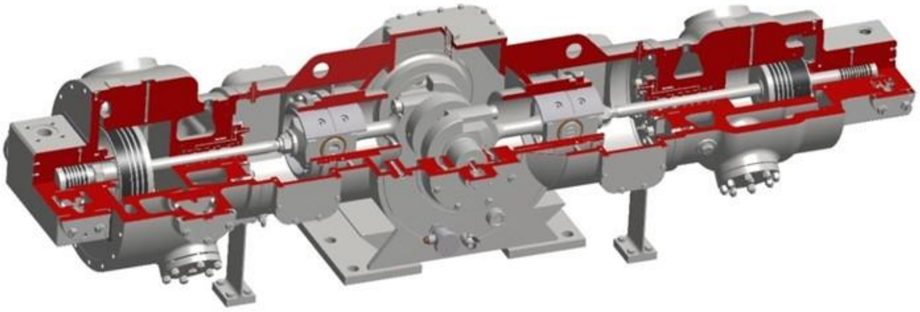
- **Advantages**
  - Flow controllable by speed variation.

  - Vibration free operation.
  - No special foundation required, lowering civil costs.
  - Pulsation free gas discharge.
  - Valve less porting means no drop off in efficiency between overhauls, and no valves to maintain or break in service.
  - No oil in contact with gas.
  - Resistant to damage by particulate.

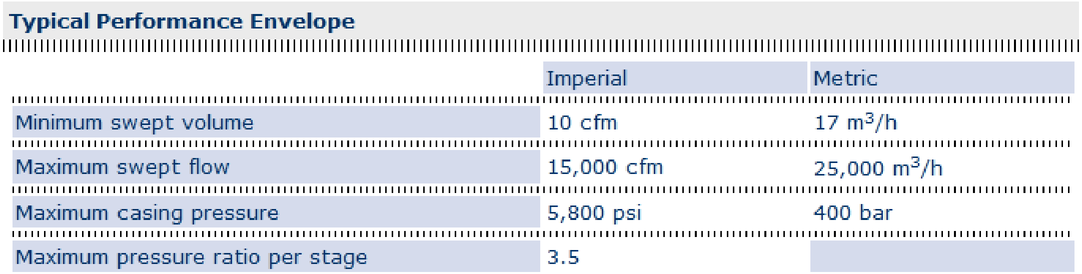
- **Disadvantages**
  - High capital cost.
  - Low pressure ratio per stage, but can be mounted in series.

- **Common applications**
  - Refinery service.
  - Flare gas recovery.

12.3.6 Reciprocating compressor



Similar to an automotive combustion engine, except passive non return valves replace actuated valves. A piston travels up and down inside a cylinder, and is connected to a crank shaft by a connecting rod. On the intake stroke, the discharge valves are forced shut, and gas is therefore sucked into the cylinder. On the compression stroke the suction valves are forced shut, and gas is expelled into the discharge port. On multi-stage machines, the gas must be cooled before entering the next stage.



Typical Performance Envelope

	Imperial	Metric
Minimum swept volume	10 cfm	17 m^3/h
Maximum swept flow	15,000 cfm	25,000 m^3/h
Maximum casing pressure	5,800 psi	400 bar
Maximum pressure ratio per stage	3.5	

8.1.1. Diaphragm compressor

Based on a reciprocating compressor frame. In place of conventional cylinders, is a saucer shaped stainless steel head, inside of which is a thin stainless steel diaphragm. The diaphragm oscillates up and down, powered by oil that is in turn pushed up and down by the piston. Gas is drawn in to the top of the head, and pushed out, in a similar manner to a reciprocating compressor, by passive poppet valves. The diaphragm totally insulates the gas stream from the mechanics and lubrication system, and so is often specified for hazardous or poisonous gas applications.

Typical Performance Envelope

	Imperial	Metric
Minimum swept volume	6 cfm	10 m^3/h
Maximum swept flow	1,800 cfm	3,000 m^3/h
Maximum casing pressure	15,000 psi	1,000 bar
Maximum pressure ratio per stage	20	

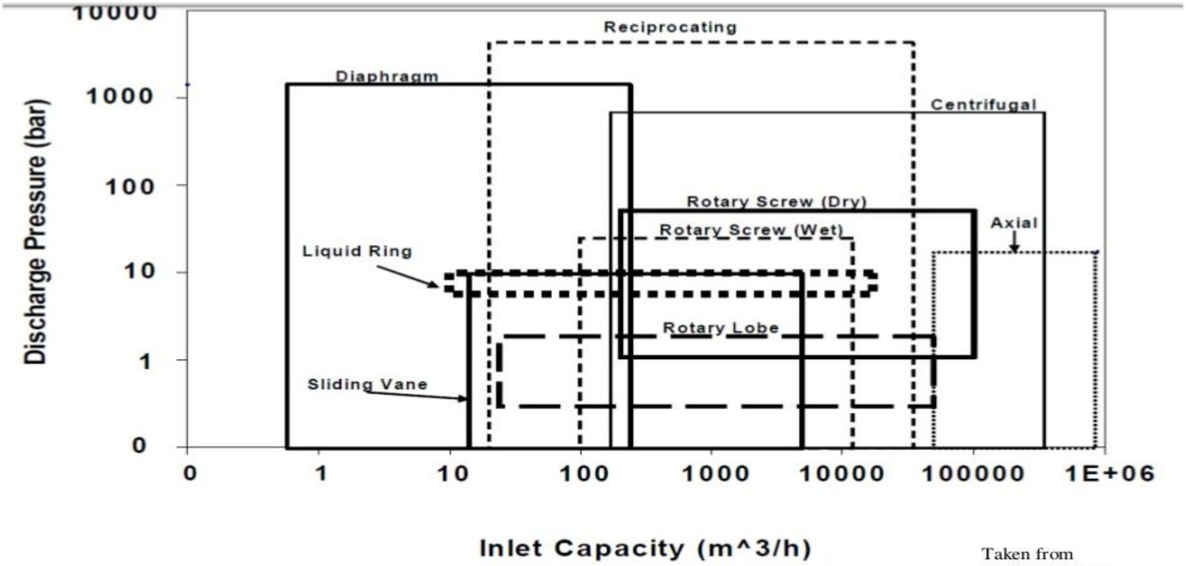
12.3.7 Centrifugal compressor

An impeller is attached to a rotating shaft within a cylindrical housing. Gas drawn into the housing near the centre, is then thrown towards the perimeter. The imparted velocity of the gas causes a pressure rise and flow. Multi-stage machines direct the gas back to the centre of the next stage. Differs from centrifugal blower in that pressure containment housing is much stronger. Two main layouts are Integrally Geared type, where several stages are mounted radially on a central speed increaser gearbox, and Barrel type, where stages are all mounted on a single shaft.

Typical Performance Envelope

	Imperial	Metric
Minimum swept volume	10,000 cfm	17,000 m^3/h
Maximum swept flow	180,000 cfm	300,000 m^3/h
Maximum casing pressure	2,200 psi	150 bar
Maximum pressure ratio	4	

Graph showing operating regions of various compressors



Taken from
PIP REEC001
Compressor Selection

Table showing operating conditions of various compressors

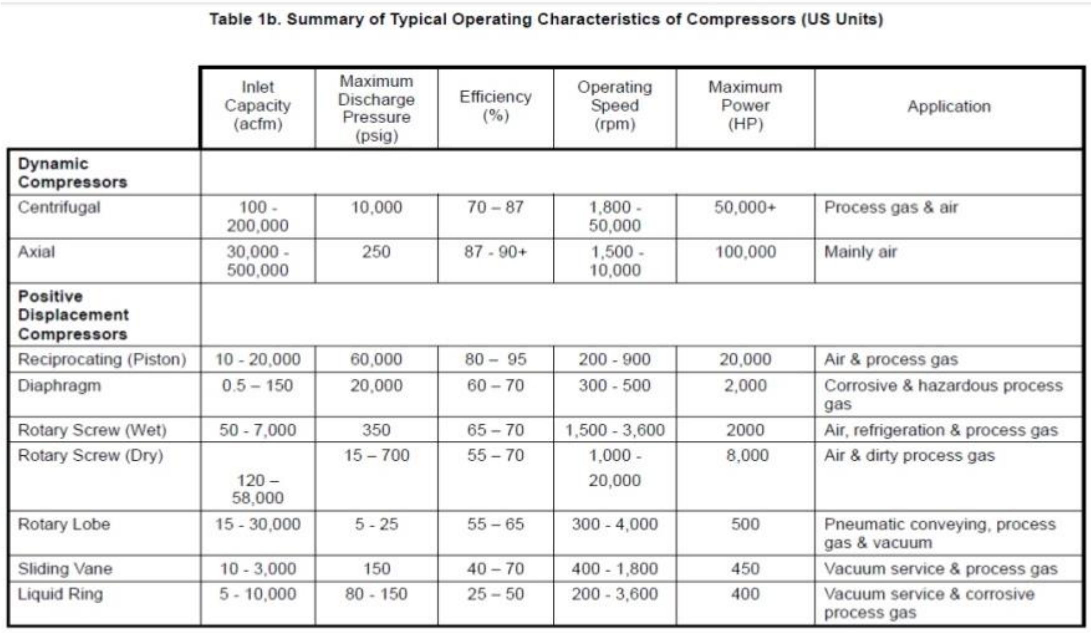
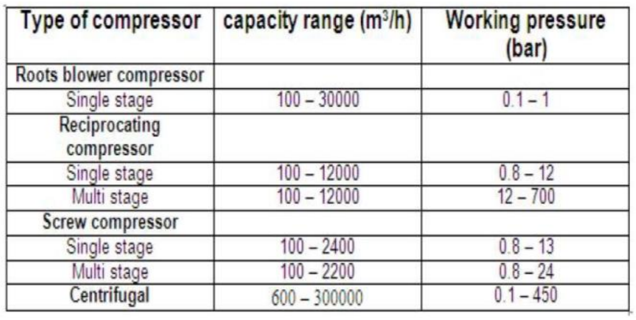


Table 1b. Summary of Typical Operating Characteristics of Compressors (US Units)

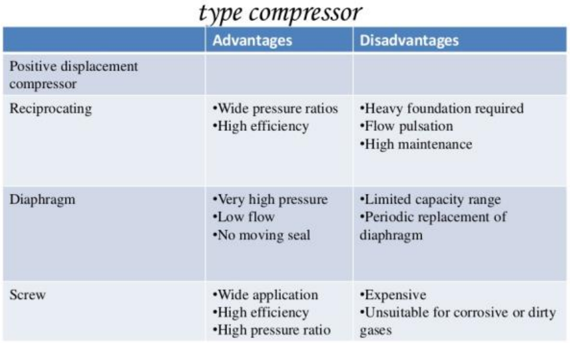
	Inlet Capacity (acfm)	Maximum Discharge Pressure (psig)	Efficiency (%)	Operating Speed (rpm)	Maximum Power (HP)	Application
Dynamic Compressors						
Centrifugal	100 - 200,000	10,000	70 – 87	1,800 - 50,000	50,000+	Process gas & air
Axial	30,000 - 500,000	250	87 - 90+	1,500 - 10,000	100,000	Mainly air
Positive Displacement Compressors						
Reciprocating (Piston)	10 - 20,000	60,000	80 – 95	200 - 900	20,000	Air & process gas
Diaphragm	0.5 – 150	20,000	60 – 70	300 - 500	2,000	Corrosive & hazardous process gas
Rotary Screw (Wet)	50 - 7,000	350	65 – 70	1,500 - 3,600	2000	Air, refrigeration & process gas
Rotary Screw (Dry)	120 – 58,000	15 – 700	55 – 70	1,000 - 20,000	8,000	Air & dirty process gas
Rotary Lobe	15 - 30,000	5 - 25	55 – 65	300 - 4,000	500	Pneumatic conveying, process gas & vacuum
Sliding Vane	10 - 3,000	150	40 – 70	400 - 1,800	450	Vacuum service & process gas
Liquid Ring	5 - 10,000	80 - 150	25 – 50	200 - 3,600	400	Vacuum service & corrosive process gas

Capacity and Pressure Range of various compressors



Type of compressor	capacity range (m^3/h)	Working pressure (bar)
Roots blower compressor		
Single stage	100 – 30000	0.1 – 1
Reciprocating compressor		
Single stage	100 – 12000	0.8 – 12
Multi stage	100 – 12000	12 – 700
Screw compressor		
Single stage	100 – 2400	0.8 – 13
Multi stage	100 – 2200	0.8 – 24
Centrifugal	600 – 300000	0.1 – 450

Advantages and disadvantages of positive displacement type compressor



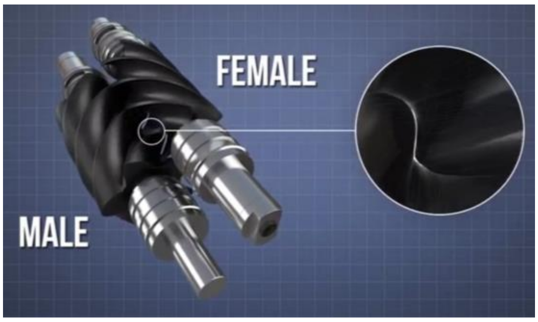
	Advantages	Disadvantages
Positive displacement compressor		
Reciprocating	•Wide pressure ratios •High efficiency	•Heavy foundation required •Flow pulsation •High maintenance
Diaphragm	•Very high pressure •Low flow •No moving seal	•Limited capacity range •Periodic replacement of diaphragm
Screw	•Wide application •High efficiency •High pressure ratio	•Expensive •Unsuitable for corrosive or dirty gases

selection of compressor lubricants

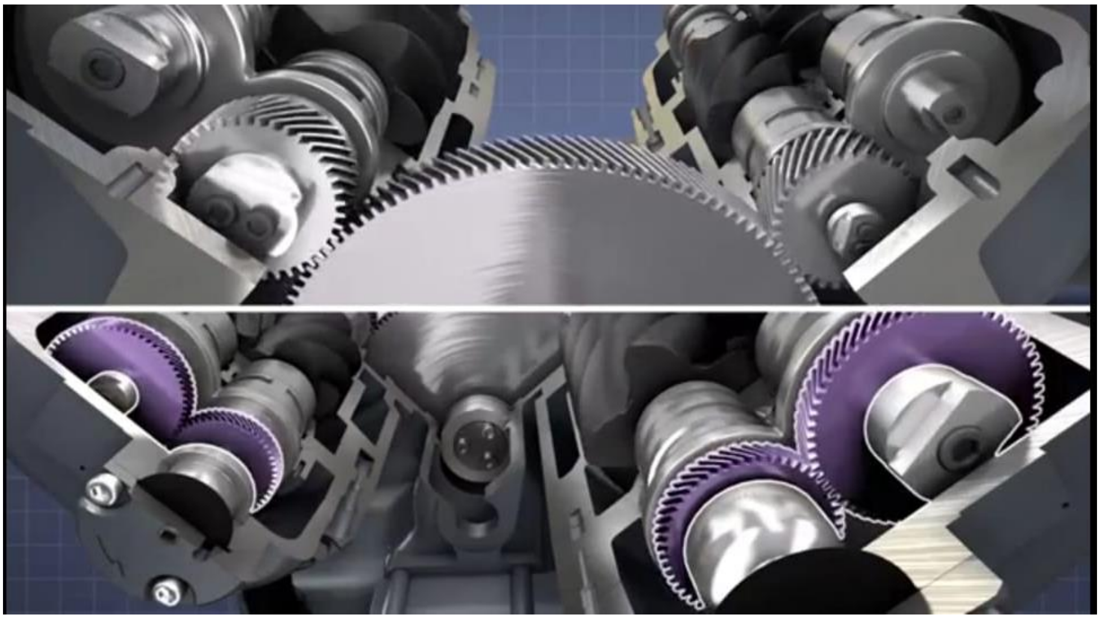
The major factors involved in the selection of compressor lubricants include:

- Type, size and speed of compressor
- Gas being compressed
- Number of stages
- Pressure and temperature at each stage
- Environment
- Type of lubrication system

12.4 Oil-free screw air compressor process

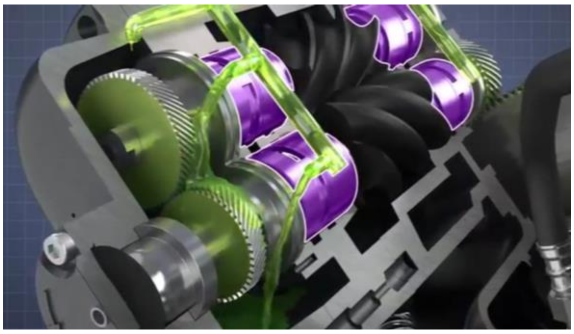
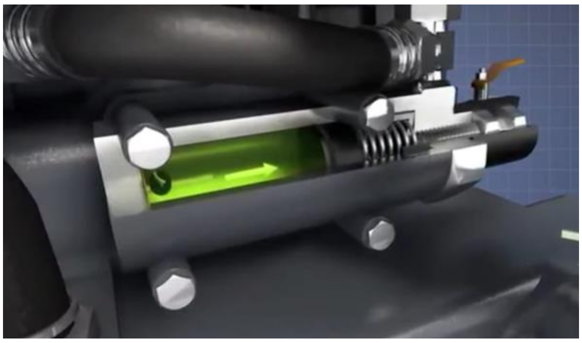


The oil-free industrial air compressor is a two-stage oil-free compressor unit. both compression stages comprise male and female rotors, with special protective coating. there's no physical contact either between the matched rotor pairs or the rotors and the air and casing. everything is separated by a precisely engineered air gap. The male rotors of both the first and second stages are driven by a single main gear at the back of the air end.



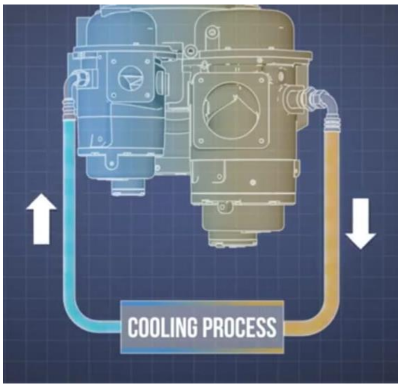
Helical timing gears at the front of both sets of rotors ensure perfect synchronization is kept between the rotor pairs at all times. This means no oil is needed to seal the compression process, making this air end a perfect solution wear oil-free compressed air is a critical requirement. Oil never enters the compression chambers, but is used to keep gears and bearings lubricated and cool. Special seals between the rotors and bearings prevent air passing into the oil system and oil passing into the compression chambers.

Hot oil drains to an oil reservoir located below the air and via to oil returned pipes. The hot oil is then pumped to a cooler and returns to the air environ oil filter. A pressure relief valve fitted to the front of the air and ensures that oil pressure doesn't exceed 2.5 bar or 36 psi.

Oil is topped up via a fillip pipe at the front to the air end. The compression process is kept cool by a constant flow of water passing through channels that surround the air end rotors. Heat transfers to the water which is then pumped through an external cooler before returning to the air end.

Air enters the third stage via the air intake valve and is trapped between the lobes and flutes on the underside of the compression rotors. As the rotors turn the volume of the trapped air reduces compressing the air and driving it towards the delivery port at the back of the air end. After leaving the first stage the compressed air passes through a pulsation damper, then on to a first stage or inter stage cooler. This can either be air or water cooled depending on the model of compressor. It's important to cool the air before it enters the second stage as hot air will have expanded.

When cooled, the air contract providing a greater number of air molecules in the same volume, this results in more efficient second stage compression. The cooled compressed air passes through a moisture separator, then on to the inlet port of the second stage. The volume of the air is greatly reduced after first stage compression, which means that the size of the second stage rotors can be smaller. The second stage further compresses the air to the required pressure in the same manner as the first stage. However, this time, the compression process takes place on the upper side of the rotors. the compressed air exits the air and fire a delivery silencer then through a non-return valve.

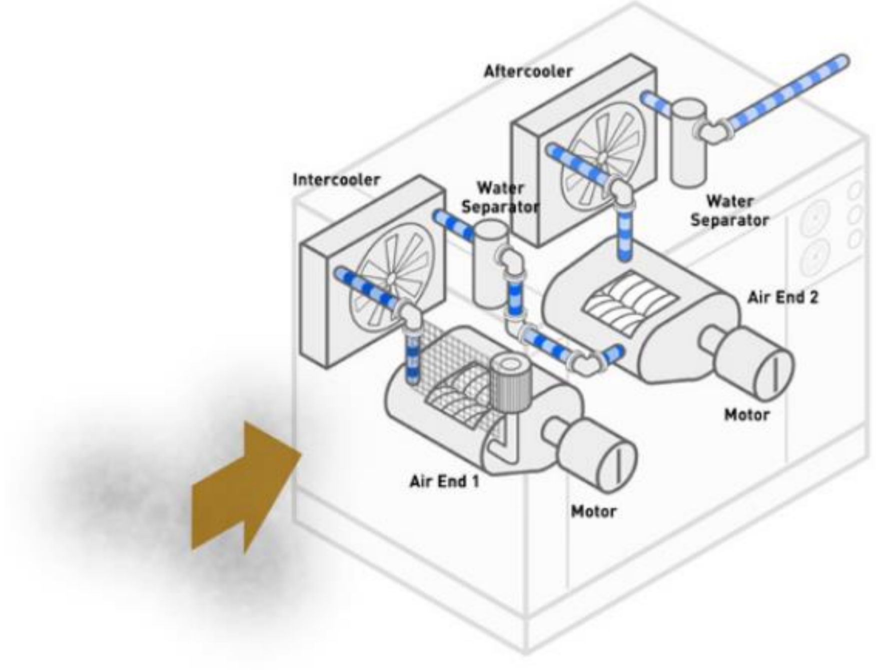
The air then passes through a final second stage air or water cooling process to ensure the delivery air is at the right temperature. Then after a final journey through a moisture separator, the air is ready to exit the compressor at the delivery port.

12.5 Overview of Screw Compressor Operation Oil Free

The obvious thought is that the term ‘Oil free compressor’ describes a compressor containing no oil. Unfortunately, that is not the case for most oil free compressors. An oil free compressor is the term used to describe a compressor that does not use oil in its compression stage.

Basic Operation – Oil Free Rotary Screw Compressor

Intake Filter → LPAir End → Inter Cooler → Liquid Separator → HP Air End → After Cooler → Liquid Separator →



Drive

Oil free rotary screw compressors are typically multi stage, driven by a single drive motor. This motor will drive a gear which in turn distributes the power to each air end. Some oil free screw compressors are now available where each compression stage driven by an individual motor

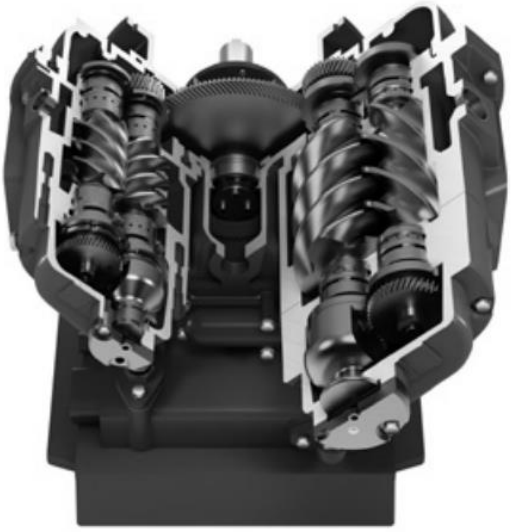
Compression

Unlike the oil injected screw compressor which uses oil to seal the gaps between the rotors and provide compression, oil free variants achieve compression in an alternative way.

Rotor elements are manufactured in pairs with extremely tight tolerances to decrease the gap between them. During operation, rotors are spun at much higher speeds than an equivalent oil injected ompressor. Specialist coatings are often applied to the rotors to give some of the protection from water and heat usually provided by oil.

The rotors operate extremely close to each other, however as there is no oil in the compression stage to prevent the rotors from touching, the distance between each rotor is maintained by additional gearing.

Cooling



As there is no oil in the compression chamber to provide direct cooling, indirect cooling is used. The air end housings of oil free compression stages typically contain gelleries in which cooling water (on water cooled machines) or oil (on air cooled machines) can be circulated. This process is not as efficient as direct cooling as it only cools the casing and not the compressed air or the rotors.

Due to the lack of direct cooling in an oil free compressor, the compressed air and rotors reach much higher temperatures. Oil-free compressors therefore obtain their final discharge pressure in stages (as opposed to oil injected machines which typically use only 1 stage). Between stages they will cool the compressed air with an inter-cooler. This keeps typical air end temperatures between 180°C & 200°C.

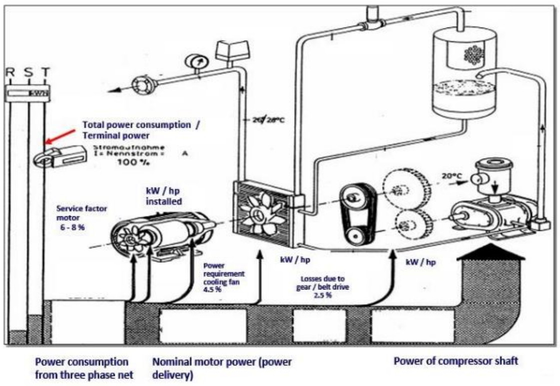
For example, on a typical oil free rotary screw compressor with 2 compression stages, an intercooler and aftercooler. Stage 1 will typically compress the air up to a pressure around 3.5 bar g, stage 2 will then compress the air to the discharge pressure of 7 bar g.

Lubrication

On an oil free screw compressor, it is not only important that the individual rotors in each air end are synchronised with gears, with only one drive motor, additional gearing is also required to drive each of the air ends. All of the gearing and bearings require lubrication. So although the name implies that an oil free compressor is "oil less", for most oil free compressors sold, this is not the case. Oil is not used in the compression stages; however, oil is still required for lubrication and cooling of other components. This oil is pumped around the compressor forming a closed loop system which lubricates bearings and gears, is filtered, cooled and recirculated.

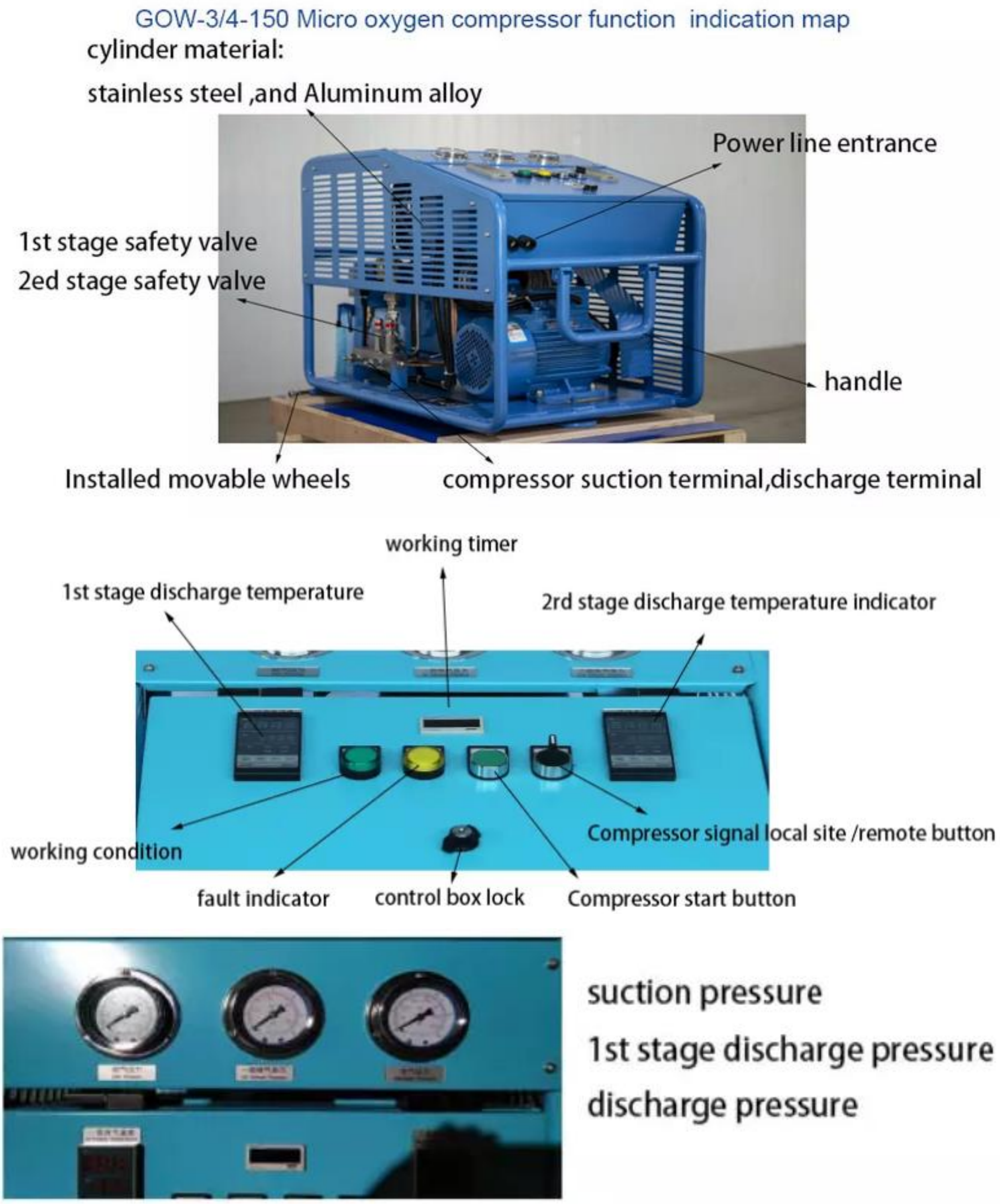
Oil Reclamation (Air / Oil Separator)

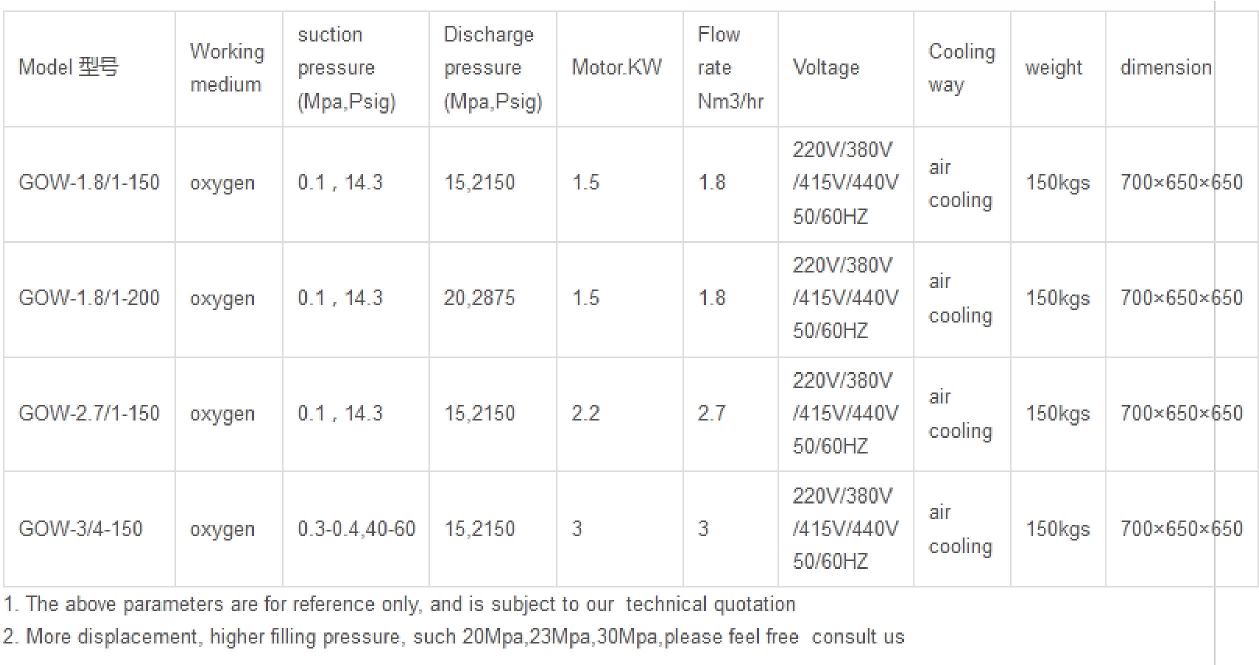
As there is no oil used in the compression stage, there is no requirement for an air / oil separator on an oil free compressor.



Compressor #1: (info completed)

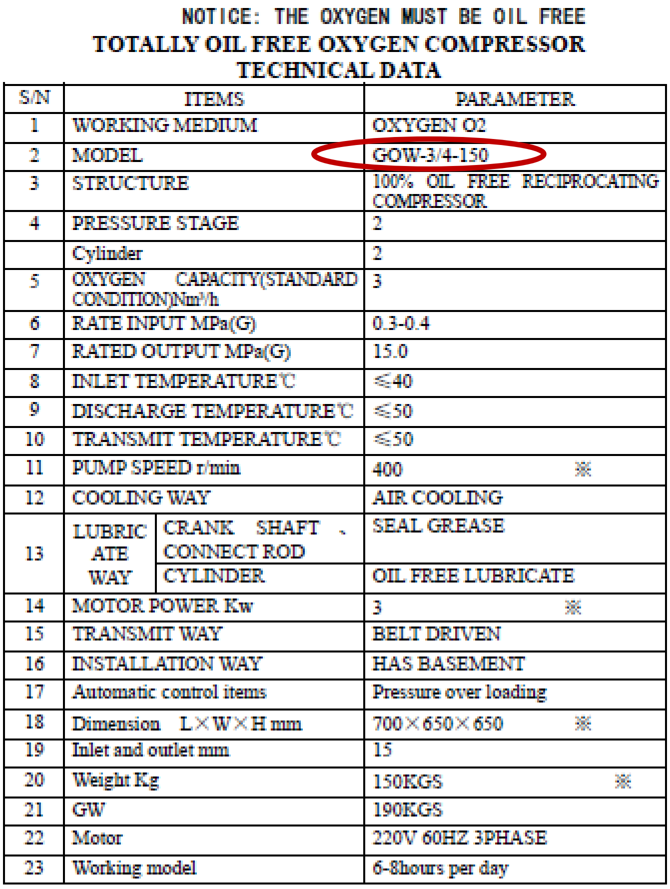
https://www.oxygen-compressors.com/2m3-High-Pressure-Industrial-Booster-Oxygen-Compressor-pd46014866.html


GOW-3/4-150 Micro oxygen compressor function indication map
cylinder material:
stainless steel ,and Aluminum alloy
Power line entrance
1st stage safety valve
2ed stage safety valve
handle
Installed movable wheels
compressor suction terminal,discharge terminal
working timer
1st stage discharge temperature
2rd stage discharge temperature indicator
working condition
Compressor signal local site /remote button
fault indicator
control box lock
Compressor start button
suction pressure
1st stage discharge pressure
discharge pressure



Model 型号	Working medium	suction pressure (Mpa,Psig)	Discharge pressure (Mpa,Psig)	Motor.KW	Flow rate Nm3/hr	Voltage	Cooling way	weight	dimension
GOW-1.8/1-150	oxygen	0.1，14.3	15,2150	1.5	1.8	220V/380V /415V/440V 50/60HZ	air cooling	150kgs	700×650×650
GOW-1.8/1-200	oxygen	0.1，14.3	20,2875	1.5	1.8	220V/380V /415V/440V 50/60HZ	air cooling	150kgs	700×650×650
GOW-2.7/1-150	oxygen	0.1，14.3	15,2150	2.2	2.7	220V/380V /415V/440V 50/60HZ	air cooling	150kgs	700×650×650
GOW-3/4-150	oxygen	0.3-0.4,40-60	15,2150	3	3	220V/380V /415V/440V 50/60HZ	air cooling	150kgs	700×650×650

1. The above parameters are for reference only, and is subject to our technical quotation
2. More displacement, higher filling pressure, such 20Mpa,23Mpa,30Mpa,please feel free consult us



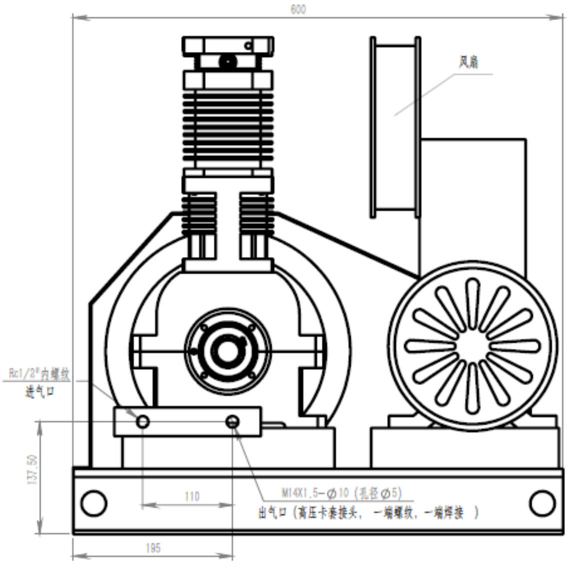
NOTICE: THE OXYGEN MUST BE OIL FREE

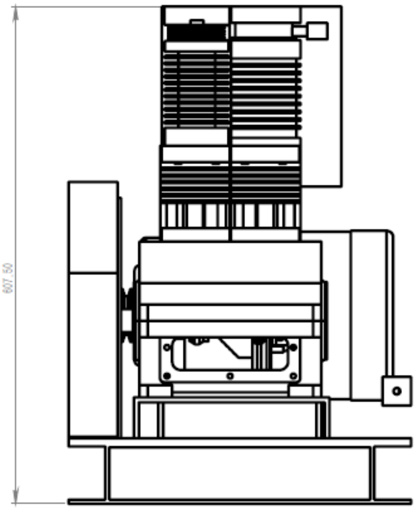
TOTALLY OIL FREE OXYGEN COMPRESSOR

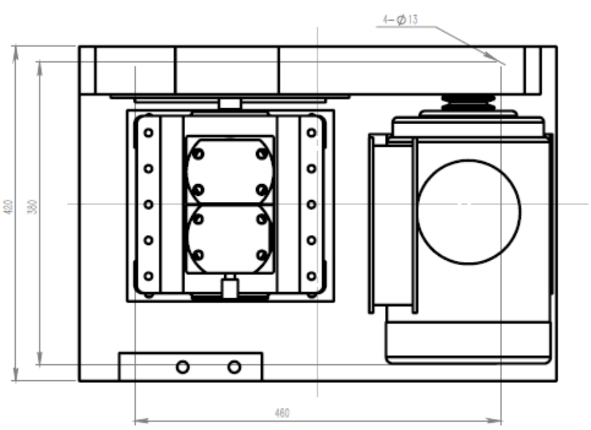
TECHNICAL DATA

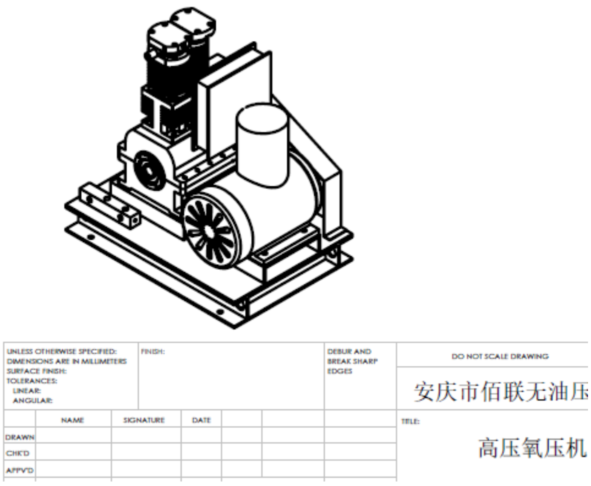
S/N	ITEMS		PARAMETER
1	WORKING MEDIUM		OXYGEN O2
2	MODEL		GOW-3/4-150
3	STRUCTURE		100% OIL FREE RECIPROCATING COMPRESSOR
4	PRESSURE STAGE		2
	Cylinder		2
5	OXYGEN CAPACITY(STANDARD CONDITION)Nm³/h		3
6	RATE INPUT MPa(G)		0.3-0.4
7	RATED OUTPUT MPa(G)		15.0
8	INLET TEMPERATURE℃		≤40
9	DISCHARGE TEMPERATURE℃		≤50
10	TRANSMIT TEMPERATURE℃		≤50
11	PUMP SPEED r/min		400 ※
12	COOLING WAY		AIR COOLING
13	LUBRICATE WAY	CRANK SHAFT 、CONNECT ROD	SEAL GREASE
		CYLINDER	OIL FREE LUBRICATE
14	MOTOR POWER Kw		3 ※
15	TRANSMIT WAY		BELT DRIVEN
16	INSTALLATION WAY		HAS BASEMENT
17	Automatic control items		Pressure over loading
18	Dimension L×W×H mm		700×650×650 ※
19	Inlet and outlet mm		15
20	Weight Kg		150KGS ※
21	GW		190KGS
22	Motor		220V 60HZ 3PHASE
23	Working model		6-8hours per day

GOW-3/4-150 FOB SHANGHAI USD8000/PC



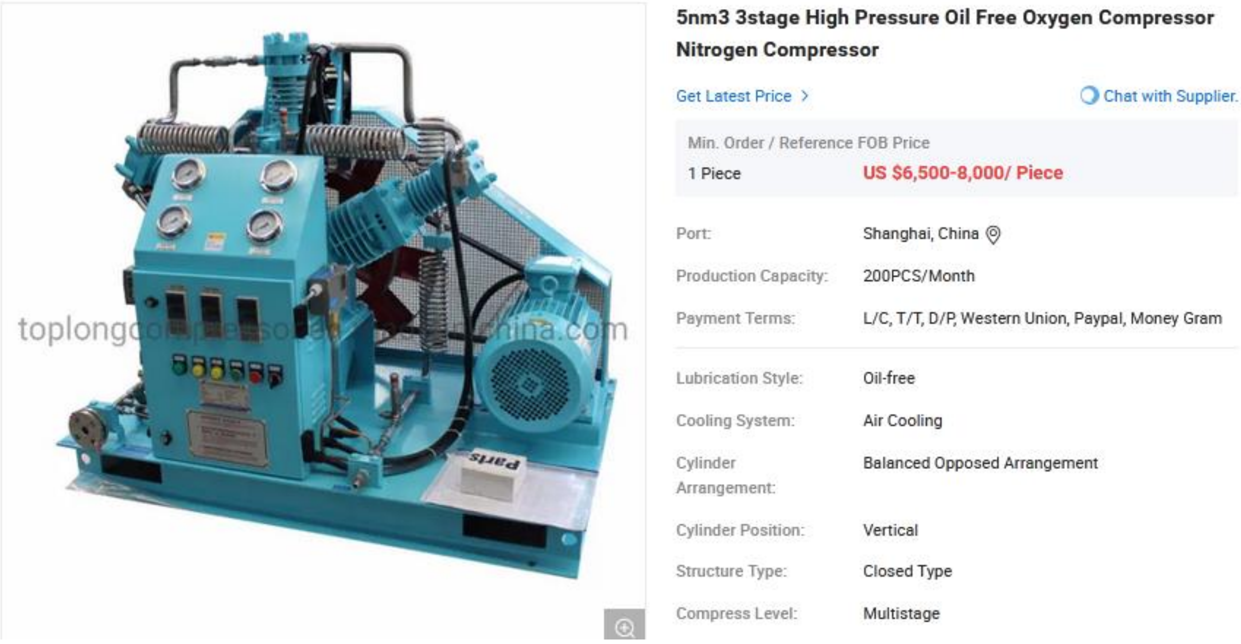






Compressor #2: (info uncompleted)

https://toplongcompressor.en.made-in-china.com/product/IvVmtGBbhyhA/China-5nm3-3stage-High-Pressure-Oil-Free-Oxygen-Compressor-Nitrogen-Compressor.html



5nm3 3stage High Pressure Oil Free Oxygen Compressor Nitrogen Compressor

Get Latest Price >

Chat with Supplier.

Min. Order / Reference FOB Price	
1 Piece	US $6,500-8,000/ Piece

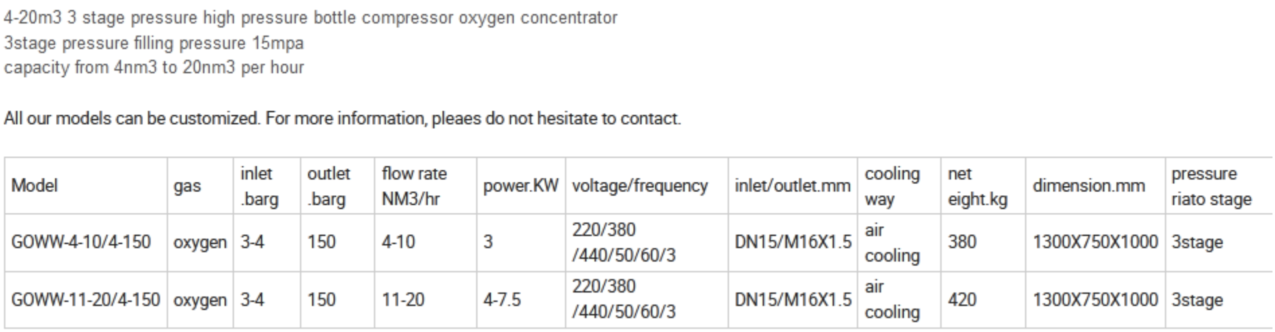
Port:	Shanghai, China
Production Capacity:	200PCS/Month
Payment Terms:	L/C, T/T, D/P, Western Union, Paypal, Money Gram
Lubrication Style:	Oil-free
Cooling System:	Air Cooling
Cylinder Arrangement:	Balanced Opposed Arrangement
Cylinder Position:	Vertical
Structure Type:	Closed Type
Compress Level:	Multistage

Product Description
Oil-free Special Gas Compressor

Oil-free special gas compressor booster is the kind of semi-hermetic compressor, it adopts hermetic construction for its motor without pollution to the medium to be compressed and without leakage. This series compressor has numerous advantage of reliable performance, simple operation, compact construction, quick connection and so on. It can be applied in the compression and recovery of toxic, rare and precious gas such as SF6, helium, methane, ammonia, Freon, carbon dioxide and so on.

Performance Characteristics

Oil free high pressure oxygen nitrogen helium Co2 gas compressor
Principle 1: Oil-free type reciprocating piston
2 Cooling Type: Air-cooled or water-cooled
(3) Power consumption: ≤ 110kw4 Speed: . 300-560rpm
5 Flow: . ≤ 2000Nm3 / h6
Suction pressure: . 0-5Mpa7
Exhaust pressure: . ≤ 16.5Mpa8 Compression Level: 1-4Winds oil-free compressors
Product Features: No oil lubrication with clean and non-polluting.
High efficiency, low energy consumption. High reliability, continuous 24-hour operation. The unit uses air-cooled or water-cooled, compact structure, operation and low maintenance cost



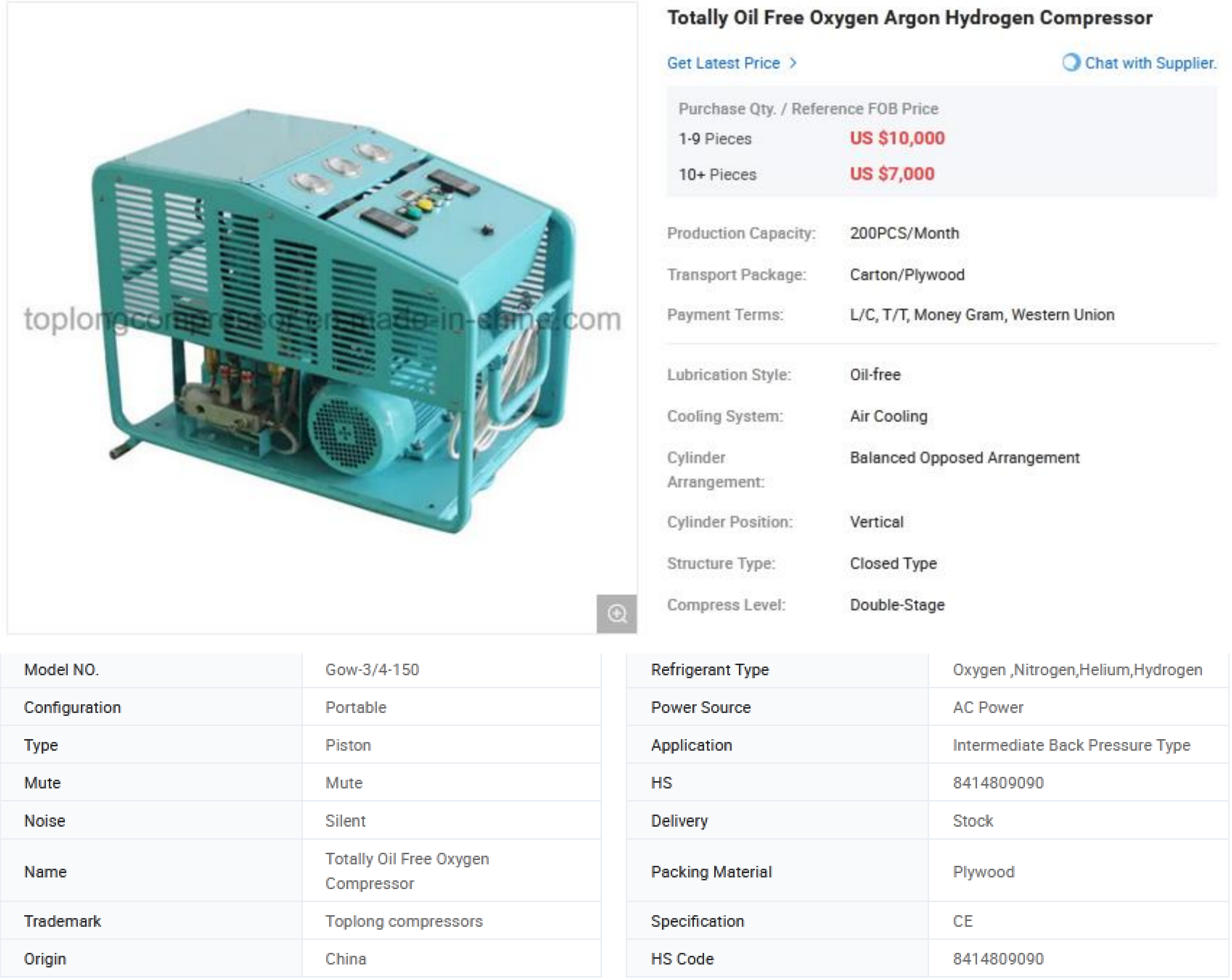
4-20m3 3 stage pressure high pressure bottle compressor oxygen concentrator
3stage pressure filling pressure 15mpa
capacity from 4nm3 to 20nm3 per hour

All our models can be customized. For more information, pleaes do not hesitate to contact.

Model	gas	inlet .barg	outlet .barg	flow rate NM3/hr	power.KW	voltage/frequency	inlet/outlet.mm	cooling way	net eight.kg	dimension.mm	pressure riato stage
GOWW-4-10/4-150	oxygen	3-4	150	4-10	3	220/380 /440/50/60/3	DN15/M16X1.5	air cooling	380	1300X750X1000	3stage
GOWW-11-20/4-150	oxygen	3-4	150	11-20	4-7.5	220/380 /440/50/60/3	DN15/M16X1.5	air cooling	420	1300X750X1000	3stage

Compressor #3: (info uncompleted)

https://toplongcompressor.en.made-in-china.com/product/oXcQMuqdpshw/China-Totally-Oil-Free-Oxygen-Argon-Hydrogen-Compressor.html

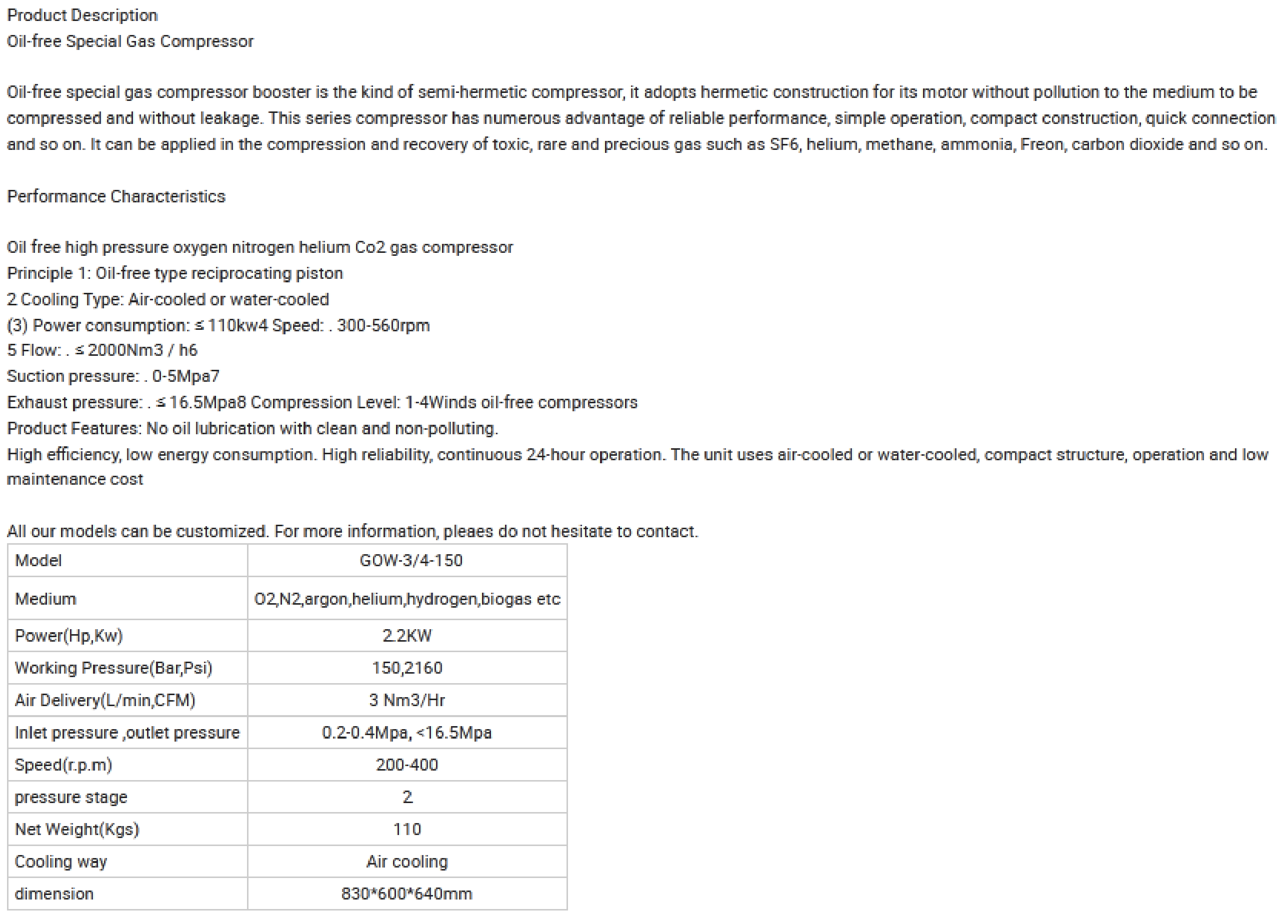


Totally Oil Free Oxygen Argon Hydrogen Compressor

Purchase Qty. / Reference FOB Price	
1-9 Pieces	US $10,000
10+ Pieces	US $7,000

Production Capacity:	200PCS/Month
Transport Package:	Carton/Plywood
Payment Terms:	L/C, T/T, Money Gram, Western Union
Lubrication Style:	Oil-free
Cooling System:	Air Cooling
Cylinder Arrangement:	Balanced Opposed Arrangement
Cylinder Position:	Vertical
Structure Type:	Closed Type
Compress Level:	Double-Stage

Model NO.	Gow-3/4-150	Refrigerant Type	Oxygen ,Nitrogen,Helium,Hydrogen
Configuration	Portable	Power Source	AC Power
Type	Piston	Application	Intermediate Back Pressure Type
Mute	Mute	HS	8414809090
Noise	Silent	Delivery	Stock
Name	Totally Oil Free Oxygen Compressor	Packing Material	Plywood
Trademark	Toplong compressors	Specification	CE
Origin	China	HS Code	8414809090



Product Description
Oil-free Special Gas Compressor

Oil-free special gas compressor booster is the kind of semi-hermetic compressor, it adopts hermetic construction for its motor without pollution to the medium to be compressed and without leakage. This series compressor has numerous advantage of reliable performance, simple operation, compact construction, quick connection and so on. It can be applied in the compression and recovery of toxic, rare and precious gas such as SF6, helium, methane, ammonia, Freon, carbon dioxide and so on.

Performance Characteristics

Oil free high pressure oxygen nitrogen helium Co2 gas compressor
Principle 1: Oil-free type reciprocating piston
2 Cooling Type: Air-cooled or water-cooled
(3) Power consumption: ≤ 110kw4 Speed: . 300-560rpm
5 Flow: . ≤ 2000Nm3 / h6
Suction pressure: . 0-5Mpa7
Exhaust pressure: . ≤ 16.5Mpa8 Compression Level: 1-4Winds oil-free compressors
Product Features: No oil lubrication with clean and non-polluting.
High efficiency, low energy consumption. High reliability, continuous 24-hour operation. The unit uses air-cooled or water-cooled, compact structure, operation and low maintenance cost

All our models can be customized. For more information, pleaes do not hesitate to contact.

Model	GOW-3/4-150
Medium	O2,N2,argon,helium,hydrogen,biogas etc
Power(Hp,Kw)	2.2KW
Working Pressure(Bar,Psi)	150,2160
Air Delivery(L/min,CFM)	3 Nm3/Hr
Inlet pressure ,outlet pressure	0.2-0.4Mpa, <16.5Mpa
Speed(r.p.m)	200-400
pressure stage	2
Net Weight(Kgs)	110
Cooling way	Air cooling
dimension	830*600*640mm

Compressor #4: (same family of compressor #1)

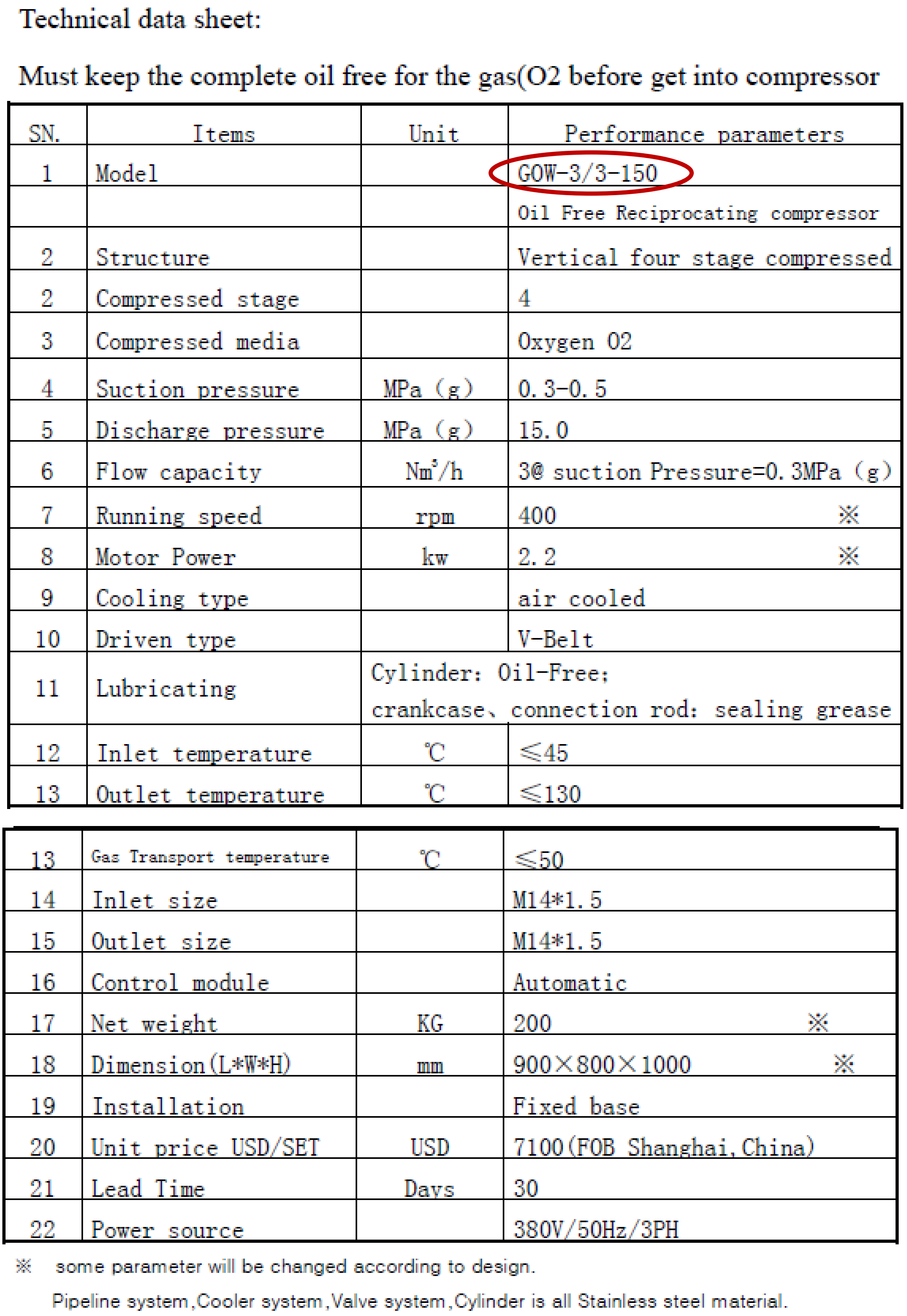
http://www.cnsouair.com/compressor/CompAirsGasCompressor/1326.html

https://souair.en.alibaba.com/

email: ironcai@cnsouair.com

WhatsApp:008618121319076

Oil-Free Lubricating Oxygen O2 Gas Compressor



Technical data sheet:

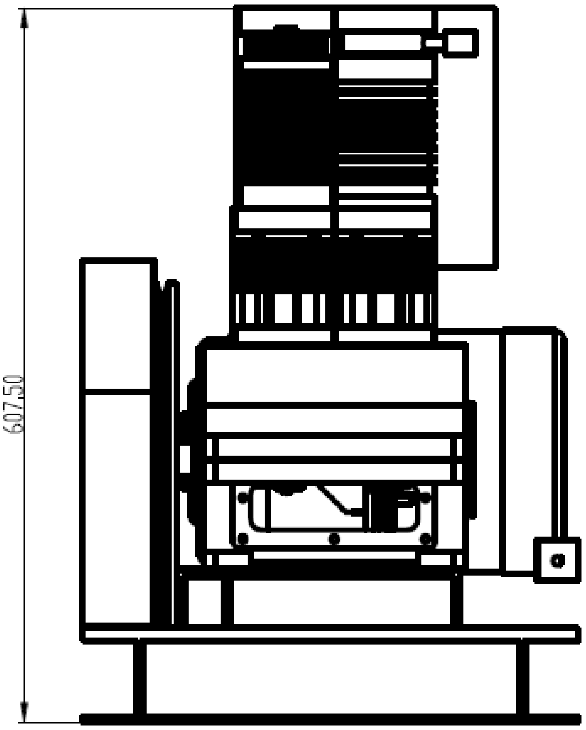
Must keep the complete oil free for the gas(O2 before get into compressor

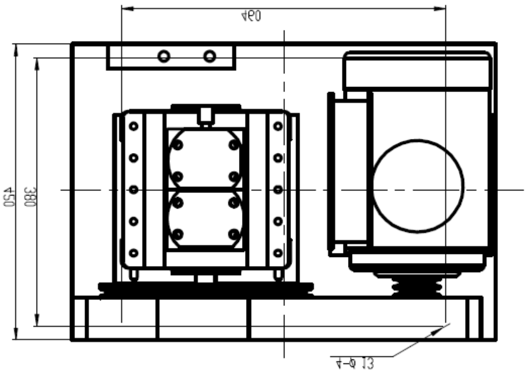
SN.	Items	Unit	Performance parameters
1	Model		GOW-3/3-150
			Oil Free Reciprocating compressor
2	Structure		Vertical four stage compressed
2	Compressed stage		4
3	Compressed media		Oxygen O2
4	Suction pressure	MPa（g）	0.3-0.5
5	Discharge pressure	MPa（g）	15.0
6	Flow capacity	Nm^3/h	3@ suction Pressure=0.3MPa（g）
7	Running speed	rpm	400 ※
8	Motor Power	kw	2.2 ※
9	Cooling type		air cooled
10	Driven type		V-Belt
11	Lubricating	Cylinder: Oil-Free; crankcase、connection rod: sealing grease	
12	Inlet temperature	℃	≤45
13	Outlet temperature	℃	≤130
13	Gas Transport temperature	℃	≤50
14	Inlet size		M14*1.5
15	Outlet size		M14*1.5
16	Control module		Automatic
17	Net weight	KG	200 ※
18	Dimension(L*W*H)	mm	900×800×1000 ※
19	Installation		Fixed base
20	Unit price USD/SET	USD	7100(FOB Shanghai, China)
21	Lead Time	Days	30
22	Power source		380V/50Hz/3PH

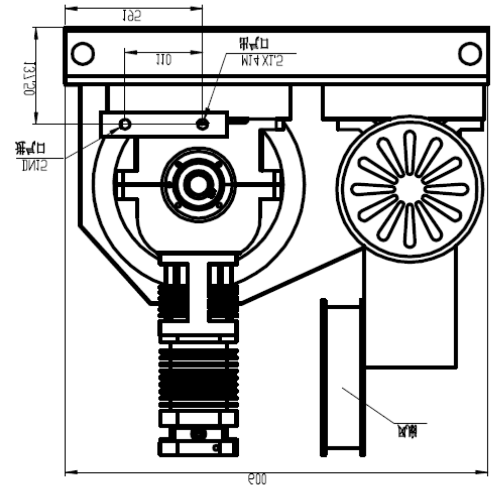
※ some parameter will be changed according to design.

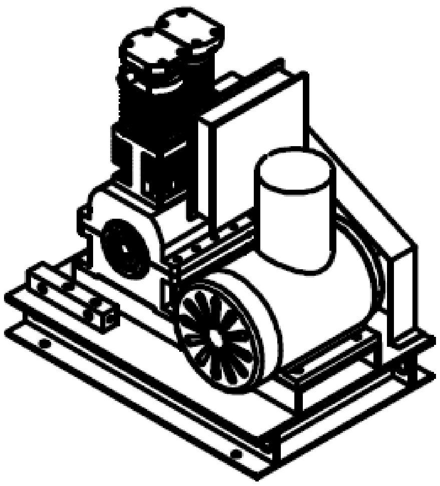
Pipeline system, Cooler system, Valve system, Cylinder is all Stainless steel material.

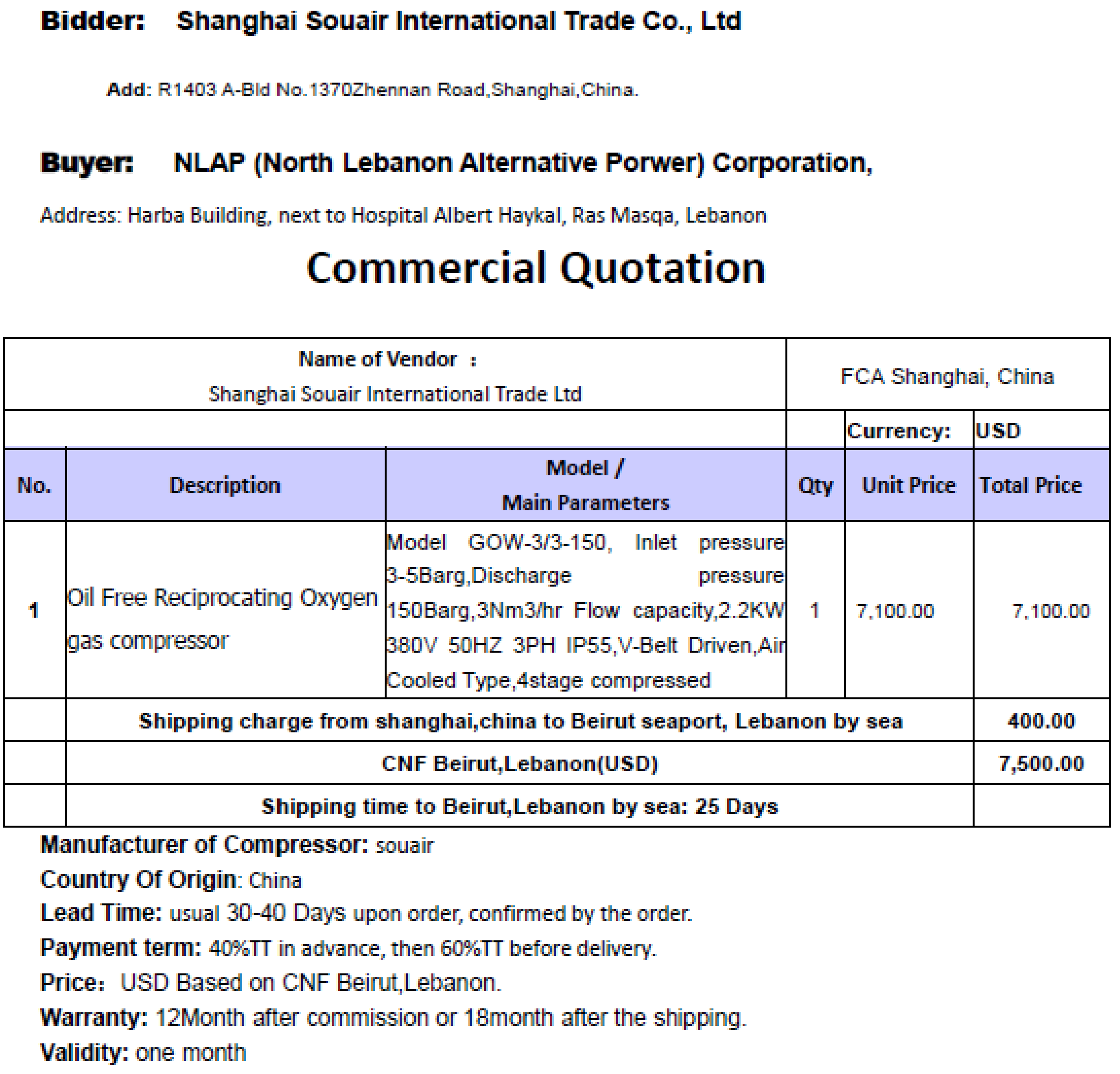
GOW-3/4-150











Bidder: **Shanghai Souair International Trade Co., Ltd**

Add: R1403 A-Bld No.1370Zhennan Road,Shanghai,China.

Buyer: **NLAP (North Lebanon Alternative Porwer) Corporation,**

Address: Harba Building, next to Hospital Albert Haykal, Ras Masqa, Lebanon

Commercial Quotation

Name of Vendor ： Shanghai Souair International Trade Ltd			FCA Shanghai, China		
				Currency:	**USD**
No.	**Description**	**Model / Main Parameters**	**Qty**	**Unit Price**	**Total Price**
1	Oil Free Reciprocating Oxygen gas compressor	Model GOW-3/3-150, Inlet pressure 3-5Barg,Discharge pressure 150Barg,3Nm3/hr Flow capacity,2.2KW 380V 50HZ 3PH IP55,V-Belt Driven,Air Cooled Type,4stage compressed	1	7,100.00	7,100.00
	Shipping charge from shanghai,china to Beirut seaport, Lebanon by sea				**400.00**
	CNF Beirut,Lebanon(USD)				**7,500.00**
	Shipping time to Beirut,Lebanon by sea: 25 Days				

Manufacturer of Compressor: souair
Country Of Origin: China
Lead Time: usual 30-40 Days upon order, confirmed by the order.
Payment term: 40%TT in advance, then 60%TT before delivery.
Price: USD Based on CNF Beirut,Lebanon.
Warranty: 12Month after commission or 18month after the shipping.
Validity: one month

Compressor #5:

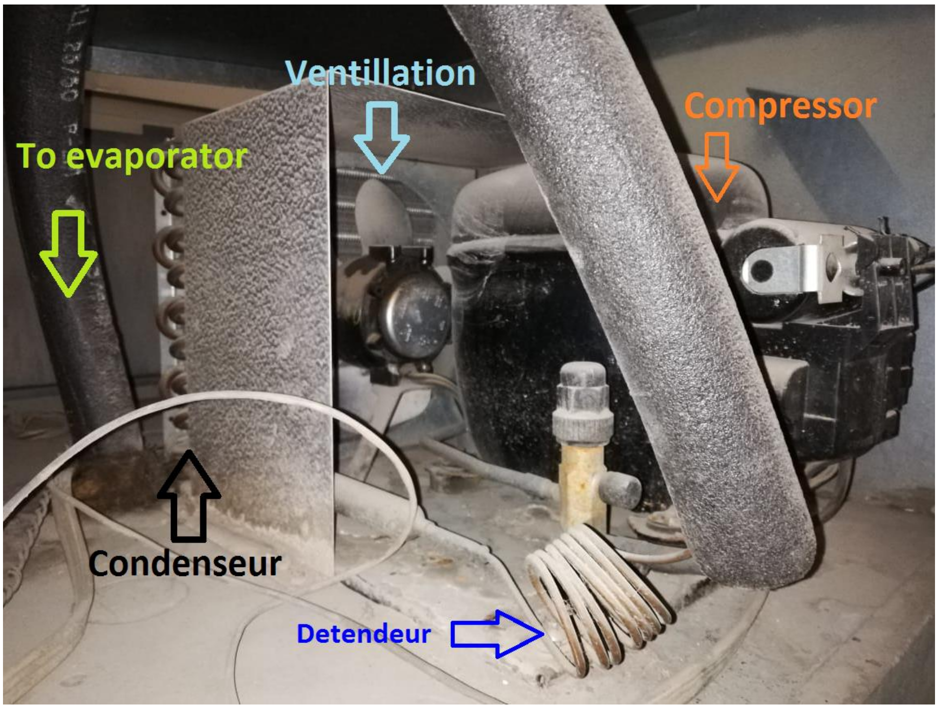
https://www.oxywise.com/en/products/oxygen-hp-compressor?gclid=EAIaIQobChMI84-M8euo7wIVQe7tCh2CnAb-EAAYASAAEgLM3vD_BwE

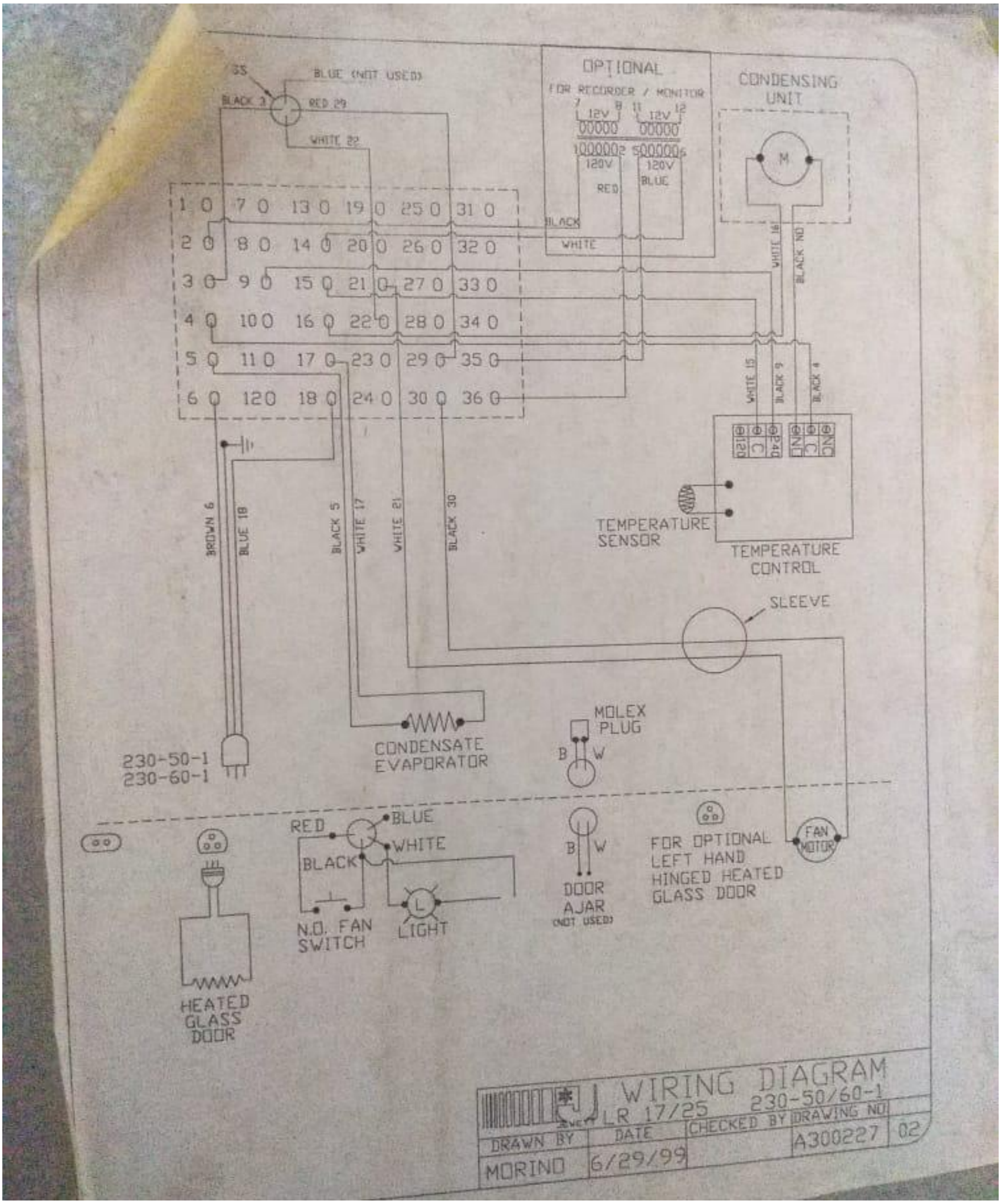
I am looking for an oxygen compressor (oil-free) taht has the following specifications:
inlet pressure : 1 bar - 5 bar
outlet pressure : 100 bar
flow rate: more than 800 L/hr

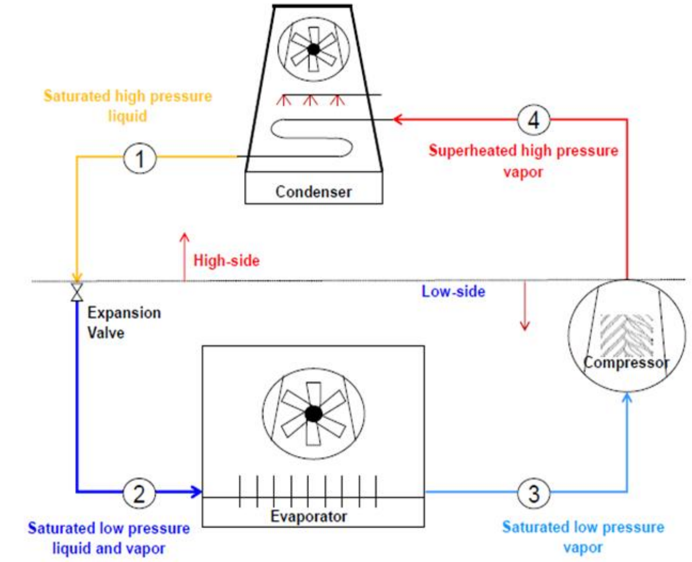
Oxywise Answer: (Monday 15.3.2021)
I'm sorry we don't have a RIX unit that small.
I can offer an unbranded CE marked Oxygen compressor?
Price is circa €8k. Leadtime 5 weeks.

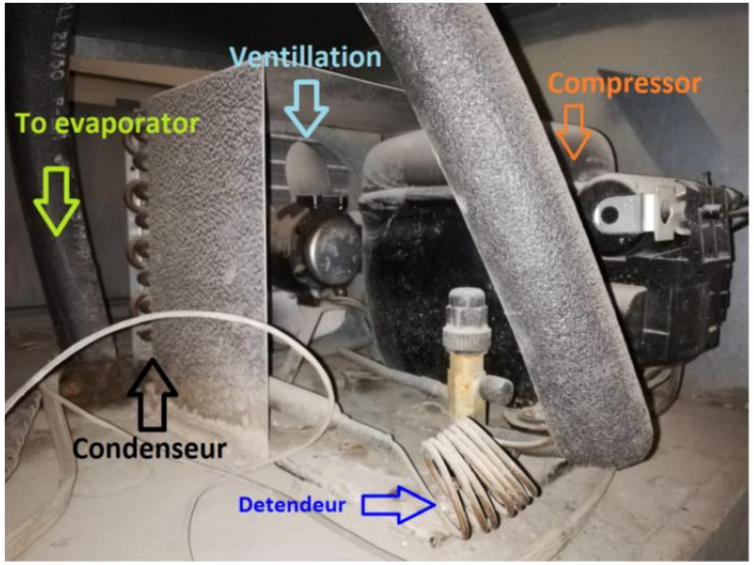
13 Project D and E in 21: Analysis of refrigerator devices in AECENAR Center

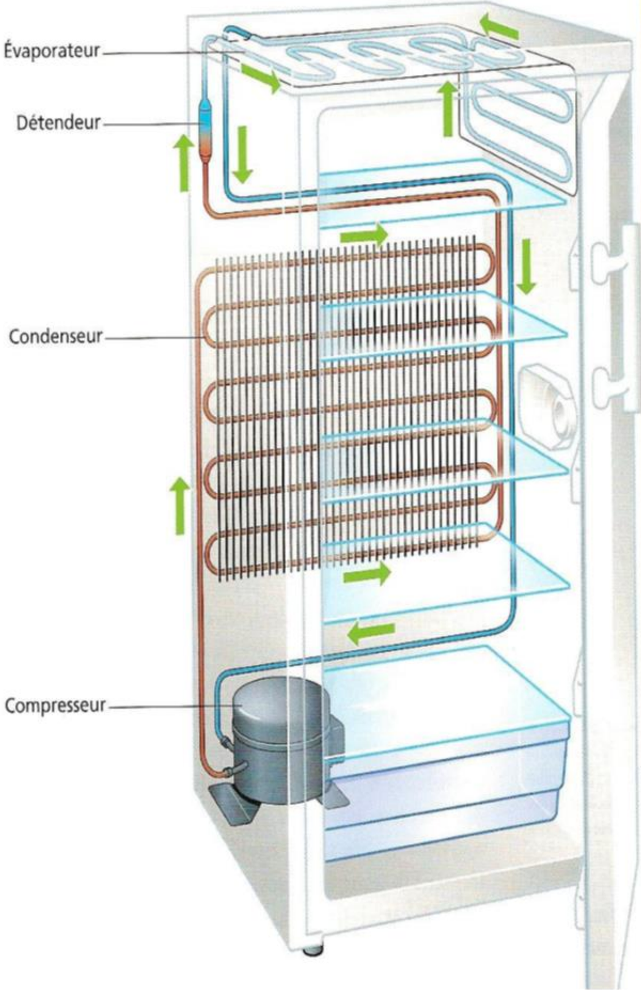
13.1 Device1 : Laboratory fridge

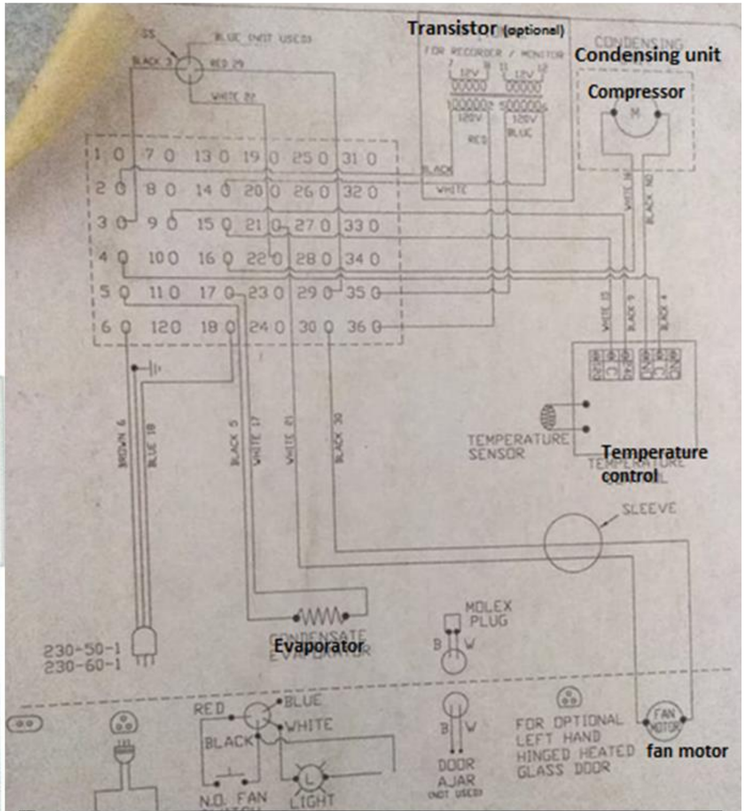



SS
BLUE (NOT USED)
BLACK 3
RED 29
WHITE 22
OPTIONAL
FOR RECORDER / MONITOR
12V
12V
120V
120V
RED
BLUE
BLACK
WHITE
CONDENSING UNIT
M
WHITE 18
BLACK NO
1 0
7 0
13 0
19 0
25 0
31 0
2 0
8 0
14 0
20 0
26 0
32 0
3 0
9 0
15 0
21 0
27 0
33 0
4 0
10 0
16 0
22 0
28 0
34 0
5 0
11 0
17 0
23 0
29 0
35 0
6 0
12 0
18 0
24 0
30 0
36 0
WHITE 15
BLACK 9
BLACK 4
120
C
P4
NO
C
NC
TEMPERATURE SENSOR
TEMPERATURE CONTROL
BROWN 6
BLUE 18
BLACK 5
WHITE 17
WHITE 21
BLACK 30
SLEEVE
MOLEX PLUG
B
W
CONDENSATE EVAPORATOR
230-50-1
230-60-1
RED
BLUE
WHITE
BLACK
N.O. FAN SWITCH
L
LIGHT
B
W
DOOR AJAR (NOT USED)
FOR OPTIONAL LEFT HAND HINGED HEATED GLASS DOOR
FAN MOTOR
HEATED GLASS DOOR
WIRING DIAGRAM
LR 17/25
230-50/60-1
DRAWN BY
DATE
CHECKED BY
DRAWING NO
MORINO
6/29/99
A300227
02

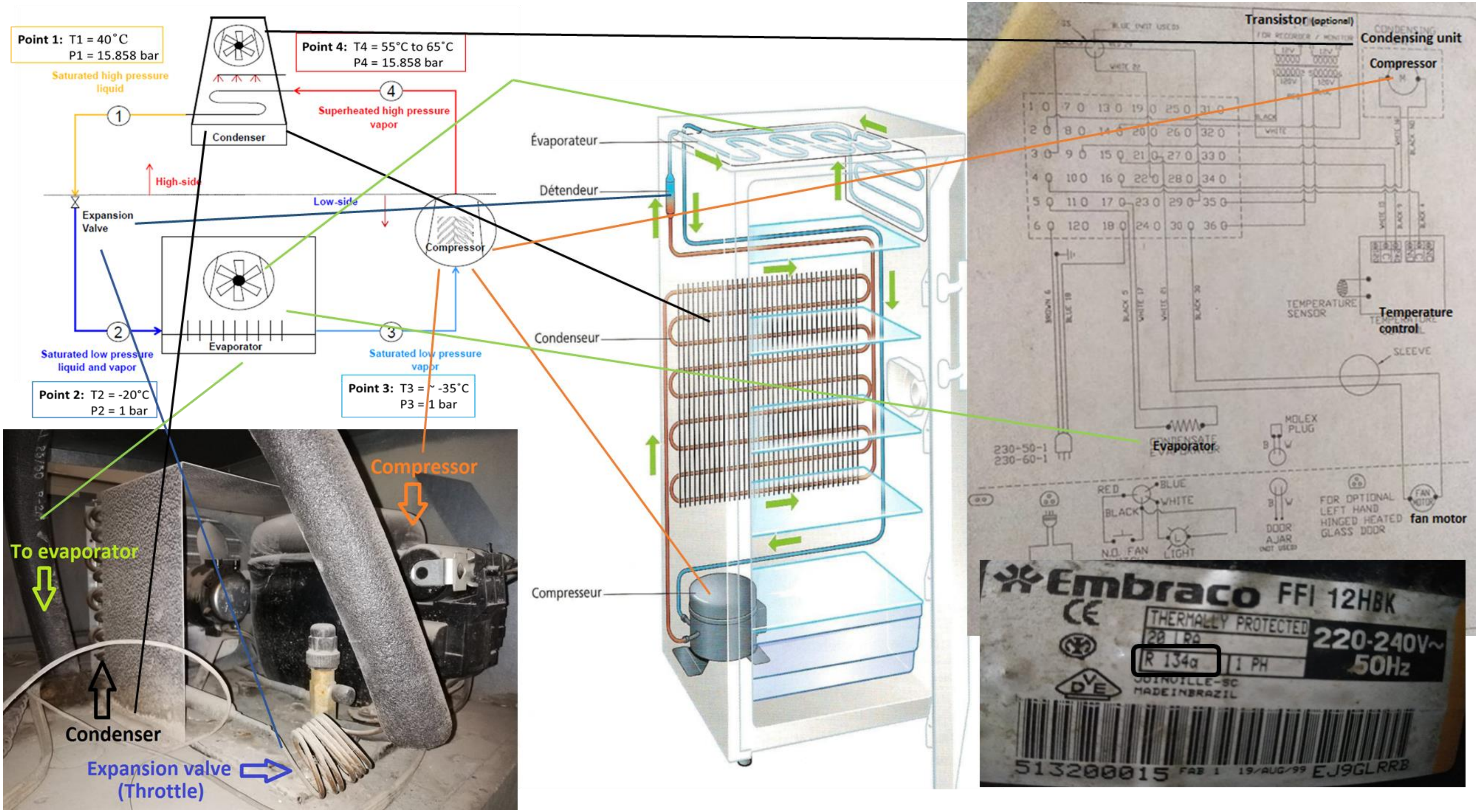

Saturated high pressure liquid
1
Condenser
4
Superheated high pressure vapor
High-side
Low-side
Expansion Valve
Compressor
2
Evaporator
3
Saturated low pressure liquid and vapor
Saturated low pressure vapor

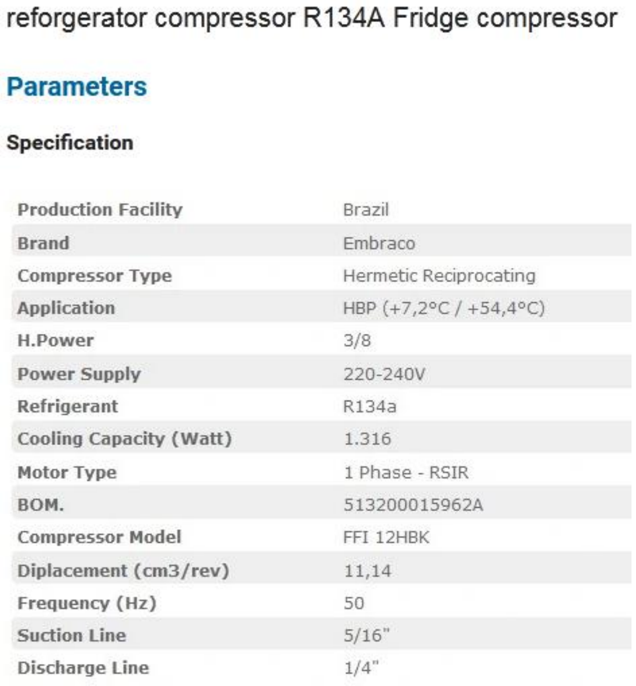

Ventillation
Compressor
To evaporator
Condenseur
Detendeur


Évaporateur
Détendeur
Condenseur
Compresseur


Transistor (optional)
Condensing unit
Compressor
TEMPERATURE SENSOR
Temperature control
SLEEVE
Evaporator
MOLEX PLUG
230-50-1
230-60-1
RED
BLUE
WHITE
BLACK
N.O. FAN
LIGHT
DOOR AJAR
FOR OPTIONAL LEFT HAND HINGED HEATED GLASS DOOR
fan motor


Embraco FFI 12HBK
CE
THERMALLY PROTECTED
R 134a
1 PH
220-240V~
50Hz
JOINVILLE-SC
MADE IN BRAZIL
513200015
19/AUG/99
EJ9GLRRB


Point 1: T1 = 40°C
P1 = 15.858 bar
Saturated high pressure liquid
Condenser
Point 4: T4 = 55°C to 65°C
P4 = 15.858 bar
Superheated high pressure vapor
High-side
Low-side
Expansion Valve
Compressor
Evaporator
Saturated low pressure liquid and vapor
Saturated low pressure vapor
Point 2: T2 = -20°C
P2 = 1 bar
Point 3: T3 = ~ -35°C
P3 = 1 bar
1
2
3
4
Évaporateur
Détendeur
Condenseur
Compresseur
To evaporator
Compressor
Condenser
Expansion valve (Throttle)
Transistor (optional)
Condensing unit
Compressor
Temperature control
TEMPERATURE SENSOR
SLEEVE
Evaporator
MOLEX PLUG
fan motor
230-50-1
230-60-1
RED
BLUE
WHITE
BLACK
N.O. FAN
LIGHT
DOOR AJAR
FOR OPTIONAL LEFT HAND HINGED HEATED GLASS DOOR
Embraco FFI 12HBK
CE
THERMALLY PROTECTED
R 134a
1 PH
220-240V~ 50Hz
JOINVILLE-SC
MADE IN BRAZIL
513200015
FAB 1
19/AUG/99
EJ9GLRRB

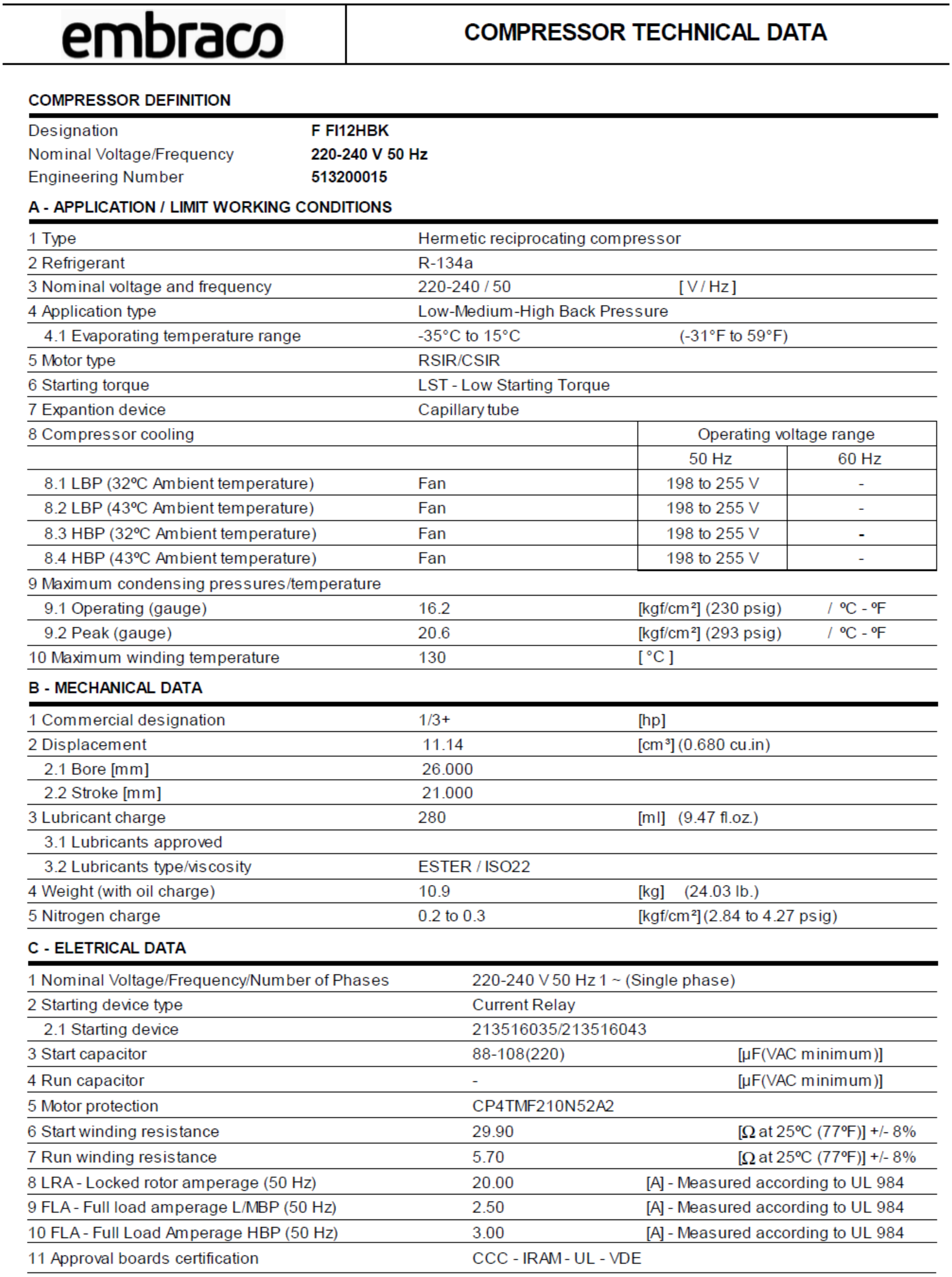


reforgerator compressor R134A Fridge compressor

Parameters

Specification

Production Facility	Brazil
Brand	Embraco
Compressor Type	Hermetic Reciprocating
Application	HBP (+7,2°C / +54,4°C)
H.Power	3/8
Power Supply	220-240V
Refrigerant	R134a
Cooling Capacity (Watt)	1.316
Motor Type	1 Phase - RSIR
BOM.	513200015962A
Compressor Model	FFI 12HBK
Diplacement (cm3/rev)	11,14
Frequency (Hz)	50
Suction Line	5/16"
Discharge Line	1/4"



embraco

COMPRESSOR TECHNICAL DATA

COMPRESSOR DEFINITION

Designation	**F FI12HBK**
Nominal Voltage/Frequency	**220-240 V 50 Hz**
Engineering Number	**513200015**

A - APPLICATION / LIMIT WORKING CONDITIONS

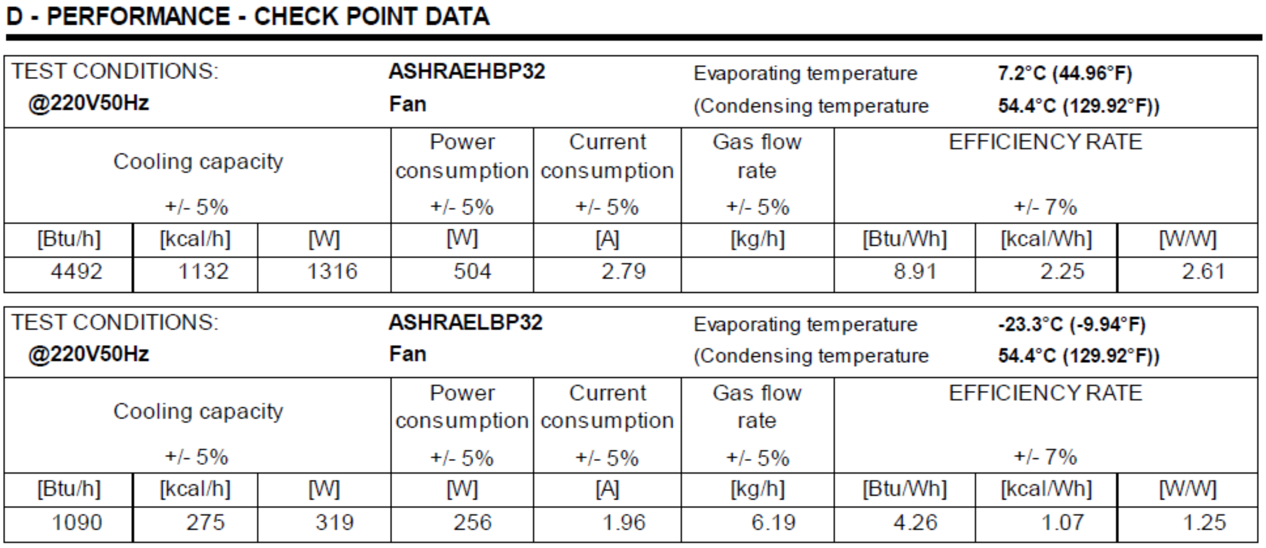
1 Type	Hermetic reciprocating compressor		
2 Refrigerant	R-134a		
3 Nominal voltage and frequency	220-240 / 50	[V / Hz]	
4 Application type	Low-Medium-High Back Pressure		
4.1 Evaporating temperature range	-35°C to 15°C	(-31°F to 59°F)	
5 Motor type	RSIR/CSIR		
6 Starting torque	LST - Low Starting Torque		
7 Expantion device	Capillary tube		
8 Compressor cooling		Operating voltage range	
		50 Hz	60 Hz
8.1 LBP (32ºC Ambient temperature)	Fan	198 to 255 V	-
8.2 LBP (43ºC Ambient temperature)	Fan	198 to 255 V	-
8.3 HBP (32ºC Ambient temperature)	Fan	198 to 255 V	-
8.4 HBP (43ºC Ambient temperature)	Fan	198 to 255 V	-
9 Maximum condensing pressures/temperature			
9.1 Operating (gauge)	16.2	[kgf/cm^2] (230 psig)	/ ºC - ºF
9.2 Peak (gauge)	20.6	[kgf/cm^2] (293 psig)	/ ºC - ºF
10 Maximum winding temperature	130	[°C]	

B - MECHANICAL DATA

1 Commercial designation	1/3+	[hp]
2 Displacement	11.14	[cm^3] (0.680 cu.in)
2.1 Bore [mm]	26.000	
2.2 Stroke [mm]	21.000	
3 Lubricant charge	280	[ml] (9.47 fl.oz.)
3.1 Lubricants approved		
3.2 Lubricants type/viscosity	ESTER / ISO22	
4 Weight (with oil charge)	10.9	[kg] (24.03 lb.)
5 Nitrogen charge	0.2 to 0.3	[kgf/cm^2] (2.84 to 4.27 psig)

C - ELETRICAL DATA

1 Nominal Voltage/Frequency/Number of Phases	220-240 V 50 Hz 1 ~ (Single phase)	
2 Starting device type	Current Relay	
2.1 Starting device	213516035/213516043	
3 Start capacitor	88-108(220)	[µF(VAC minimum)]
4 Run capacitor	-	[µF(VAC minimum)]
5 Motor protection	CP4TMF210N52A2	
6 Start winding resistance	29.90	[Ω at 25ºC (77ºF)] +/- 8%
7 Run winding resistance	5.70	[Ω at 25ºC (77ºF)] +/- 8%
8 LRA - Locked rotor amperage (50 Hz)	20.00	[A] - Measured according to UL 984
9 FLA - Full load amperage L/MBP (50 Hz)	2.50	[A] - Measured according to UL 984
10 FLA - Full Load Amperage HBP (50 Hz)	3.00	[A] - Measured according to UL 984
11 Approval boards certification	CCC - IRAM - UL - VDE	



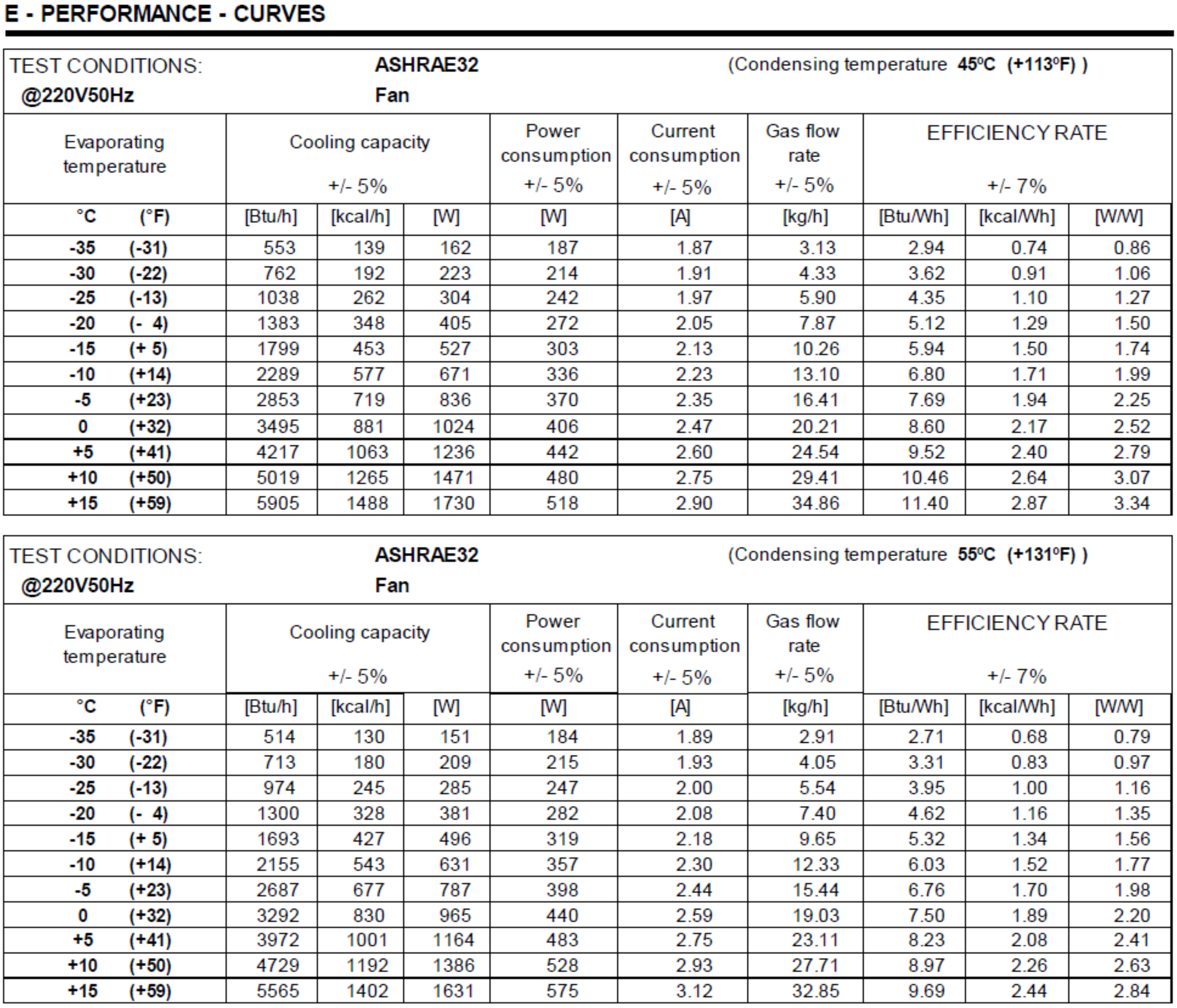
D - PERFORMANCE - CHECK POINT DATA

TEST CONDITIONS: **ASHRAEHBP32** Evaporating temperature **7.2°C (44.96°F)**
@220V50Hz **Fan** (Condensing temperature **54.4°C (129.92°F))**

Cooling capacity +/- 5%			Power consumption +/- 5%	Current consumption +/- 5%	Gas flow rate +/- 5%	EFFICIENCY RATE +/- 7%		
[Btu/h]	[kcal/h]	[W]	[W]	[A]	[kg/h]	[Btu/Wh]	[kcal/Wh]	[W/W]
4492	1132	1316	504	2.79		8.91	2.25	2.61

TEST CONDITIONS: **ASHRAELBP32** Evaporating temperature **-23.3°C (-9.94°F)**
@220V50Hz **Fan** (Condensing temperature **54.4°C (129.92°F))**

Cooling capacity +/- 5%			Power consumption +/- 5%	Current consumption +/- 5%	Gas flow rate +/- 5%	EFFICIENCY RATE +/- 7%		
[Btu/h]	[kcal/h]	[W]	[W]	[A]	[kg/h]	[Btu/Wh]	[kcal/Wh]	[W/W]
1090	275	319	256	1.96	6.19	4.26	1.07	1.25



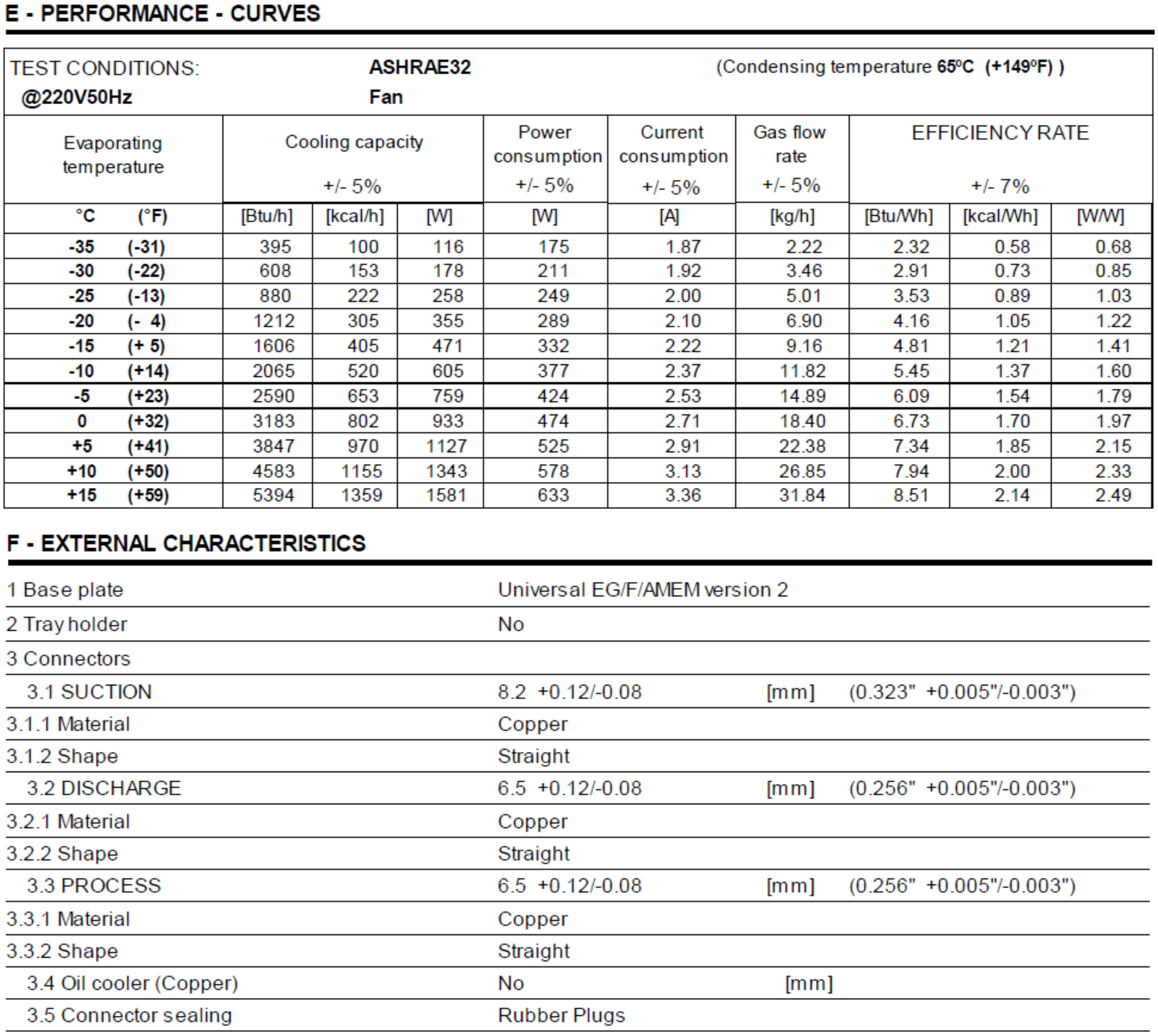
E - PERFORMANCE - CURVES

TEST CONDITIONS: **ASHRAE32** (Condensing temperature **45ºC (+113ºF)**)
@220V50Hz **Fan**

Evaporating temperature		Cooling capacity +/- 5%			Power consumption +/- 5%	Current consumption +/- 5%	Gas flow rate +/- 5%	EFFICIENCY RATE +/- 7%		
°C	(°F)	[Btu/h]	[kcal/h]	[W]	[W]	[A]	[kg/h]	[Btu/Wh]	[kcal/Wh]	[W/W]
-35	**(-31)**	553	139	162	187	1.87	3.13	2.94	0.74	0.86
-30	**(-22)**	762	192	223	214	1.91	4.33	3.62	0.91	1.06
-25	**(-13)**	1038	262	304	242	1.97	5.90	4.35	1.10	1.27
-20	**(- 4)**	1383	348	405	272	2.05	7.87	5.12	1.29	1.50
-15	**(+ 5)**	1799	453	527	303	2.13	10.26	5.94	1.50	1.74
-10	**(+14)**	2289	577	671	336	2.23	13.10	6.80	1.71	1.99
-5	**(+23)**	2853	719	836	370	2.35	16.41	7.69	1.94	2.25
0	**(+32)**	3495	881	1024	406	2.47	20.21	8.60	2.17	2.52
+5	**(+41)**	4217	1063	1236	442	2.60	24.54	9.52	2.40	2.79
+10	**(+50)**	5019	1265	1471	480	2.75	29.41	10.46	2.64	3.07
+15	**(+59)**	5905	1488	1730	518	2.90	34.86	11.40	2.87	3.34

TEST CONDITIONS: **ASHRAE32** (Condensing temperature **55ºC (+131ºF)**)
@220V50Hz **Fan**

Evaporating temperature		Cooling capacity +/- 5%			Power consumption +/- 5%	Current consumption +/- 5%	Gas flow rate +/- 5%	EFFICIENCY RATE +/- 7%		
°C	(°F)	[Btu/h]	[kcal/h]	[W]	[W]	[A]	[kg/h]	[Btu/Wh]	[kcal/Wh]	[W/W]
-35	**(-31)**	514	130	151	184	1.89	2.91	2.71	0.68	0.79
-30	**(-22)**	713	180	209	215	1.93	4.05	3.31	0.83	0.97
-25	**(-13)**	974	245	285	247	2.00	5.54	3.95	1.00	1.16
-20	**(- 4)**	1300	328	381	282	2.08	7.40	4.62	1.16	1.35
-15	**(+ 5)**	1693	427	496	319	2.18	9.65	5.32	1.34	1.56
-10	**(+14)**	2155	543	631	357	2.30	12.33	6.03	1.52	1.77
-5	**(+23)**	2687	677	787	398	2.44	15.44	6.76	1.70	1.98
0	**(+32)**	3292	830	965	440	2.59	19.03	7.50	1.89	2.20
+5	**(+41)**	3972	1001	1164	483	2.75	23.11	8.23	2.08	2.41
+10	**(+50)**	4729	1192	1386	528	2.93	27.71	8.97	2.26	2.63
+15	**(+59)**	5565	1402	1631	575	3.12	32.85	9.69	2.44	2.84



E - PERFORMANCE - CURVES

TEST CONDITIONS: **ASHRAE32** (Condensing temperature **65°C (+149°F)**)
@220V50Hz **Fan**

Evaporating temperature		Cooling capacity +/- 5%			Power consumption +/- 5%	Current consumption +/- 5%	Gas flow rate +/- 5%	EFFICIENCY RATE +/- 7%		
°C	(°F)	[Btu/h]	[kcal/h]	[W]	[W]	[A]	[kg/h]	[Btu/Wh]	[kcal/Wh]	[W/W]
-35	**(-31)**	395	100	116	175	1.87	2.22	2.32	0.58	0.68
-30	**(-22)**	608	153	178	211	1.92	3.46	2.91	0.73	0.85
-25	**(-13)**	880	222	258	249	2.00	5.01	3.53	0.89	1.03
-20	**(- 4)**	1212	305	355	289	2.10	6.90	4.16	1.05	1.22
-15	**(+ 5)**	1606	405	471	332	2.22	9.16	4.81	1.21	1.41
-10	**(+14)**	2065	520	605	377	2.37	11.82	5.45	1.37	1.60
-5	**(+23)**	2590	653	759	424	2.53	14.89	6.09	1.54	1.79
0	**(+32)**	3183	802	933	474	2.71	18.40	6.73	1.70	1.97
+5	**(+41)**	3847	970	1127	525	2.91	22.38	7.34	1.85	2.15
+10	**(+50)**	4583	1155	1343	578	3.13	26.85	7.94	2.00	2.33
+15	**(+59)**	5394	1359	1581	633	3.36	31.84	8.51	2.14	2.49

F - EXTERNAL CHARACTERISTICS

1 Base plate	Universal EG/F/AMEM version 2		
2 Tray holder	No		
3 Connectors			
3.1 SUCTION	8.2 +0.12/-0.08	[mm]	(0.323" +0.005"/-0.003")
3.1.1 Material	Copper		
3.1.2 Shape	Straight		
3.2 DISCHARGE	6.5 +0.12/-0.08	[mm]	(0.256" +0.005"/-0.003")
3.2.1 Material	Copper		
3.2.2 Shape	Straight		
3.3 PROCESS	6.5 +0.12/-0.08	[mm]	(0.256" +0.005"/-0.003")
3.3.1 Material	Copper		
3.3.2 Shape	Straight		
3.4 Oil cooler (Copper)	No	[mm]	
3.5 Connector sealing	Rubber Plugs		

- R134a refrigerant:

R134a is also known as Tetrafluoroethane (CF3CH2F) from the family of HFC refrigerant. With the discovery of the damaging effect of CFCs and HCFCs refrigerants to the ozone layer, the HFC family of refrigerant has been widely used as their replacement.

It is now being used as a replacement for R-12 CFC refrigerant in the area of centrifugal, rotary screw, scroll and reciprocating compresssors. It is safe for normal handling as it is non-toxic, non-flammable and non-corrosive.

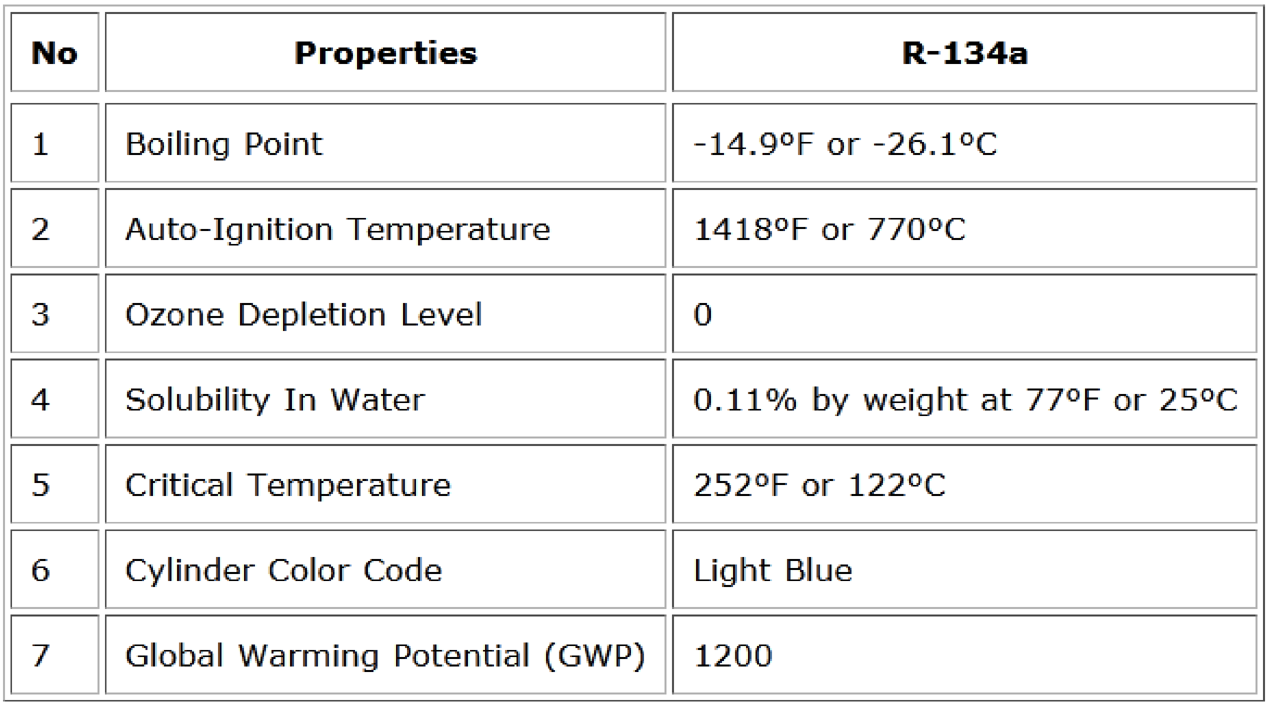
Currently it is also being widely used in the air conditioning system in newer automotive vehicles. The manufacturing industry use it in plastic foam blowing. Pharmaceuticals industry use it as a propellant.

It exists in gas form when expose to the environment as the boiling temperature is -14.9°F or -26.1°C.

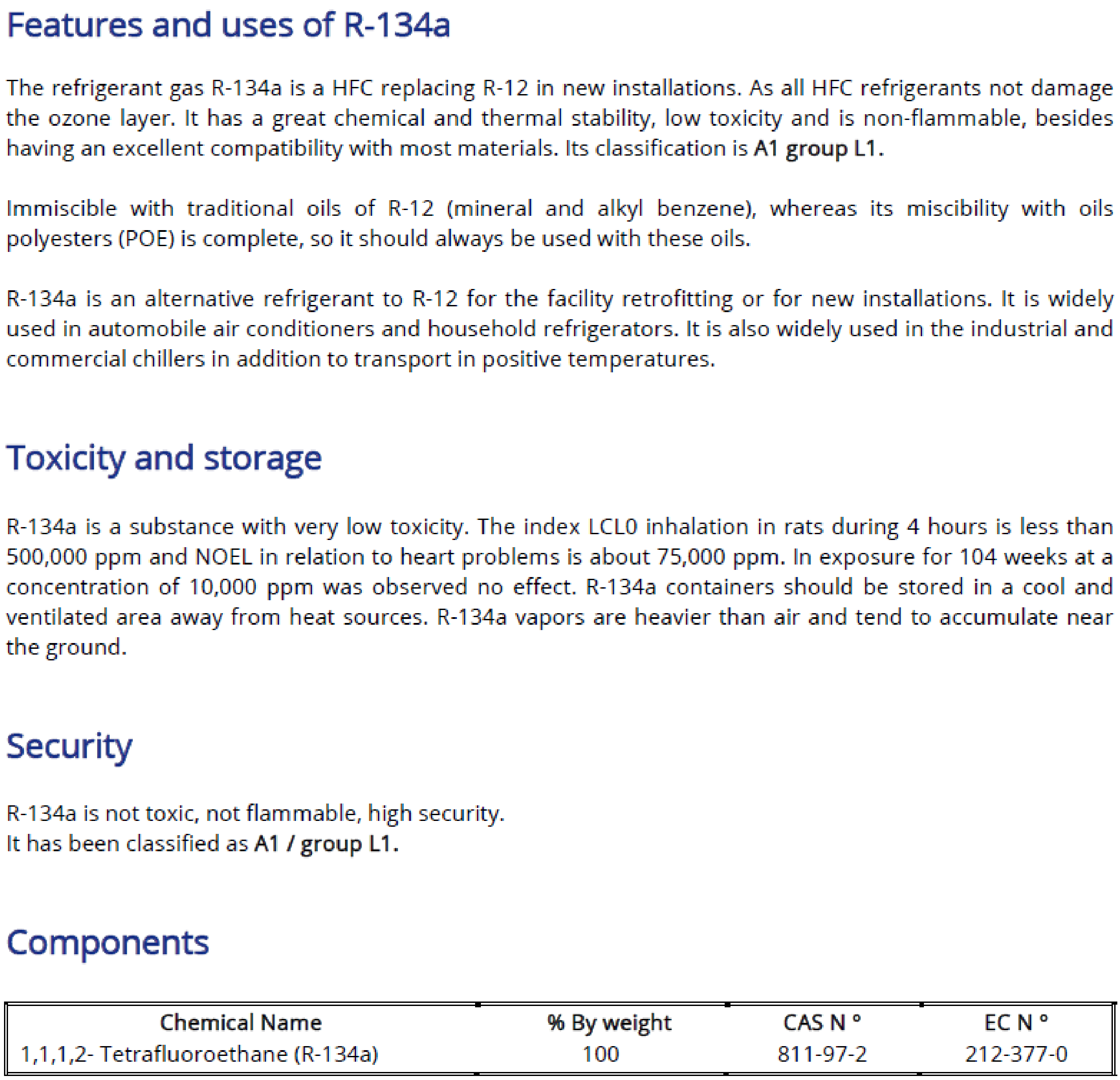
This refrigerant is not 100% compatible with the lubricants and mineral-based refrigerant currently used in R-12. Design changes to the condenser and evaporator need to be done to use this refrigerant.

The use of smaller hoses and 30% increase in control pressure regulations also have to be done to the system.

Properties of R-134a



No	Properties	R-134a
1	Boiling Point	-14.9°F or -26.1°C
2	Auto-Ignition Temperature	1418°F or 770°C
3	Ozone Depletion Level	0
4	Solubility In Water	0.11% by weight at 77°F or 25°C
5	Critical Temperature	252°F or 122°C
6	Cylinder Color Code	Light Blue
7	Global Warming Potential (GWP)	1200



Features and uses of R-134a

The refrigerant gas R-134a is a HFC replacing R-12 in new installations. As all HFC refrigerants not damage the ozone layer. It has a great chemical and thermal stability, low toxicity and is non-flammable, besides having an excellent compatibility with most materials. Its classification is **A1 group L1.**

Immiscible with traditional oils of R-12 (mineral and alkyl benzene), whereas its miscibility with oils polyesters (POE) is complete, so it should always be used with these oils.

R-134a is an alternative refrigerant to R-12 for the facility retrofitting or for new installations. It is widely used in automobile air conditioners and household refrigerators. It is also widely used in the industrial and commercial chillers in addition to transport in positive temperatures.

Toxicity and storage

R-134a is a substance with very low toxicity. The index LCL0 inhalation in rats during 4 hours is less than 500,000 ppm and NOEL in relation to heart problems is about 75,000 ppm. In exposure for 104 weeks at a concentration of 10,000 ppm was observed no effect. R-134a containers should be stored in a cool and ventilated area away from heat sources. R-134a vapors are heavier than air and tend to accumulate near the ground.

Security

R-134a is not toxic, not flammable, high security.
It has been classified as **A1 / group L1.**

Components

Chemical Name	% By weight	CAS N °	EC N °
1,1,1,2- Tetrafluoroethane (R-134a)	100	811-97-2	212-377-0

[32]

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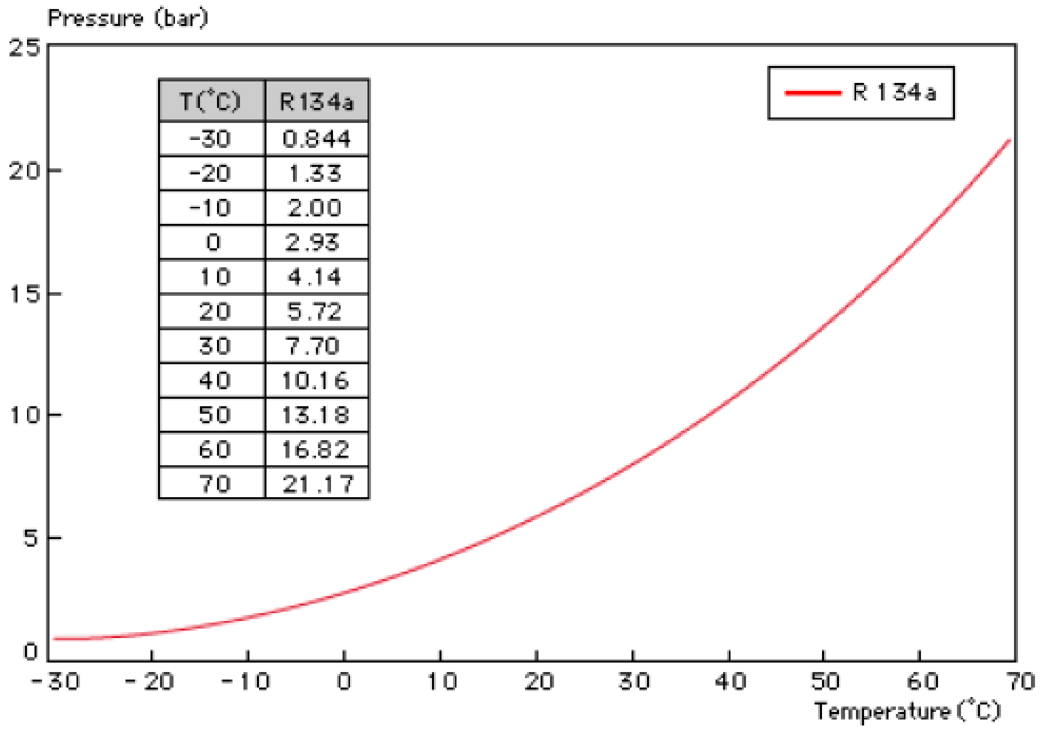
[32] https://gas-servei.com/shop/docs/technical-data-sheet-r-134a-gas-servei.pdf

Chart Pressure / Temperature

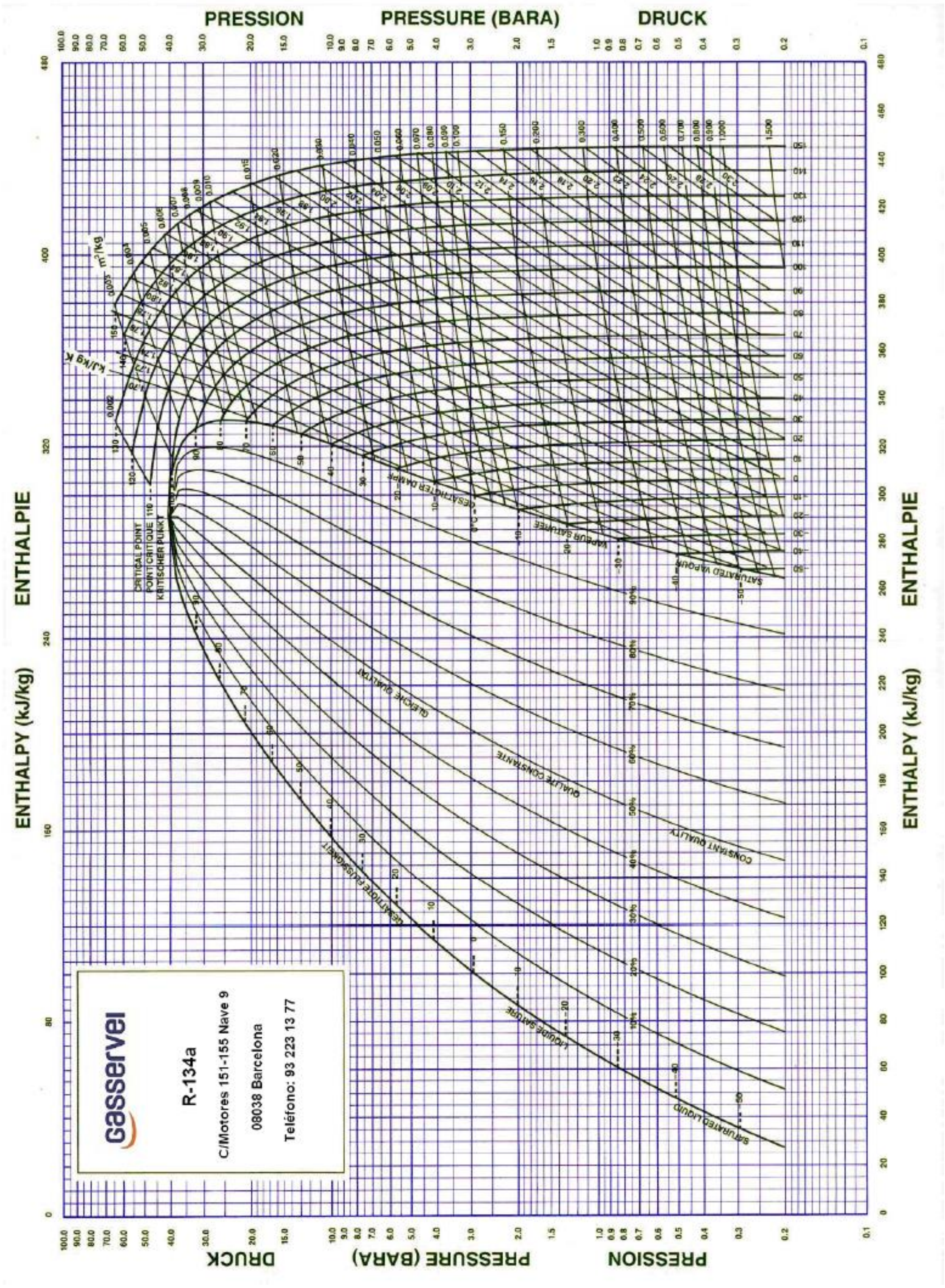


T(°C)	R134a
-30	0.844
-20	1.33
-10	2.00
0	2.93
10	4.14
20	5.72
30	7.70
40	10.16
50	13.18
60	16.82
70	21.17

Thermodynamic properties

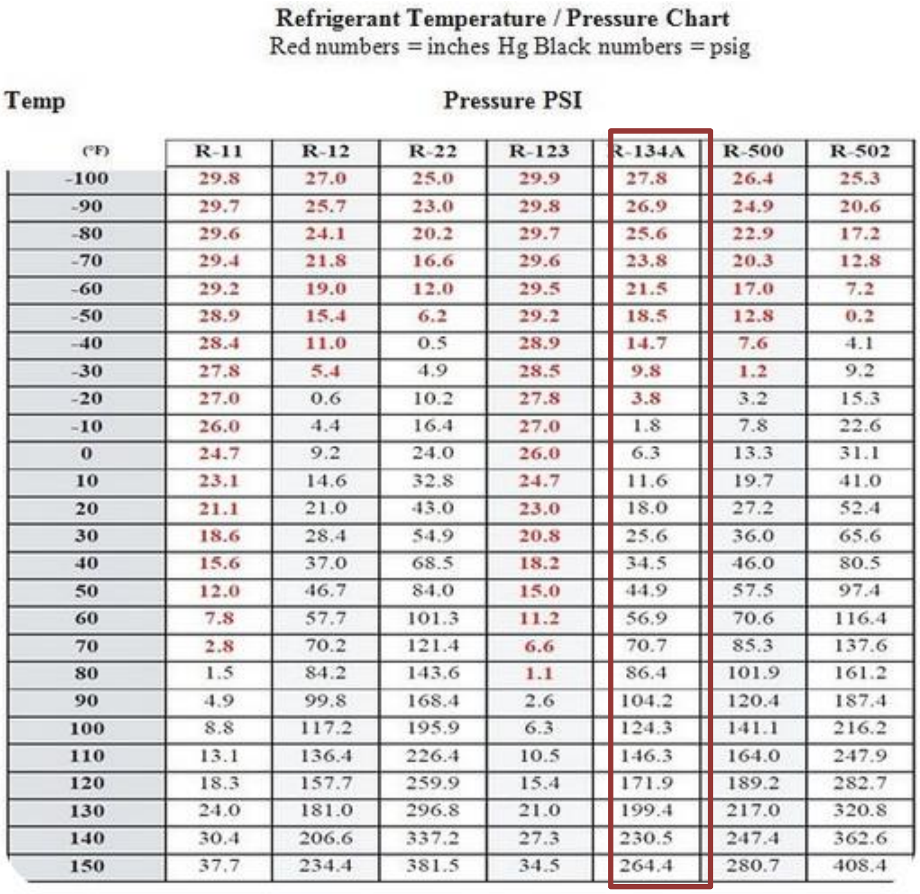
TEMP. (°C)	ABSOLUTE PRESSURE (bar)		DENSITY (Kg/m³)		ENTHALPY (kJ/Kg)		ENTROPY (kJ/Kg.K)	
	BUBBLE	DEW	BUBBLE	DEW	BUBBLE	DEW	BUBBLE	BUBBLE
-40	0.51	0.51	1413.94	2.76	149.45	375.65	0.8008	1.7710
-35	0.66	0.66	1399.95	3.50	155.53	378.93	0.8266	1.7646
-30	0.84	0.84	1385.72	4.39	161.67	382.20	0.8521	1.7590
-25	1.06	1.06	1371.24	5.45	167.88	385.45	0.8773	1.7540
-20	1.32	1.32	1356.46	6.71	174.16	388.69	0.9023	1.7497
-15	1.63	1.63	1341.36	8.19	180.51	391.90	0.9270	1.7458
-10	2.00	2.00	1325.92	9.92	186.93	395.07	0.9515	1.7425
-5	2.42	2.42	1310.10	11.92	193.43	398.20	0.9759	1.7395
0	2.92	2.92	1293.86	14.23	200.00	401.28	1.0000	1.7369
5	3.49	3.49	1277.17	16.89	206.65	404.30	1.0240	1.7346
10	4.14	4.14	1259.99	19.93	213.38	407.25	1.0478	1.7325
15	4.88	4.88	1242.27	23.40	220.20	410.13	1.0714	1.7306
20	5.71	5.71	1223.96	27.34	227.11	412.92	1.0950	1.7288
25	6.65	6.65	1205.00	31.81	234.11	415.62	1.1184	1.7272
30	7.70	7.70	1185.33	36.88	241.21	418.20	1.1417	1.7256
35	8.88	8.88	1164.89	42.61	248.42	420.67	1.1650	1.7240
40	10.18	10.18	1143.58	49.08	255.74	423.01	1.1882	1.7223
45	11.62	11.62	1121.32	56.40	263.19	425.20	1.2114	1.7206
50	13.20	13.20	1197.98	64.66	270.77	427.23	1.2346	1.7187

Mollier Diagram



- Expansion valve:

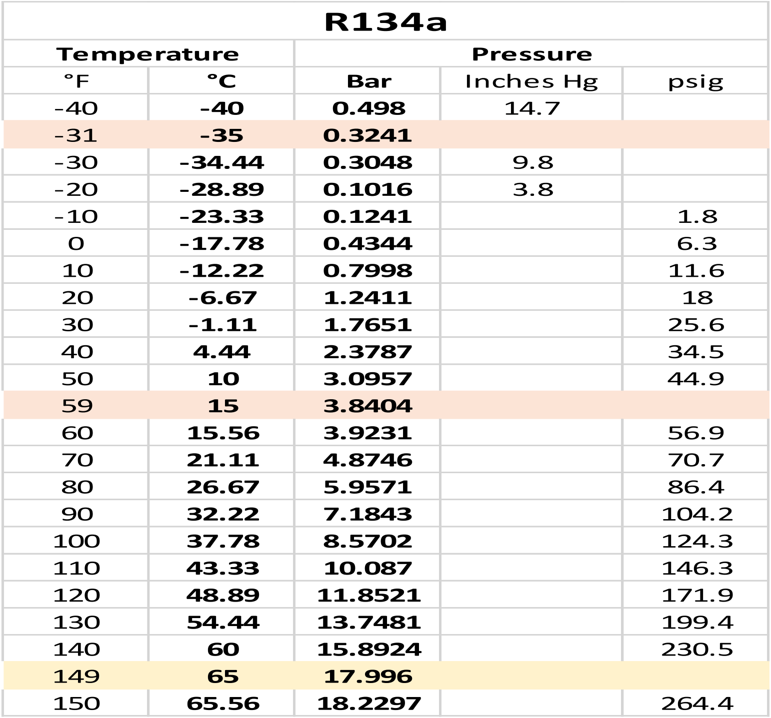
R134a refrigerant gas pressure – temperature chart



Refrigerant Temperature / Pressure Chart
Red numbers = inches Hg Black numbers = psig

Temp	Pressure PSI						
(°F)	R-11	R-12	R-22	R-123	R-134A	R-500	R-502
-100	29.8	27.0	25.0	29.9	27.8	26.4	25.3
-90	29.7	25.7	23.0	29.8	26.9	24.9	20.6
-80	29.6	24.1	20.2	29.7	25.6	22.9	17.2
-70	29.4	21.8	16.6	29.6	23.8	20.3	12.8
-60	29.2	19.0	12.0	29.5	21.5	17.0	7.2
-50	28.9	15.4	6.2	29.2	18.5	12.8	0.2
-40	28.4	11.0	0.5	28.9	14.7	7.6	4.1
-30	27.8	5.4	4.9	28.5	9.8	1.2	9.2
-20	27.0	0.6	10.2	27.8	3.8	3.2	15.3
-10	26.0	4.4	16.4	27.0	1.8	7.8	22.6
0	24.7	9.2	24.0	26.0	6.3	13.3	31.1
10	23.1	14.6	32.8	24.7	11.6	19.7	41.0
20	21.1	21.0	43.0	23.0	18.0	27.2	52.4
30	18.6	28.4	54.9	20.8	25.6	36.0	65.6
40	15.6	37.0	68.5	18.2	34.5	46.0	80.5
50	12.0	46.7	84.0	15.0	44.9	57.5	97.4
60	7.8	57.7	101.3	11.2	56.9	70.6	116.4
70	2.8	70.2	121.4	6.6	70.7	85.3	137.6
80	1.5	84.2	143.6	1.1	86.4	101.9	161.2
90	4.9	99.8	168.4	2.6	104.2	120.4	187.4
100	8.8	117.2	195.9	6.3	124.3	141.1	216.2
110	13.1	136.4	226.4	10.5	146.3	164.0	247.9
120	18.3	157.7	259.9	15.4	171.9	189.2	282.7
130	24.0	181.0	296.8	21.0	199.4	217.0	320.8
140	30.4	206.6	337.2	27.3	230.5	247.4	362.6
150	37.7	234.4	381.5	34.5	264.4	280.7	408.4

[33]



R134a				
Temperature		Pressure		
°F	°C	Bar	Inches Hg	psig
-40	-40	0.498	14.7	
-31	-35	0.3241		
-30	-34.44	0.3048	9.8	
-20	-28.89	0.1016	3.8	
-10	-23.33	0.1241		1.8
0	-17.78	0.4344		6.3
10	-12.22	0.7998		11.6
20	-6.67	1.2411		18
30	-1.11	1.7651		25.6
40	4.44	2.3787		34.5
50	10	3.0957		44.9
59	15	3.8404		
60	15.56	3.9231		56.9
70	21.11	4.8746		70.7
80	26.67	5.9571		86.4
90	32.22	7.1843		104.2
100	37.78	8.5702		124.3
110	43.33	10.087		146.3
120	48.89	11.8521		171.9
130	54.44	13.7481		199.4
140	60	15.8924		230.5
149	65	17.996		
150	65.56	18.2297		264.4

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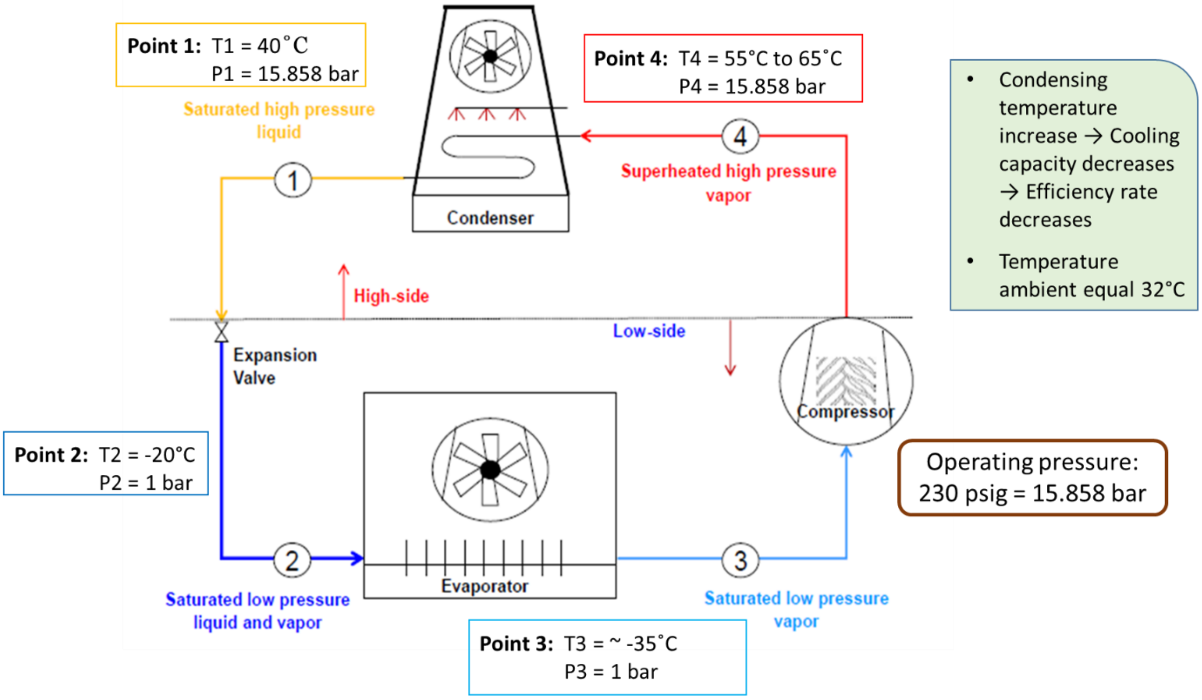
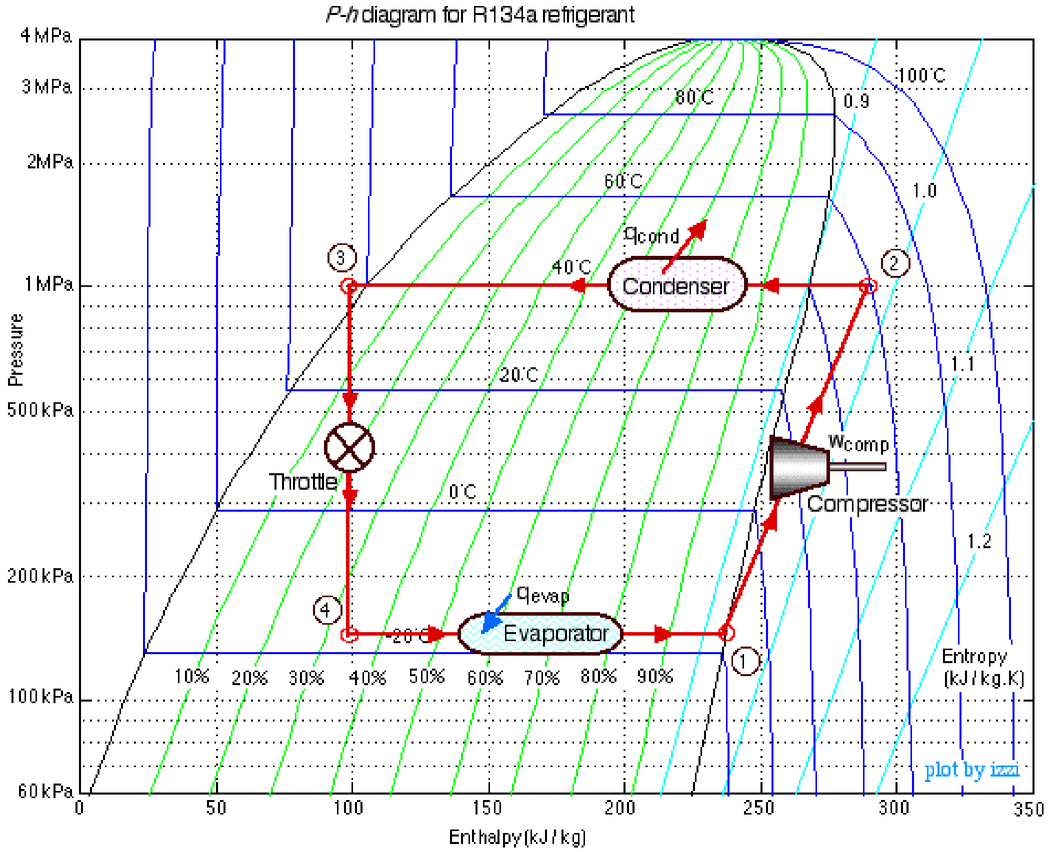
[33] https://www.pinterest.com/pin/333829391133607747/



- Condensing temperature increase → Cooling capacity decreases → Efficiency rate decreases
- Temperature ambient equal 32°C

Operating pressure: 230 psig = 15.858 bar



[34]

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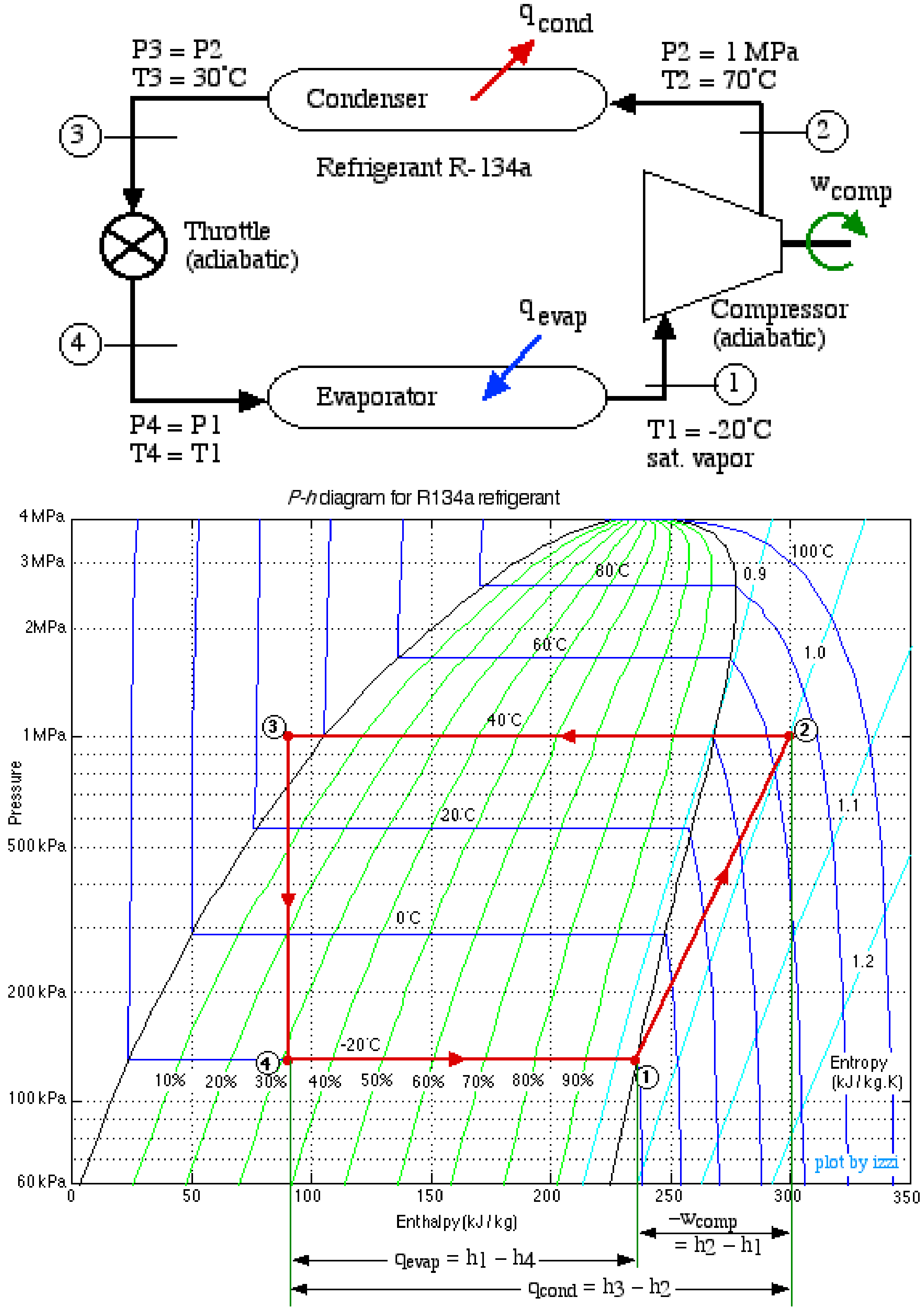
[34] https://www.ohio.edu/mechanical/thermo/Intro/Chapt.1_6/refrigerator/refrig_problems.html



[35]

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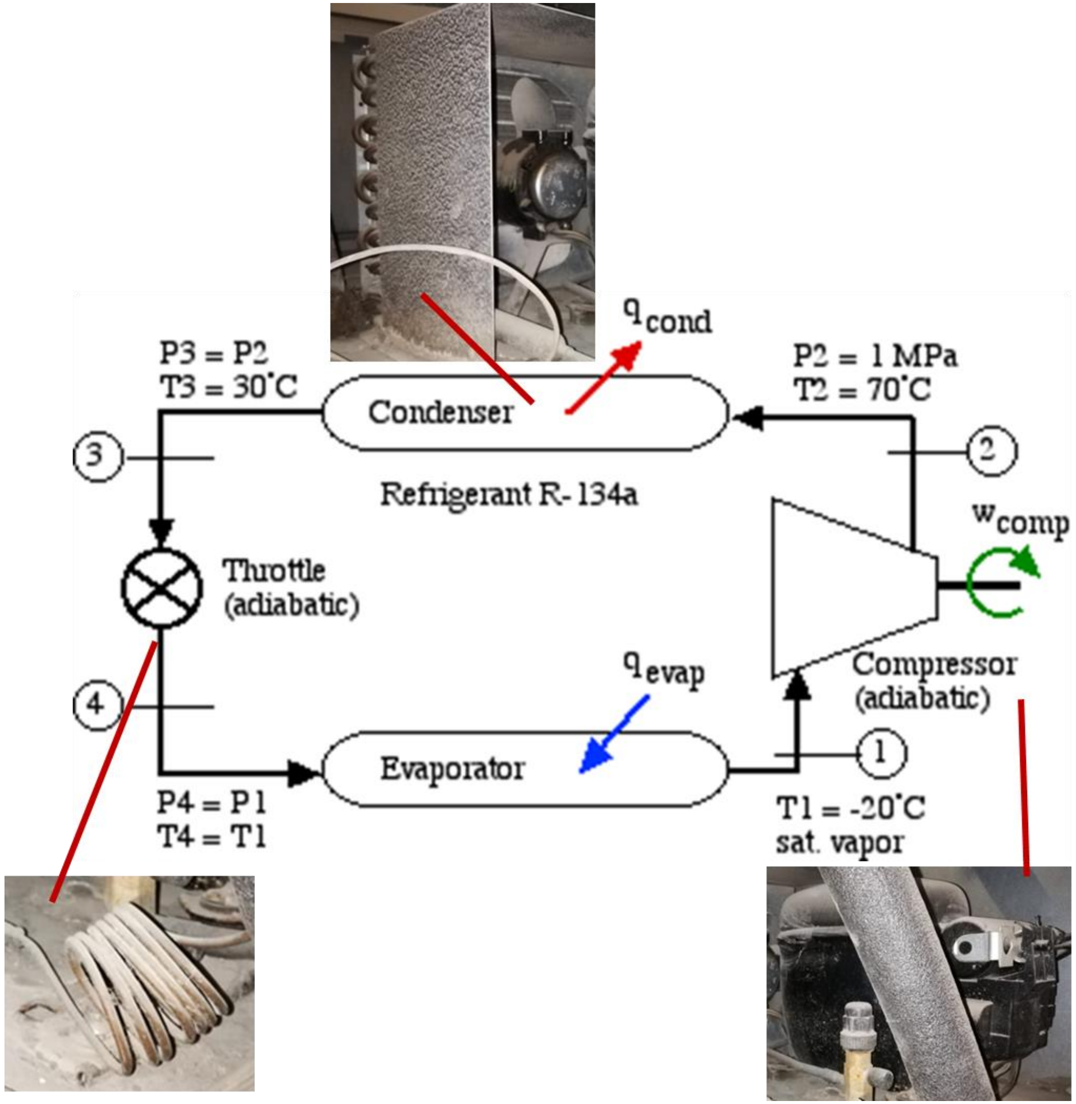
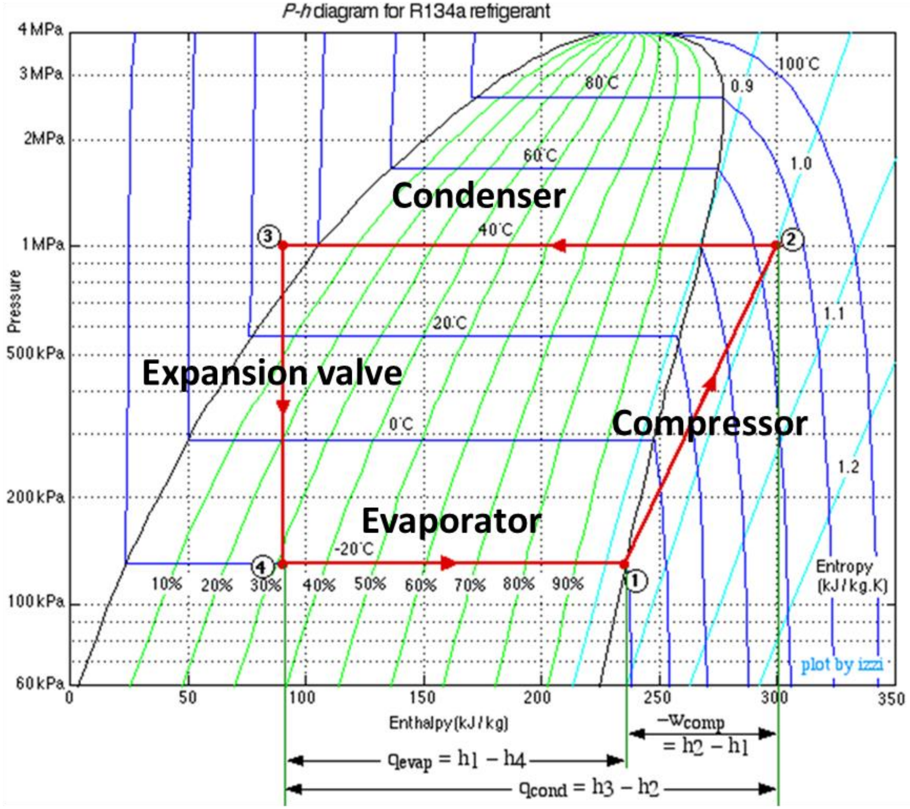
[35] https://www.ohio.edu/mechanical/thermo/Intro/Chapt.1_6/Chapter4c.html


q_cond
P3 = P2
T3 = 30°C
Condenser
P2 = 1 MPa
T2 = 70°C
3
2
Refrigerant R-134a
w_comp
Throttle
(adiabatic)
q_evap
Compressor
(adiabatic)
4
1
Evaporator
P4 = P1
T4 = T1
T1 = -20°C
sat. vapor


P-h diagram for R134a refrigerant
4 MPa
3 MPa
2MPa
1 MPa
500 kPa
200 kPa
100 kPa
60 kPa
Pressure
100°C
80°C
60°C
40°C
20°C
0°C
-20°C
0.9
1.0
1.1
1.2
Entropy (kJ/kg.K)
Condenser
Expansion valve
Compressor
Evaporator
③
②
④
①
10%
20%
30%
40%
50%
60%
70%
80%
90%
0
50
100
150
200
250
300
350
Enthalpy (kJ/kg)
plot by izzi
−w_comp = h2 − h1
q_evap = h1 − h4
q_cond = h3 − h2

13.2 Device 2: Carrier Air conditioner

CARRIER
Model: CRVD243M-0B

Cooling Capacity:
24000 BTU/hr
Cooling Capacity (SASO):
5420 W
Heating Capacity: 5.0 KW

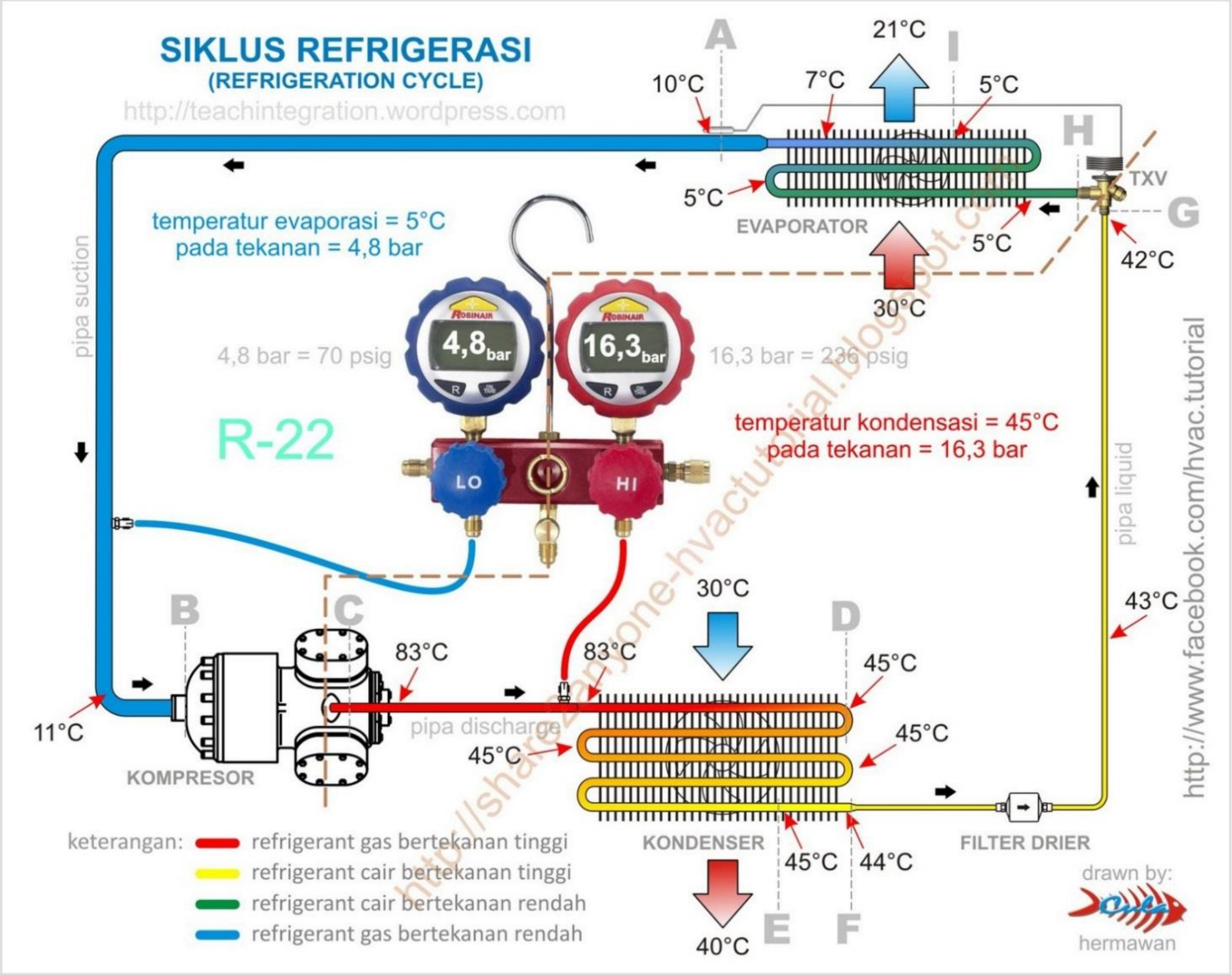
Electrical:
220V / 1Ph / 60Hz
Power (Cool)
2880W - 13.5A
Power (SASO)
3250W - 15A
Power (Heat)
5220W - 24A

Refrigerant: R22 - 946g
DESIGN PSIG HI 400 LO 150
Class 1 - IPX4

Serial Number:
DB722201390

SASO

Made in Saudi Arabia


SIKLUS REFRIGERASI
(REFRIGERATION CYCLE)
http://teachintegration.wordpress.com
A
21°C
I
10°C
7°C
5°C
H
TXV
5°C
EVAPORATOR
5°C
G
42°C
temperatur evaporasi = 5°C
pada tekanan = 4,8 bar
pipa suction
30°C
4,8 bar
16,3 bar
4,8 bar = 70 psig
16,3 bar = 236 psig
R-22
temperatur kondensasi = 45°C
pada tekanan = 16,3 bar
LO
HI
pipa liquid
http://www.facebook.com/hvac.tutorial
http://sharingappone-hvactutorial.blogspot.com
30°C
43°C
B
C
D
83°C
83°C
45°C
11°C
pipa discharge
45°C
45°C
KOMPRESOR
KONDENSER
FILTER DRIER
45°C
44°C
keterangan:
refrigerant gas bertekanan tinggi
refrigerant cair bertekanan tinggi
refrigerant cair bertekanan rendah
refrigerant gas bertekanan rendah
40°C
E
F
drawn by:
hermawan

13.2.1 Filter dryer: 36

So the refrigerant enters through the inlet, it passes across the spring, then surrounds the outside of the solid core. The refrigerant then passes through the solid core and as it does so the dirt, moisture and acids are absorbed, the refrigerant then collects in the groove at the centre of the core and then pass through the screen. It then passes through the perforated plate and exits the unit having been filtered and dried, it then continues to the expansion valve.

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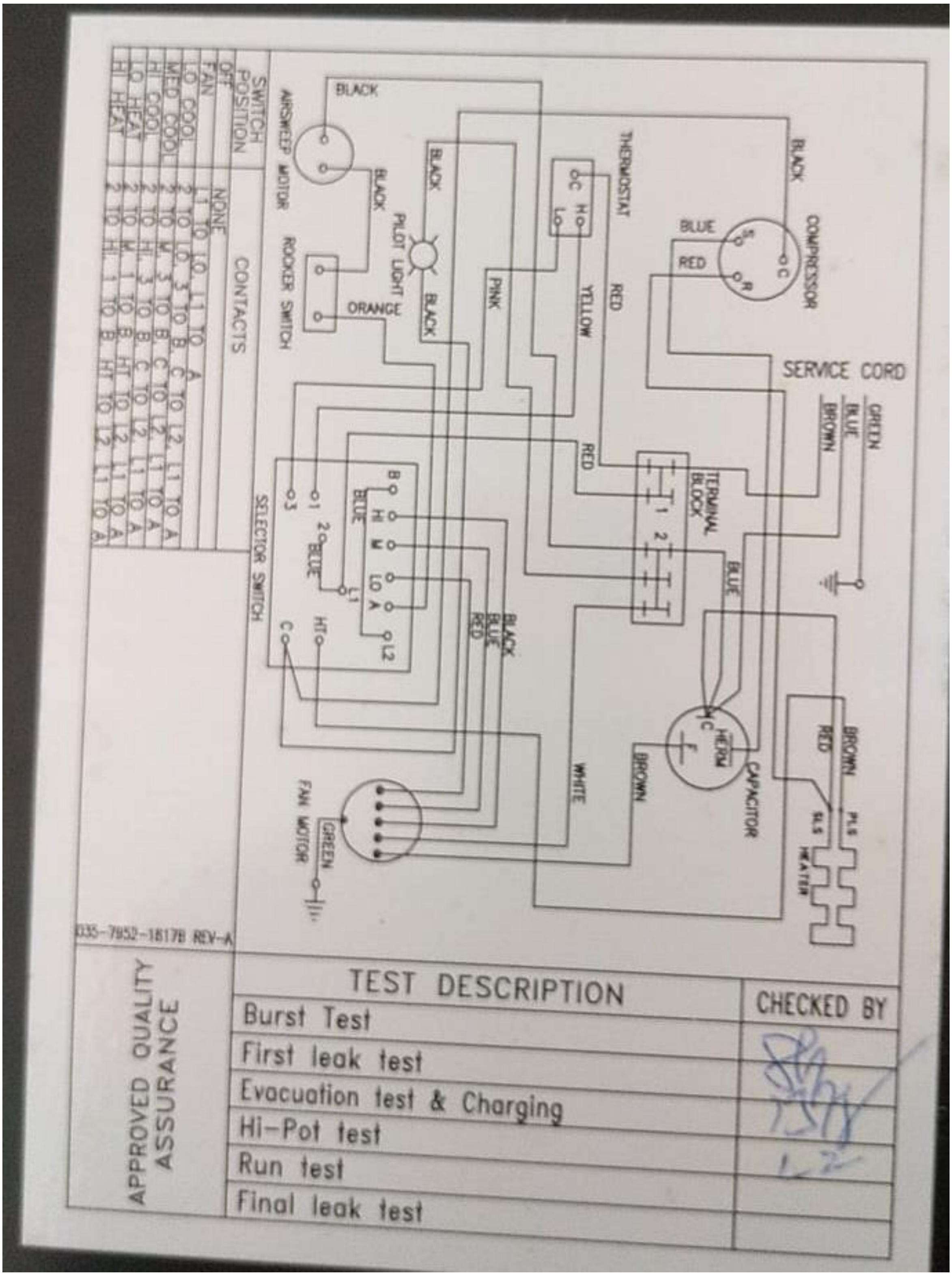
36 https://theengineeringmindset.com/filter-driers-how-do-they-work/



SWITCH POSITION	CONTACTS
OFF	NONE
FAN	L1 TO LO, L1 TO A
LO COOL	2 TO LO, 3 TO B, C TO L2, L1 TO A
MED COOL	2 TO M, 3 TO B, C TO L2, L1 TO A
HI COOL	2 TO HI, 3 TO B, C TO L2, L1 TO A
LO HEAT	2 TO M, 1 TO B, HT TO L2, L1 TO A
HI HEAT	2 TO HI, 1 TO B, HT TO L2, L1 TO A

APPROVED QUALITY ASSURANCE

TEST DESCRIPTION	CHECKED BY
Burst Test	
First leak test	
Evacuation test & Charging	
Hi-Pot test	
Run test	
Final leak test	

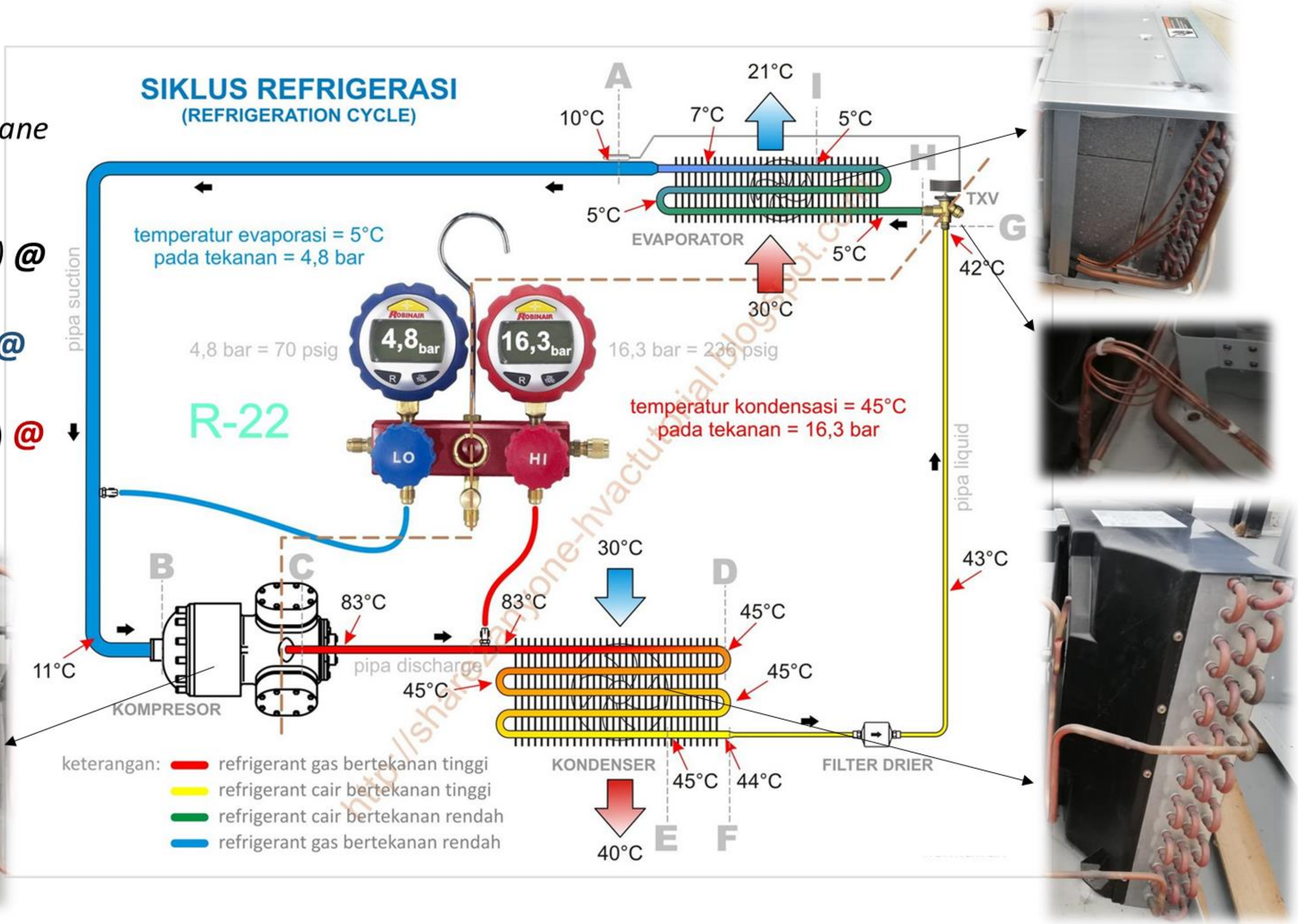
R-22

- **Nomenclature:** *Chlorodifluoromethane*
- **Symbol:** $CHClF_2$
- **Boiling point :**

T= *- 40.7°C* *(232.5 K)* @ *1 bar*

T= *4.9°C* (278.05 K) **@ 4.8 bar**

T= 45.6°C (318.75 K) **@ 16.3 bar**



[37]

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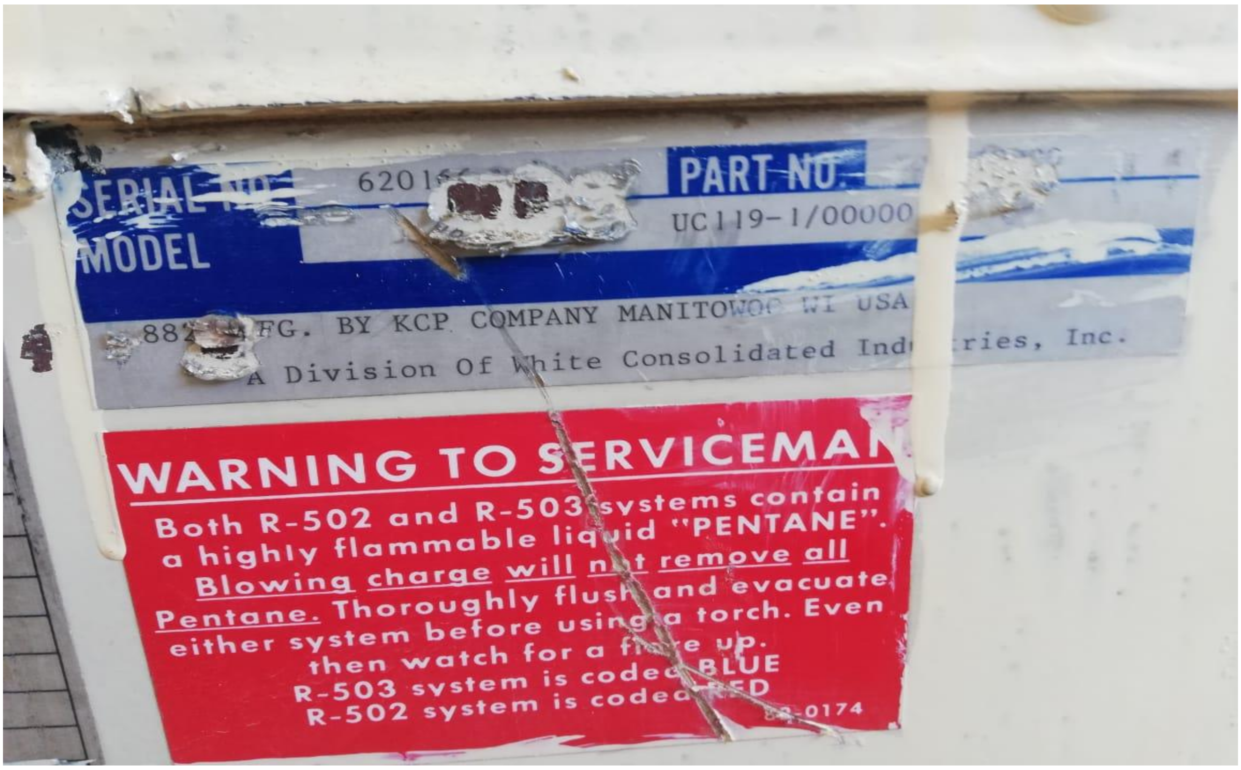
[37] https://refrigerants.com/product/r22/

13.3 Device 3 : Kelvinator fridge

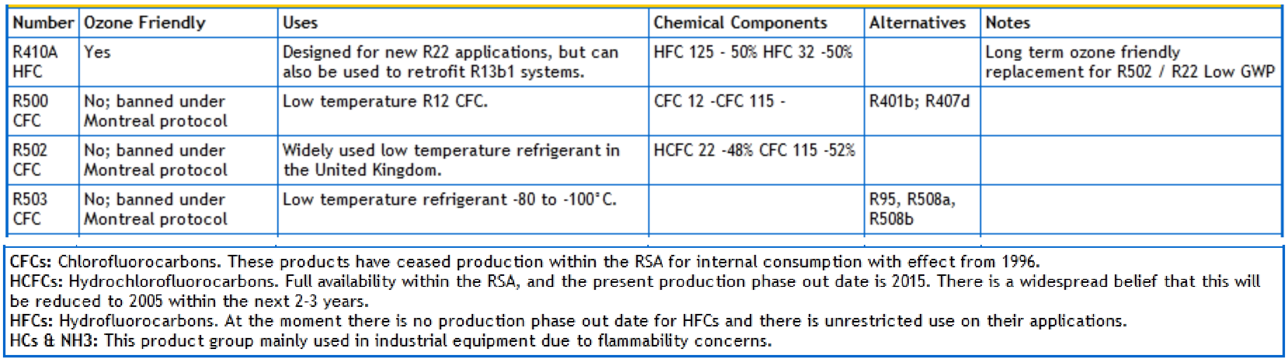
		HIGH STAGE			STAGE		
SSURE	L.S.	162			1		
	H.S.	375					
REFRIGERANT CHARGE		502	9.5	OZ.	503	5	OZ.
				OZ.			OZ.
	PENTANE	35		C.C.	35		C.C.
AMPERES	RATED LOAD						
	LOCKED ROTOR						
	FANS						
	COND. HTR.						
	TOTAL CAB.	12					
	H.P.						
	VOLTAG	230					
		50					



SERIAL NO. 6201
MODEL
PART NO.
UC119-1/00000
88 FG. BY KCP COMPANY MANITOWOC WI USA
A Division Of White Consolidated Industries, Inc.

WARNING TO SERVICEMAN

Both R-502 and R-503 systems contain a highly flammable liquid "PENTANE". Blowing charge will not remove all Pentane. Thoroughly flush and evacuate either system before using a torch. Even then watch for a flare up.
R-503 system is coded BLUE
R-502 system is coded RED
-0174



Number	Ozone Friendly	Uses	Chemical Components	Alternatives	Notes
R410A HFC	Yes	Designed for new R22 applications, but can also be used to retrofit R13b1 systems.	HFC 125 - 50% HFC 32 -50%		Long term ozone friendly replacement for R502 / R22 Low GWP
R500 CFC	No; banned under Montreal protocol	Low temperature R12 CFC.	CFC 12 -CFC 115 -	R401b; R407d	
R502 CFC	No; banned under Montreal protocol	Widely used low temperature refrigerant in the United Kingdom.	HCFC 22 -48% CFC 115 -52%		
R503 CFC	No; banned under Montreal protocol	Low temperature refrigerant -80 to -100°C.		R95, R508a, R508b	

CFCs: Chlorofluorocarbons. These products have ceased production within the RSA for internal consumption with effect from 1996.
HCFCs: Hydrochlorofluorocarbons. Full availability within the RSA, and the present production phase out date is 2015. There is a widespread belief that this will be reduced to 2005 within the next 2-3 years.
HFCs: Hydrofluorocarbons. At the moment there is no production phase out date for HFCs and there is unrestricted use on their applications.
HCs & NH3: This product group mainly used in industrial equipment due to flammability concerns.

[38]

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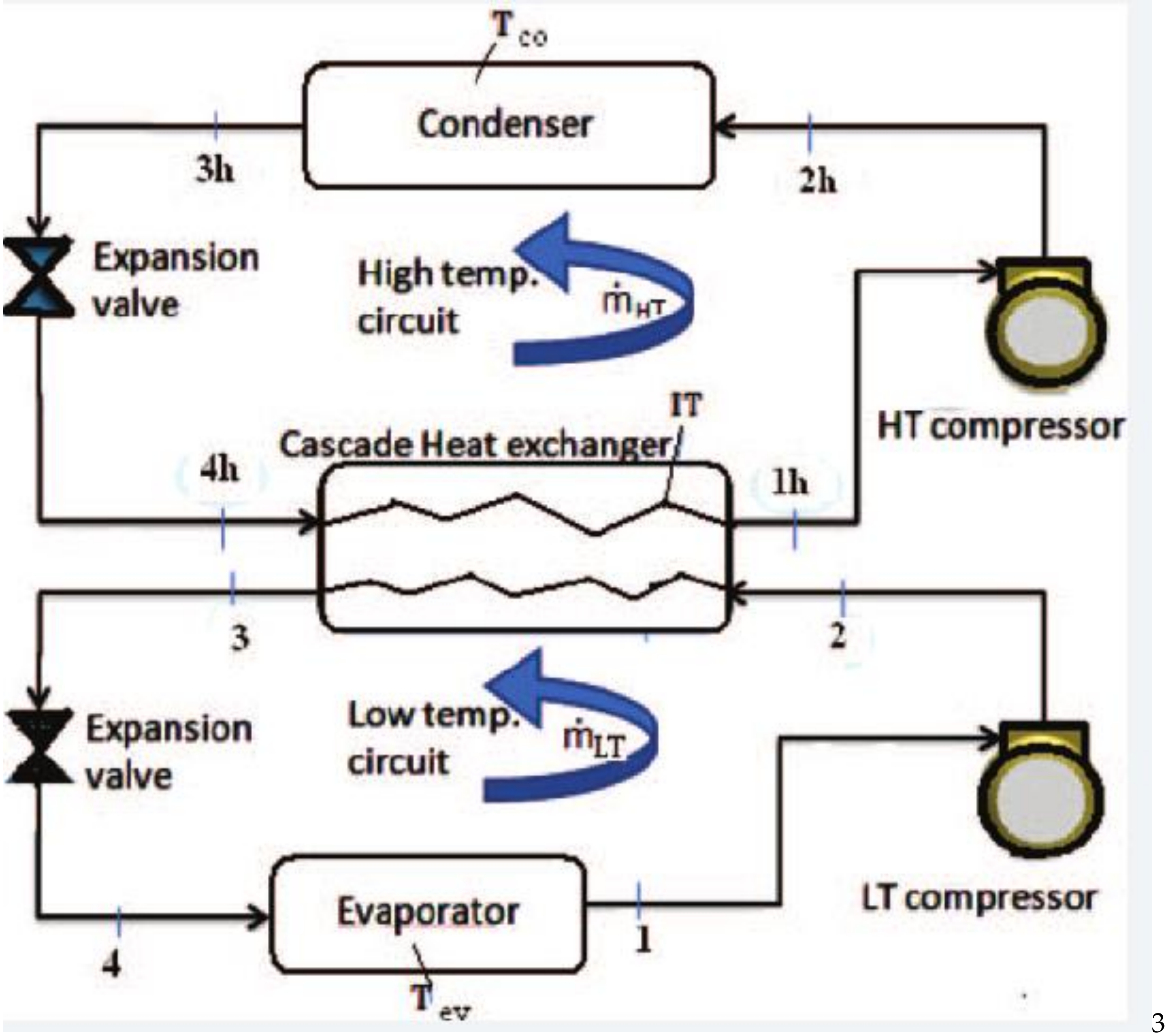
[38] http://www.proairlda.com/gases.htm



[39]

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[39] https://www.eevblog.com/forum/chat/refrigerator-with-two-compressors-how-do-they-do-it/

R-502 (High stage)

- **Nomenclature:** Chlorodifluoromethane, Chloropentafluoroethane
- **Symbol:** CHC1F2, CC1F2CF3
- **Compress:** 375 psi = 25.85 bar
- **Boiling point :**

T= - *45.6°C* *(227.4 K)* **@ 1 bar**

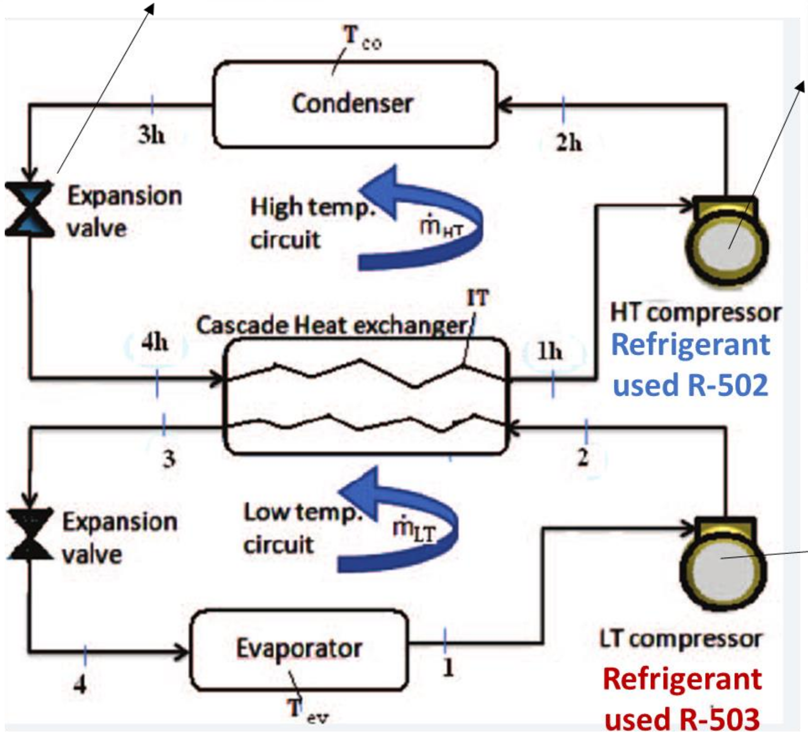
T= 61.5°C (334.7 K) **@ 25.85 bar**

R-503 (Low stage)

- **Nomenclature:** Azeotropic Blend
- **Symbol:** CHF3
- **Compress:** 375 psi = 25.85 bar
- **Boiling point :**

T= - *88.9°C* *(184.1 K)* **@ 1 bar**

T= - 20°C (253.2 K) **@ 25.85 bar**



[40] [41] [42]

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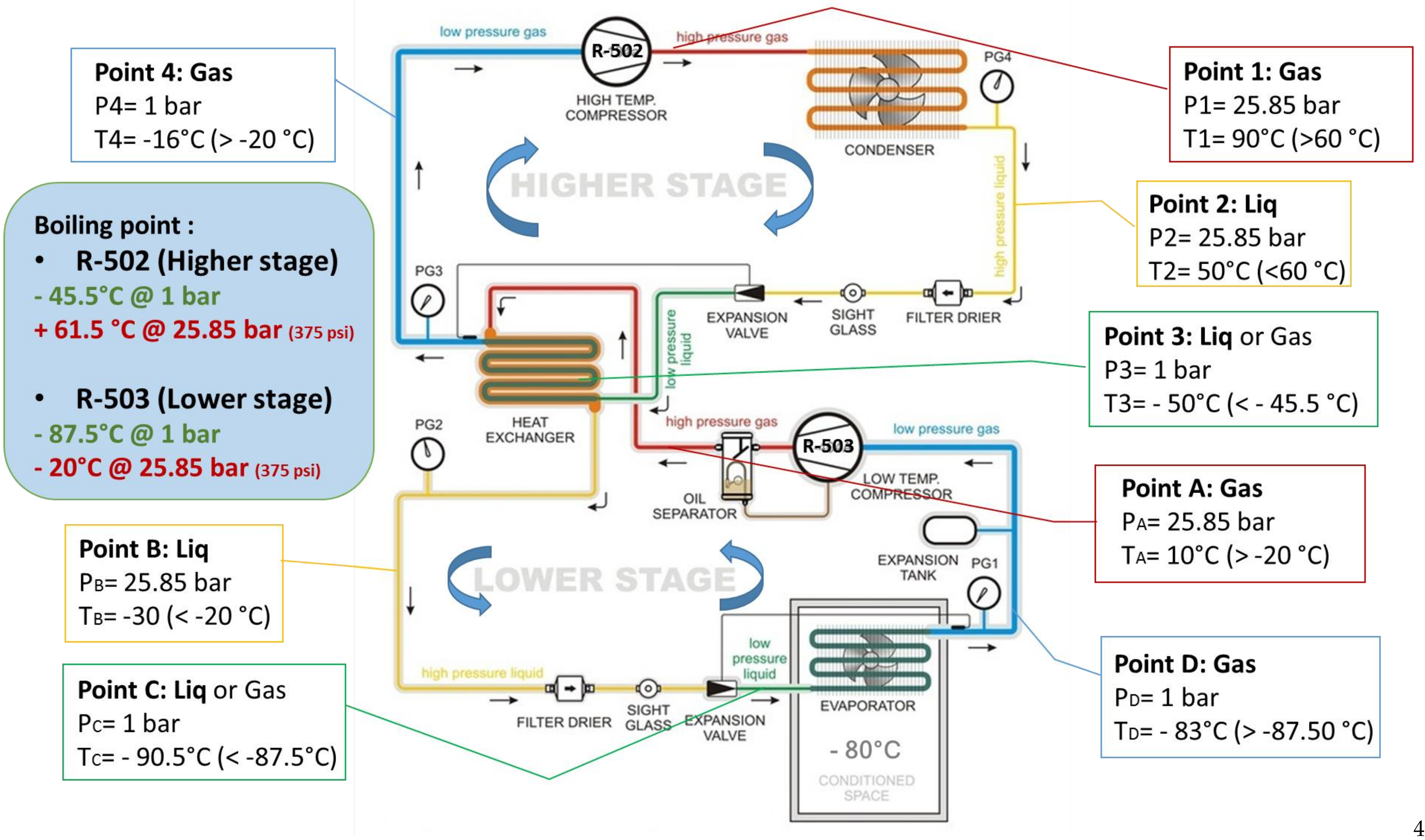
40 https://secureservercdn.net/198.71.233.179/m9v.7b6.myftpupload.com/wp-content/uploads/2019/12/SDS-R22.pdf?time=1618519493

41 https://www.cc.kyushu-u.ac.jp/scp/system/library/PROPATH/manuals/p-propath/r503.pdf

42 https://www.arma.org.au/wp-content/uploads/2017/02/SDS-R503.pdf



Point 4: Gas
P4= 1 bar
T4= -16°C (> -20 °C)

Boiling point :

- **R-502 (Higher stage)**

- 45.5°C @ 1 bar
+ 61.5 °C @ 25.85 bar (375 psi)

- **R-503 (Lower stage)**

- 87.5°C @ 1 bar
- 20°C @ 25.85 bar (375 psi)

Point B: Liq
PB= 25.85 bar
TB= -30 (< -20 °C)

Point C: Liq or Gas
PC= 1 bar
TC= - 90.5°C (< -87.5°C)

Point 1: Gas
P1= 25.85 bar
T1= 90°C (>60 °C)

Point 2: Liq
P2= 25.85 bar
T2= 50°C (<60 °C)

Point 3: Liq or Gas
P3= 1 bar
T3= - 50°C (< - 45.5 °C)

Point A: Gas
PA= 25.85 bar
TA= 10°C (> -20 °C)

Point D: Gas
PD= 1 bar
TD= - 83°C (> -87.50 °C)

[43]

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43 https://www.quora.com/What-is-a-cascade-refrigeration-system

The cascade refrigeration system consists of a low-temperature loop (Low stage) and a high-temperature loop (high stage).

Each stage consists of a compressor, condenser, expansion valve and evaporator

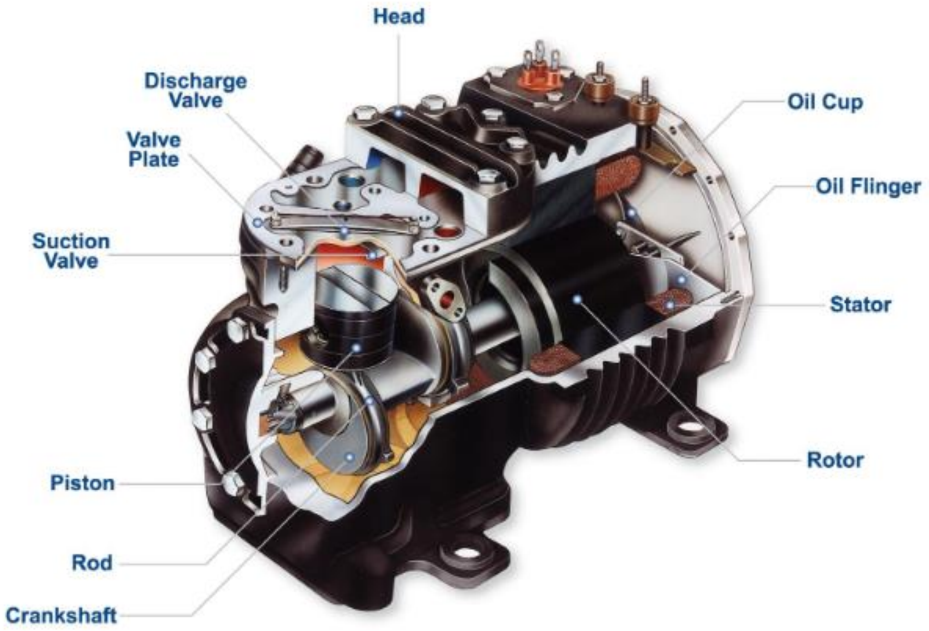
The high stage condenser is cooled by air cooled, while the low stage condenser is cooled by the high stage evaporator.

So the high stage evaporator acts as a coolant for the pressurized refrigerant in the low stage.

Advantages of a cascade cooling system:

- Repair is easy
- The Cascade refrigeration allows to low-temperature operation.
- You can reduce the use of power up to 10% with the help of cascade refrigeration.

Basic Components



N.B. (process):

1- Pressure Controls

With the exception of a reverse acting control, the pressure controls will be standard, and used in the normal way. A high pressure control will usually be found on all second and third stages, and in some cases on the first stage. This protects the system against excessive pressures during pull-down, or if there is a failure of the first stage system. The control may cycle a few times at the start. A high pressure control with a 100 pound differential (to allow pressures to equalize) is sometimes used rather than a back pressure regulator.

Where continuous operation at the lowest temperature is desired, the high pressure control only is used on the low stage. Where control of the low side or fixture temperature is desired, a thermostat, connected in series with the high pressure control, is used. In special applications and on older units, a liquid line solenoid may be used with a low pressure control on the low stage. (A solenoid for such an application requires a waterproof coil in a well sealed housing.)

The addition of a reverse acting pressure control provides automatic operation even when starting warm. With the interstage condenser at room temperature, a pressure of 700 pounds or more would be required to condense the low temperature refrigerant, therefore the low stage compressor cannot be allowed to start until the high stage has lowered the temperature in the interstage condenser to operating temperatures. This has been accomplished in several ways, such as a thermostat sensing the temperature of the heat exchanger, or pressure controls with reverse acting contacts which open on pressure increase and close on a decrease. This control would be connected to the low side of the high stage.

2-Control Of High Pressure Equipment

Up until a few years ago, most cascade equipment used expansion valves and a low temperature refrigerant charge of at least 3 to 5 pounds which necessitated an interstage condenser receiver capable of holding the refrigerant pressure at 500 to 700 psi so that the charge could be contained there. To put the system in operation, the high stage had to be started and the inlet and outlet valves of the interstage condenser receiver opened when it was down to the working temperature. Any power failure or loss of refrigeration due to any failure in the high stage meant the loss of the low temperature refrigerant charge through the relief valve or rupture disc. The system could not be shut down until the low stage was pumped down and the charge locked in the interstage condenser receiver.

Small self-contained systems using less than 2 pounds of the low temperature refrigerants can be made completely automatic, if space is available to provide expansion tanks of sufficient volume to store the refrigerant in the vapor stage at or below 200 pounds pressure. Some of the small chest type units for temperatures down to -130°F using capillary tubes and hermetic compressors can hold the charge in the low side, oil separators, heat exchangers, etc., plus the dome or shell of the unit. As the size of the low side is increased and more refrigerant is required, one or more expansion tanks are required for automatic operation. Good practice limits the maximum pressure to 150 or 200 pounds.

In some cases, the connection to the expansion tank may be a capillary tube. When the unit is shut down, the rise in pressure is slow and most of the charge is stored in the tank. This capillary tube is sized so that the charge in the tank is fed slowly into the system during a pull-down from room temperature. In larger installations where a pull-down imposes a severe load on the motor and compressor, the charge may be admitted to the expansion tanks through a check valve and returned through a pressure reducing valve which can be adjusted to the capacity of the unit during such periods.

3- Water Cooling Circuitry

The condenser of a high stage does not always receive the incoming water first.

Water is used to remove superheat from the compressed low stage refrigerant before entering the interstage condenser and is also used in some motor cooling jackets. If it were also used on the compressor heads, the flow would be inadequate when the water regulator reduced the flow according to the demand of the high stage. By feeding the condenser last, an adequate flow is maintained at all times.

4- Frost Suppressors

While not so common today, these will be found on some units in the form of a heat exchanger between the low temperature suction line and the low temperature hot gas line before it enters the interstage condenser.

5- Liquid Line Accumulator

On some small units using capillary tubes in both systems, a small liquid accumulator may be found in the liquid line of the high stage. This is required, as the capillary tube is sized for continuous operation at low temperature, and during a start-up it can not pass the volume of refrigerant condensed by the unit at high temperatures, thus filling the condenser and causing excessively high pressures. The accumulator or reservoir prevents this pressure during the few minutes required to cool the interstage condenser.

6- SYSTEM CLEANUP

Cleanup is required any time a system has to be opened, for whatever reason, excluding the addition of refrigerant. Recover the charge according to EPA-approved procedures, and remove the dryer, disconnect the suction line from the compressor, and backflush the entire system with solvent to remove any contaminants or oil from the system. This is most important when replacing a compressor.

13.3.1 Connecting two compressors to get combined pressure and volume

In order to achieve the desired pressure and volume for our pneumatic equipment, I need to interconnect 2 compressors.

I need advice on how to go about doing it and need a couple of questions answered:

1) Is it necessary that both compressors share the same specs ?

2) Will the resultant pressure and volume be a sum of both compressors?

Both good questions, and both covered extensively on the pages of this site already.

Answer to question #1 – no.

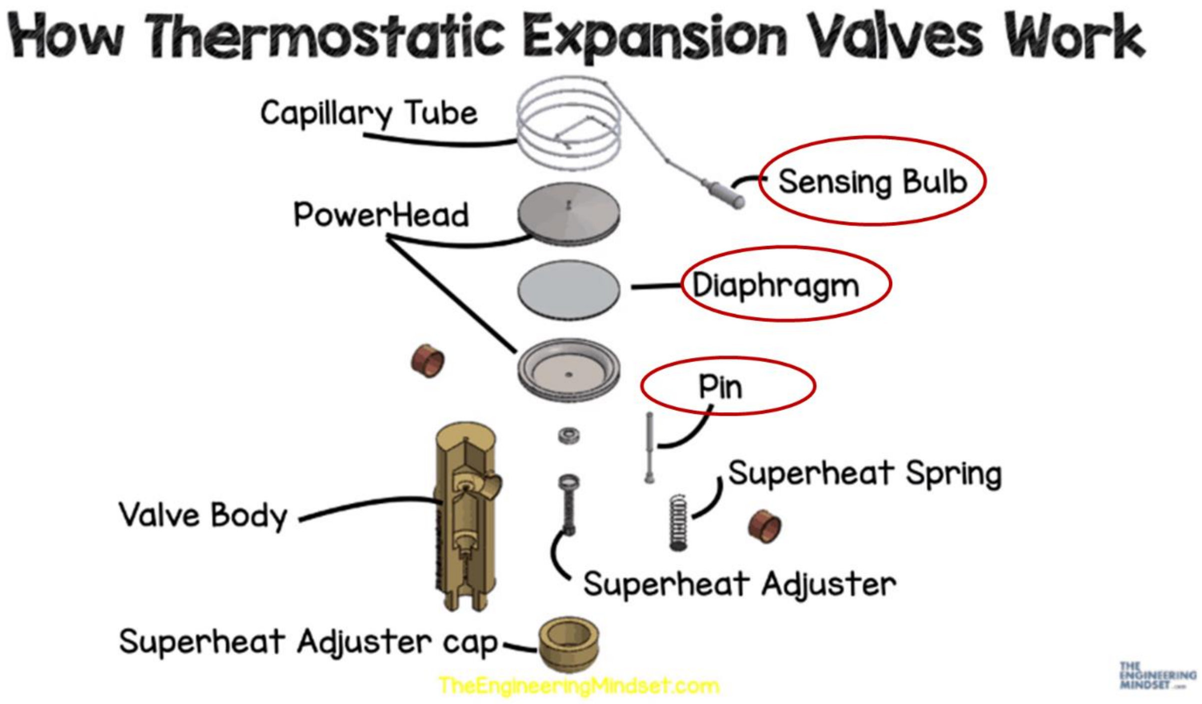
Answer to #2 – no. If each compressor puts out 100 PSI, your downstream air line will not see 200 PSI. What you will do is increase the available compressed air flow at the pressure the system needs.

Both compressors will plumb to the same air main to your plant.

Both air compressors will have a one-way or check valve in their lines before the two lines connect to the single main.

In order for one compressor not to be the one that's always on first, undergoing greater wear, periodically change the pressure switch settings so that the alternate compressor comes on first.

13.3.1.1 Expansion valve



[44]

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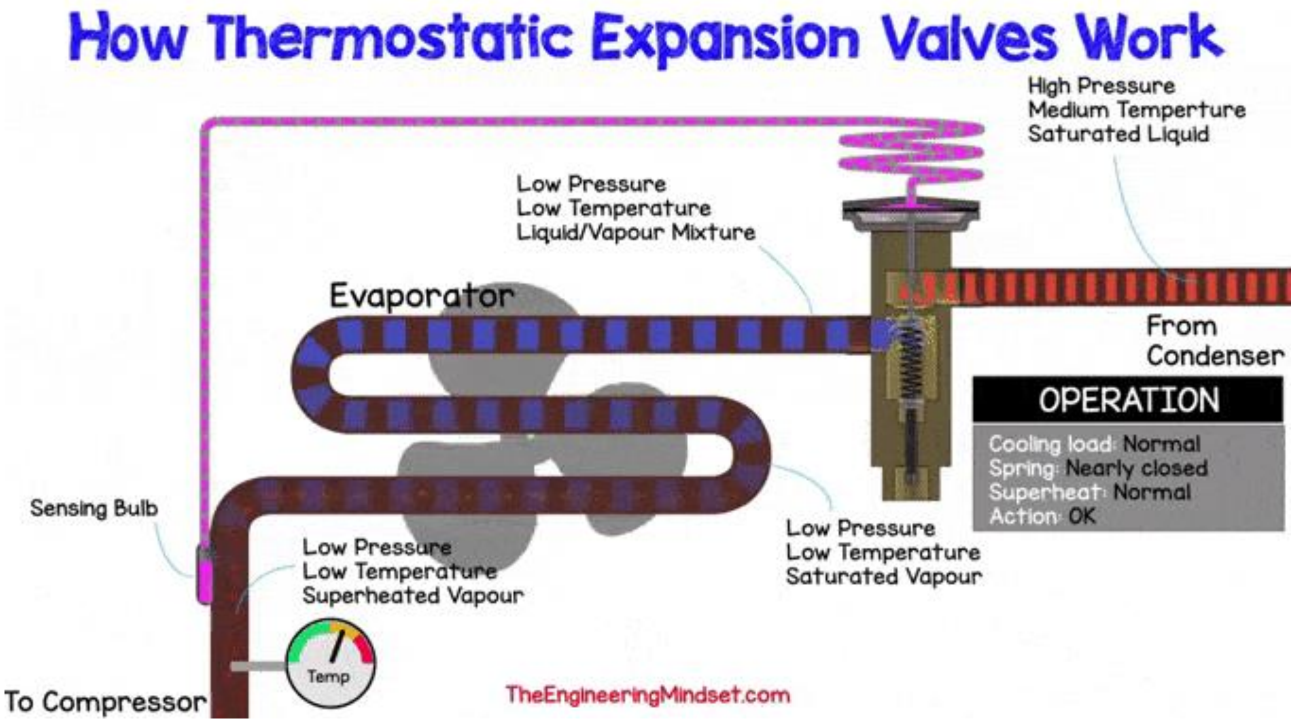
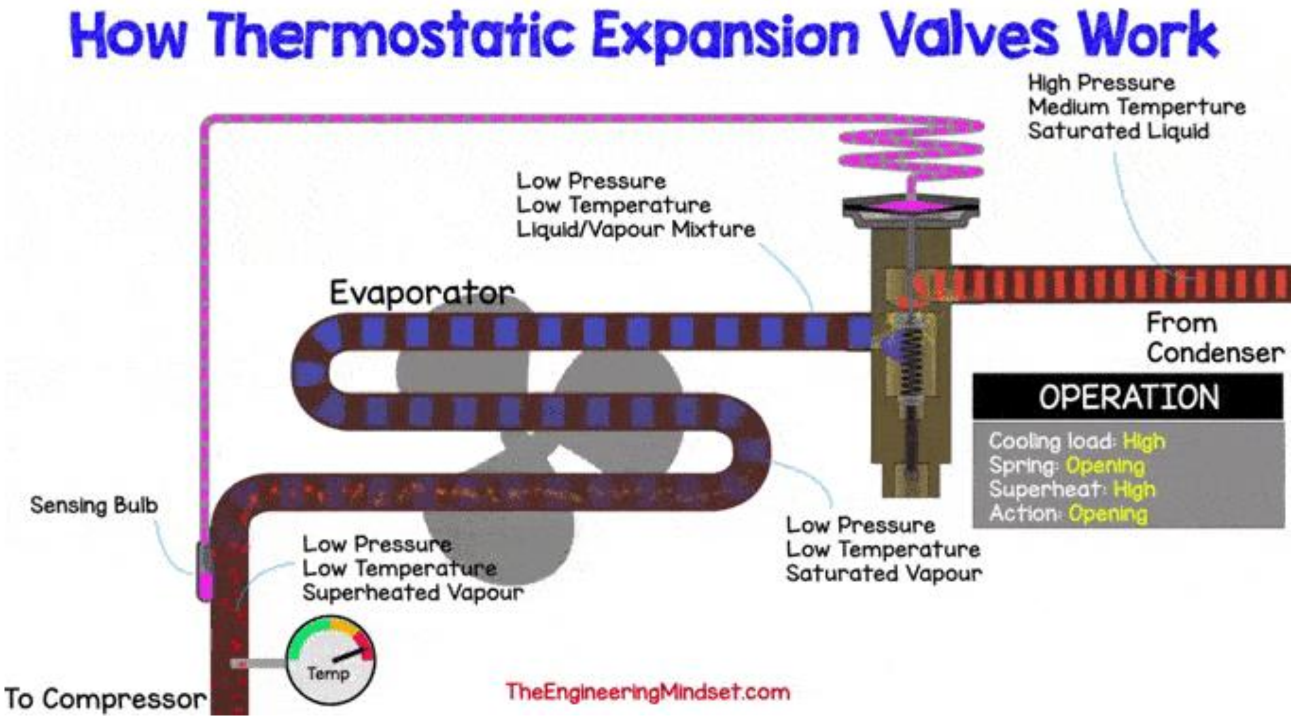
44 https://theengineeringmindset.com/thermostatic-expansion-valves-work/





The TXV is used in many refrigeration systems, they can be found in the same location which is just before the evaporator.

The valve decreases the pressure to allow the refrigerant to boil at lower temperatures. The boiling is essential as the refrigerant will absorb the heat from the ambient air and carry this away to the compressor. Just remember that refrigerants have a much lower boiling point than water.

The high pressure liquid refrigerant is forced through a small orifice which causes a pressure reduction as it passes through. During this pressure reduction, some of the refrigerant will vaporise and the rest will remain as liquid.

13.3.1.2 Types of bulbs

There are three different types of bulbs:

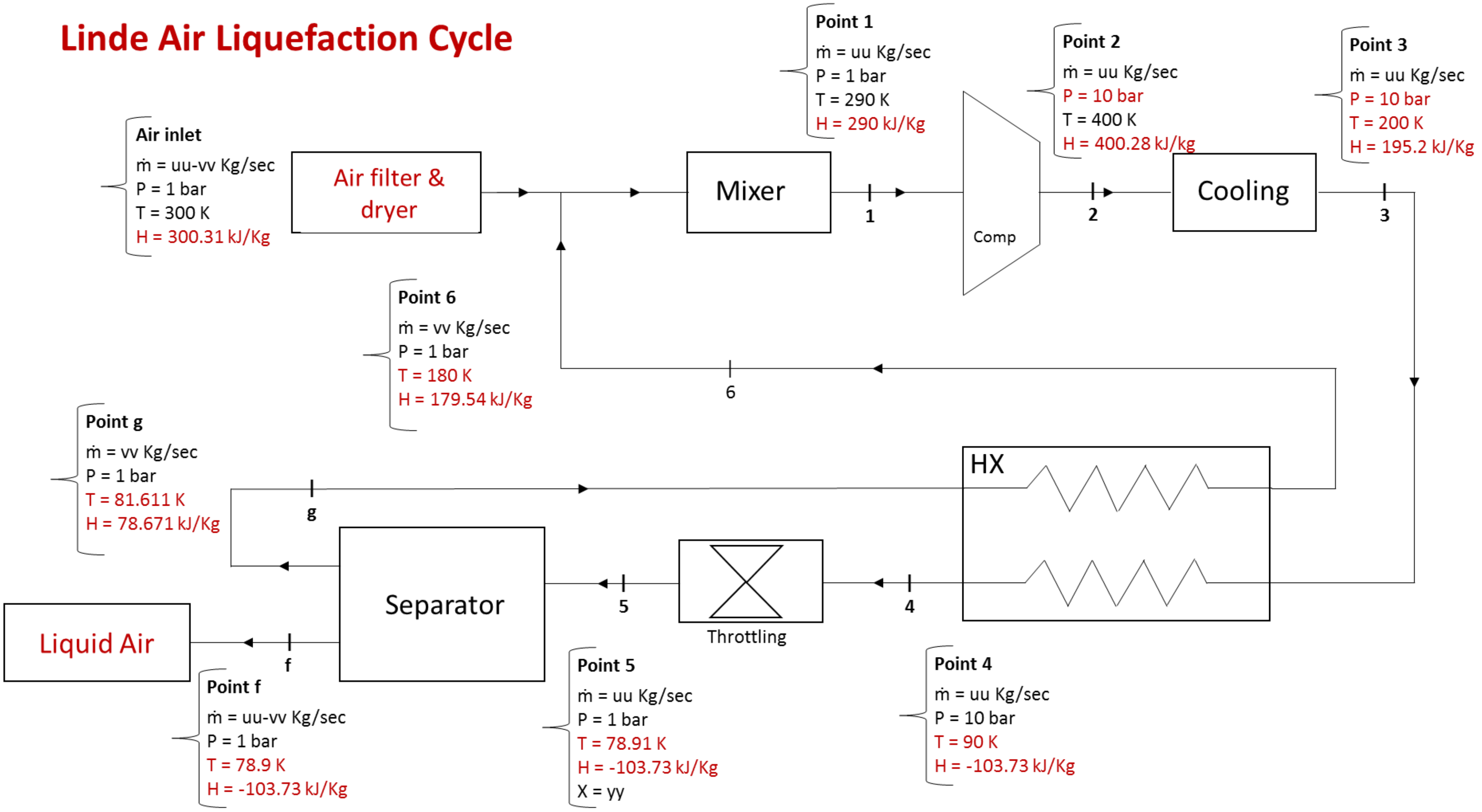
- **Liquid-charged bulbs**
- MOP (Maximum Operating Pressure) bulbs – also called gas-charged bulbs
- Adsorption-filled bulbs

A **liquid-charged bulb** has a large charge of refrigerant and will never "run dry". It will always contain both liquid and gaseous refrigerant. The pressure inside the bulb increases as the superheating increases, due to additional evaporation. Historically, the refrigerant in the bulb was the same as the working refrigerant in the system (parallel-charged). However, better characteristics have been achieved by using different refrigerants (cross-charged), which is now the most common arrangement.

An **MOP bulb**, also called gas-charged, has a much smaller quantity of refrigerant mixture inside the bulb than a liquid-charged bulb. As the evaporation pressure increases, the suction pipe will become increasingly warm as a result. A limited refrigerant charge in an MOP bulb will be totally evaporated at a predefined pressure, the MOP pressure. When the liquid refrigerant mixture has boiled off, the pressure inside the bulb will not increase greatly even if the evaporating pressure does. The needle valve will not open further, thus limiting the maximum mass flow through the valve. The reason for this is to protect the compressor from electrical overload, especially during start-up when the evaporation pressure can be much higher than under normal operating conditions. A disadvantage of the MOP valve is that the bulb always has to be colder than the valve housing to prevent the limited refrigerant charge from migrating and condensing at the membrane surface. If the MOP bulb were instead warmer than the valve housing, the MOP valve would close even if the operating pressure were well below the maximum operating pressure.

TEVs may also have **an adsorption** charge, where the bulb also contains a solid adsorbent such as charcoal or silica gel. The adsorbed refrigerant reacts more slowly to temperature changes than direct-charged bulbs, and gives a slower response. This can sometimes help to stabilize oscillation tendencies. However, adsorption-filled bulbs work best over a limited range, which is why they are often specially designed for the operating conditions.

Linde Air Liquefaction Cycle



Project D and E in 21: Analysis of refrigerator devices in AECENAR Center

In this project (Liquefaction of air), We need to cool the air from 27 °C (300 K) to -194.35 °C (78.8 K), and to achieve this we will use an air compressor (10 bar). The compressor will compress ambient air from 1 bar (27 °C, 300 K) to 10 bar (126.85 °C, 400 K).

To cool the air from 400 K to 90 K, two heat exchangers will be used, the first will be a heat exchanger to cool the compressed air from (126.85 °C, 400 K) up to (-73.15 °C, 200 K) due to the cascade refrigeration cycle (R-502 and R-503 (Kelvinator fridge)) and a second heat exchanger to cool the compressed air from 200 K to 90 K, this exchanger will work with the temperature of the non-liquefied cold air (about -195 °C, 78.8 K).

After the cooling process, the compressed air will pass into the expansion valve, where the air will be subjected to a sudden pressure drop, causing a similar temperature drop, from 10 bar (-183.15 °C, 90 K) to 1 bar (-194.24 °C, 78.91 K).).

After expanding, the liquefied air (air liquid) will be separated from the non-liquefied air (air in gas state). Where the liquid will be stored in special containers, while the non-liquefied cold air will be used to cool the compressed air as mentioned earlier (in the second heat exchanger).

Therefore, to obtain liquefied air with a 10 bar compressor, the air must be cooled to 90 K (-183 ° C).

# of	Point 3	Point 4 (10 bar, 1 MPa)		Point 5 (1 bar, 0.1 MPa)	Point g	Point 6
cycle	T (K)	T (K)	H (kJ/Kg)	T (K)	T (K)	T (K)
1	200	200	195.2	195.54	300	300
2	200	249.06	246.092	246.11	246.11	249.49
3	200	222.17	218.32	218.5	218.5	223.97
4	200	208.79	204.39	204.66	204.66	209.45
5	200	202.2	197.5	197.82	197.82	202.4
6	200	198.98	194.13	194.47	194.47	198.88
7	200	197.41	192.48	192.46	192.46	197.14
8	200	196.47	191.49	191.48	191.48	196.1
9	200	196.01	191	190.99	190.99	195.59
10	200	195.78	190.76	190.75	190.75	195.33
11	200	195.67	190.64	190.64	190.64	195.21
12	200	195.62	190.59	190.58	190.58	195.15
13	200	195.59	190.56	190.55	190.55	195.12
14	200	195.58	190.55	190.54	190.54	195.11
15	200	195.57	190.54	190.53	190.53	195.1
|	|	|	|	|	|	|
|	|	|	|	|	|	|
~ 1000	200	90	-103.73	78.91	80	131.86

We notice that the temperatures in the first five stages were changing significantly as the heat exchanger was cooling down, then with the beginning of the sixth stage, the heat exchanger began to play its primary role, which is cooling the air entering the exchanger before passing through the expansion valve, but after several stages we notice that the heat difference between The stages due to the decrease in the temperature difference before and after the expansion valve (+ -5 degrees), which slows down the process of cooling the air and prevents it from reaching temperatures as low as 90 kelvin except after many many stages. Here the problem appears in practice, as in the event of any thermal leakage from the thermal insulating materials, this leakage will further delay the process of liquefying the air, and we may be vulnerable to not reaching the liquefaction temperature.

---

14 Project D 21: LOX Prototype System Concept & Mechanical Design

AECENAR
Association for Economical and Technological Cooperation in the Euro-Asian and North-African Region
www.aecenar.com

Air Liquefaction and Cryogenics – Report 1 (2021),

Part II: **LOX Prototype System Concept & Mechanical Design**

Author: Mariam El Rez
Editor: Samir Mourad

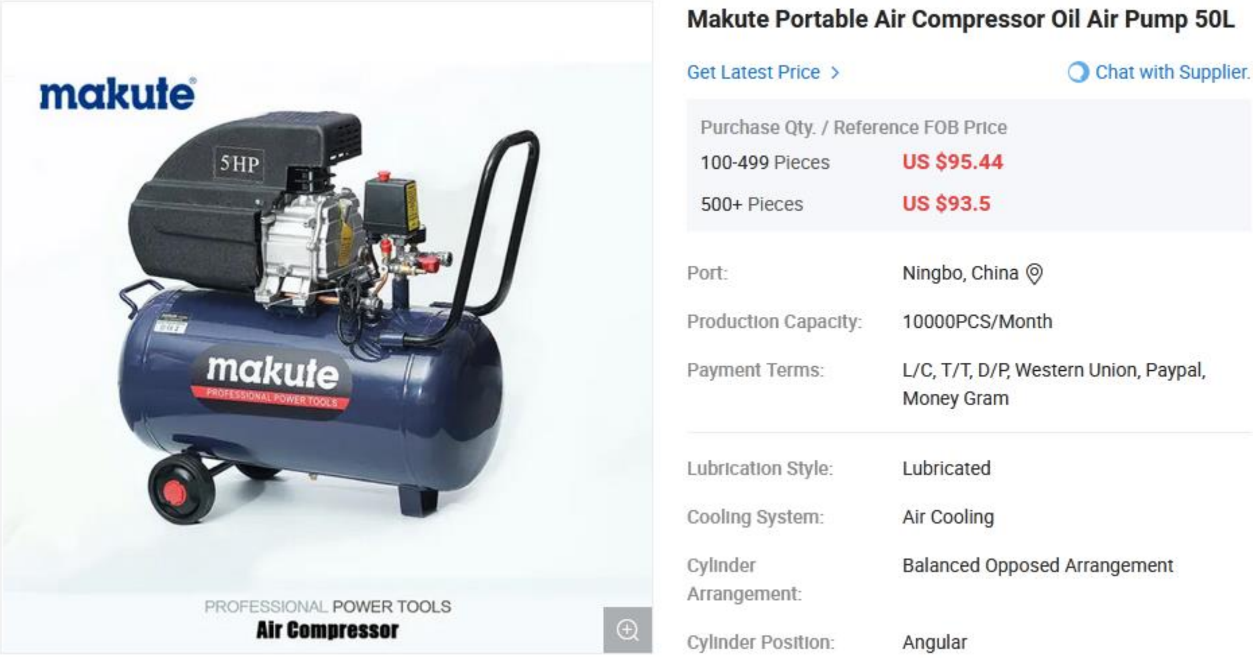
Last update: Aug 2021

Contents

14.1 System Design of LOX Production Prototype

14.1.1 Air Compressor

#1 (with oil)



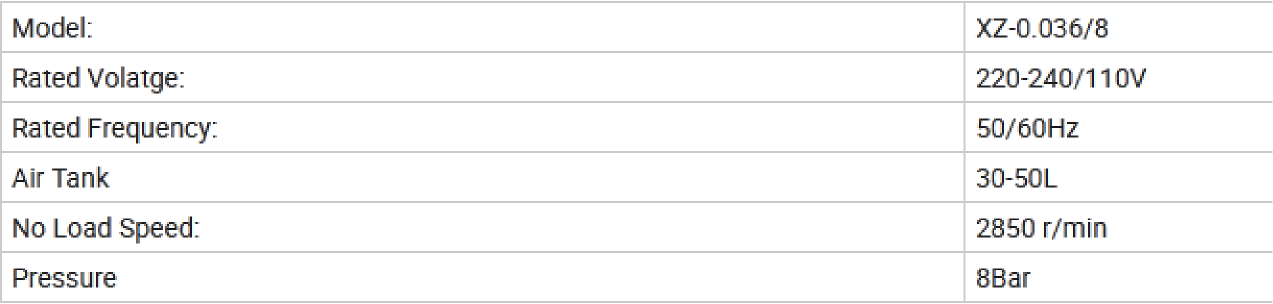
Makute Portable Air Compressor Oil Air Pump 50L

Get Latest Price >

Chat with Supplier.

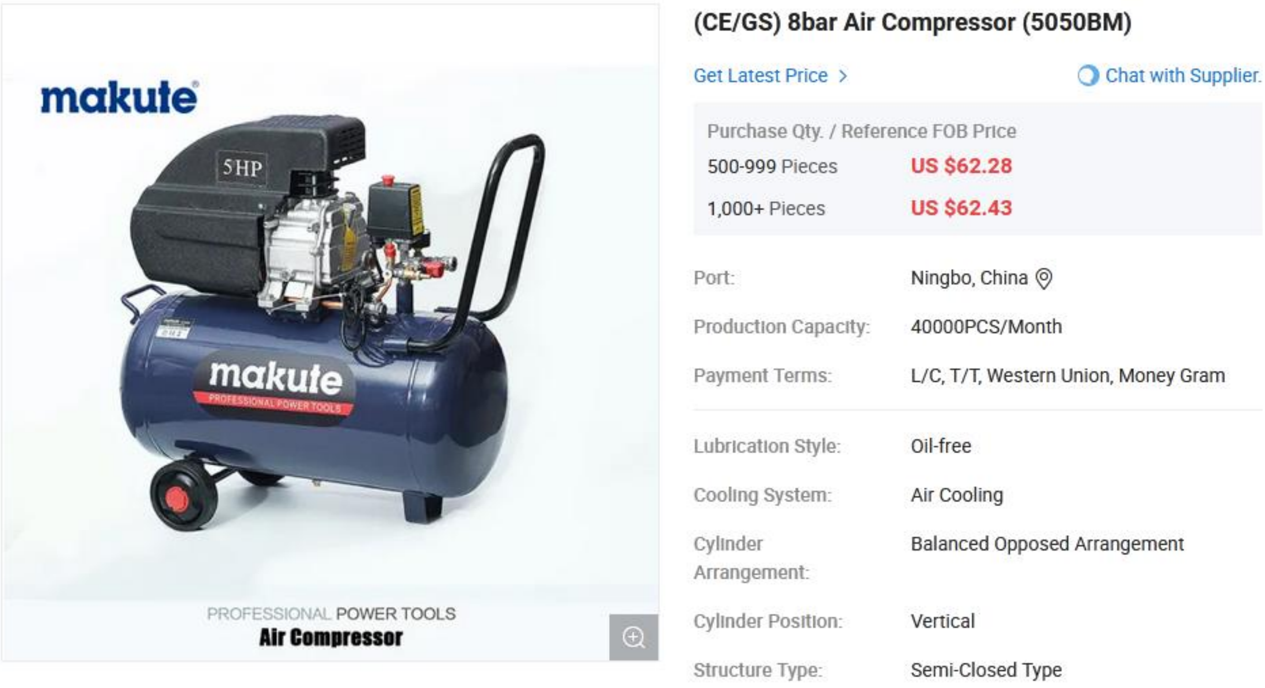
Purchase Qty. / Reference FOB Price	
100-499 Pieces	US $95.44
500+ Pieces	US $93.5

Port:	Ningbo, China
Production Capacity:	10000PCS/Month
Payment Terms:	L/C, T/T, D/P, Western Union, Paypal, Money Gram
Lubrication Style:	Lubricated
Cooling System:	Air Cooling
Cylinder Arrangement:	Balanced Opposed Arrangement
Cylinder Position:	Angular



Model:	XZ-0.036/8
Rated Volatge:	220-240/110V
Rated Frequency:	50/60Hz
Air Tank	30-50L
No Load Speed:	2850 r/min
Pressure	8Bar

#2 (oil free)



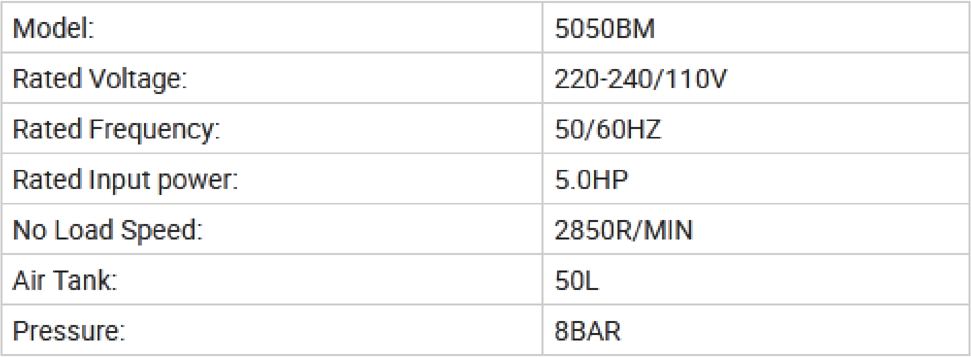
PROFESSIONAL POWER TOOLS
Air Compressor

(CE/GS) 8bar Air Compressor (5050BM)

Get Latest Price >
Chat with Supplier

Purchase Qty. / Reference FOB Price	
500-999 Pieces	US $62.28
1,000+ Pieces	US $62.43

Port:	Ningbo, China
Production Capacity:	40000PCS/Month
Payment Terms:	L/C, T/T, Western Union, Money Gram
Lubrication Style:	Oil-free
Cooling System:	Air Cooling
Cylinder Arrangement:	Balanced Opposed Arrangement
Cylinder Position:	Vertical
Structure Type:	Semi-Closed Type



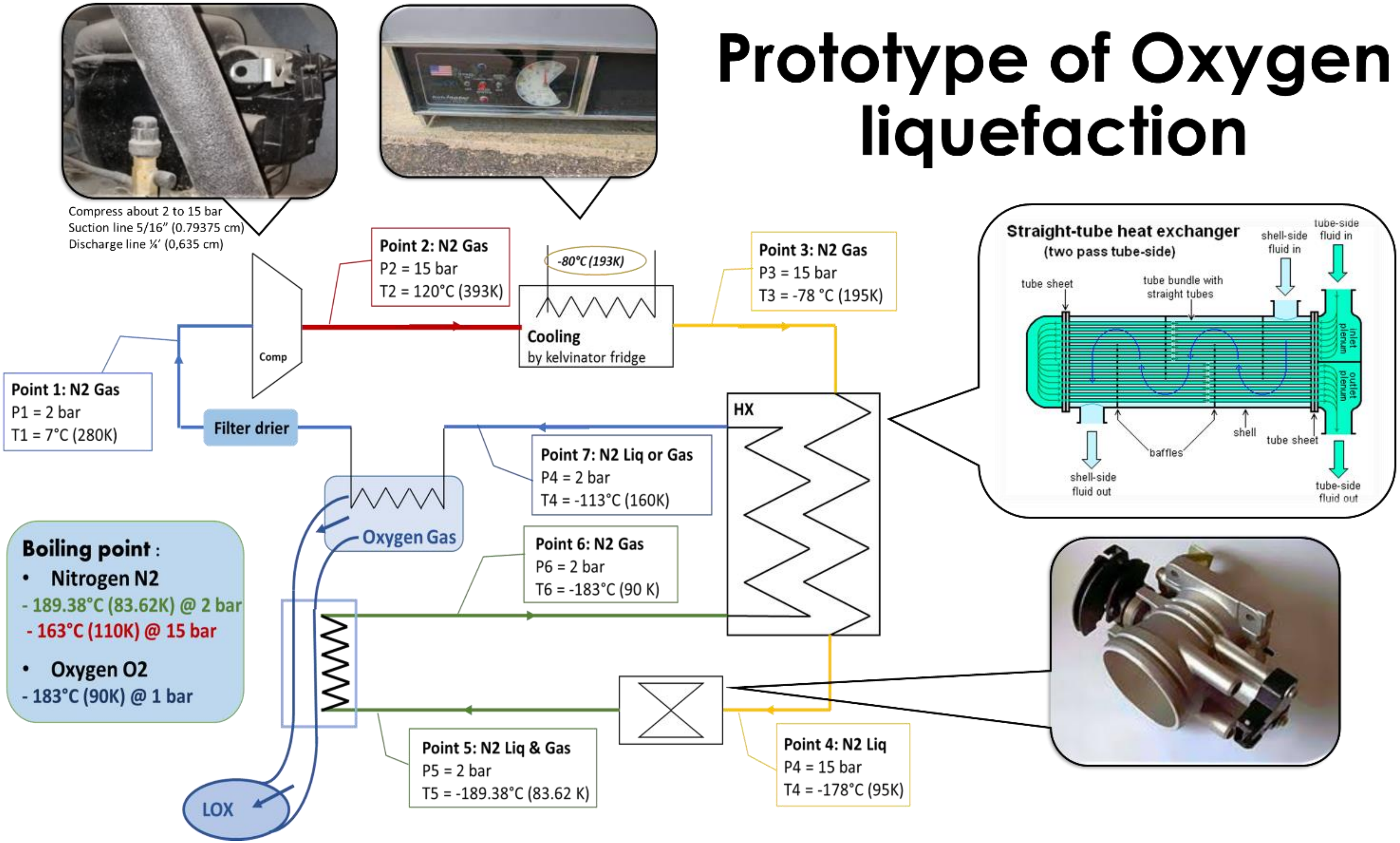
Model:	5050BM
Rated Voltage:	220-240/110V
Rated Frequency:	50/60HZ
Rated Input power:	5.0HP
No Load Speed:	2850R/MIN
Air Tank:	50L
Pressure:	8BAR

Air Compressor (Antar store)

- 10 bar , 50L price 165 dollars (makute company)
- 10 bar, 150L price 395 dollars
- 10 bar, 200 L price 450 dollars

14.1.2 Prototype cycle of Oxygen liquefaction

Prototype of Oxygen liquefaction



Compress about 2 to 15 bar
Suction line 5/16" (0.79375 cm)
Discharge line ¼' (0,635 cm)

Point 1: N2 Gas
$P1 = 2$ bar
$T1 = 7°C$ (280K)

Point 2: N2 Gas
$P2 = 15$ bar
$T2 = 120°C$ (393K)

Point 3: N2 Gas
$P3 = 15$ bar
$T3 = -78 °C$ (195K)

Point 4: N2 Liq
$P4 = 15$ bar
$T4 = -178°C$ (95K)

Point 5: N2 Liq & Gas
$P5 = 2$ bar
$T5 = -189.38°C$ (83.62 K)

Point 6: N2 Gas
$P6 = 2$ bar
$T6 = -183°C$ (90 K)

Point 7: N2 Liq or Gas
$P4 = 2$ bar
$T4 = -113°C$ (160K)

Comp

-80°C (193K)

Cooling
by kelvinator fridge

Filter drier

HX

Oxygen Gas

LOX

Boiling point :
- Nitrogen N2
  - 189.38°C (83.62K) @ 2 bar
  - 163°C (110K) @ 15 bar
- Oxygen O2
  - 183°C (90K) @ 1 bar

Straight-tube heat exchanger
(two pass tube-side)

In this prototype the oxygen will be liquefied by cascade cooling of nitrogen.

The nitrogen gas will be compressed (from 2 bar to about 15 bar)[use for that the laboratory refrigerator], The nitrogen will then be cooled down to 195 K by means of a Kelvinator fridge operated with a cascade of R-502 and R-503 refrigerants.

Then the nitrogen will be cooled to lower temperatures (83.6 K) using the expansion valve and heat exchanger.

This nitrogen temperature (<90 K) would be sufficient to liquefy the oxygen at 1atm.

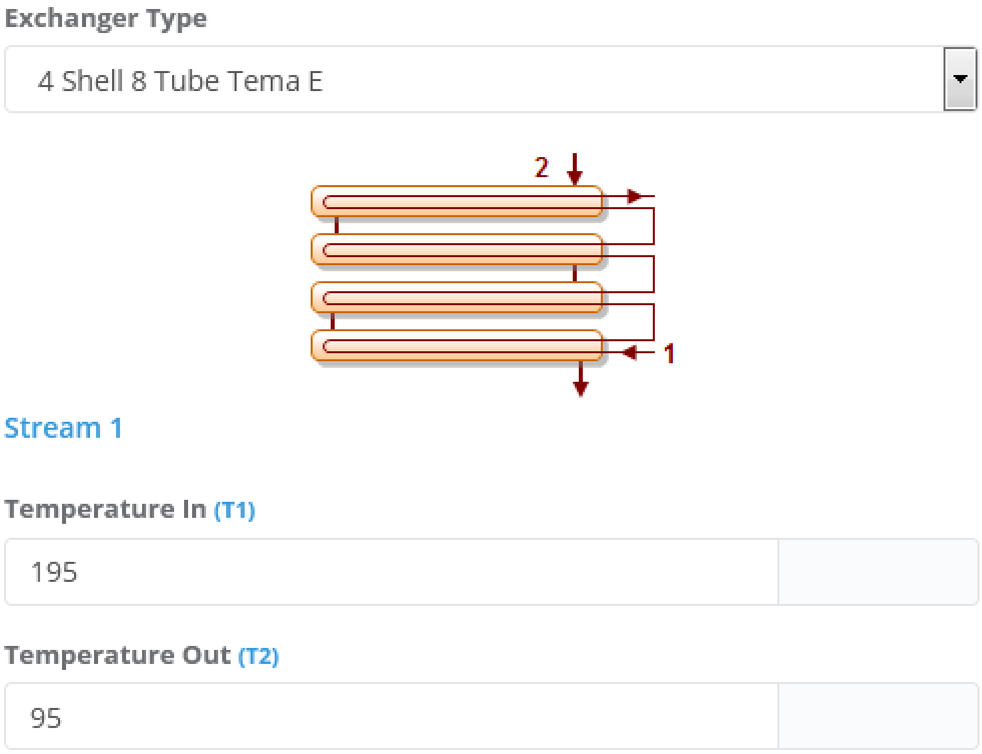
Oxygen gas can also be prepared and cooled to about 170 K in nitrogen before returning directly to the compressor (160 K).

14.1.3 Prototype Heat exchanger (HX - N_2/N_2)

LMTD Correction Factor Charts

Calculates Logarithmic Mean Temperature Difference (LMTD) Correction factor for different configuration of exchangers.

14.1.3.1 Data:



Exchanger Type

4 Shell 8 Tube Tema E

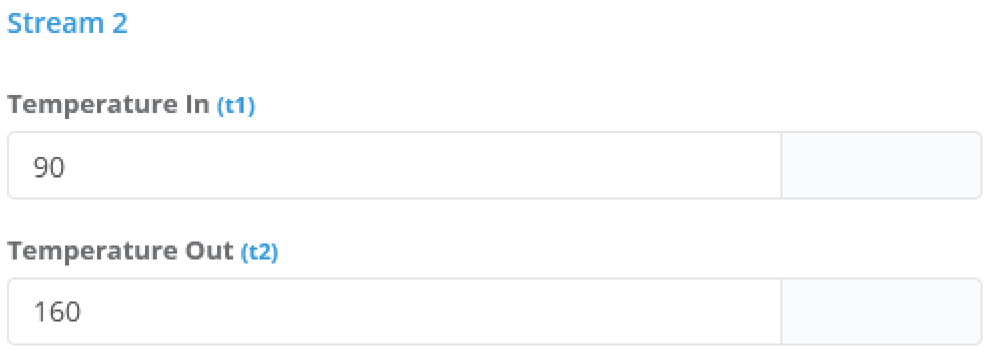
Stream 1

Temperature In (T1)

195

Temperature Out (T2)

95



Stream 2

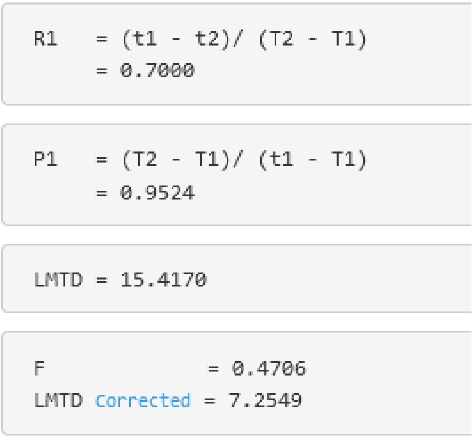
Temperature In (t1)

90

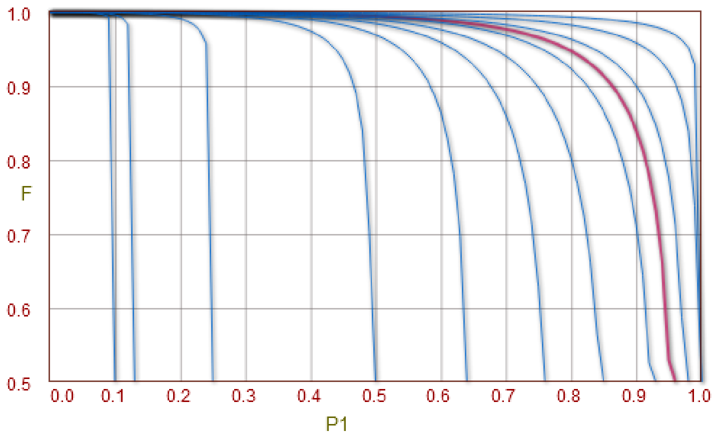
Temperature Out (t2)

160

14.1.3.2 Result:



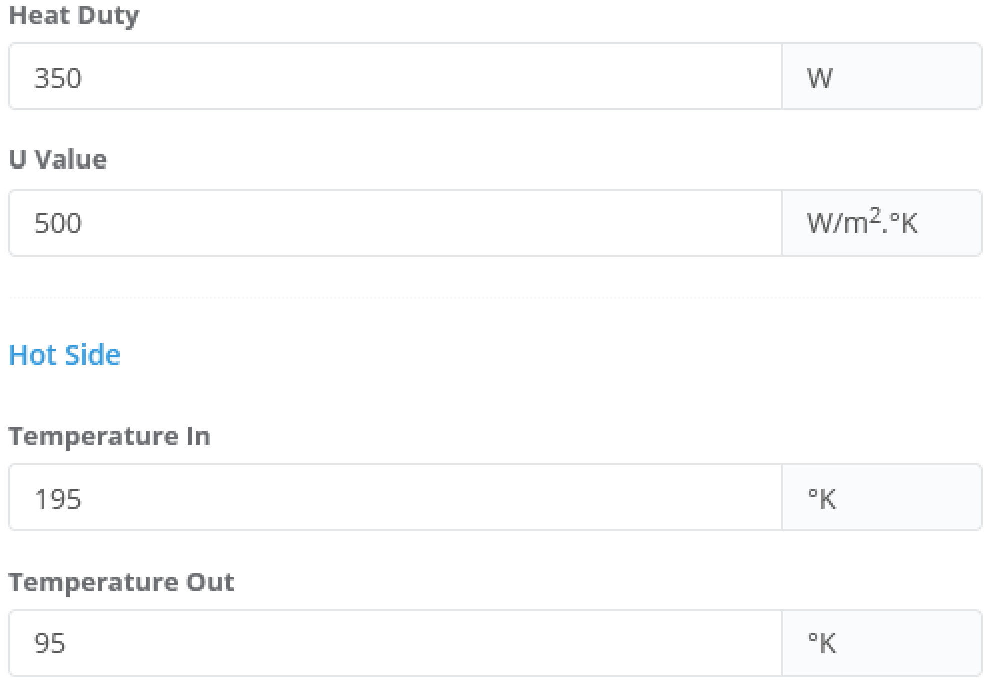
```
R1    = (t1 - t2)/ (T2 - T1)
      = 0.7000

P1    = (T2 - T1)/ (t1 - T1)
      = 0.9524

LMTD = 15.4170

F               = 0.4706
LMTD Corrected  = 7.2549
```



Shortcut Heat Exchanger Sizing

Estimates LMTD (Log Mean Temperature Difference), Exchanger surface area, number of tubes, shell diameter and number of shell in series.

14.1.3.3 Data



Heat Duty

350 W

U Value

500 W/m^2.°K

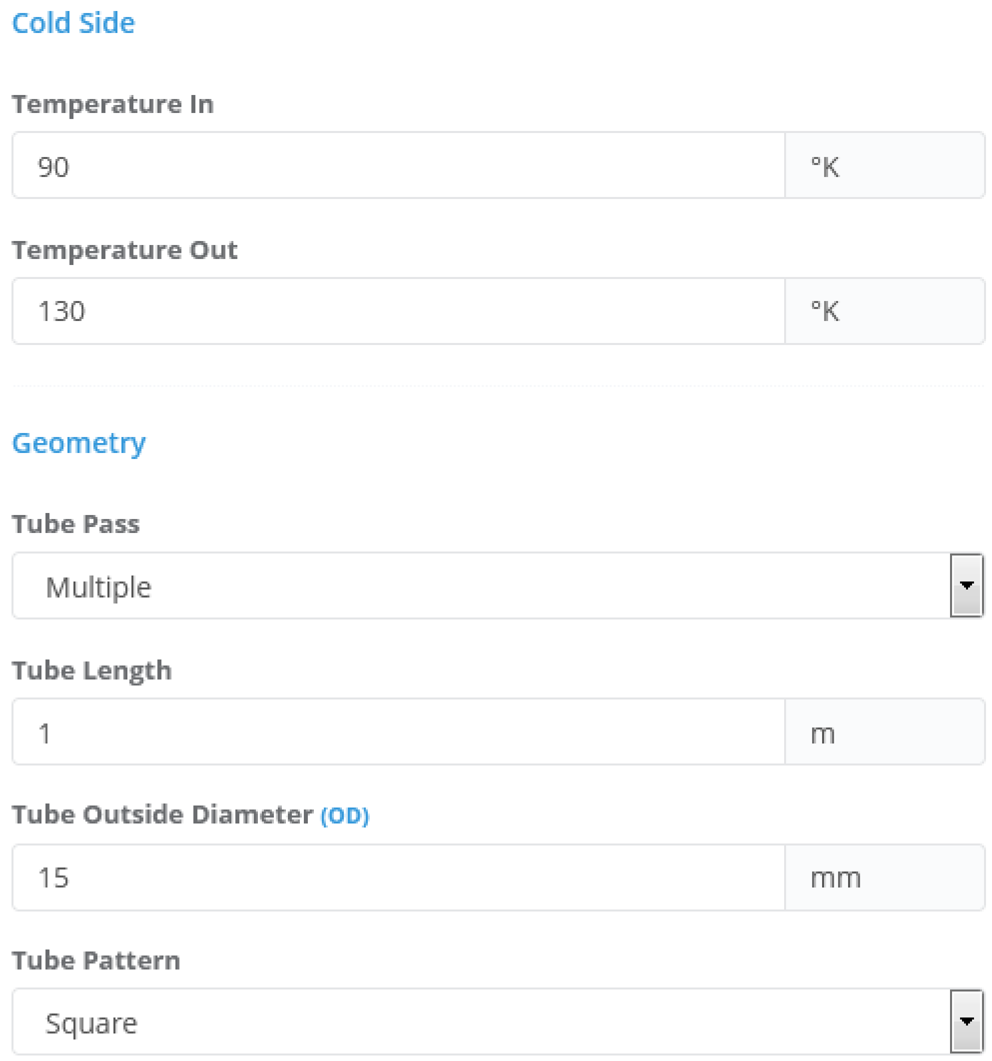
Hot Side

Temperature In

195 °K

Temperature Out

95 °K



Cold Side

Temperature In: 90 °K

Temperature Out: 130 °K

Geometry

Tube Pass: Multiple

Tube Length: 1 m

Tube Outside Diameter (OD): 15 mm

Tube Pattern: Square

14.1.3.4 Result

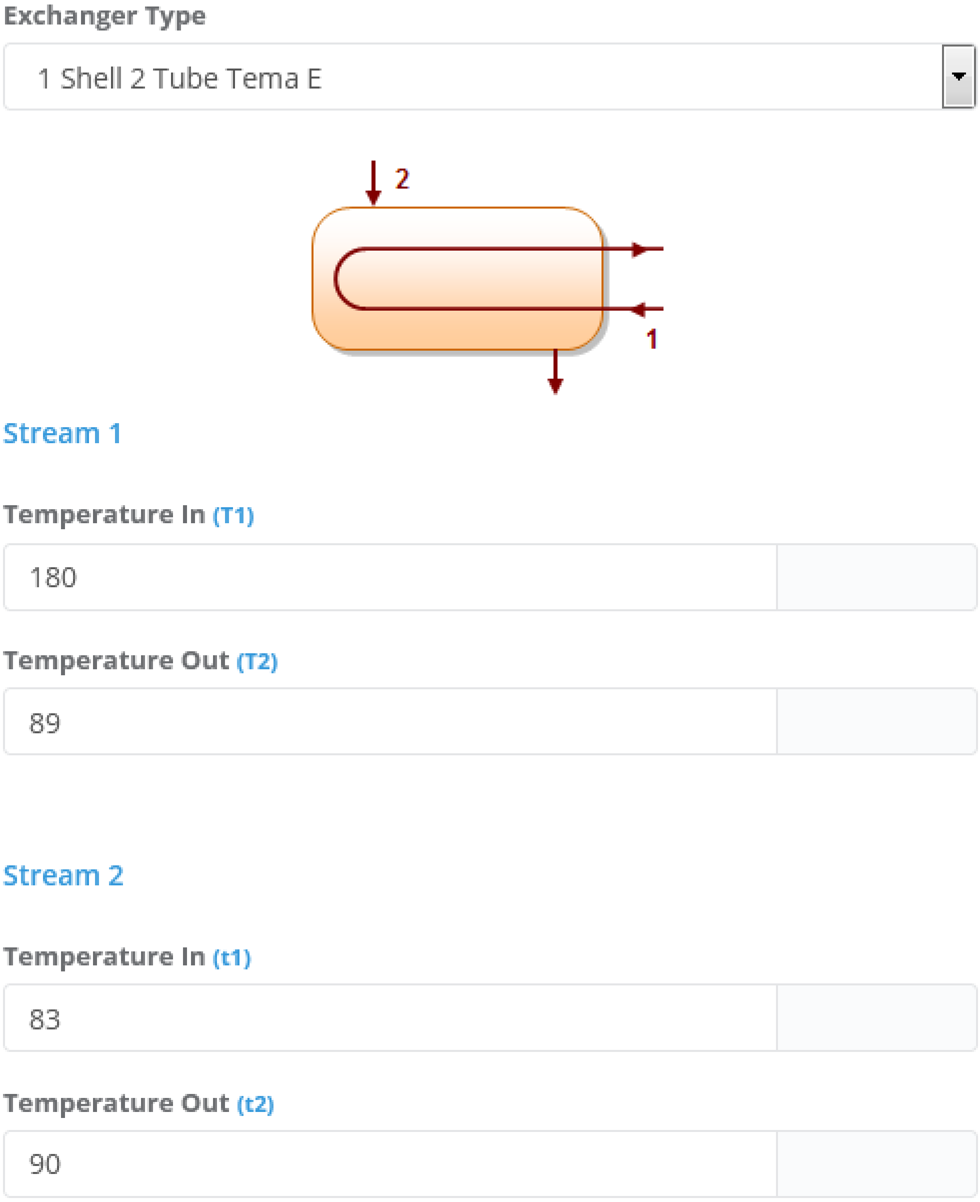
Tube Pitch	21.3500	mm
LMTD	23.39	°K
Correction Factor (F)	0.8381	
LMTD (Corrected)	19.61	°K
Shell in Series	3	
Total Area	0.04	m^2
Area per Shell	0.01	m^2
Tubes per Shell	0	
Shell ID (Estimate)	88.31	mm

14.1.4 Prototype Heat exchanger (HX - N_2/O_2)

LMTD Correction Factor Charts

Calculates Logarithmic Mean Temperature Difference (LMTD) Correction factor for different configuration of exchangers.

14.1.4.1 Data:



Exchanger Type

1 Shell 2 Tube Tema E

Stream 1

Temperature In (T1)

180

Temperature Out (T2)

89

Stream 2

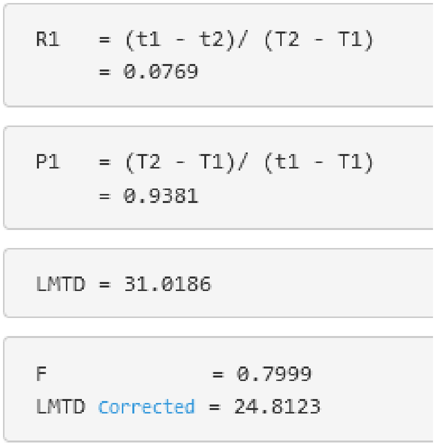
Temperature In (t1)

83

Temperature Out (t2)

90

14.1.4.2 Result:

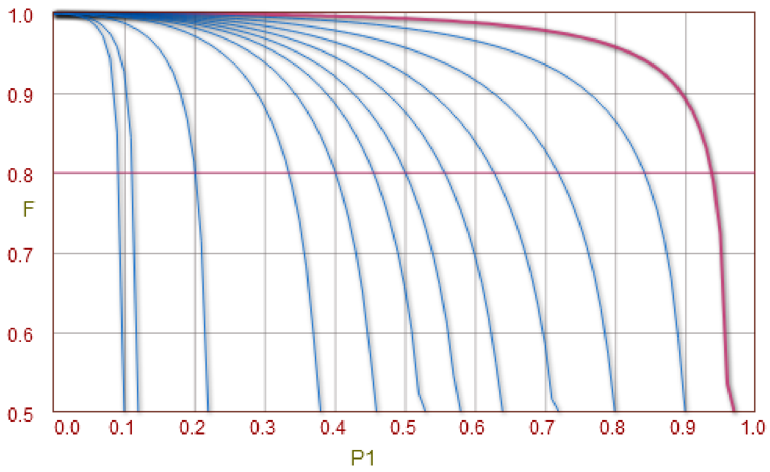


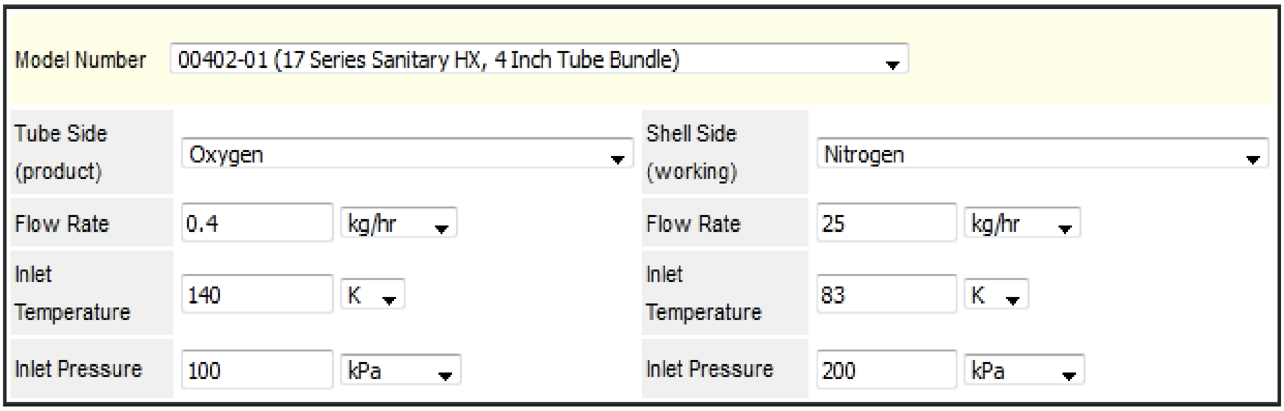
```
R1   = (t1 - t2)/ (T2 - T1)
     = 0.0769
```

```
P1   = (T2 - T1)/ (t1 - T1)
     = 0.9381
```

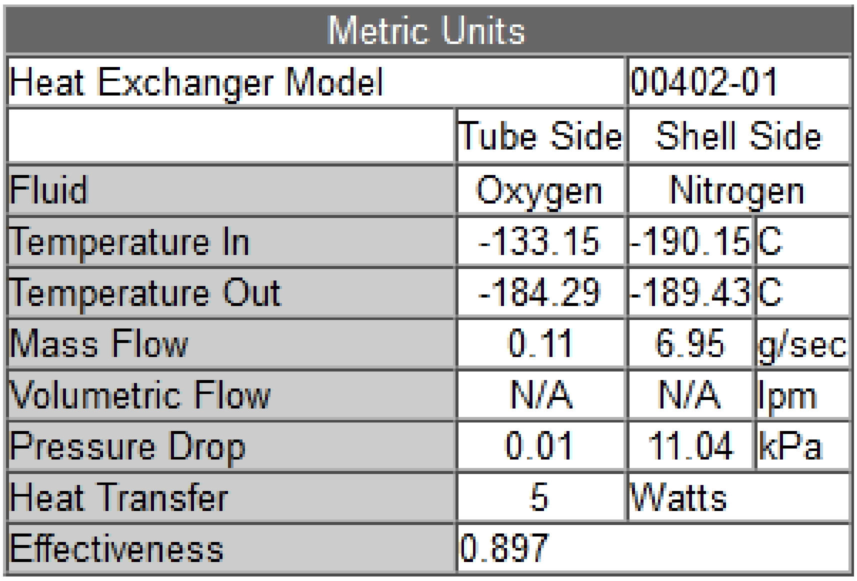
```
LMTD = 31.0186
```

```
F              = 0.7999
LMTD Corrected = 24.8123
```





Model Number	00402-01 (17 Series Sanitary HX, 4 Inch Tube Bundle)				
Tube Side (product)	Oxygen		Shell Side (working)	Nitrogen	
Flow Rate	0.4	kg/hr	Flow Rate	25	kg/hr
Inlet Temperature	140	K	Inlet Temperature	83	K
Inlet Pressure	100	kPa	Inlet Pressure	200	kPa

[45]

Metric Units			
Heat Exchanger Model		00402-01	
	Tube Side	Shell Side	
Fluid	Oxygen	Nitrogen	
Temperature In	-133.15	-190.15	C
Temperature Out	-184.29	-189.43	C
Mass Flow	0.11	6.95	g/sec
Volumetric Flow	N/A	N/A	lpm
Pressure Drop	0.01	11.04	kPa
Heat Transfer	5	Watts	
Effectiveness	0.897		

Shortcut Heat Exchanger Sizing

Estimates LMTD (Log Mean Temperature Difference), Exchanger surface area, number of tubes, shell diameter and number of shell in series.

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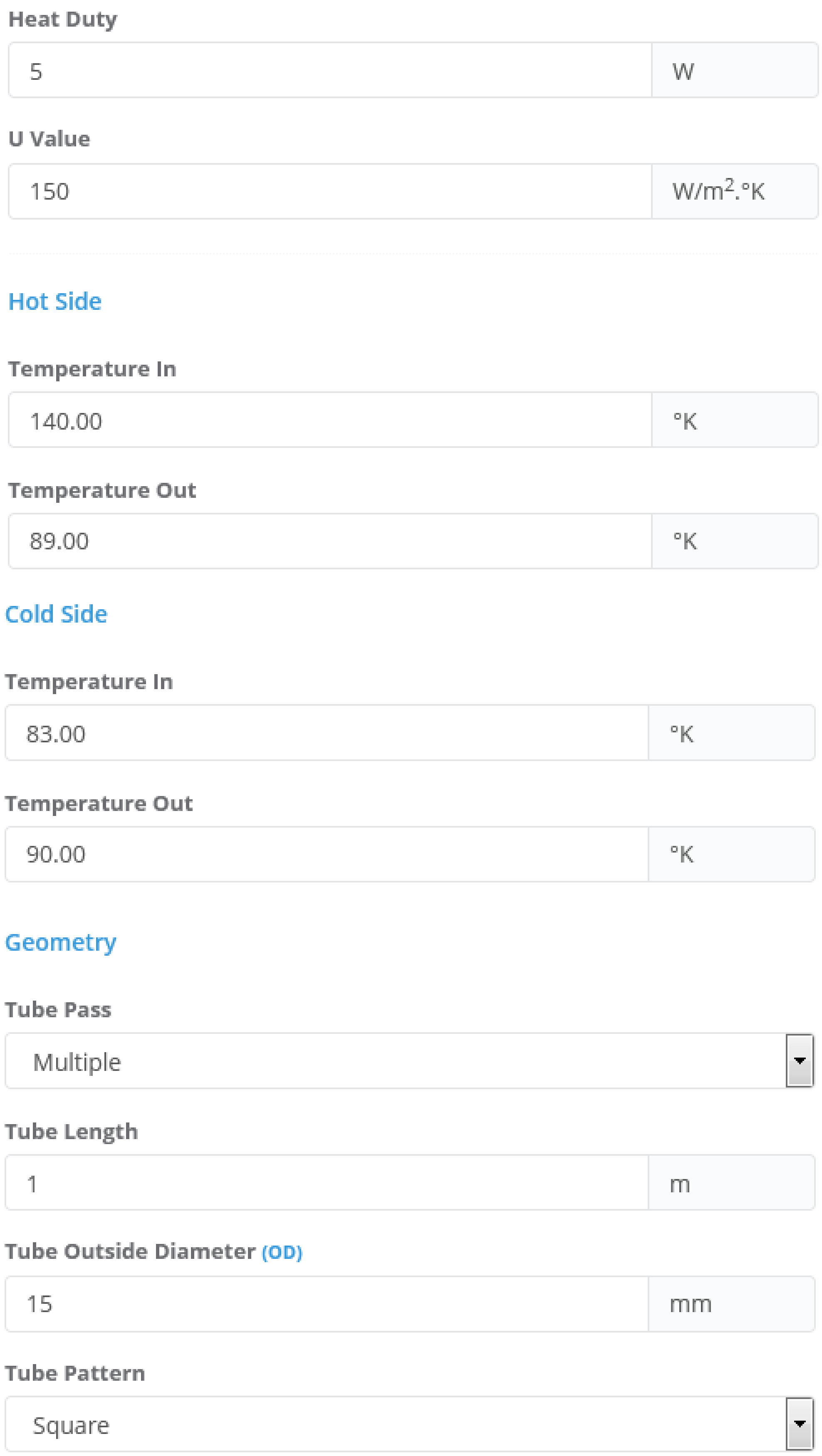
[45] http://calc.exergyllc.com/

14.1.4.3 Data:



Heat Duty

5 W

U Value

150 W/m^2.°K

Hot Side

Temperature In

140.00 °K

Temperature Out

89.00 °K

Cold Side

Temperature In

83.00 °K

Temperature Out

90.00 °K

Geometry

Tube Pass

Multiple

Tube Length

1 m

Tube Outside Diameter (OD)

15 mm

Tube Pattern

Square

14.1.4.4 Result:

Tube Pitch	21.3500	mm
LMTD	20.75	°K
Correction Factor (F)	0.9623	
LMTD (Corrected)	19.97	°K
Shell in Series	2	
Total Area	0.00	m²
Area per Shell	0.00	m²
Tubes per Shell	0	
Shell ID (Estimate)	79.41	mm

[46]

---

[46] https://checalc.com/calc/ShortExch.html

14.2 Components of Oxygen liquefaction prototype

14.2.1 Overview

- Compressor: It is LR25B Laboratory refrigerator compressor
- Cooling of N2: using kelvinator refrigerator
- Heat exchanger (HX-N2 / N2): should be manufactured
- Heat exchanger (HX-N2 / O2): should be manufactured
- Cooling of O2: should be manufactured
- Expansion valve: Purchase
- Filter drier: Purchase
- Cryometer (measures up to 80 K): Purchase
- Connections: The available LR25B Laboratory refrigerator and air-conditioner parts can be used if they are suitable for work.
- Gaseous oxygen preservation tank: manufacture / purchase
- Liquid oxygen storage tank: manufacture / purchase
- Gaseous oxygen (volume?)
- Nitrogen (volume?)
- Thermal isolations

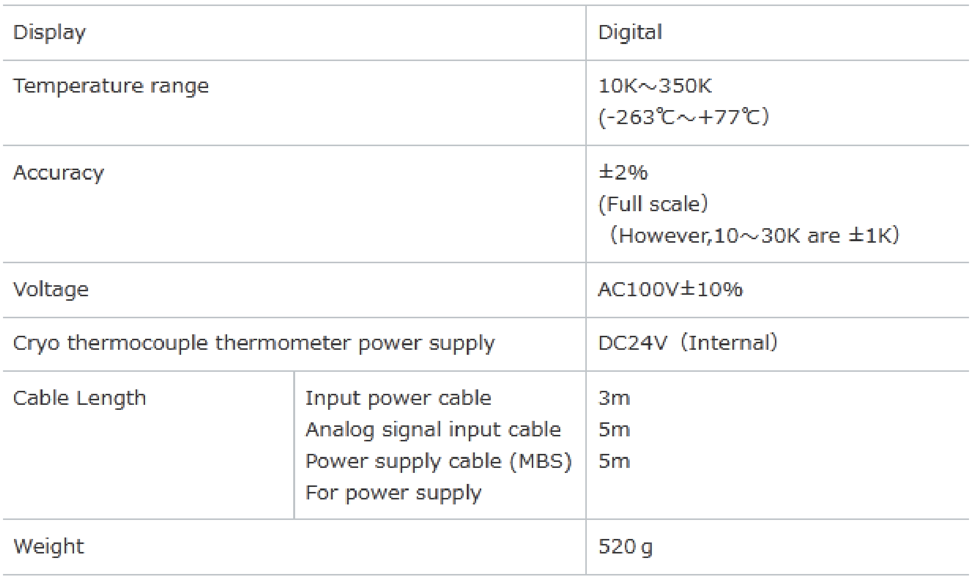
14.2.2 Cryometer

14.2.2.1 Features

Digitized the conventional type (MBM) to a more compact design.

- In combination with the MBS CRYO-METER, the accurate temperature can be obsrved at remote position.
- MBD CRYO-METER can be used as a power sorce unit of the MBS CRYO-METER.

14.2.2.2 Specification



Display		Digital
Temperature range		10K～350K (-263℃～+77℃)
Accuracy		±2% (Full scale) （However,10～30K are ±1K)
Voltage		AC100V±10%
Cryo thermocouple thermometer power supply		DC24V（Internal)
Cable Length	Input power cable Analog signal input cable Power supply cable (MBS) For power supply	3m 5m 5m
Weight		520 g

14.3 Heat exchangers for prototype project

The central variables in any heat exchanger analysis are the heat transfer rate q [W], heat transfer area A [m2], heat capacity rates $\dot{C}$ (=$\dot{m}$ cp) [W/K], and the overall heat transfer coefficient U. On the basis of these variables and the fluid temperatures, we can write two basic equations for the heat transfer rate; first, for heat transfer rate it must hold that

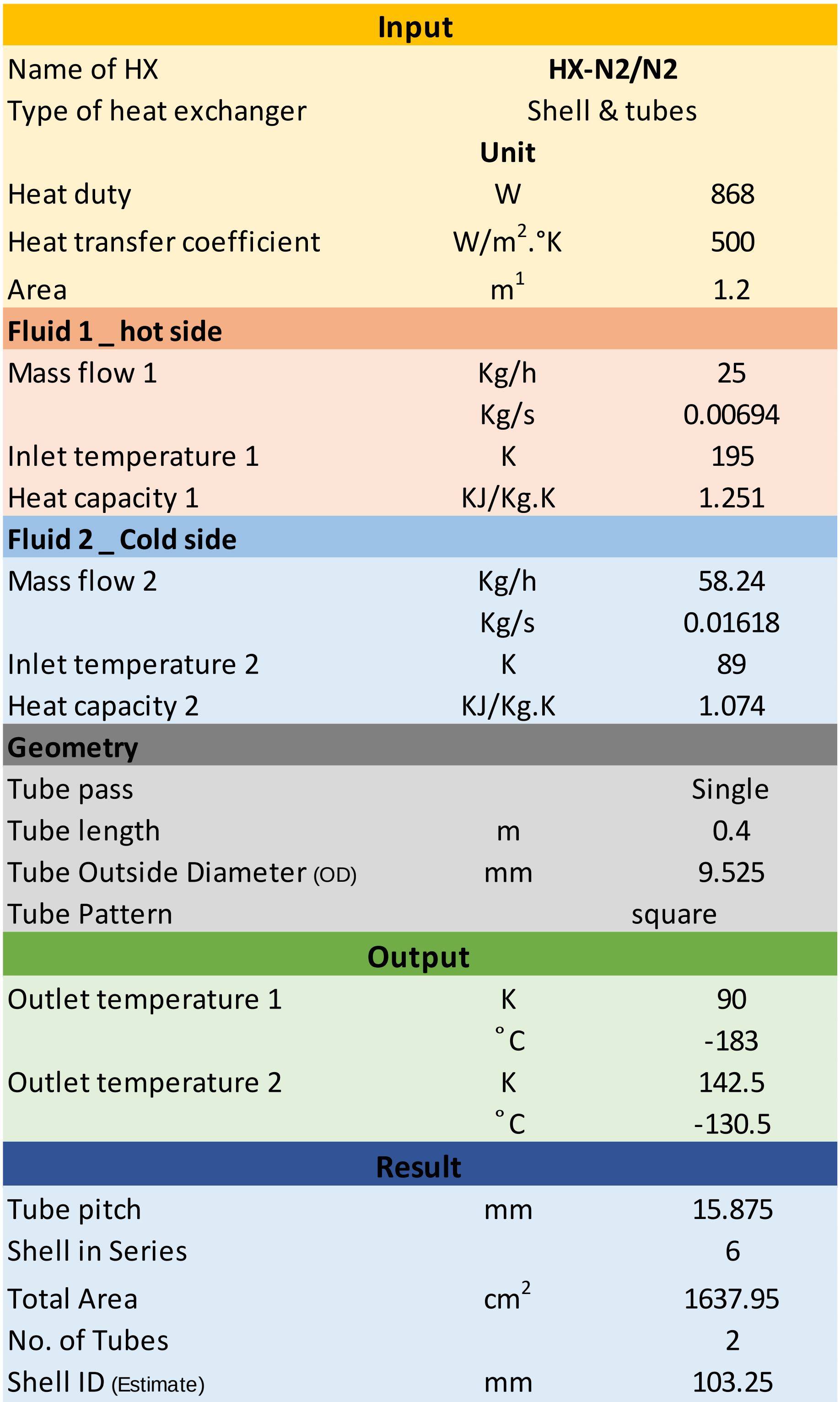
$$q = U\,A\,\Delta T_{\mathrm{m}}$$

where ΔT_{m} is the average (mean) temperature difference of the two fluids in the heat exchanger, and the area A in equation the heat transfer area, meaning the contact area between one of the fluids, and the surface of the wall that separates the fluid.

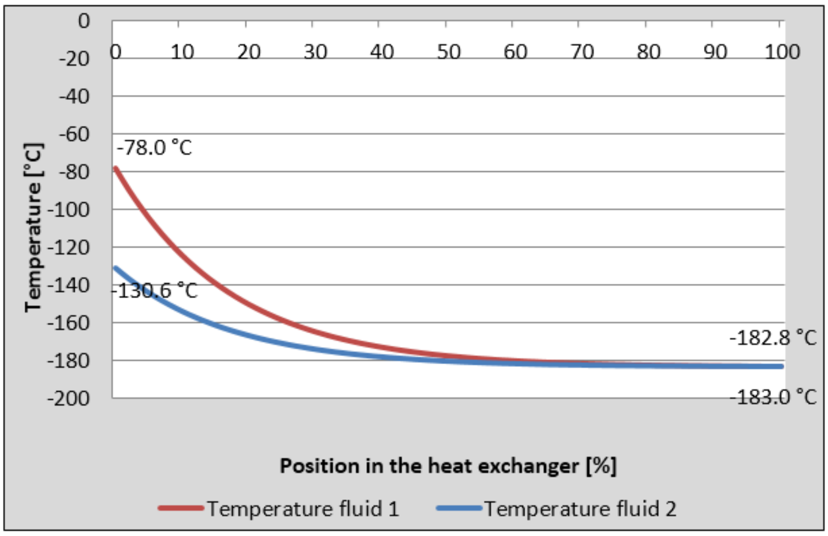
Second, on the basis of 1st law of thermodynamics, the heat transfer rate q must also equal the rate of heat lost by the hot fluid stream and gained by the cold fluid stream:

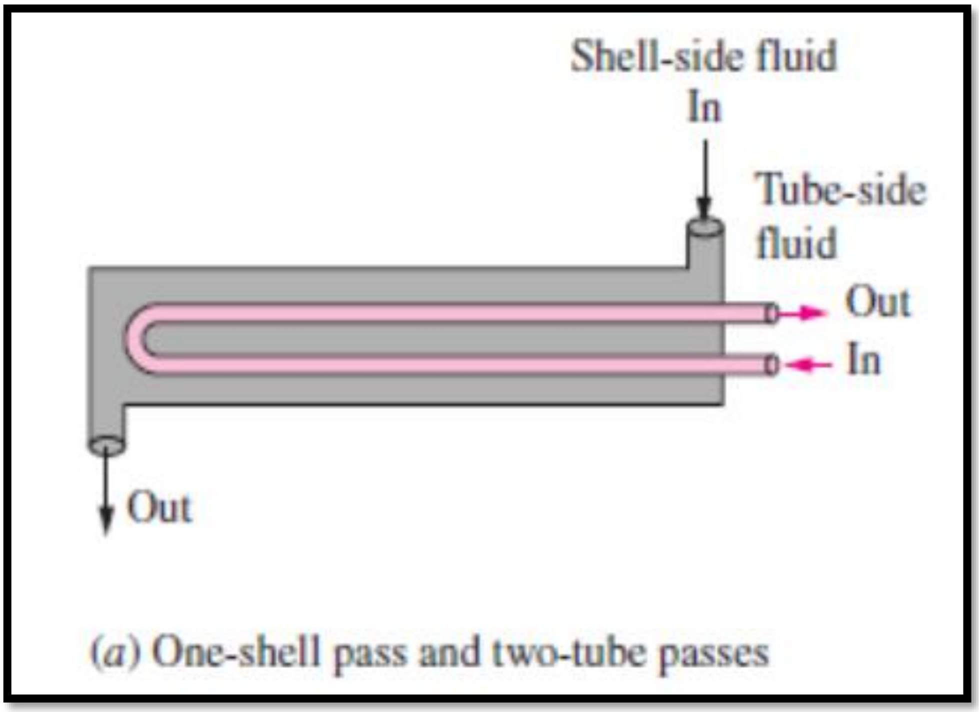
$$q = \dot{C}_{hot}\left(T_{hot,in} - T_{hot,out}\right) = \dot{C}_{cold}\left(T_{cold,out} - T_{cold,in}\right)$$

14.3.1 HX- N_2/N_2

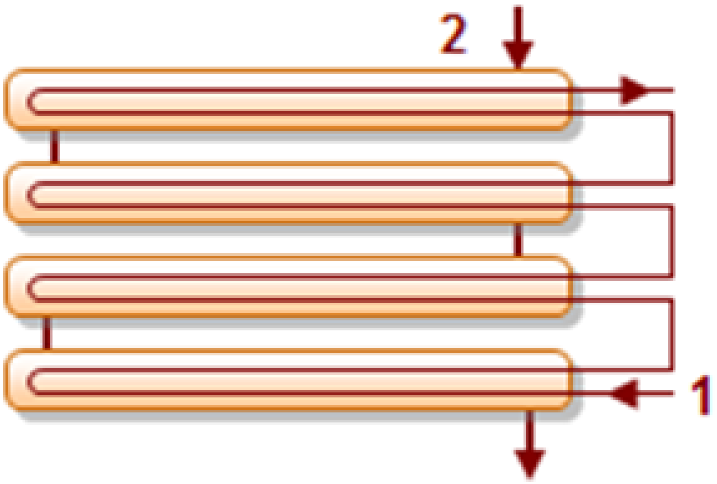


Input		
Name of HX	**HX-N2/N2**	
Type of heat exchanger	Shell & tubes	
	Unit	
Heat duty	W	868
Heat transfer coefficient	$W/m^2.°K$	500
Area	m^1	1.2
Fluid 1 _ hot side		
Mass flow 1	Kg/h	25
	Kg/s	0.00694
Inlet temperature 1	K	195
Heat capacity 1	KJ/Kg.K	1.251
Fluid 2 _ Cold side		
Mass flow 2	Kg/h	58.24
	Kg/s	0.01618
Inlet temperature 2	K	89
Heat capacity 2	KJ/Kg.K	1.074
Geometry		
Tube pass		Single
Tube length	m	0.4
Tube Outside Diameter (OD)	mm	9.525
Tube Pattern		square
Output		
Outlet temperature 1	K	90
	°C	-183
Outlet temperature 2	K	142.5
	°C	-130.5
Result		
Tube pitch	mm	15.875
Shell in Series		6
Total Area	cm^2	1637.95
No. of Tubes		2
Shell ID (Estimate)	mm	103.25



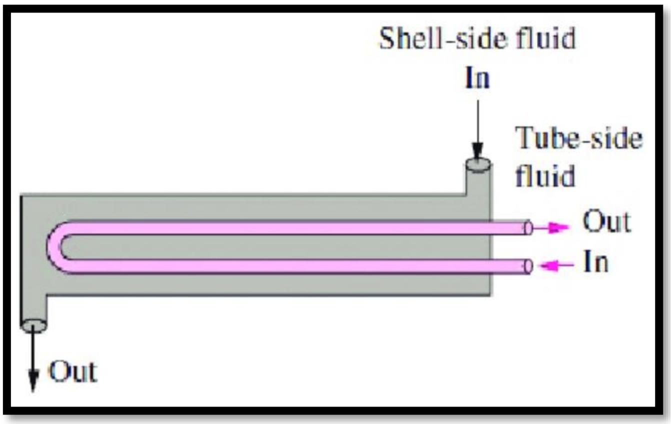


(*a*) One-shell pass and two-tube passes

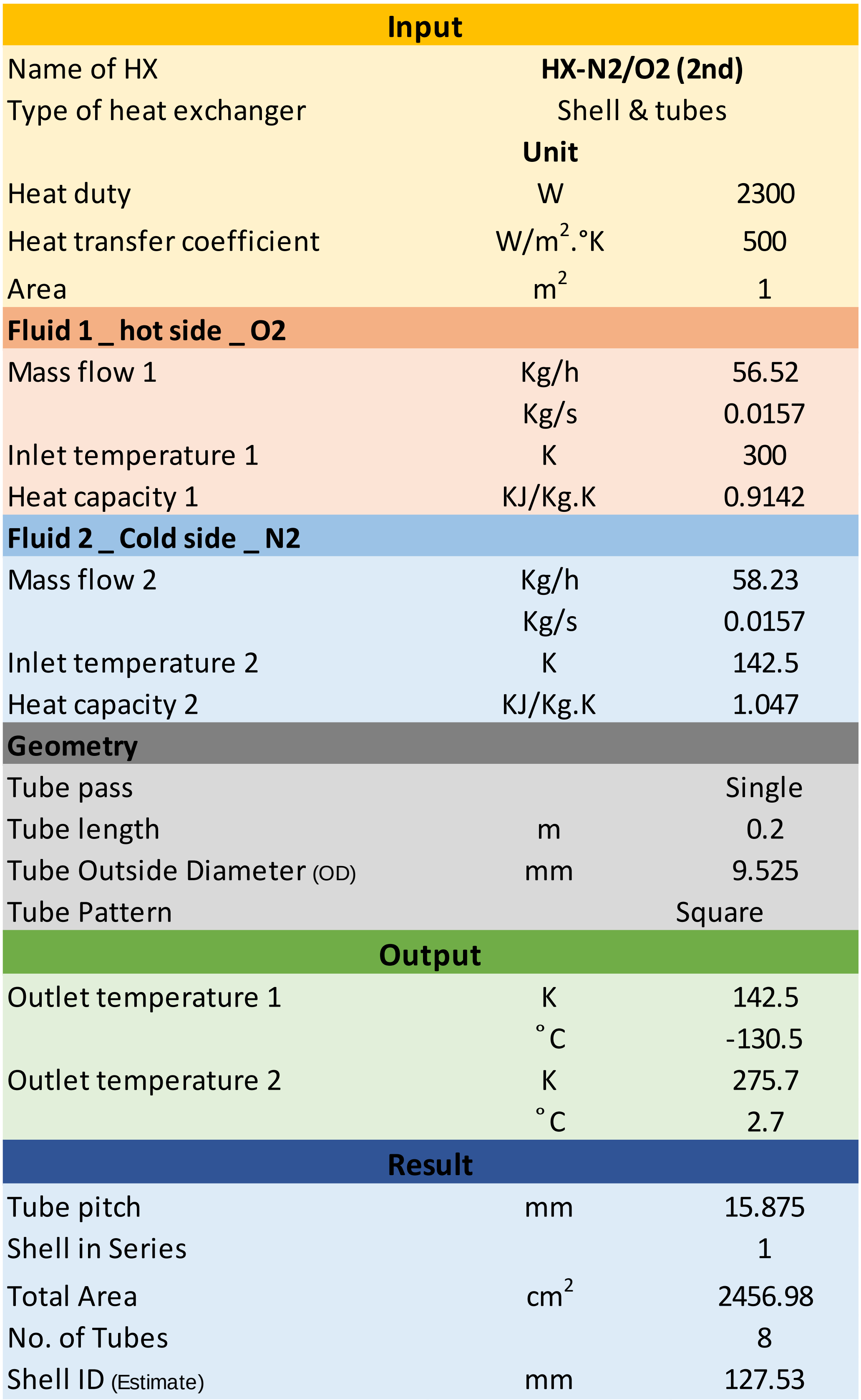


14.3.2 HX-N2/O2 main

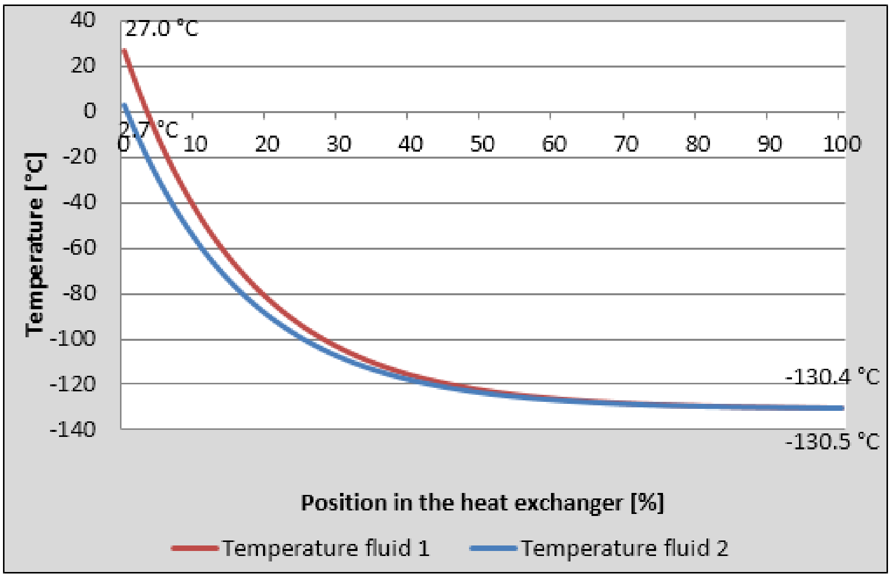
Input		
Name of HX	**HX-N2/O2 Main**	
Type of heat exchanger	shell & tubes	
	Unit	
Heat duty	W	92.42
Heat transfer coefficient	$W/m^2.°K$	500
Area	m^2	0.018
Fluid 1 _ hot side _ O2		
Mass flow 1	Kg/h	4.739
	Kg/s	0.001316
Inlet temperature 1	K	142.5
Heat capacity 1	KJ/Kg.K	0.9298
Fluid 2 _ Cold side _ N2		
Mass flow 2	Kg/h	25
	Kg/s	0.00694
Inlet temperature 2	K	83
Heat capacity 2	KJ/Kg.K	1.284
Geometry		
Tube pass		Single
Tube length	m	0.2
Tube Outside Diameter (OD)	mm	9.525
Tube Pattern		Square
Output		
Outlet temperature 1	K	88
	°C	-190.5
Outlet temperature 2	K	90
	°C	-183
Result		
Tube pitch	mm	15.875
Shell in Series		1
Total Area	cm^2	91.5
No. of Tubes		2
Shell ID (Estimate)	mm	98.35

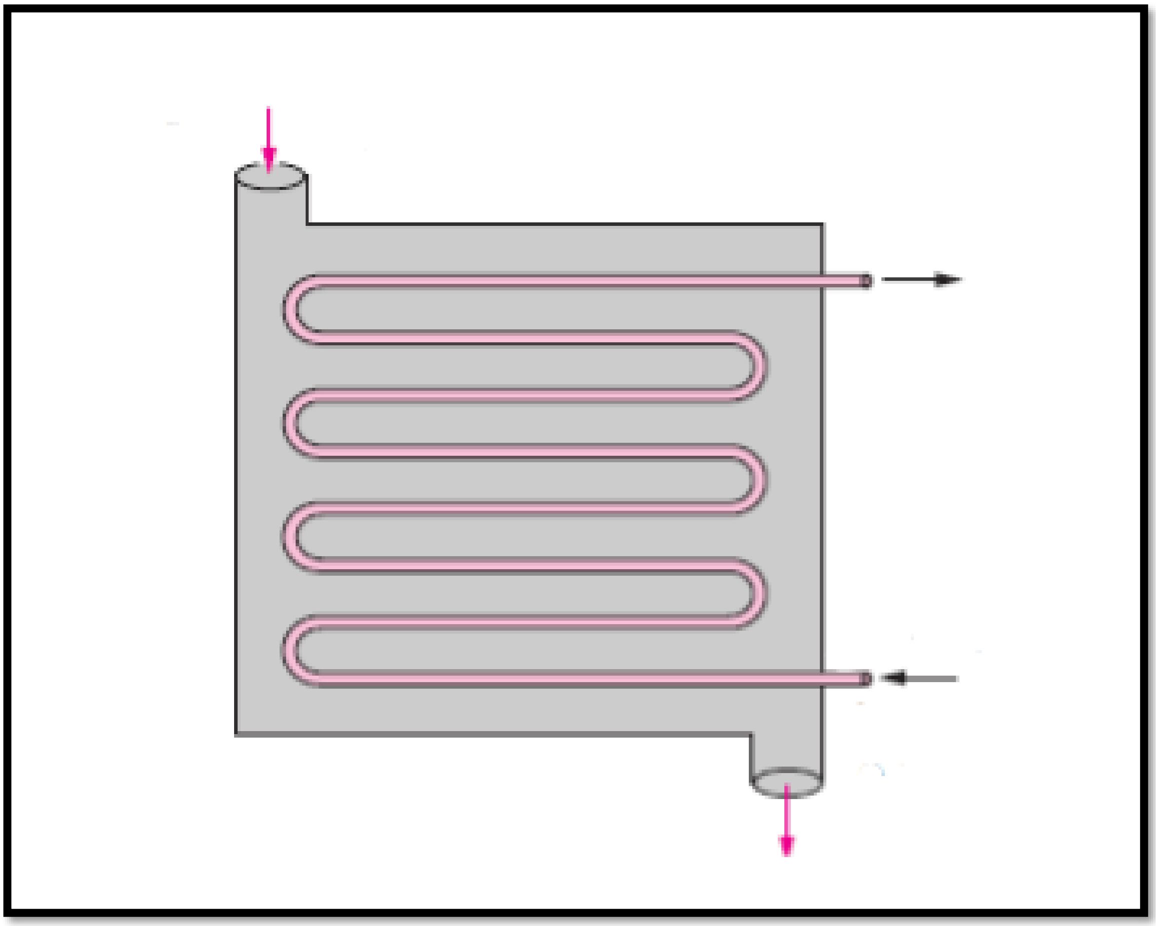


14.3.3 HX-N2/O2 (2nd)



Input		
Name of HX	**HX-N2/O2 (2nd)**	
Type of heat exchanger	Shell & tubes	
	Unit	
Heat duty	W	2300
Heat transfer coefficient	$W/m^2.°K$	500
Area	m^2	1
Fluid 1 _ hot side _ O2		
Mass flow 1	Kg/h	56.52
	Kg/s	0.0157
Inlet temperature 1	K	300
Heat capacity 1	KJ/Kg.K	0.9142
Fluid 2 _ Cold side _ N2		
Mass flow 2	Kg/h	58.23
	Kg/s	0.0157
Inlet temperature 2	K	142.5
Heat capacity 2	KJ/Kg.K	1.047
Geometry		
Tube pass		Single
Tube length	m	0.2
Tube Outside Diameter (OD)	mm	9.525
Tube Pattern		Square
Output		
Outlet temperature 1	K	142.5
	°C	-130.5
Outlet temperature 2	K	275.7
	°C	2.7
Result		
Tube pitch	mm	15.875
Shell in Series		1
Total Area	cm^2	2456.98
No. of Tubes		8
Shell ID (Estimate)	mm	127.53


Temperature [°C]
40
20
0
-20
-40
-60
-80
-100
-120
-140
27.0 °C
2.7 °C
0
10
20
30
40
50
60
70
80
90
100
-130.4 °C
-130.5 °C
Position in the heat exchanger [%]
Temperature fluid 1
Temperature fluid 2



14.3.4 HX- final calculation

For HX-N2/N2

Stream data				Results			Units	Final results			Units
	Units	Hot	Cold	Heat capacity ratio	Cr	0.3995		LMDT	LMDT	25.05	
Flow rate	Kg/hr	**25**	**58.24**	Number of transfer units	NTU	7.3548		Surface Area	S	0.65133467	m2
Inlet temp.	K	**195**	**89**	Effectivenes	ξ	0.9434		Diameter of pipe	D	0.009525	m
Specific heat	KJ/Kg.K	1.1163	1.1995	Heat transfer	Q	**775.17**	W	Length	L	21.76653698	m
Outlet temp.	K	**95**	**128.947**	Overall U	U	**47.51**	W/m2.K	Length per shell	$L_{/shell}$	3.627756163	m
				Heat exchanger area	A	**1.2**	m2	Tube lenght	**T_L**	**1.793928082**	**m**

For HX-N2/O2 [2nd]

Stream data				Results			Units	Final results			Units
	Units	Hot	Cold	Heat capacity ratio	Cr	0.8363		LMDT	LMDT	60.5	
Flow rate	Kg/hr	**56.52**	**58.23**	Number of transfer units	NTU	3.5192		Surface Area	S	0.507249982	m2
Inlet temp.	K	**300**	**129**	Effectivenes	ξ	0.6316		Diameter of pipe	D	0.02222	m
Specific heat	KJ/Kg.K	0.9199	1.0677	Heat transfer	Q	**1559.78**	W	Length	L	7.266547442	m
Outlet temp.	K	**192**	**219.317**	Overall U	U	**50.826**	W/m2.K	Tube length	**T_L**	**0.85599343**	**m**
				Heat exchanger area	A	**1**	m2				

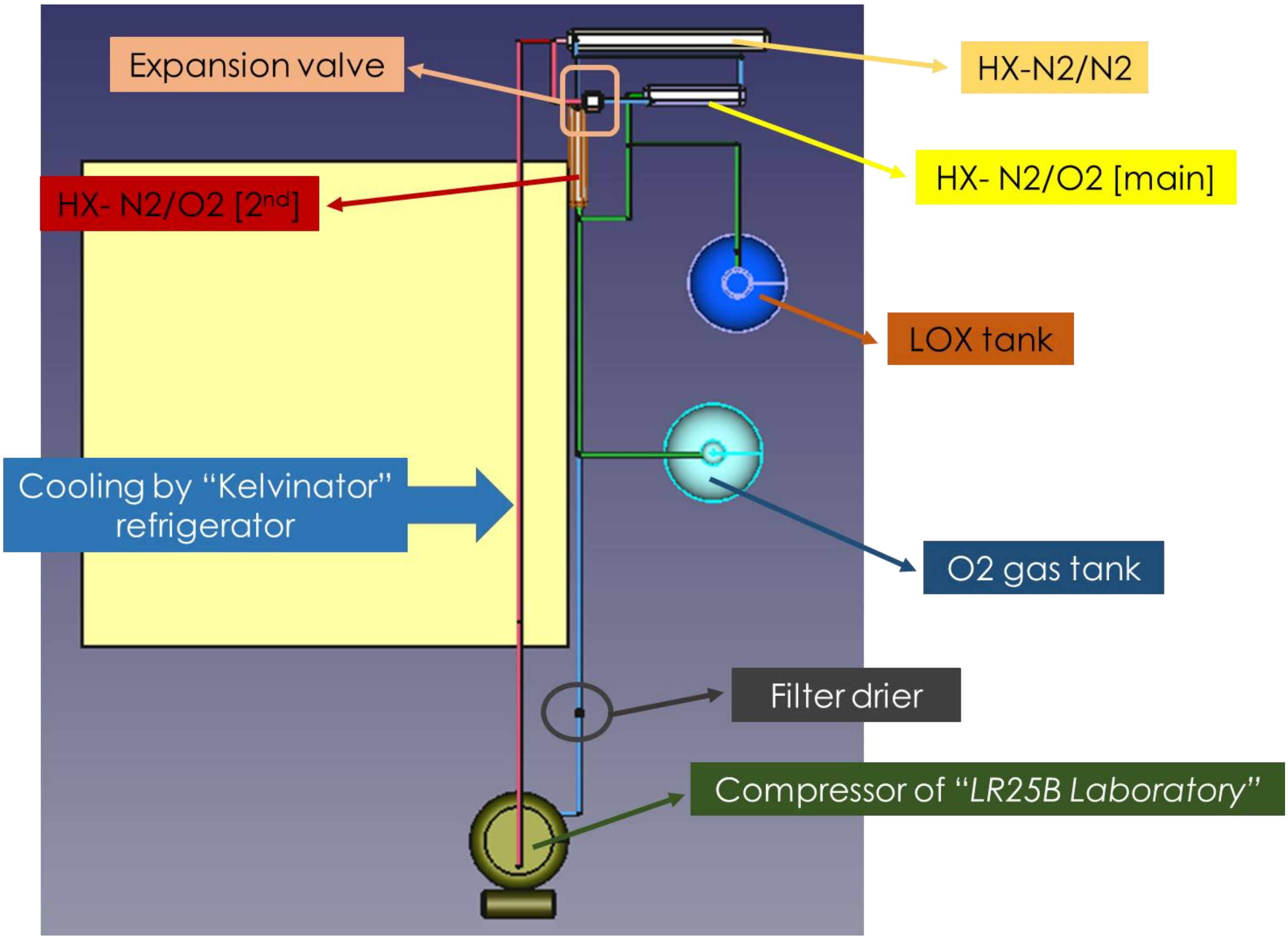
For HX-N2/O2 [Main]

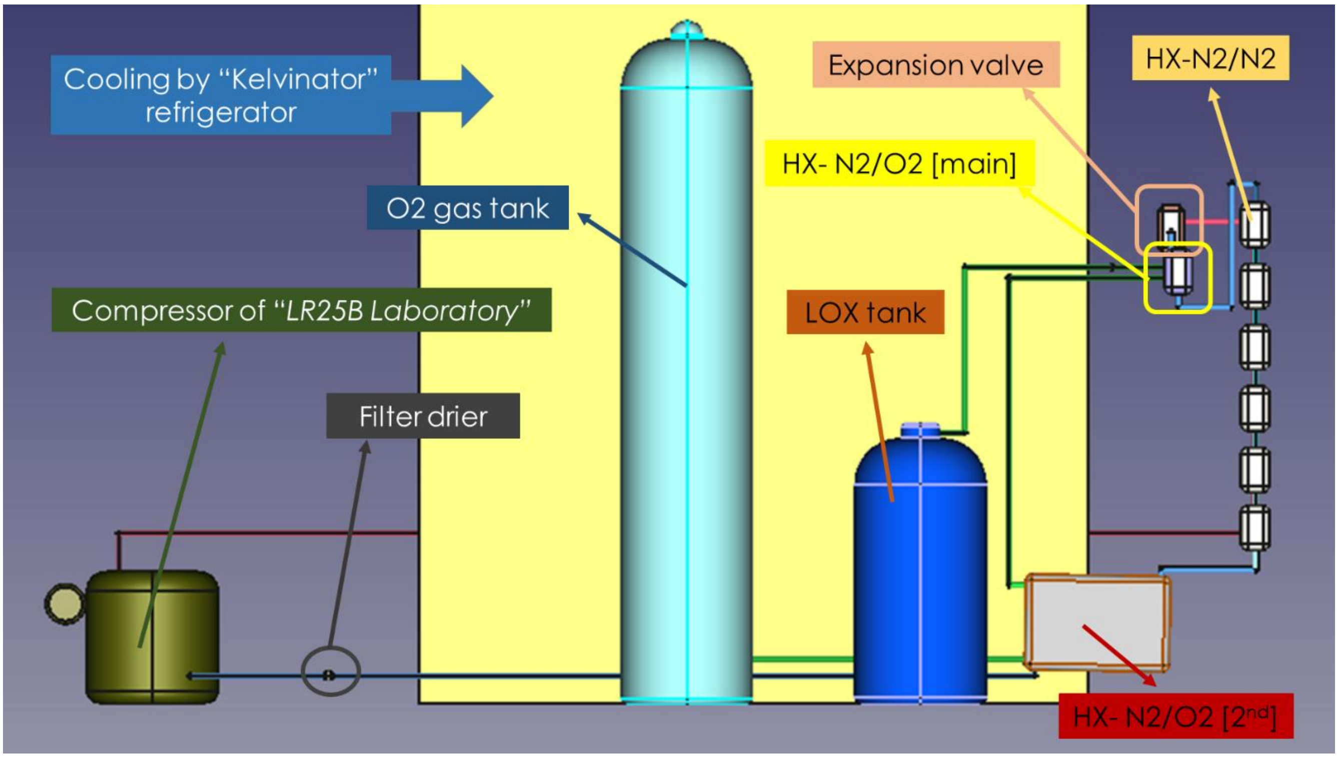
Stream data				Results			Units	Final results			Units
	Units	Hot	Cold	Heat capacity ratio	Cr	0.0834		LMDT	LMDT	31.787	
Flow rate	Kg/hr	**4.739**	**25**	Number of transfer units	NTU	3.4197		Surface Area	S	0.027718617	m2
Inlet temp.	K	**192**	**83**	Effectivenes	ξ	0.9541		Diameter of pipe	D	0.0025	m
Specific heat	KJ/Kg.K	0.915	2.08	Heat transfer	Q	**52.8655**	W	Length	L	3.529243881	m
Outlet temp.	K	**88**	**91.672**	Overall U	U	**60**	W/m2.K	Tube length	**T_L**	**1.750191941**	**m**
				Heat exchanger area	A	**0.01356**	m2				

14.4 FreeCad Design

14.4.1 Prototype design on FreeCad

prototype cycle of oxygen liquefaction.FCStd





14.4.2 Heat exchanger design HX-N_2/N_2

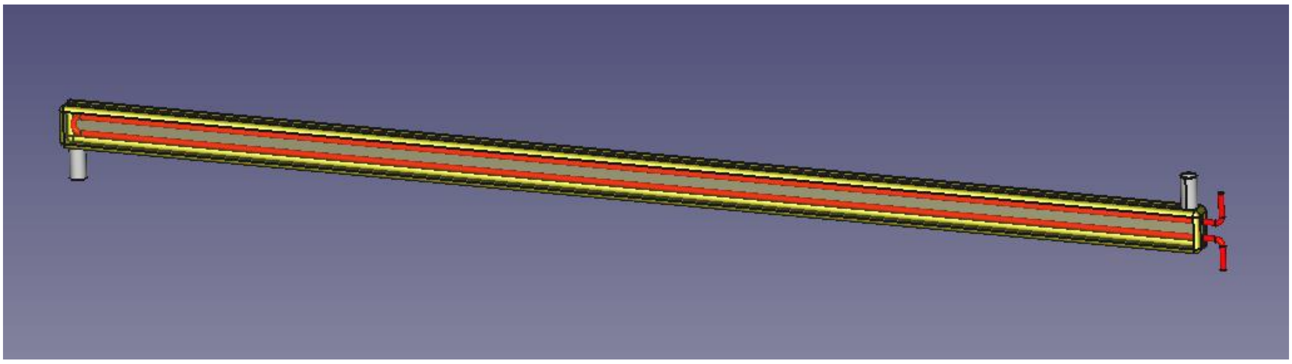
6 shell , 12 tubes

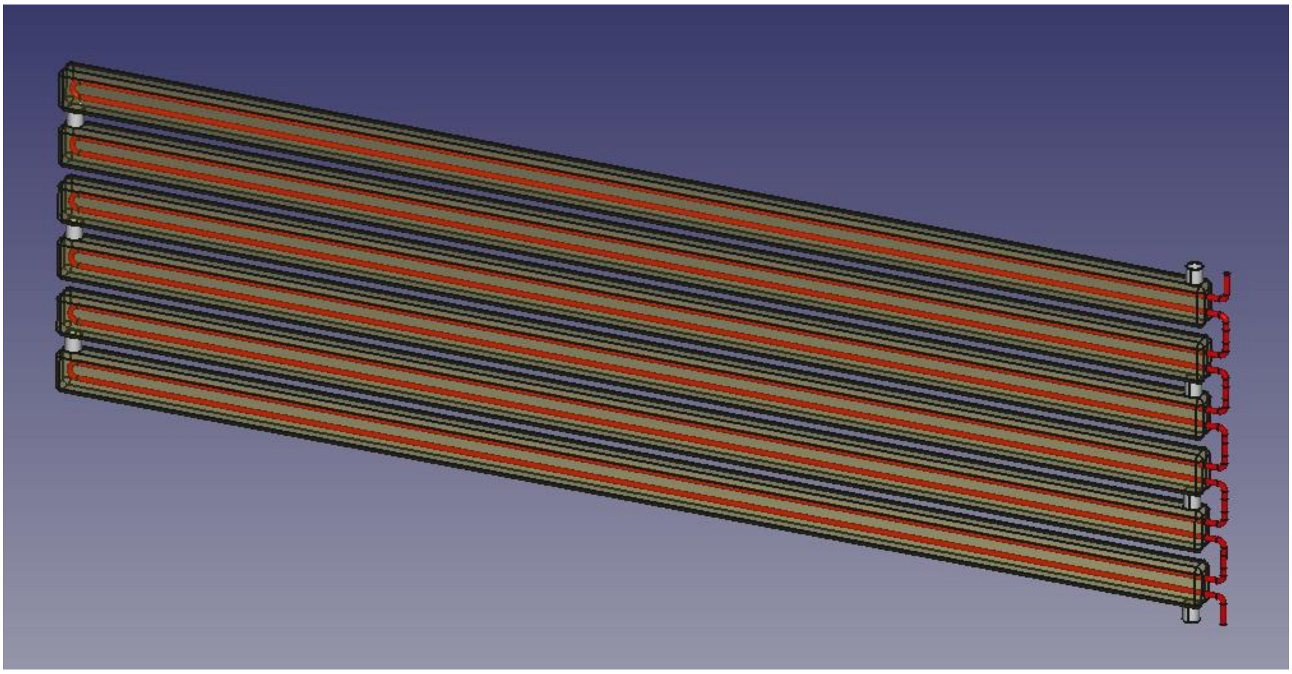
Shell – Cold side – N_2

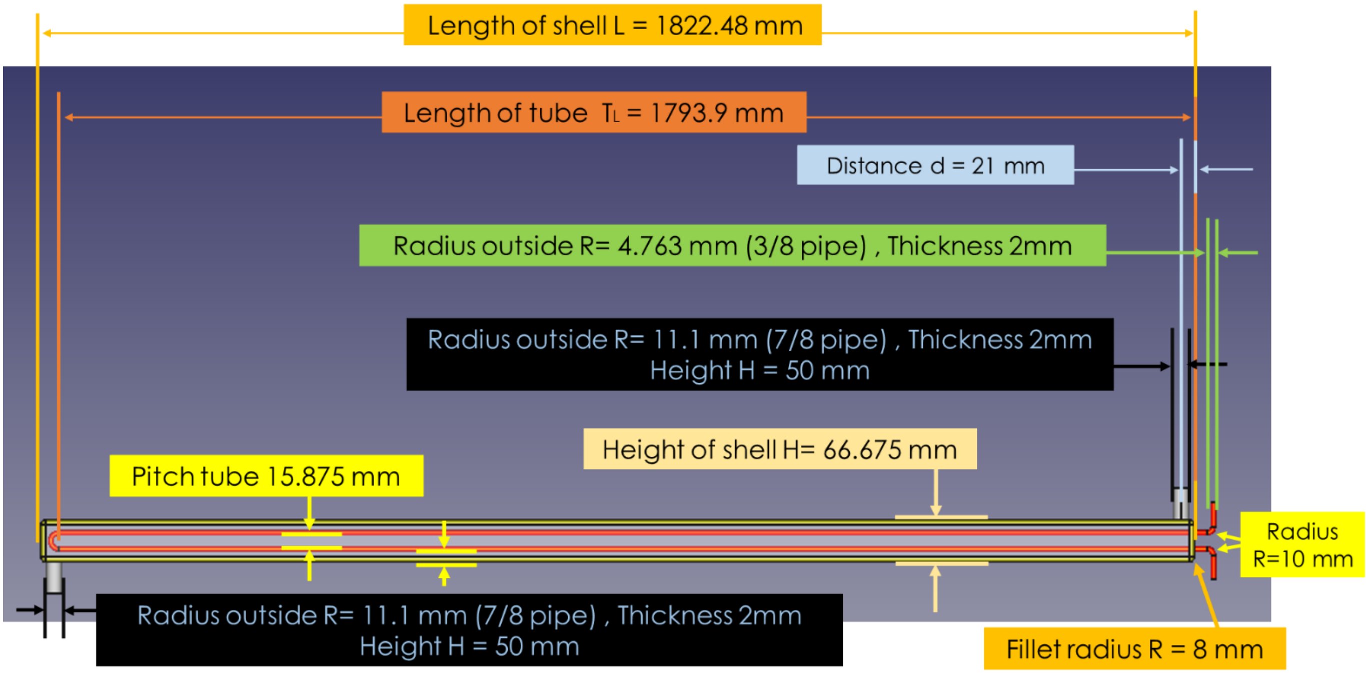
Tubes – Hot side – N_2

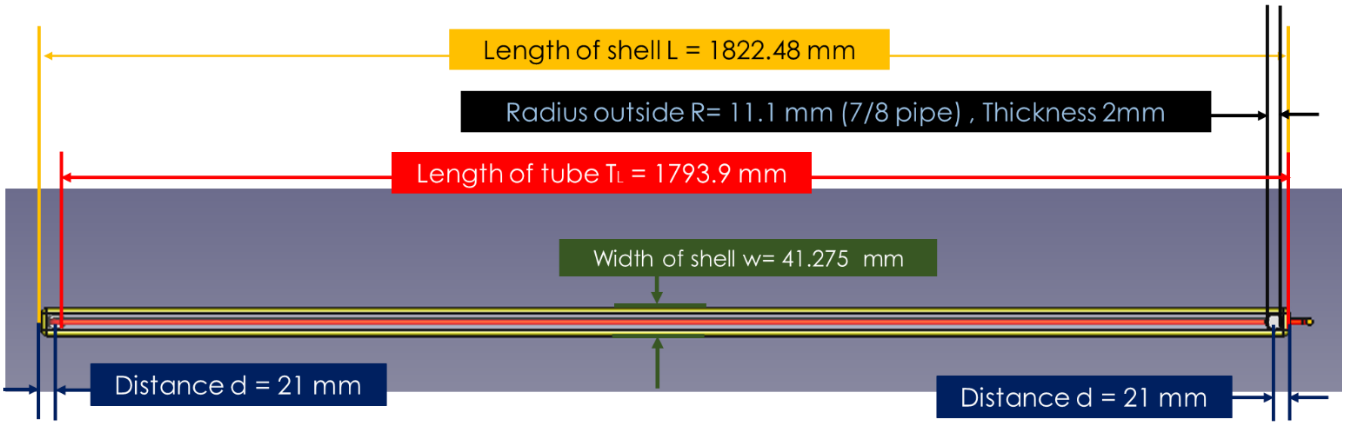
HX_N2-N2 _ ONE SHELL.FCStd

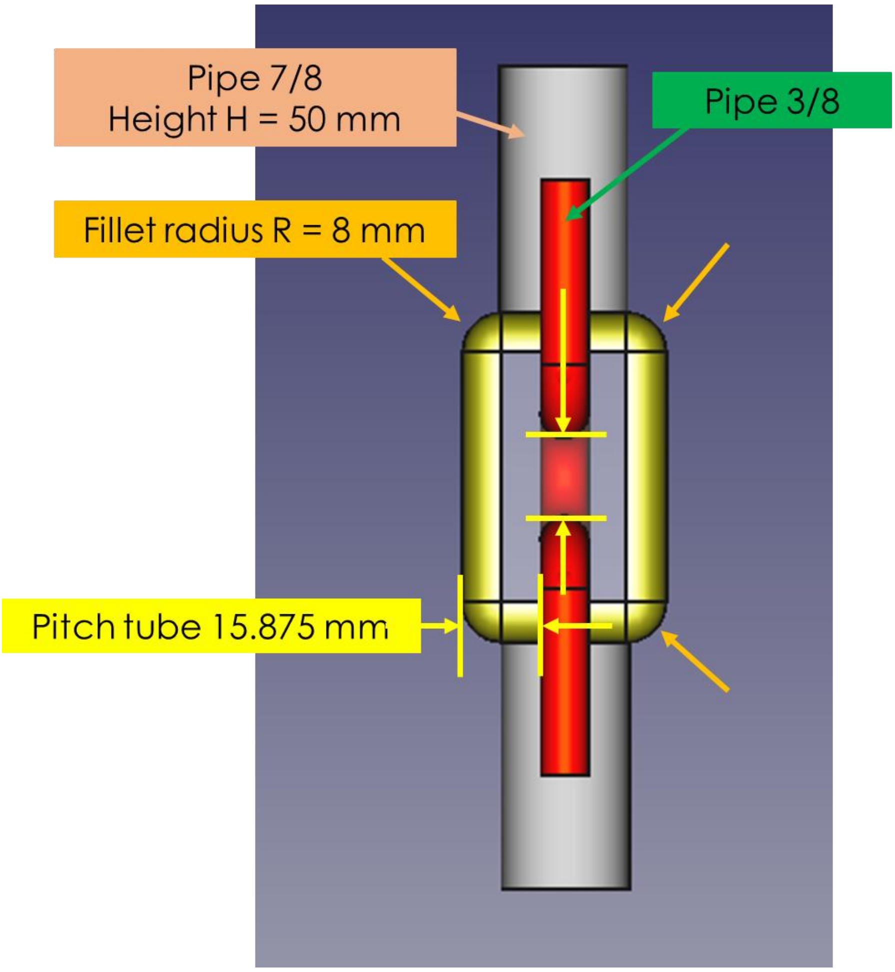
HX_N2-N2.FCStd

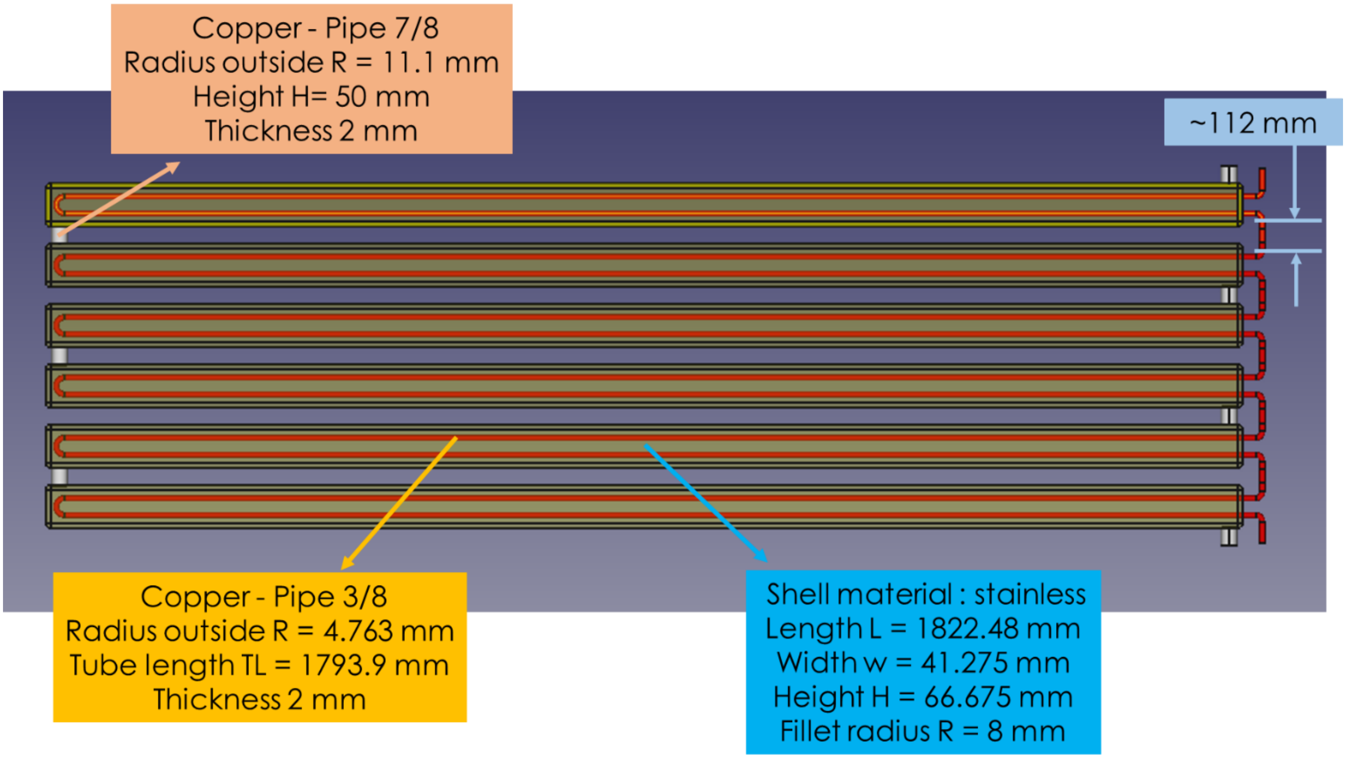





Length of shell L = 1822.48 mm
Length of tube TL = 1793.9 mm
Distance d = 21 mm
Radius outside R= 4.763 mm (3/8 pipe) , Thickness 2mm
Radius outside R= 11.1 mm (7/8 pipe) , Thickness 2mm
Height H = 50 mm
Height of shell H= 66.675 mm
Pitch tube 15.875 mm
Radius
R=10 mm
Radius outside R= 11.1 mm (7/8 pipe) , Thickness 2mm
Height H = 50 mm
Fillet radius R = 8 mm


Length of shell L = 1822.48 mm
Radius outside R= 11.1 mm (7/8 pipe) , Thickness 2mm
Length of tube T_L = 1793.9 mm
Width of shell w= 41.275 mm
Distance d = 21 mm
Distance d = 21 mm


Pipe 7/8
Height H = 50 mm
Pipe 3/8
Fillet radius R = 8 mm
Pitch tube 15.875 mm



Copper - Pipe 7/8
Radius outside R = 11.1 mm
Height H= 50 mm
Thickness 2 mm

~112 mm

Copper - Pipe 3/8
Radius outside R = 4.763 mm
Tube length TL = 1793.9 mm
Thickness 2 mm

Shell material : stainless
Length L = 1822.48 mm
Width w = 41.275 mm
Height H = 66.675 mm
Fillet radius R = 8 mm

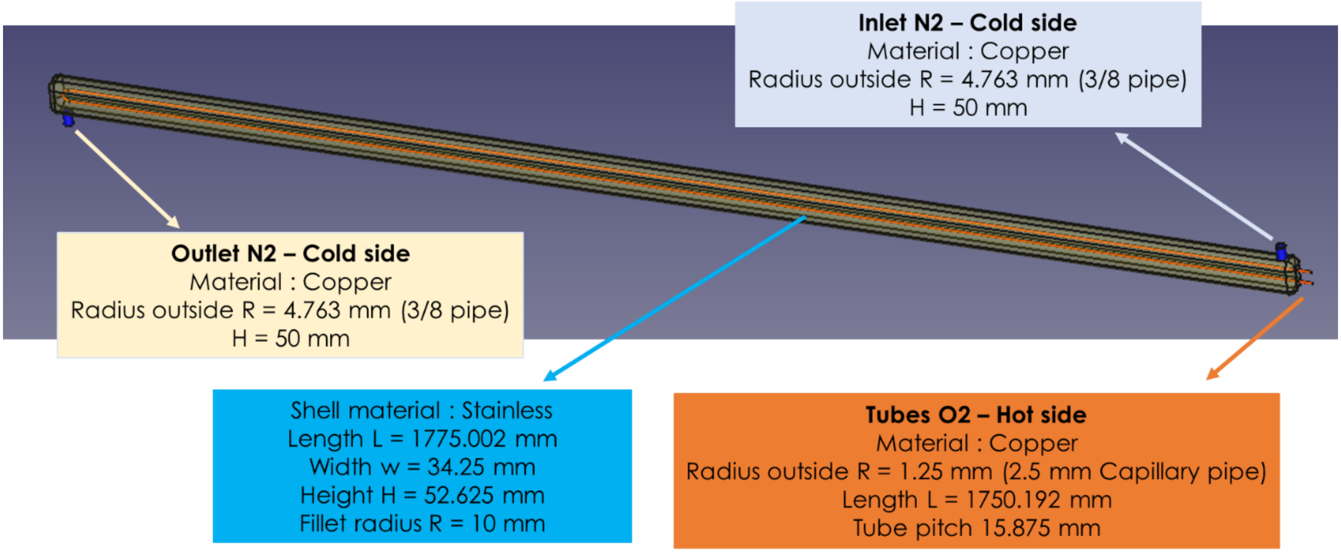
14.4.3 Heat exchanger design HX-N_2/O_2 [Main]

1 shell , 2 tubes

Shell – Cold side – N_2

Tubes – Hot side – O_2

HX_N2-O2 Main.FCStd

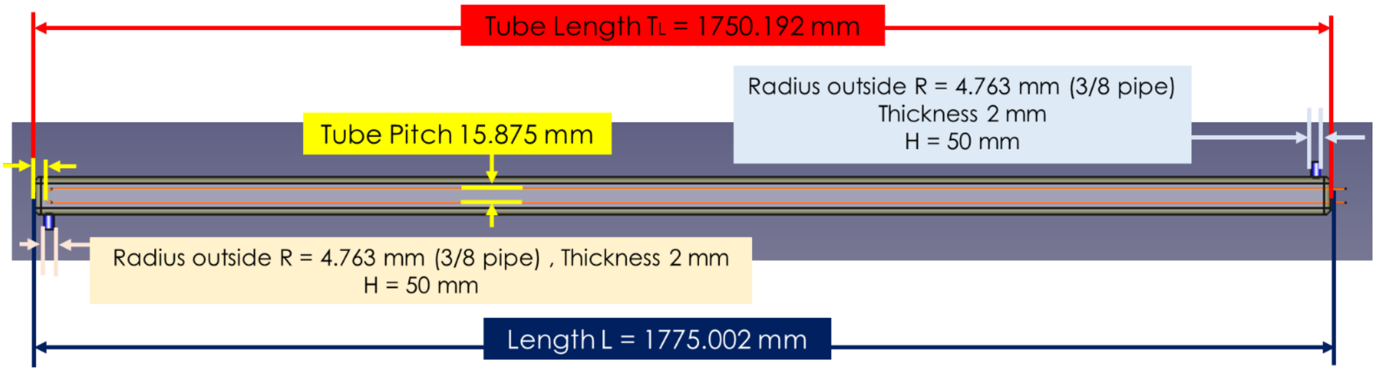


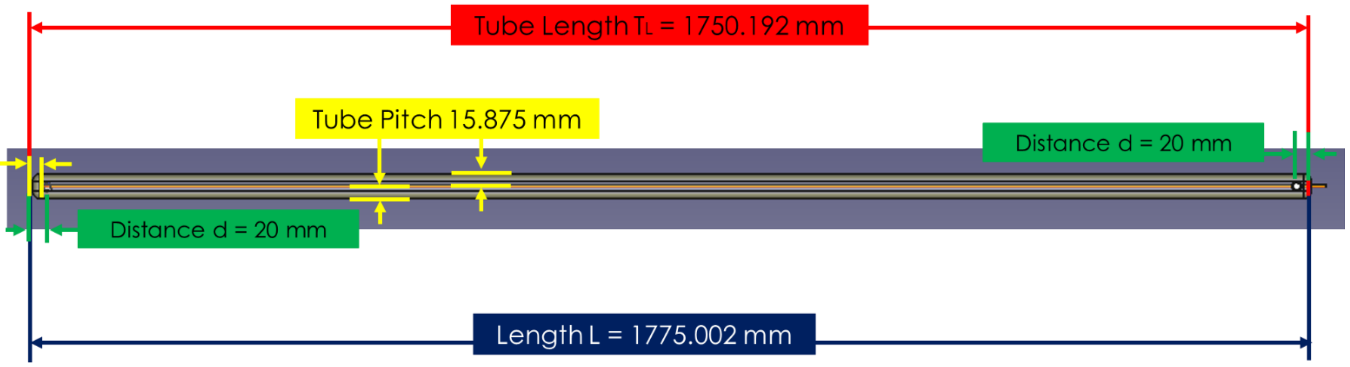
Inlet N2 – Cold side
Material : Copper
Radius outside R = 4.763 mm (3/8 pipe)
H = 50 mm

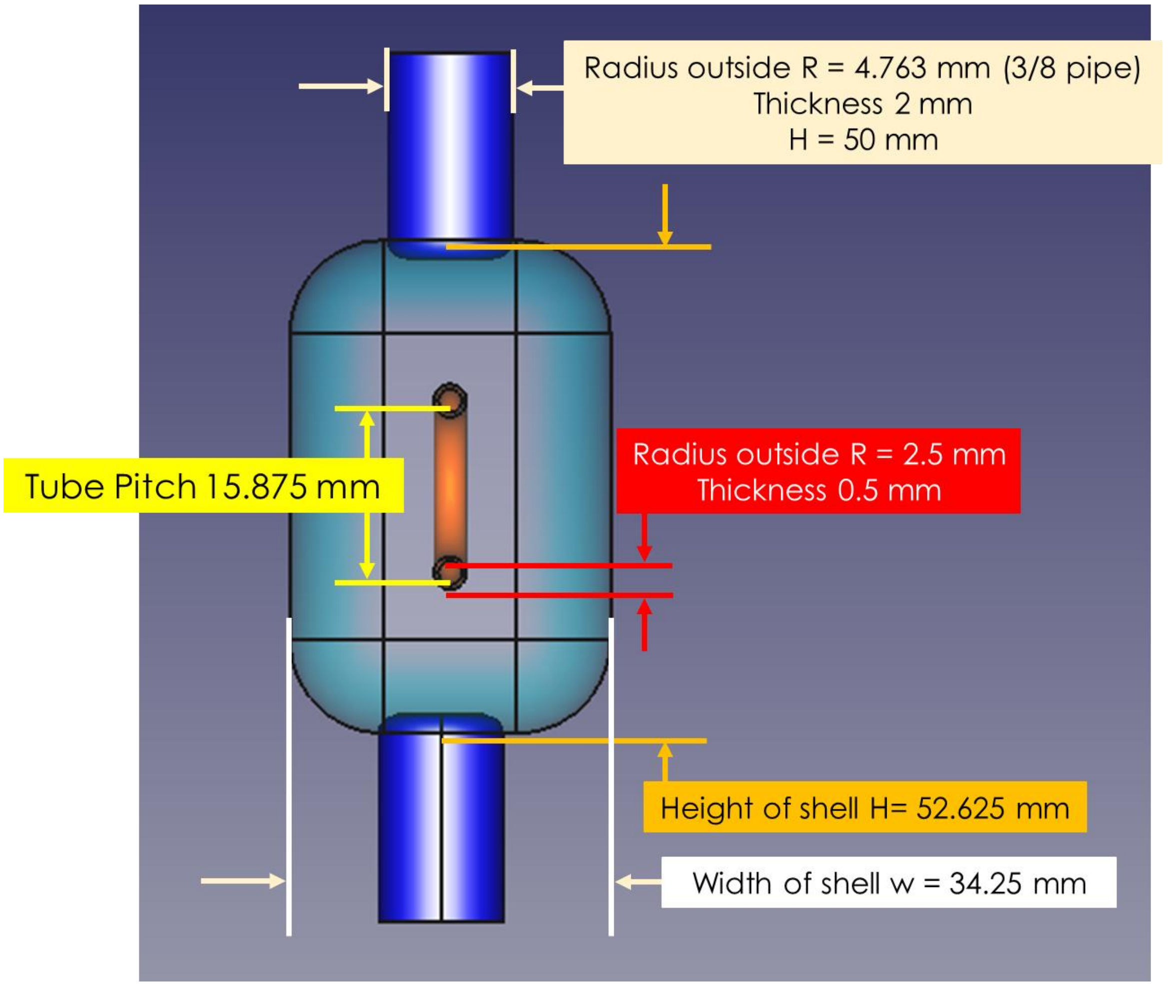
Outlet N2 – Cold side
Material : Copper
Radius outside R = 4.763 mm (3/8 pipe)
H = 50 mm

Shell material : Stainless
Length L = 1775.002 mm
Width w = 34.25 mm
Height H = 52.625 mm
Fillet radius R = 10 mm

Tubes O2 – Hot side
Material : Copper
Radius outside R = 1.25 mm (2.5 mm Capillary pipe)
Length L = 1750.192 mm
Tube pitch 15.875 mm


Tube Length T_L = 1750.192 mm
Radius outside R = 4.763 mm (3/8 pipe)
Thickness 2 mm
H = 50 mm
Tube Pitch 15.875 mm
Radius outside R = 4.763 mm (3/8 pipe) , Thickness 2 mm
H = 50 mm
Length L = 1775.002 mm


Tube Length T_L = 1750.192 mm
Tube Pitch 15.875 mm
Distance d = 20 mm
Distance d = 20 mm
Length L = 1775.002 mm


Radius outside R = 4.763 mm (3/8 pipe)
Thickness 2 mm
H = 50 mm
Tube Pitch 15.875 mm
Radius outside R = 2.5 mm
Thickness 0.5 mm
Height of shell H= 52.625 mm
Width of shell w = 34.25 mm

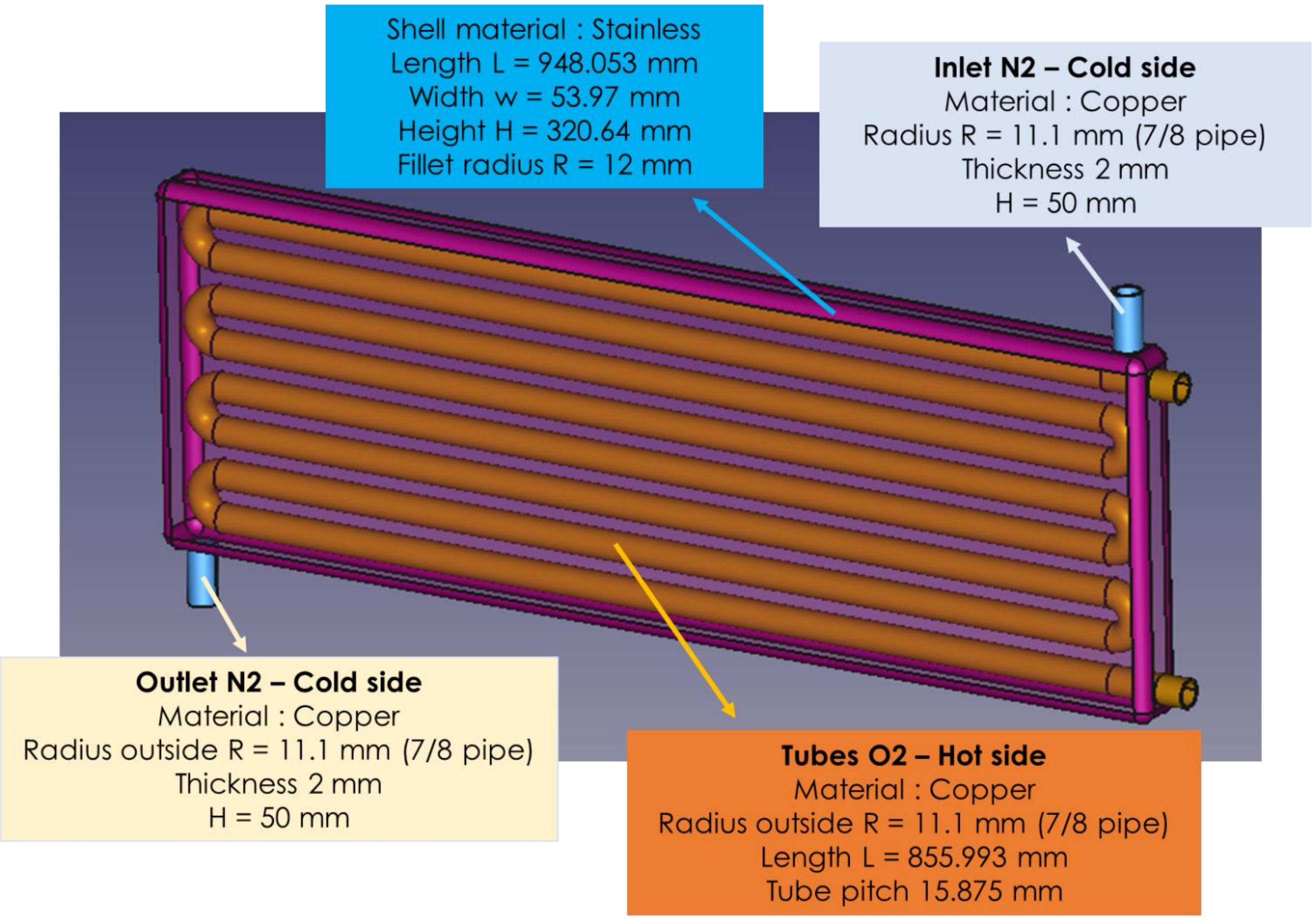
14.4.4 Heat exchanger design HX-N_2/O_2 [2nd]

1 shell , 8 tubes

Shell – Cold side – N2

Tubes – Hot side – O2

HX_N2-O2 (2nd).FCStd

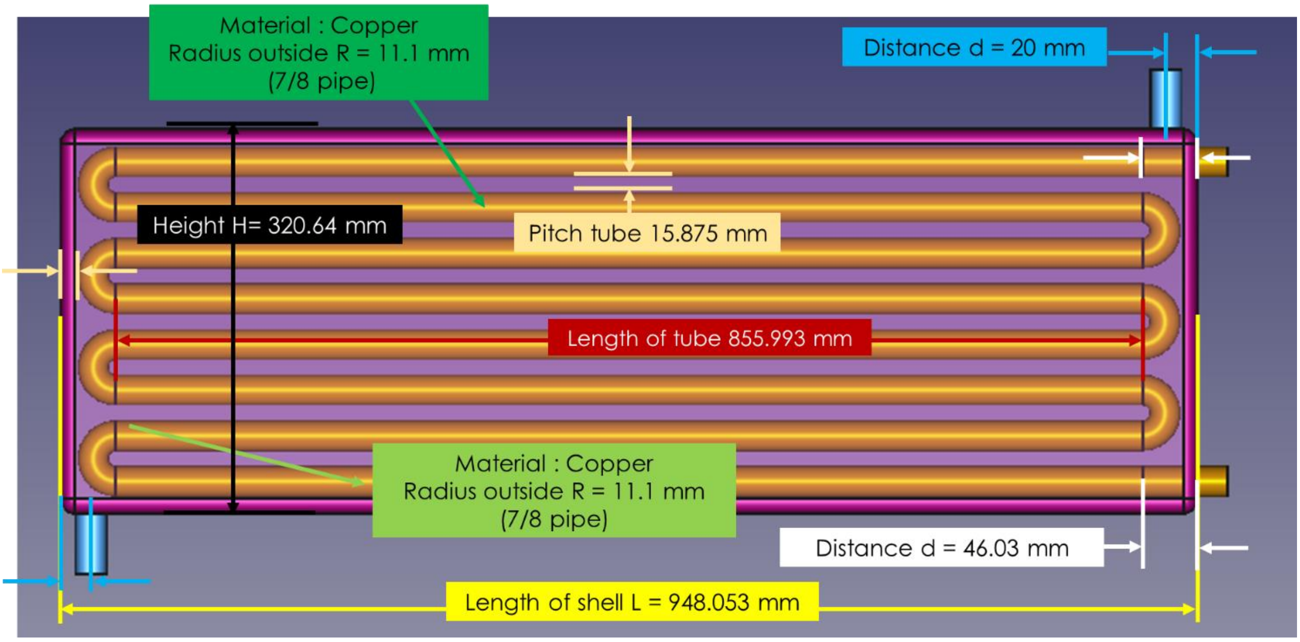


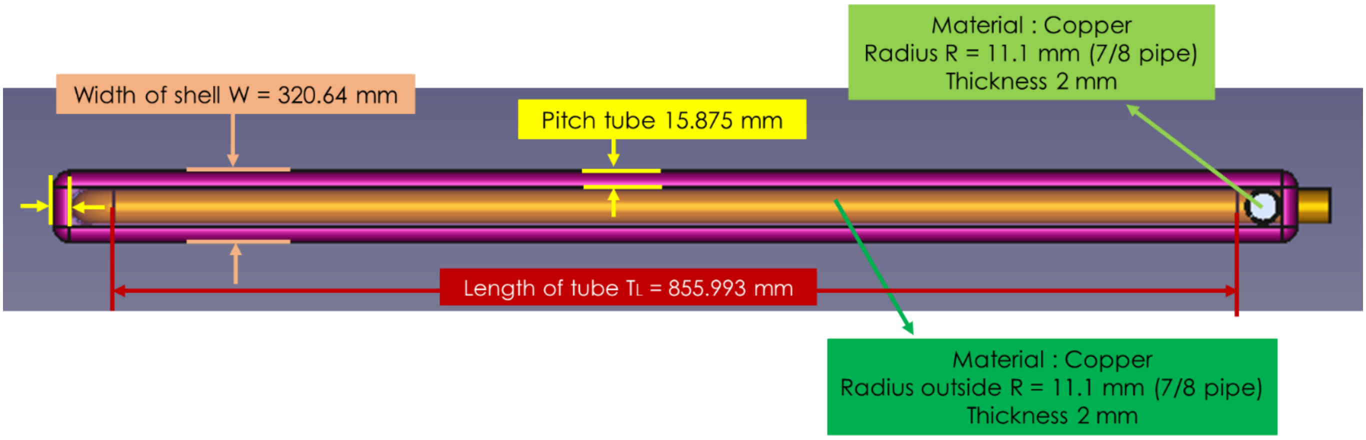
Shell material : Stainless
Length L = 948.053 mm
Width w = 53.97 mm
Height H = 320.64 mm
Fillet radius R = 12 mm

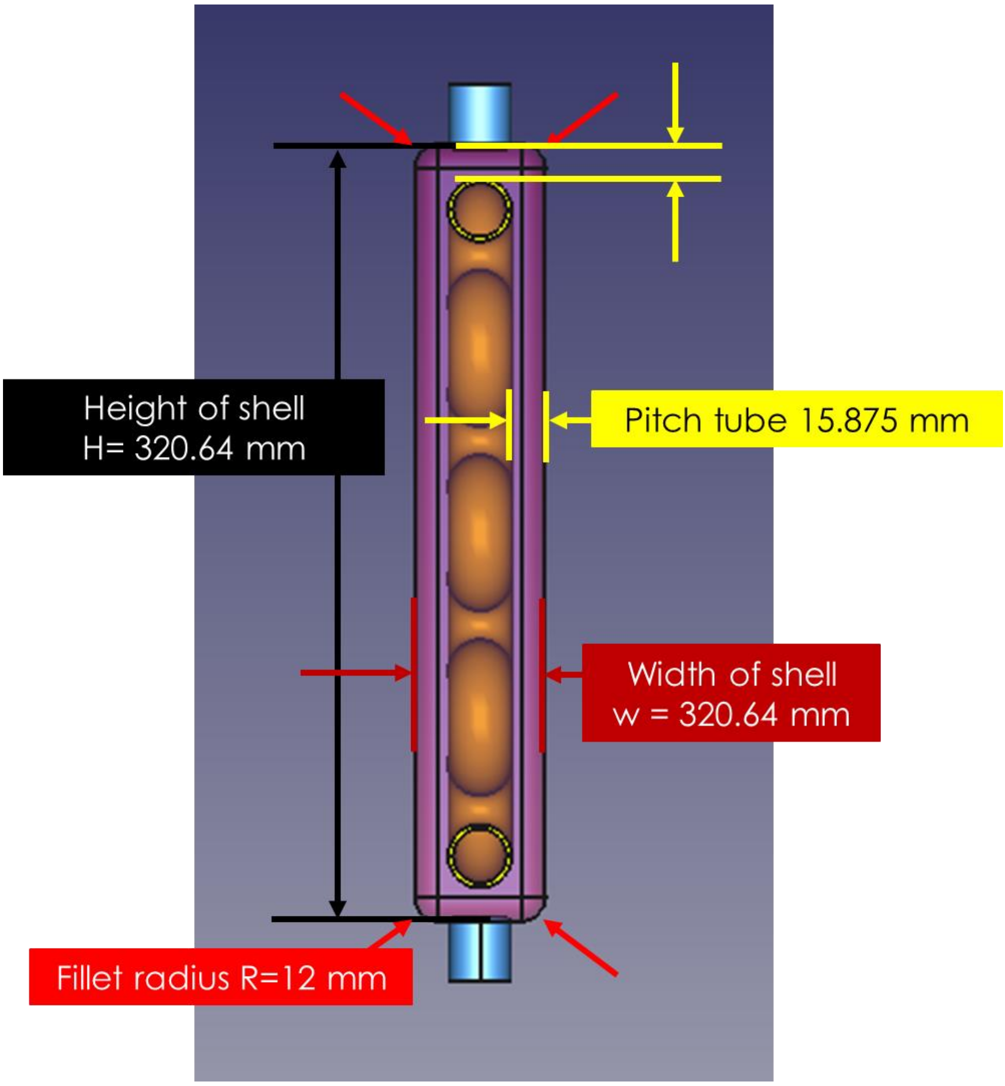
Inlet N2 – Cold side
Material : Copper
Radius R = 11.1 mm (7/8 pipe)
Thickness 2 mm
H = 50 mm

Outlet N2 – Cold side
Material : Copper
Radius outside R = 11.1 mm (7/8 pipe)
Thickness 2 mm
H = 50 mm

Tubes O2 – Hot side
Material : Copper
Radius outside R = 11.1 mm (7/8 pipe)
Length L = 855.993 mm
Tube pitch 15.875 mm


Material : Copper
Radius outside R = 11.1 mm
(7/8 pipe)
Distance d = 20 mm
Height H= 320.64 mm
Pitch tube 15.875 mm
Length of tube 855.993 mm
Material : Copper
Radius outside R = 11.1 mm
(7/8 pipe)
Distance d = 46.03 mm
Length of shell L = 948.053 mm


Material : Copper
Radius R = 11.1 mm (7/8 pipe)
Thickness 2 mm
Width of shell W = 320.64 mm
Pitch tube 15.875 mm
Length of tube T_L = 855.993 mm
Material : Copper
Radius outside R = 11.1 mm (7/8 pipe)
Thickness 2 mm



14.4.5 Cooling design [Inside kelvinator]

$Q_{conv} = m_{dot} * C_p * (T_i - T_o)$

$= 25 \text{ kg/h} * 1.088375 \text{ KJ/Kg.K} * (335 - 195)$

$= 25/3600 * 1.088375 * 140 = 1.0575 \text{ KW} = 1057.5 \text{ W}$

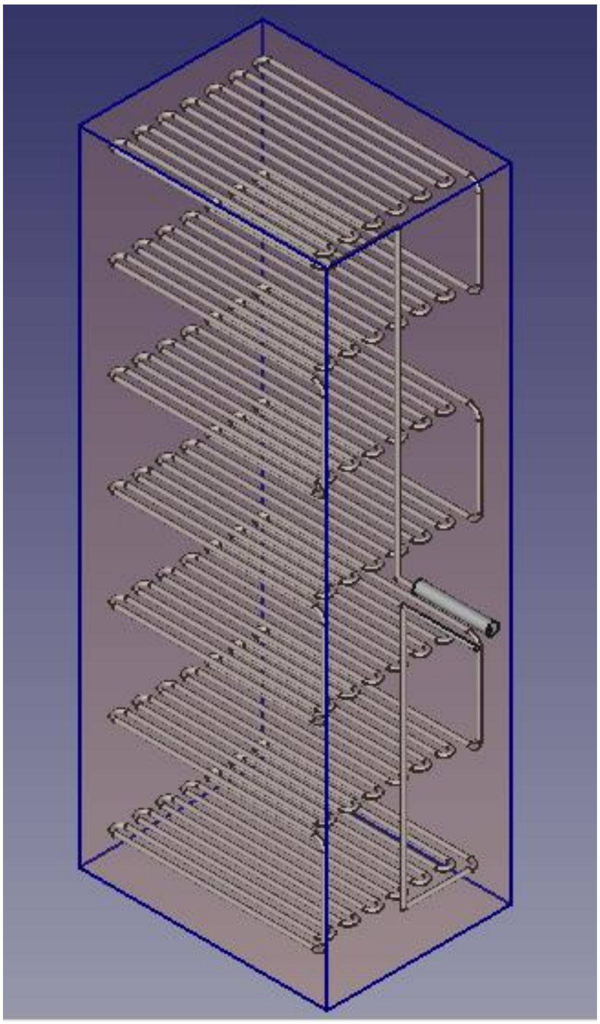
$Q_{conv} = h * A_s * LMTD$ or $LMTD = \dfrac{\Delta To - \Delta Ti}{\ln\left(\frac{\Delta To}{\Delta Ti}\right)} = 33.2$

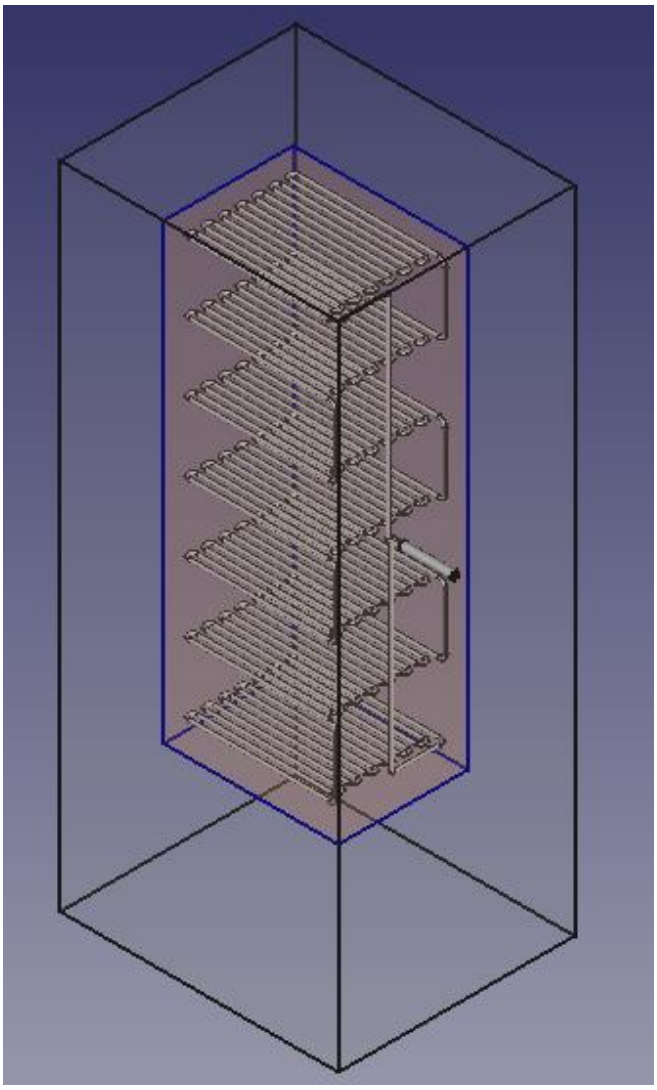
$A_s = \dfrac{1057.5}{h*33.2} = \dfrac{1057.5}{25*33.2} = 1.274 \text{ m}^2$

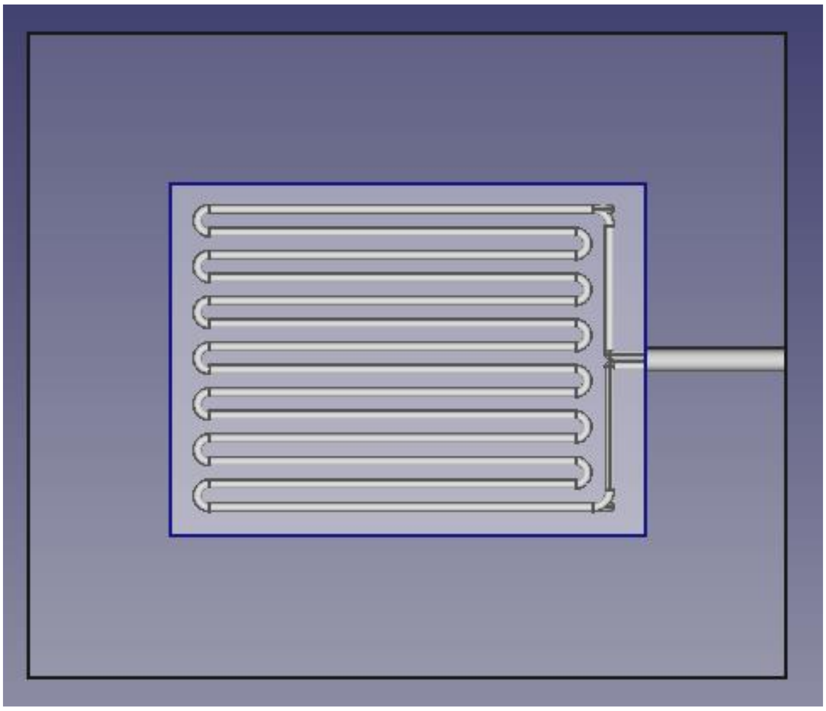
Or $A_s = 2 * \pi * R * h \rightarrow h = \dfrac{As}{2*\pi*R} = \dfrac{1.274}{\pi*9.525*10\text{^}-3} = 42.58 \text{ m}$

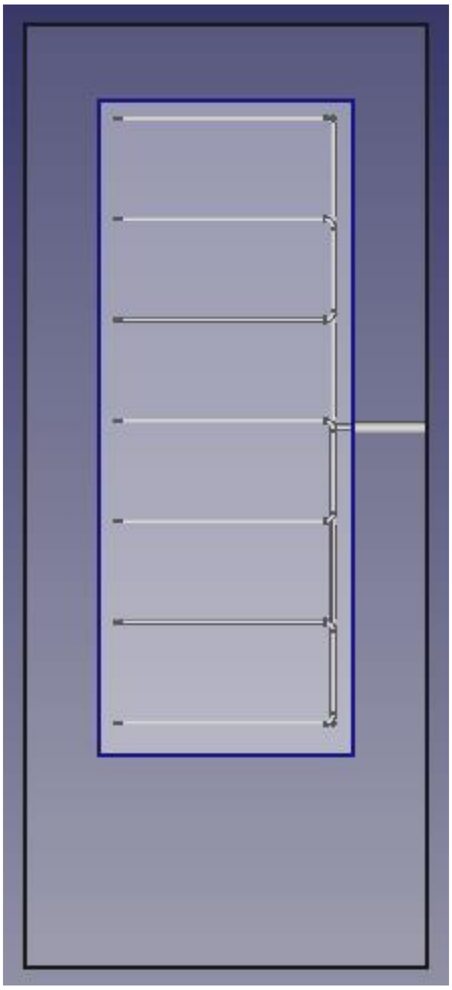
14.4.6 Cooling FreeCad design

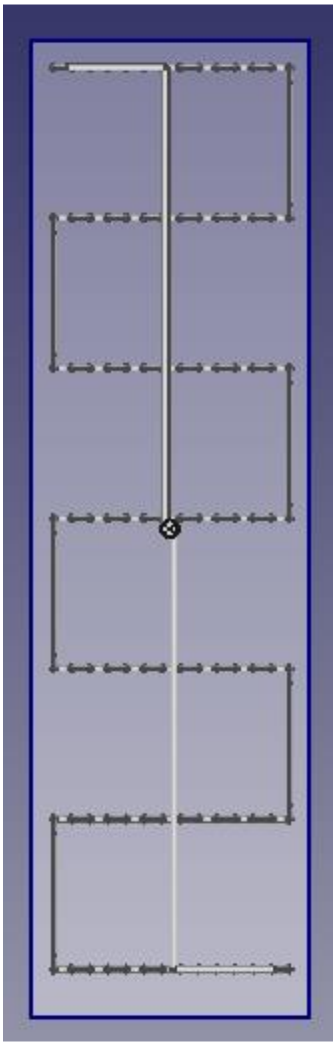
COOLING.FCStd

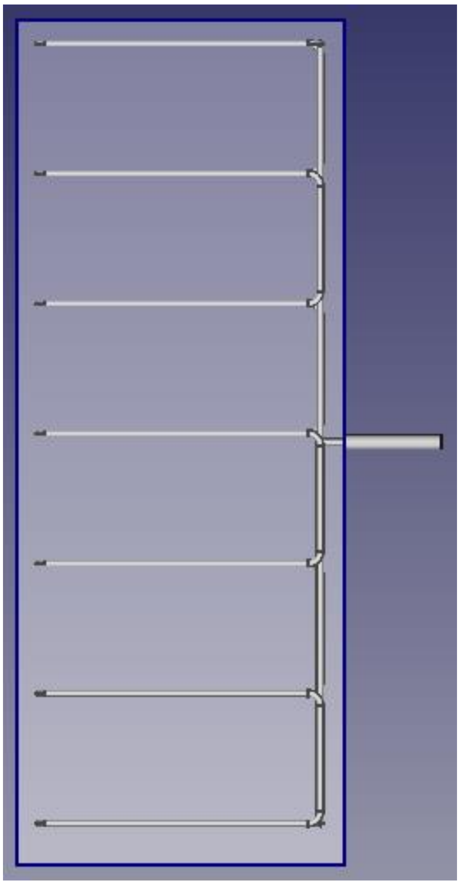


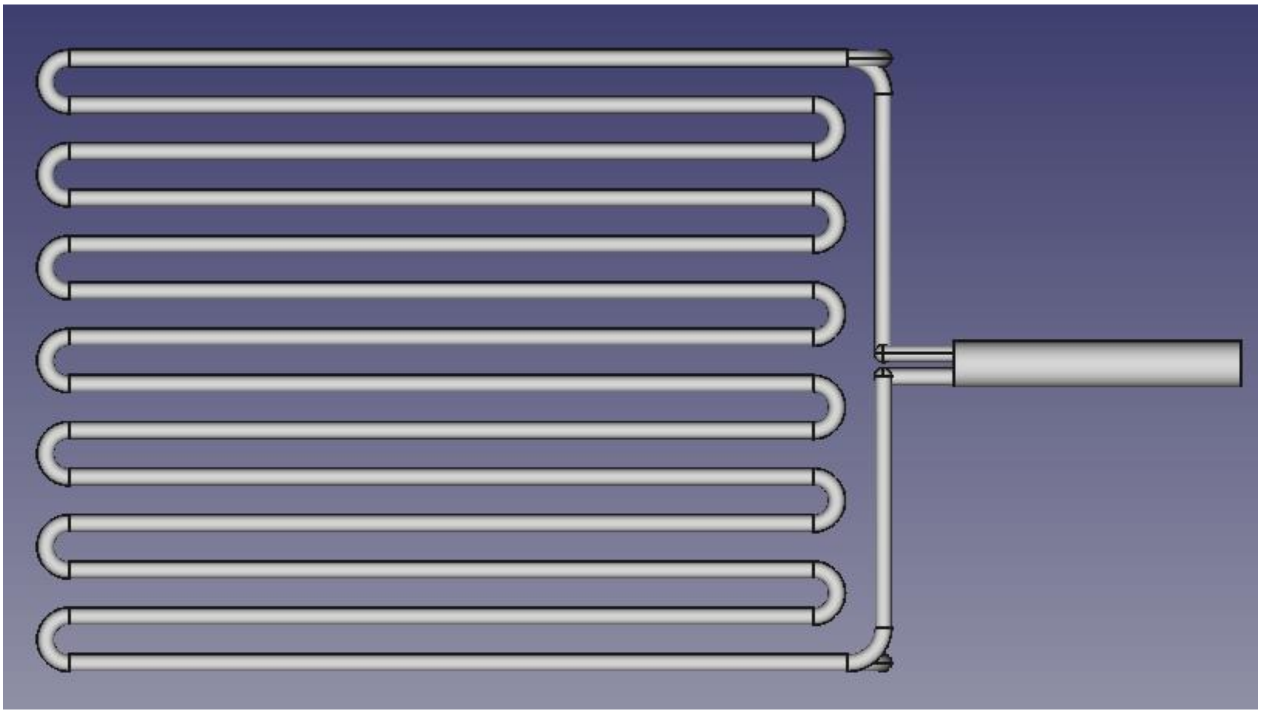


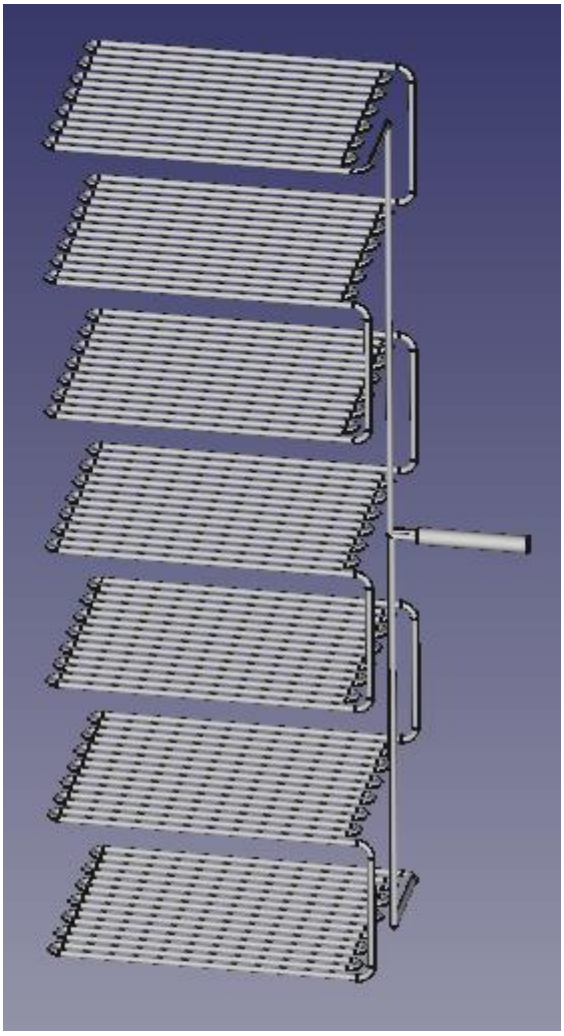


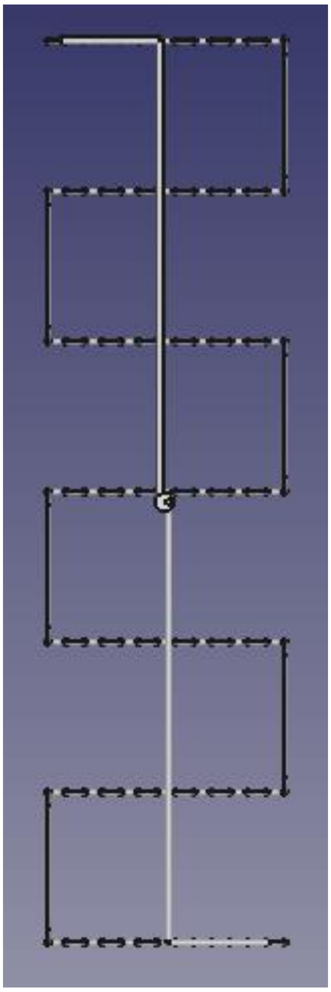


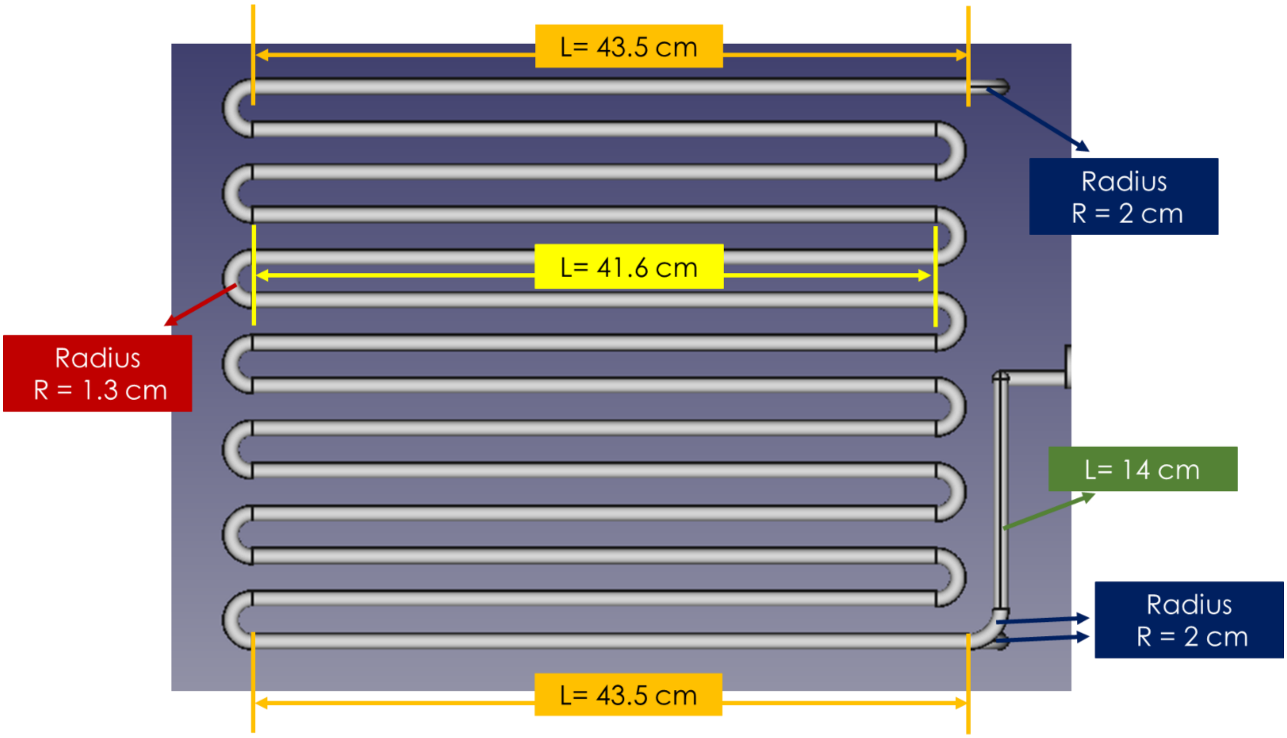


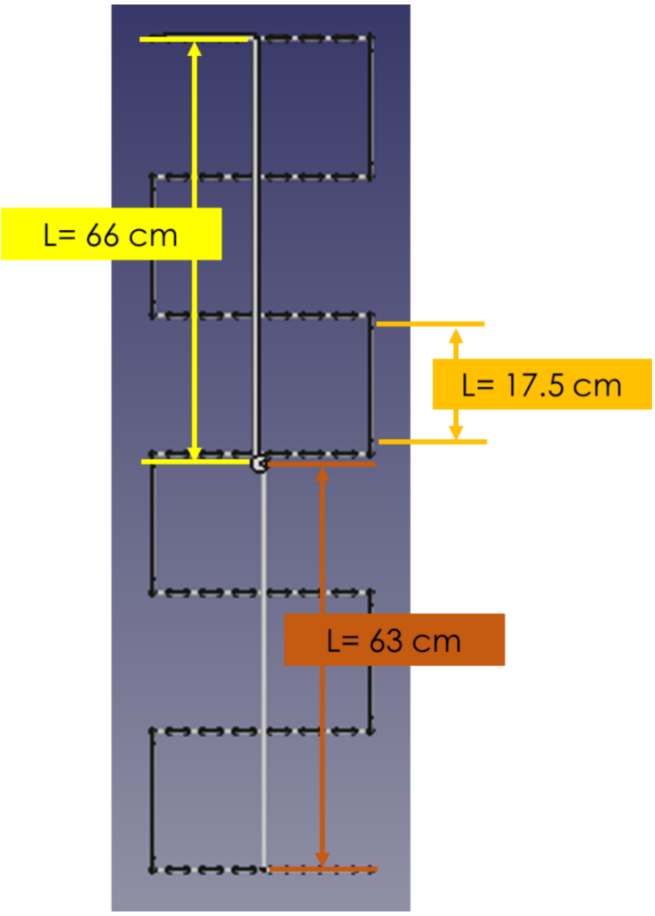




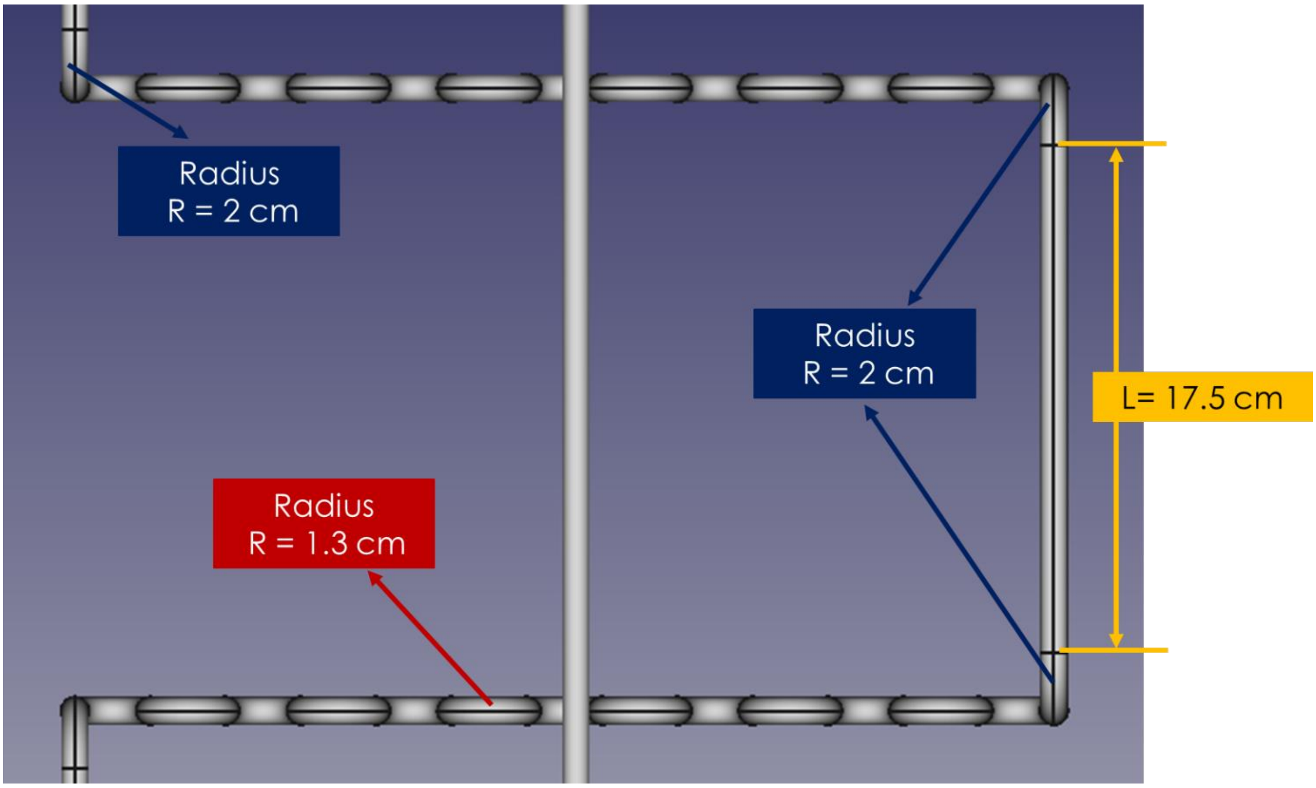





L= 43.5 cm
Radius
R = 2 cm
L= 41.6 cm
Radius
R = 1.3 cm
L= 14 cm
Radius
R = 2 cm
L= 43.5 cm


L= 66 cm
L= 17.5 cm
L= 63 cm

0



14.5 Price of prototype components

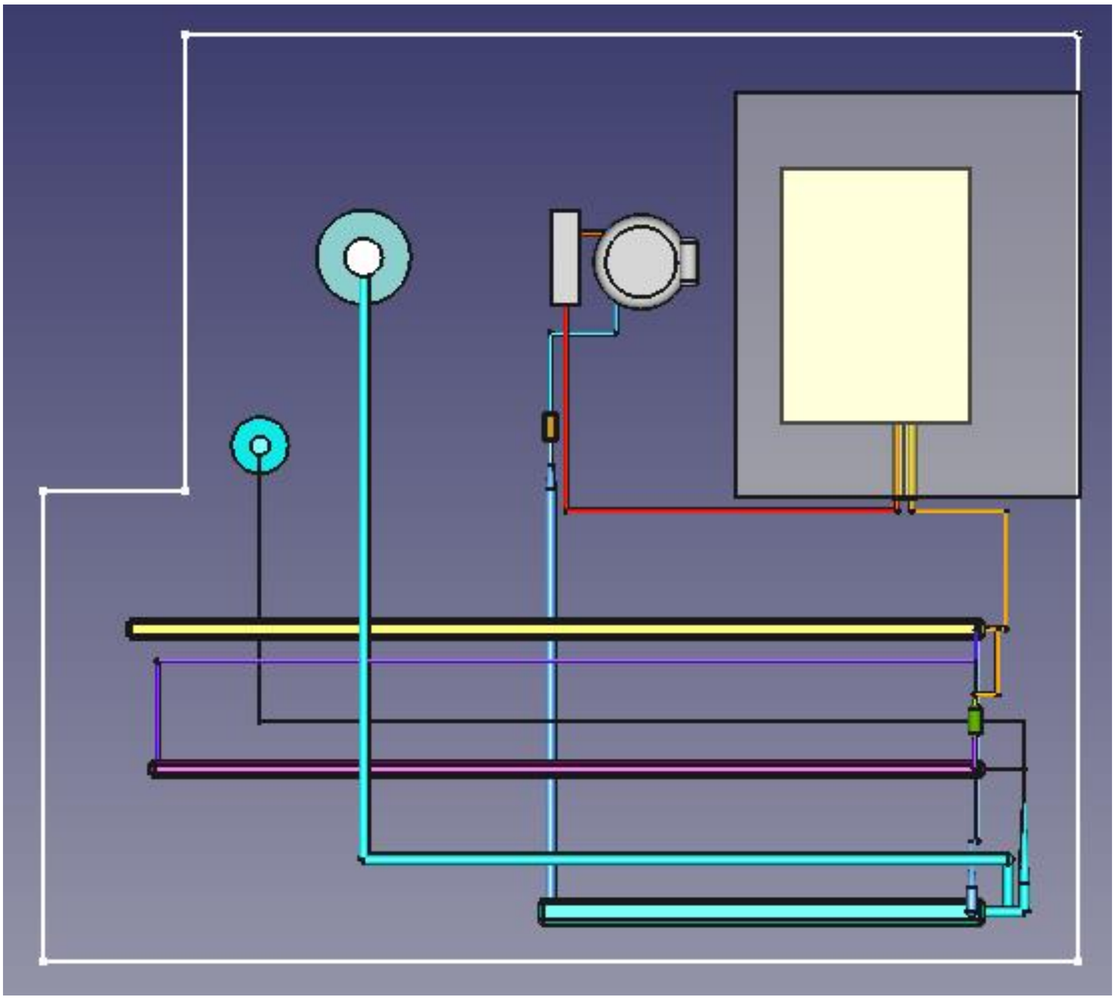
Components of prototype	Source	Characteristics	General price	# of piece	Total cost excluding hand cost	Notes
Compressor	*LR25B laboratory refrigerator*	Press 2 bar to 15 bar	___	1	___	
Condenser	*LR25B laboratory refrigerator*	Air cooling	___	1	___	
Cooling	*Kelvinator refrigerator*	Copper pipes (3/8)	pipe (3/8) : 15 m / $ 55	L= 43 m	$ 157.70	Total pipe 3/8: L= 65.8 m , cost = $ 241.3
HX - N2/N2 (6 shells , 12 tubes)	Manifacture	Copper pipes (3/8)	pipe (3/8) : 15 m / $ 55	L= 22.5 m (L= 3.63 m per shell)	$ 27.50	Total capillaries copper pipes: L = 3.7 m , Cost = 111 000 L.L.
		Copper pipes (7/8)	1.5 m / $ 15 (or Roller 15 m , 140$)	L= 0.6 m (L= 0.2 m per shell)	$ 6.00	Total pipe 7/8: L= 8.2 m , Cost = $ 82
		Shell copper or stainless		Area = 2.4115 m2 (A = 0.402 m2 per shell)	17.4 - 26.1 $ (2.9 - 4.35 $/shell)	Total volume V = 0.003391912 Kg/m3 , Costs = (Stainless 38.2 $, Steel 8.2 $, Copper 287 $)
Expansion valve	Purphase	15 bar, 80 K		1	$ 35.00	
HX - N2/O2 [main] (1 shell , 2 tubes)	Manifacture	Capillaries copper pipes (2.5 mm outside)	1 m / 30 000 L.L.	L= 3.7 m	L.L. 111 000	
		Copper pipes (3/8)	15 m / $ 55	L= 0.1m	$ 0.37	
		Shell copper or stainless		Area A = 0.3134 m2		
HX - N2/O2 [2nd] (1 shell , 8 tubes)	Manifacture	Copper pipes (7/8)	1.5 m / $ 15 (or Roller 15 m , 140$)	L= 7.4 m	$ 102.00	
		Shell copper or stainless		Area A = 0.7457 m2		
Filter drier	Purphase	N2 gas, mass flow 25 Kg/hr		1	$ 15.00	
Pressure valve	Purphase	**Gas** 15 bar		1		
Check valve	Purphase			1	$ 10.00	
Thermal insulation materials	Purphase	Area per meter				
Cryometer	Purphase (not available)	Low than 80 K		5		
Solenoid valve	Purphase			1		
N2 gas	Purphase					
O2 gas	Purphase					
O2 gas tank	Purphase			1		

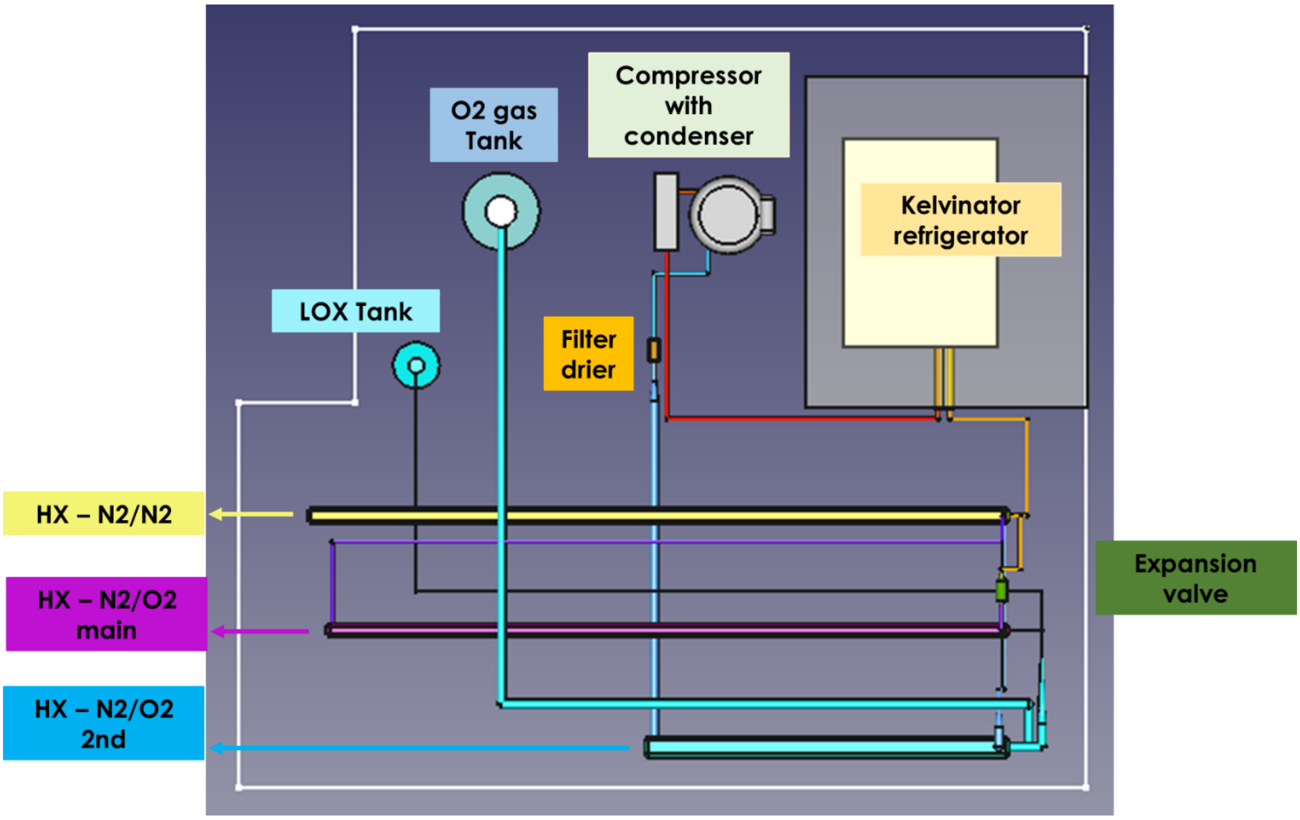
- General space of prototype is : L * W * H = 1.93 m * 2 m * 1.2 m (except height of kelvinator refrigerator = ~ 1.7 m)

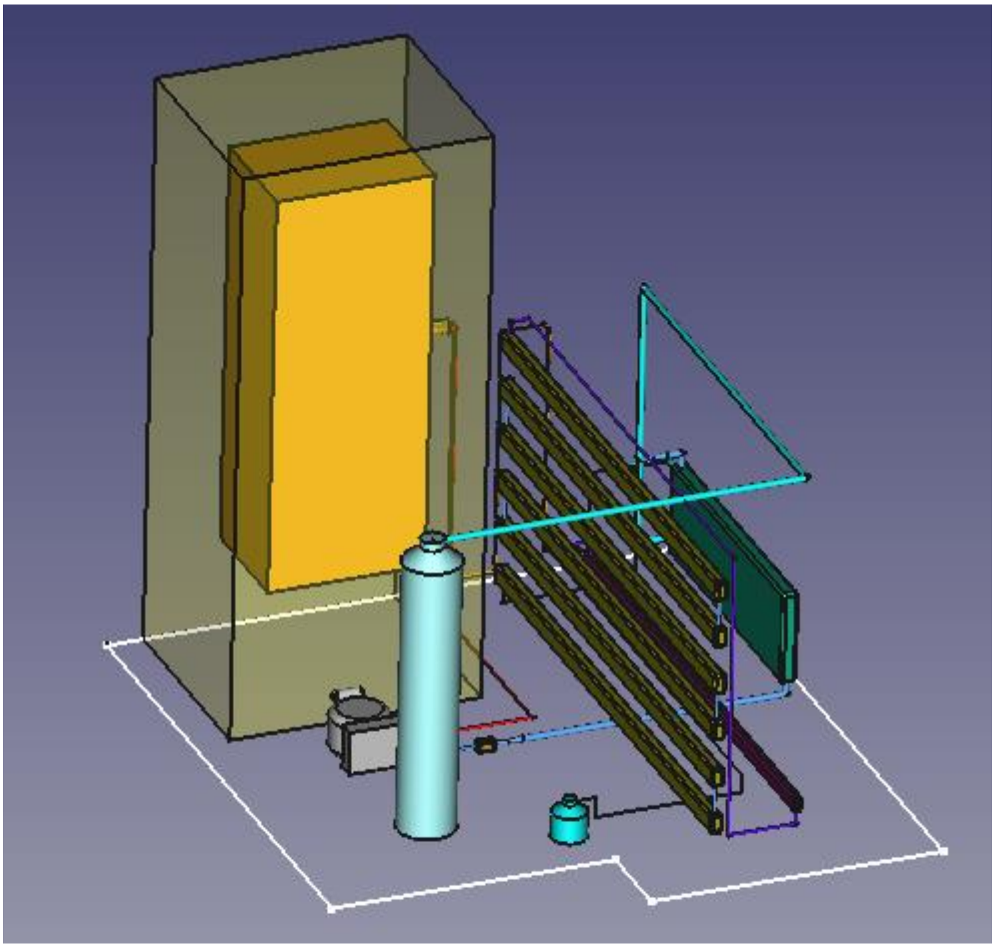
		Stainless steel	Steel	Copper
Price		1 - 1.5 $/Kg	100 - 300 $/Ton	9.35 $/Kg
Density		7500 Kg/m3	8050 Kg/m3	8.96 g/cm3
HX-N2/N2	Volume needed	0.002348004 m3	0.002348004 m3	2348.004 cm3
	Mass	17.61 Kg	18.90 Kg	21.038 Kg
	Cost	17.61 - 26.415 $	1.89 - 5.67 $	196.71 $
HX-N2/O2 main	Volume needed	0.000305524 Kg/m3	0.000305524 Kg/m3	305.524 Kg/cm3
	Mass	2.29 Kg	2.46 Kg	2.737 Kg
	Cost	2.29 - 3.435 $	0.246 - 0.738 $	25.6 $
HX-N2/O2	Volume needed	0.000738384 Kg/m3	0.000738384 Kg/m3	738.384 Kg/cm3
	Mass	5.54 Kg	5.94 Kg	6.91 Kg
	Cost	5.54 - 8.31 $	0.594 - 1.782 $	64.61 $
Total volume		0.003391912 Kg/m3	0.003391912 Kg/m3	0.003391912 Kg/m3
Total mass		25.44 Kg	27.305 Kg	30.685 Kg
Total cost		25.44 - 38.16 $	2.731 - 8.192 $	286.91 $

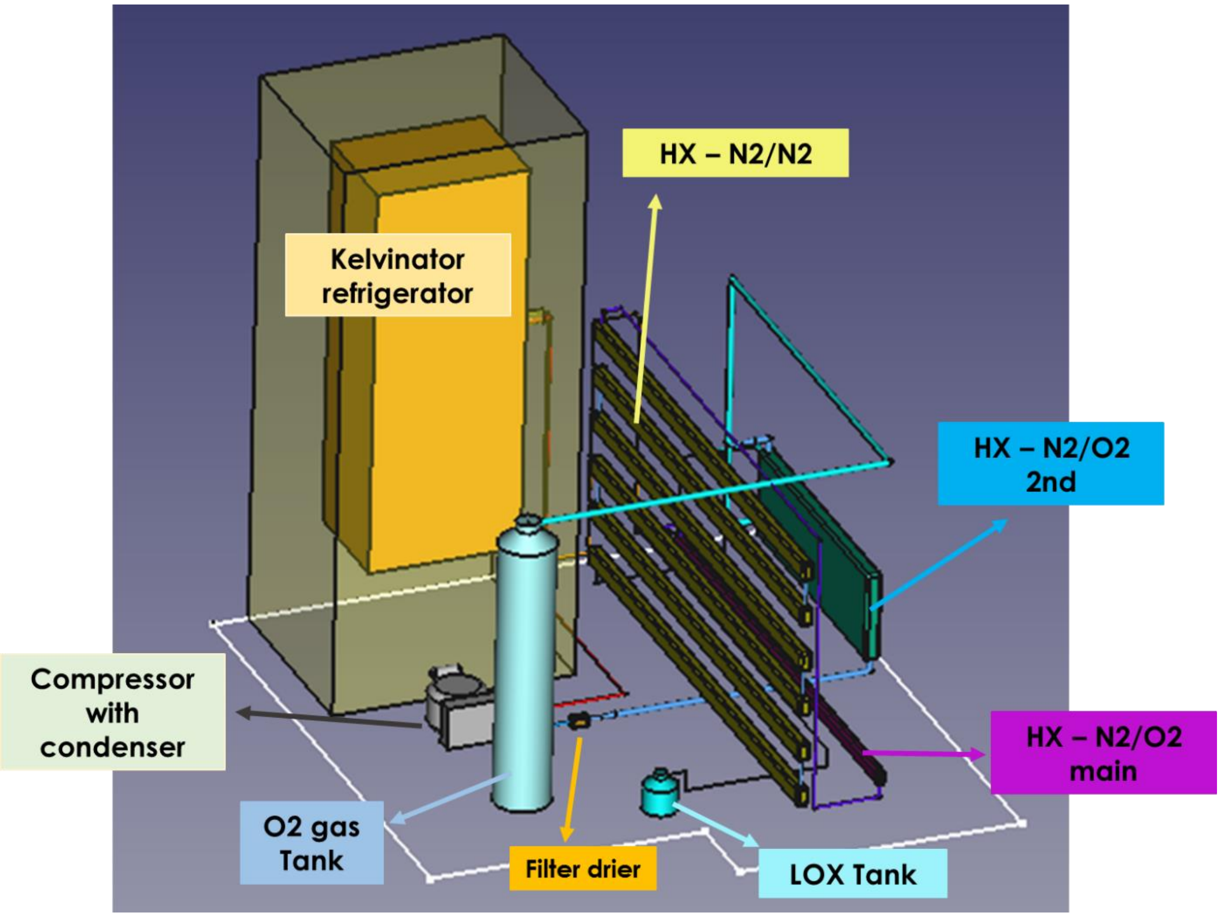
14.6 Real layout design of prototype in AECENAR Facility

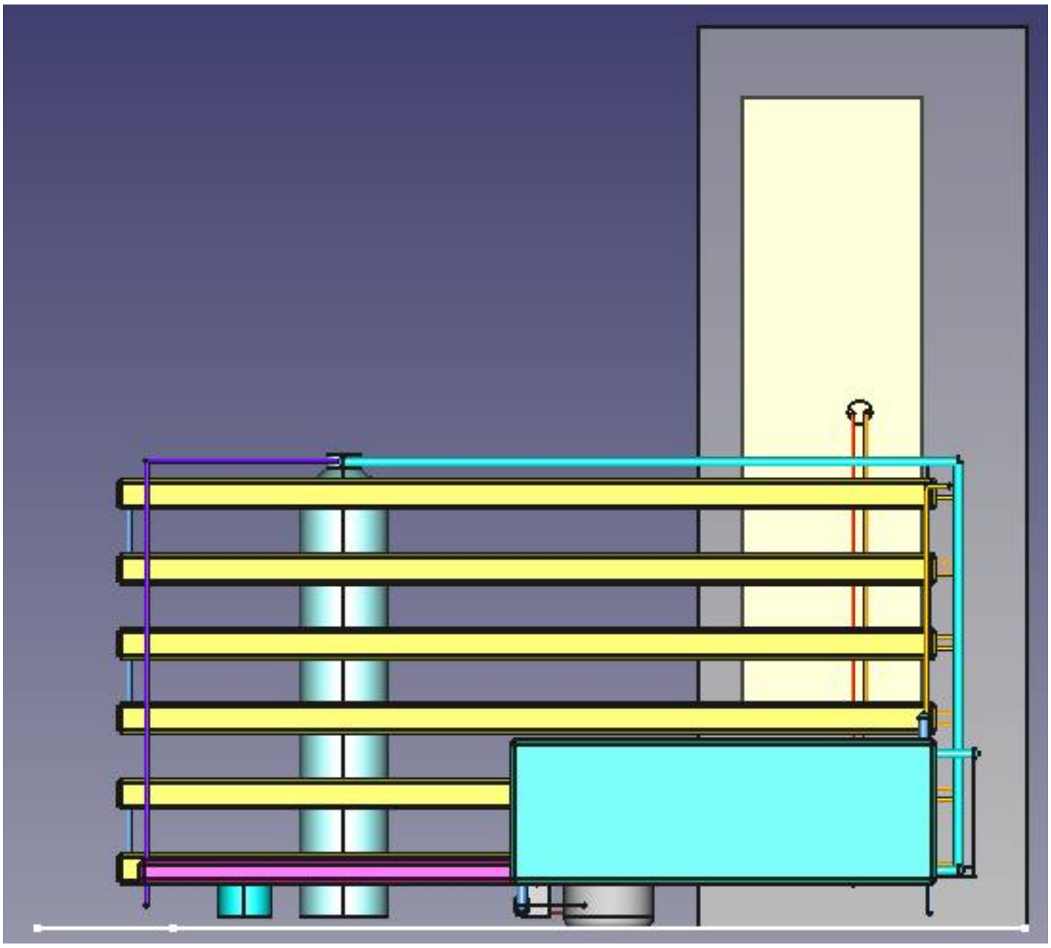
real prototype.FCStd

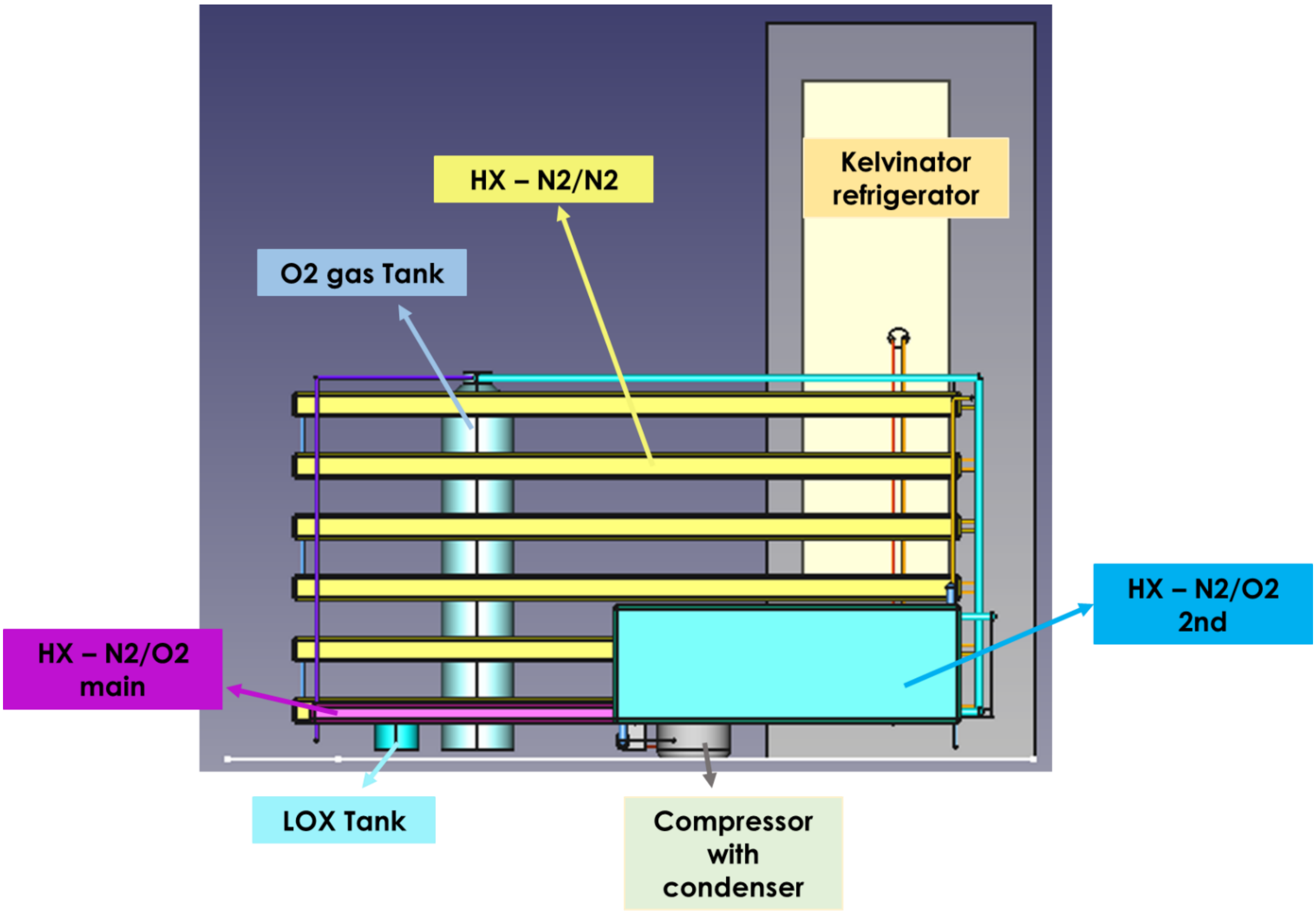



O2 gas Tank
Compressor with condenser
Kelvinator refrigerator
LOX Tank
Filter drier
HX – N2/N2
HX – N2/O2 main
HX – N2/O2 2nd
Expansion valve




HX – N2/N2
Kelvinator refrigerator
HX – N2/O2 2nd
Compressor with condenser
HX – N2/O2 main
O2 gas Tank
Filter drier
LOX Tank




HX – N2/N2
Kelvinator refrigerator
O2 gas Tank
HX – N2/O2 2nd
HX – N2/O2 main
LOX Tank
Compressor with condenser


IP Camera
NHIMMEL

14.7 Real design of cooling (inside kelvinator refrigerator)

In this evaporator, we have 20 pipes (size 3/8, length L=~ 32 cm) with 19 tees (Radius R= 1.5 cm)

So: (32cm x 20 pipes)+($\frac{2 \text{ x } \pi \text{ x } 1.5\text{cm x } 180^\circ}{360}$ x 19 tees) = 729.535 cm = ~ 7.29 m

The length required for cooling was previously calculated : 42.58 m =~43 m

43 m /7.29 m = 5.98 floor → we need 6 floor for cooling

But the measurements of evaporator are not accurate so we will use 7 floors or pieces of this evaporator

Price of one piece of evaporator = ~200 000 L.L.

Total price excluding hand cost = ~ 200 000 x 7 = ~ 1 400 000 L.L.

14.8 First experiment (Expr #1)

The first experiment (Expr #1) aims to:

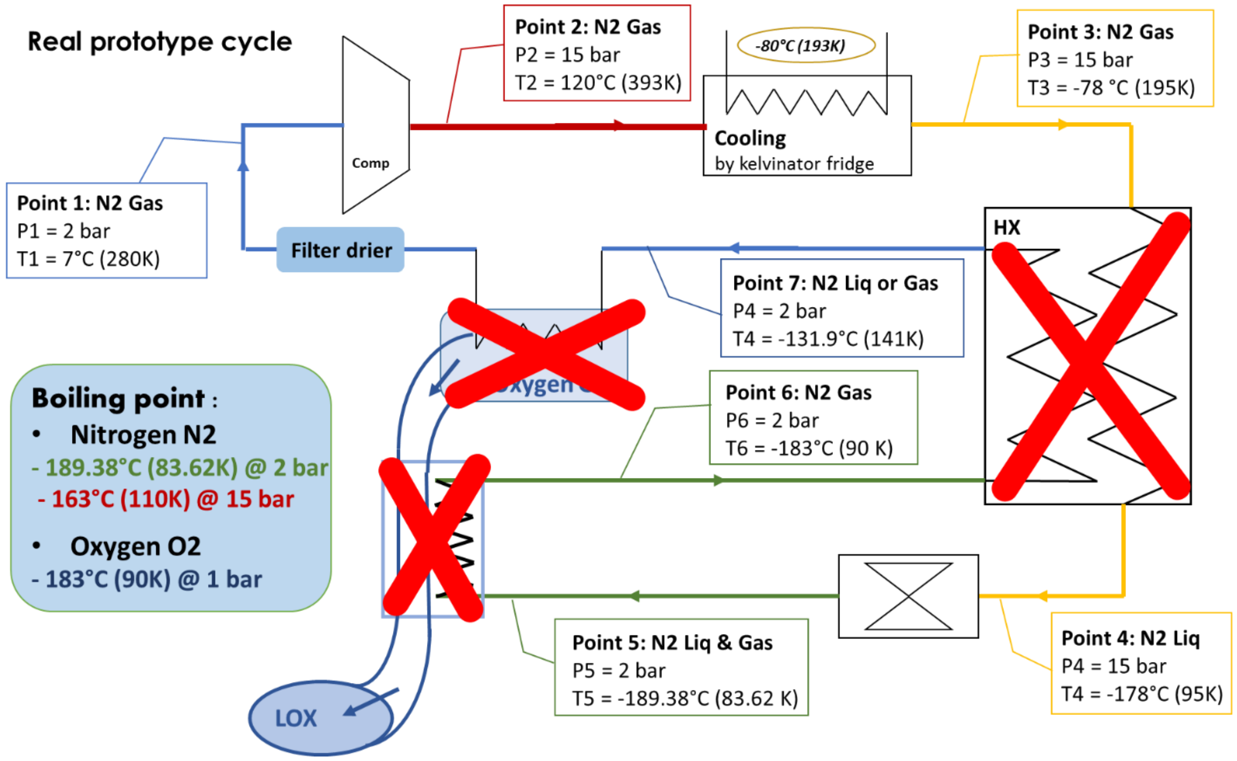
1- Compressor operation test with nitrogen gas instead of R-134a,

2- Make sure that the Kelvinator refrigerator is running correctly

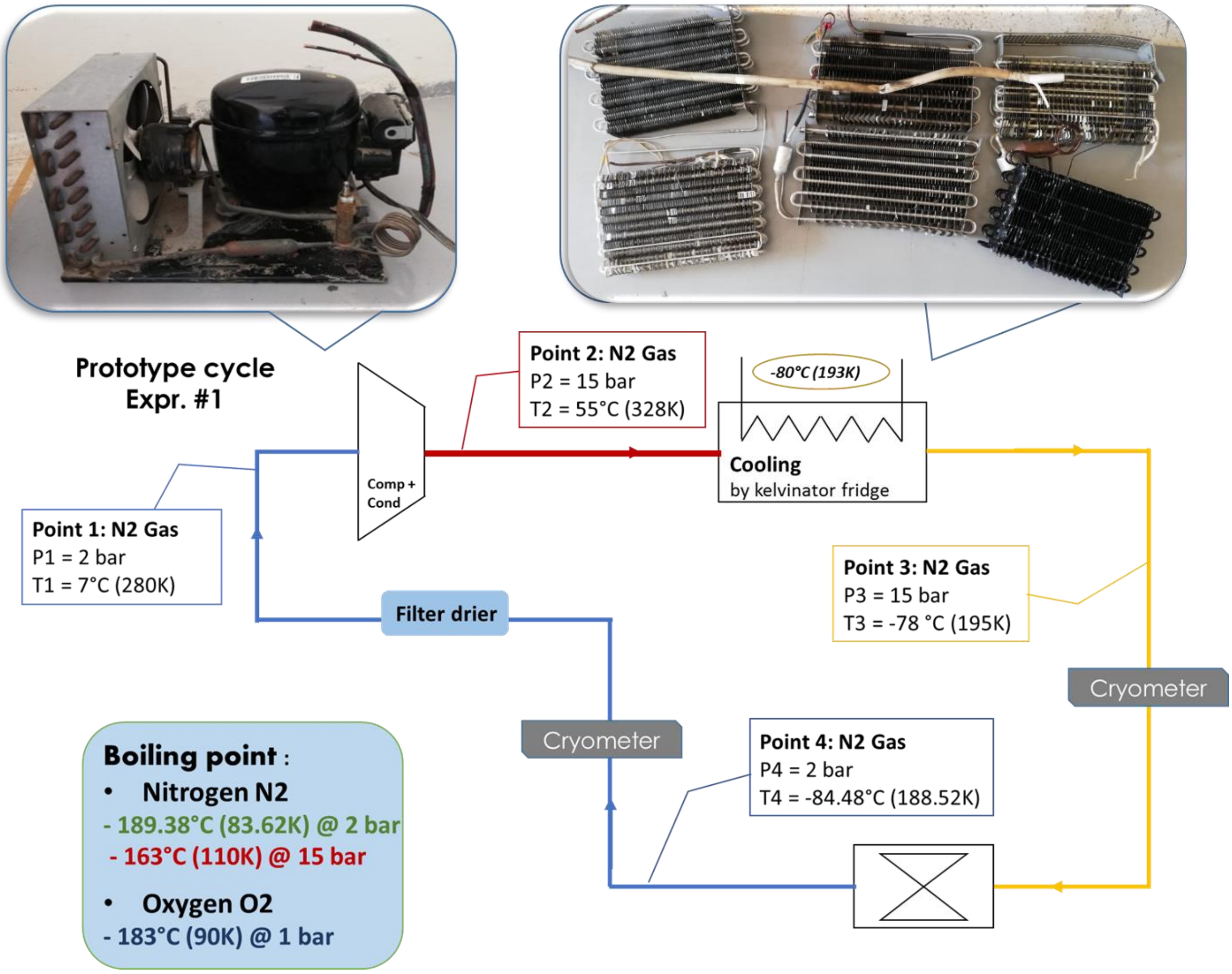
3- Ensure that the expansion valve is compatible with the design.

Therefore, the three heat exchangers (HX-N2/N2, HX-N2/O2 main, HX-N2/O2 2nd) will be excluded from this experiment.

In this experiment, the oxygen will not be liquefied, but only the components will be tested and designed to ensure the proper functioning of the refrigeration cycle.



The first experiment consists of a simple cycle consisting of a compressor (LR25B Laboratory) with a condenser, cooling through a Kelvinator refrigerator, and an expansion valve (taken from an LR25B Laboratory refrigerator).



The components that must be provided to carry out this experiment:

1. Filling the design with nitrogen gas, immediately before the pump.
2. Covering the design with a thermal insulation material to maintain the temperature of the refrigeration cycle,
3. The presence of a thermometer (below -100°C (173 K)) to measure the cooling outlet (inlet of the expansion valve) and the outlet of the expansion valve,
4. Also, a weather thermometer (from -10°C to 20°C (263 K to 293 K)) to measure the temperature of the compressor inlet.

For **the safety of the compressor**:

- In the **first hour of operation**, a 5-minute break must be taken for the compressor every 15 minutes of operation, in order to avoid an explosion of the compressor or one of the designed cables.

- Also, the compressor must **not run for more than two hours** in a row.

- Also, **cold nitrogen gas must be entered into the compressor** to reduce the speed of nitrogen flow, in addition to its role in cooling the compressor.

During this experiment (Expr. #1), the **amount of nitrogen gas filled** to the cycle, the **time of the experiment**, the **temperature reached** by the refrigeration cycle, the **pressure during operation** will be calculated.

Literature
…

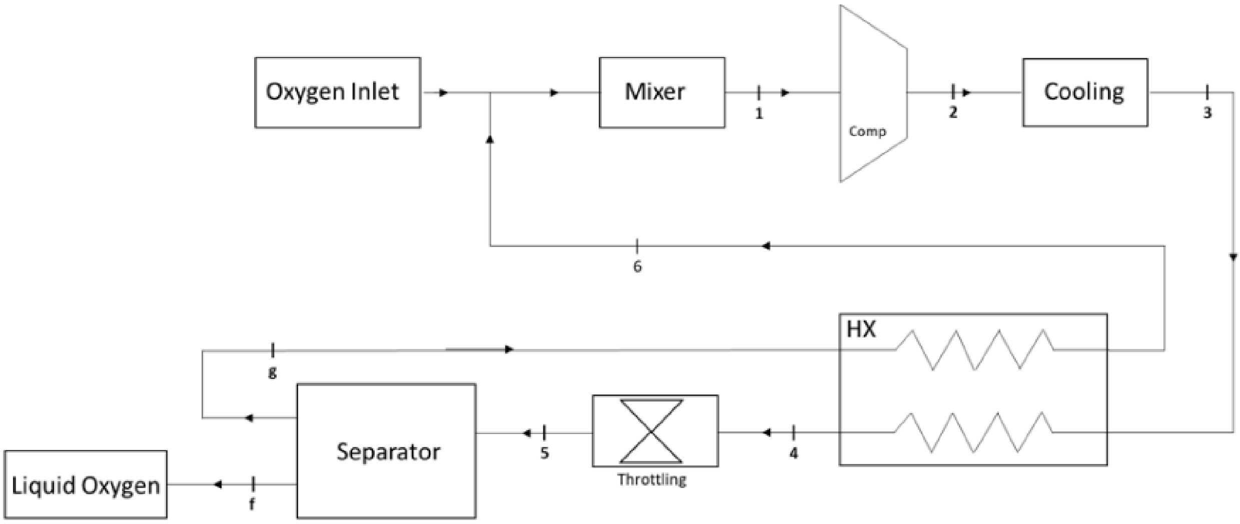
15 Project D 22 Liquefaction of Oxygen (ICPT - LOX)

15.1 Position of LOx project

Work on this project began theoretically in the past years. In this year (2022), the focus was on the practical side, as important amendments were put in place that determined the course of the project, and a large part of the project was implemented.

15.2 LOX introduction

Initially, it was suggested to replace the main cycle (open oxygen cycle for liquefaction of oxygen) with a closed cryogenic cycle running on nitrogen gas for liquefaction of oxygen. This is due to the increased cost of the oil-free oxygen compressor, but it turned out later that nitrogen gas also needs an oil-free compressor, and for this reason we decided to return to the basic suggestion attached below.



In our prototype, we decided to dispense with the heat exchanger in order to avoid expensive materials and manufacturing costs. However, through the theorical study, it was found that we will face a problem in reaching the required liquefaction temperature, in addition to the compressor failure due the low gas temperature at the compressor inlet.

Therefore, the following was decided:

1) Selection of an oil-free oxygen compressor suitable for previously installed pipes.
2) Recalculation of the oxygen liquefaction cycle.
3) Heat exchanger
    a) HX design
    b) Materials of manufacture
    c) Total costs
4) Determining the type of insulation suitable for the system

5) Manufacture of the HX and its installation in the system
6) Resizing of expansion valve
7) Design and manufacture of separator and gas mixer
8) Completing all required connections and placing the sensors (timer, pressure and temperature sensors) in their appropriate places.
9) Connect the oxygen gas bottles needed for the experiment
10) Putting the insulation materials in its proper place in the system
11) Doing the first experiments.

15.3 Cooling component

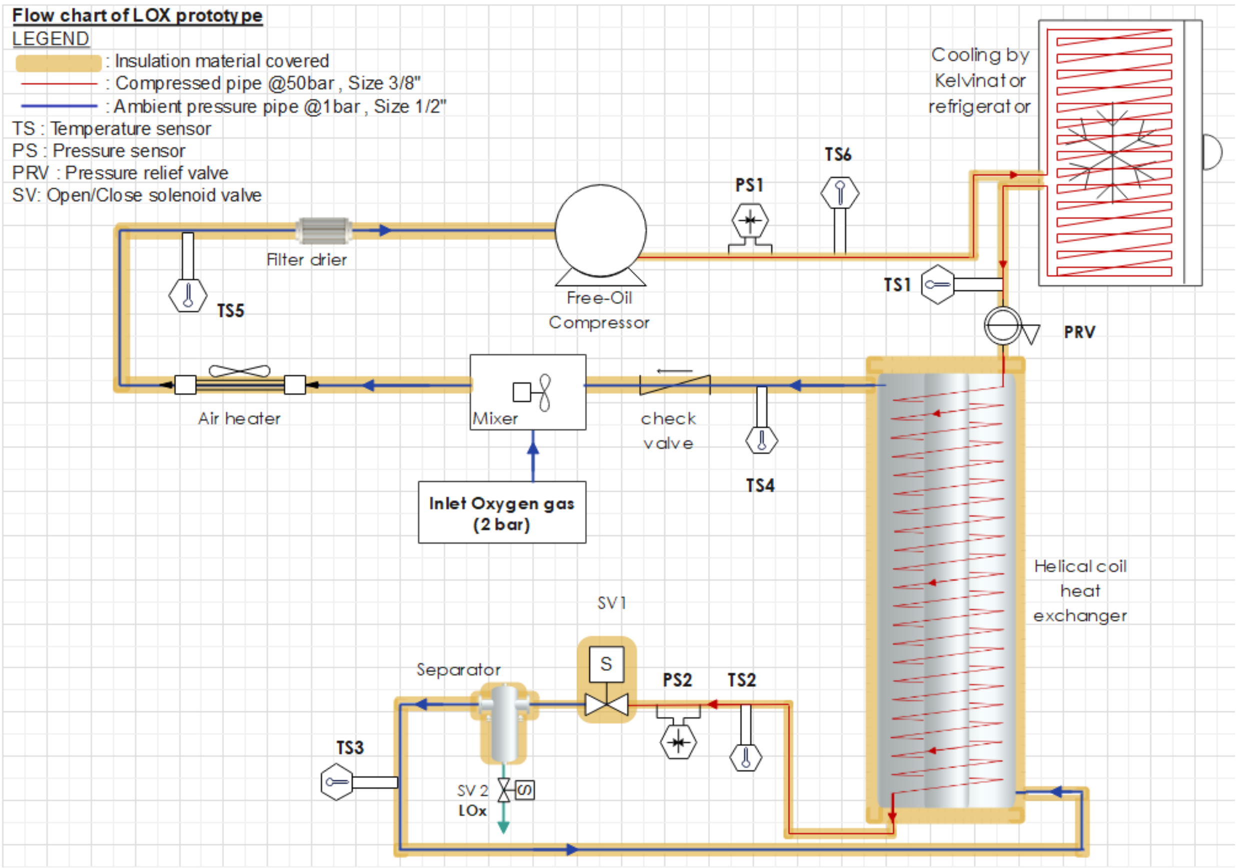
In our system, the “Kelvinator” refrigerator has been adopted as a condenser for the compressor outlet. The second refrigeration cycle in the Kelvinator works with refrigerant R-503. This refrigeration cycle needs to be filled with refrigerant R-503. Due to its unavailability in the market, it was replaced with refrigerant R-508b, due to its compatibility with compressor oil.

15.4 Project overview

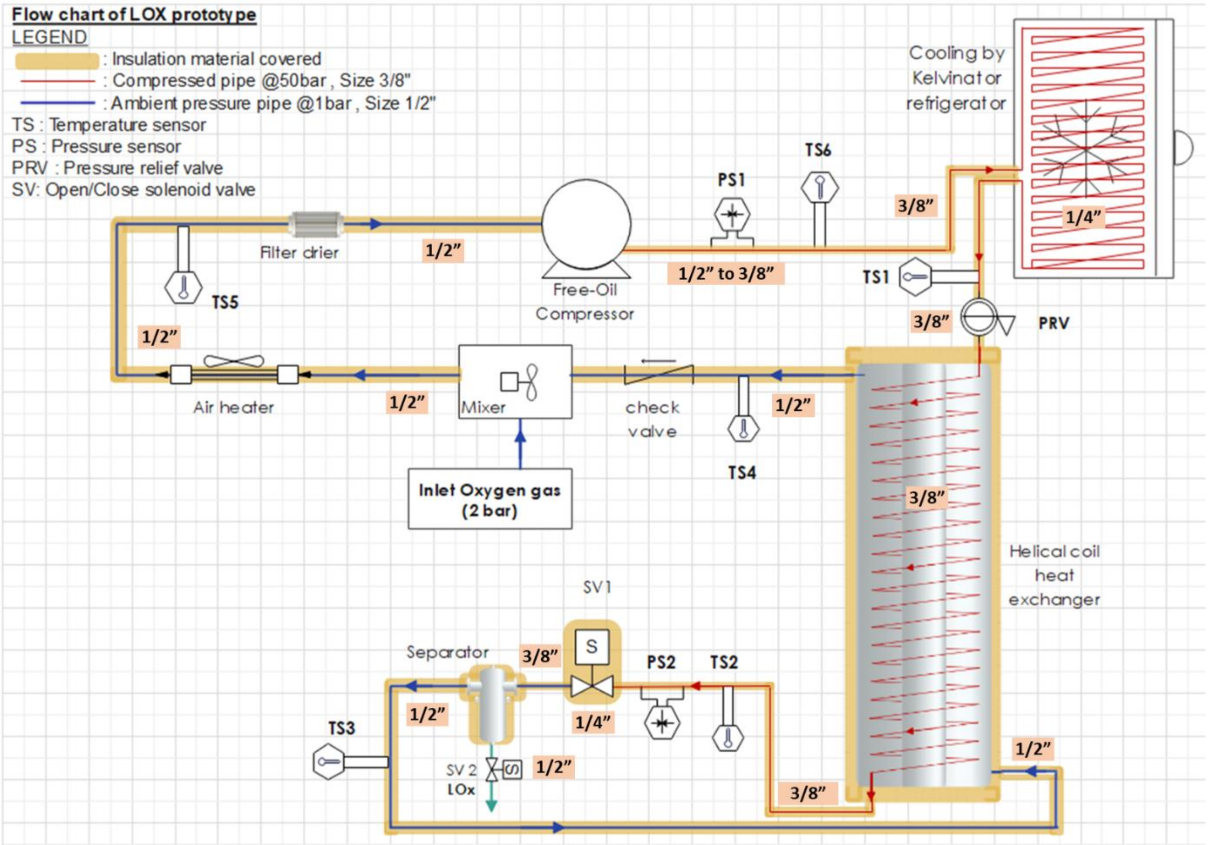
1) Overview flow chart

LOX prototype flow chart by EDraw:

29102022_ LOX
Prototype Flow char

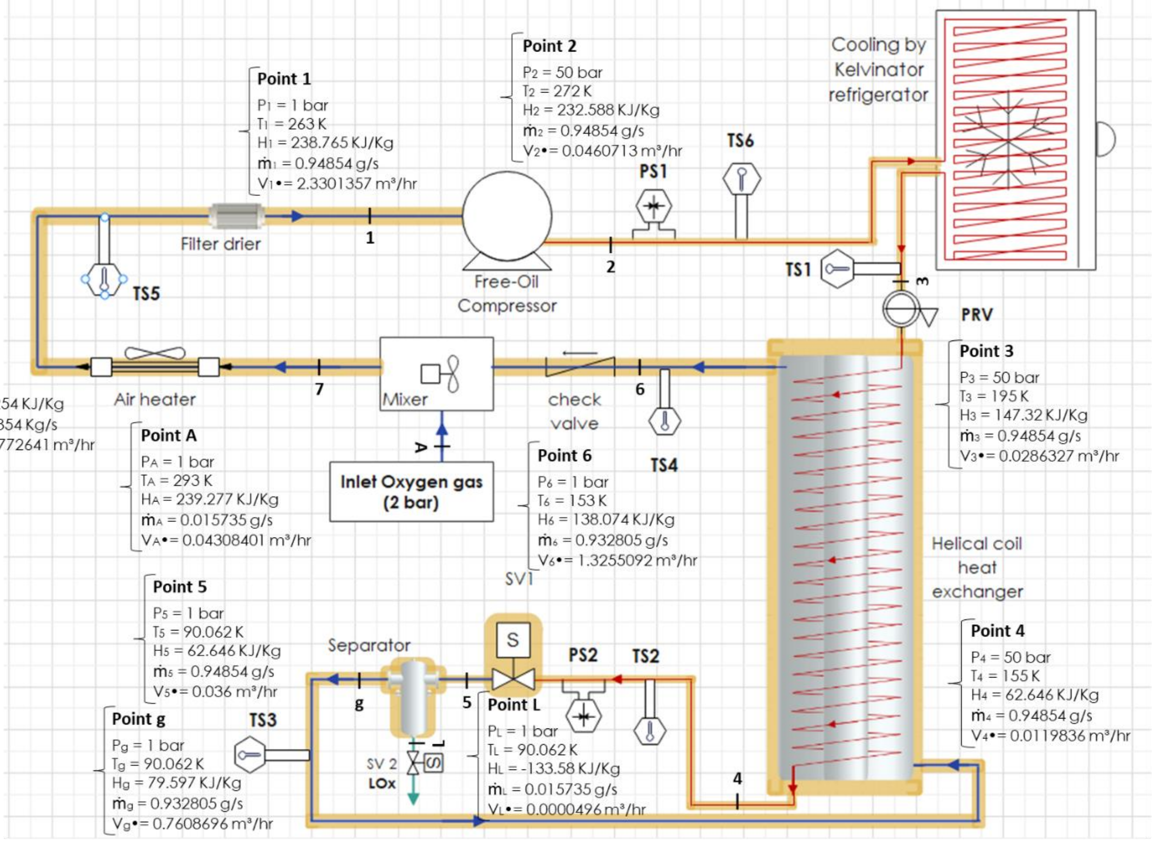


2) Pipe sizing



3) LOx cycle calculation

Calculation of oxygen liquefaction cycle



Points	Pressure	Temperature	Enthapy	Mass flow			Density	Volumetric flow		
	P [bar]	T [°K / °C]	H [KJ/Kg]	m• [Kg/s]	m• [g/s]	m• [Kg/h]	D [Kg/m³]	V• [L/s]	V• [m³/hr]	V• [L/min]
Pt 1	1	263 / -10	238.765	0.00094854	0.94854	3.414744	1.46547	0.647259923	2.330135724	38.83559541
Pt 2	50	272 / + 10	232.588	0.00094854	0.94854	3.414744	74.1186	0.012797597	0.046071351	0.767855842
Pt 3	50	195 / -78	147.32	0.00094854	0.94854	3.414744	119.26	0.007953547	0.028632769	0.477212812
Pt 4	50	155 / -118	62.646	0.00094854	0.94854	3.414744	284.95	0.003328795	0.01198366	0.199727672
Pt 5	**1**	**90.062 / -183**	**62.646**	**0.00094854**	0.94854	**3.414744**	**94.854**	**0.01**	**0.036**	**0.6**
Pt g	1	90.062 / -183	79.597	0.000932805	0.932805	3.358098	4.4135	0.211352668	0.760869605	12.68116008
Pt L	1	90.062 / -183	-133.58	0.000015735	0.015735	0.056646	1141.8	1.37809E-05	4.96111E-05	0.000826852
Pt 6	1	153 / -120	138.074	0.000932805	0.932805	3.358098	2.53344	0.368196997	1.325509189	22.09181982
Pt 6'	1	263 / -10	238.765	0.000932805	0.932805	3.358098	1.22598	0.760864778	2.739113199	45.65188665
Pt A'	1	263 / -10	238.765	0.000015735	0.015735	0.056646	1.22598	0.01283463	0.046204669	0.770077815
Pt A	1	293 / + 20	239.277	0.000015735	0.015735	0.056646	1.31478	0.011967782	0.043084014	0.718066901
Pt 7	1	163 / -110	147.254	0.00094854	0.94854	3.414744	2.3751	0.399368448	1.437726412	23.96210686

This table is based on thermodynamic properties tables of oxygen and formula of ideal gas law

4) Yield factor

Yield: $Y = m_f\bullet \,/\, m\bullet = h_1\text{-}h_2 \,/\, h_1\text{-}h_f$

Where : Point 1: before compressor (inlet)

Point 2: after compressor (outlet)

$$Y = \frac{h1-h2}{h1-hf} = \frac{238.765-232.588}{238.765-(-133.58)} = 0.016589 \approx 1.6589\ \%$$

$$Y = m_f\bullet \,/\, m\bullet \Rightarrow m_f\bullet = Y{*}m\bullet = 0.016589{*}0.003_{Kg/s} = 4.9767\times10^{-5}\ Kg/s$$

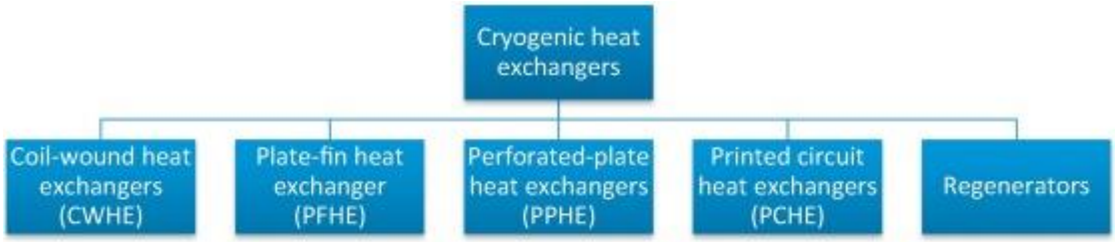
$$m_f\bullet = 4.9767\times10^{-5}\ _{Kg/s} \times 3600 = 0.1792\ Kg/hr$$

$\frac{Mass\ flow}{Density} = \frac{\mathrm{mf}\bullet}{D}$; where density D of liquid = 1141.8 Kg/m^3

$$= \frac{0.1792}{1141.8} = 0.0001569\ m^3/hr = 0.1569\ L/hr = 156.9\ mL/hr = 2.6152\ mL/min$$

15.5 Heat exchanger

1) Type of heat exchanger



Types of heat exchanger used in cryogenic systems

We chose helical coil heat exchanger for many features

a) Shape of heat exchanger

The copper pipe used has 9.62 mm outer diameter (O.D.) and 1.2 mm thickness. The coil pitch and the number of turns will be calculated in paragraph 2.c. The schema of the heat exchanger is shown in figure below. The shell inner diameter, outer diameter and height are 80 mm, 160 mm and 1.73 m, respectively.

b) Boundary condition

As can be seen in Fig. 1, hot fluid (Oxygen gas) at the specific temperature of -80 ◦C with pressure 50 bar and mass flow rate inlet boundary condition enters the helical coil at the top and leaves at the bottom. Cold fluid (Oxygen gas) at a temperature of -183 ◦C with 1 bar pressure and mass flow rate inlet boundary condition enters the shell at the bottom and leaves at the top.

Equal values of mass flow rate were specified for shell-side and coil-side fluids.

c) Performance analysis of the heat exchanger

Heat transfer enhancement was experimentally investigated by by Jamshidi et al.(2013) [2]. It was observed that the increase in coil diameter, coil pitch and mass flow rate in shell and tube can enhance the heat transfer rate.

It is also seen that the increase in tube diameter and coil diameter enhances the effectiveness because the heat transfer area increases.

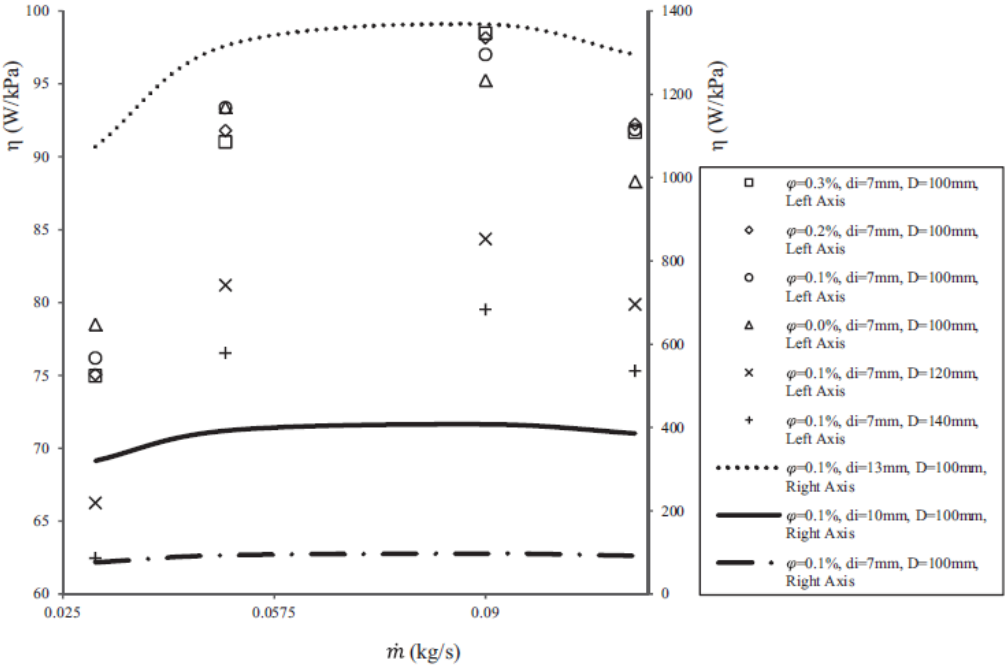


***Fig. 2: Variations of performance index vs. mass flow rate based on various parameters* [3].**

Furthermore, it can be observed from Fig. 2 that with the increase in tube diameter the performance index enhances remarkably. The reason can be attributed to the significant decrease in pressure drop, the increase in heat transfer area and enhanced secondary flow.

The heat transfer rate enhances with coil diameter due to increased heat transfer area and the pressure drop increases with coil diameter because of increased length of the tube.

The effect of coil diameter on pressure drop is more intensive than that of heat transfer rate; consequently, the performance index decreases with an increase in the coil diameter.

For all cases, the optimum value of mass flow rate corresponding to maximum performance index is found to be **0.1 kg/s**.

d) Advantage of Helical Coil Heat Exchanger

Helical coil heat exchanger has many benefits that make it a good choice:

- Highly efficient use of space, especially when it’s limited and not enough straight pipe can be laid.
- Under conditions of low flowrates, such that that the typical shell-and-tube exchangers have low heat-transfer coefficients and becoming uneconomical.
- When there is low pressure in one of the fluids.

- When one of the fluids has components in multiple phases (solids, liquids, and gases), which tends to create mechanical problems during operations, such as plugging of small-diameter tubes. Cleaning of helical coils for these multiple-phase fluids can prove to be more difficult than its shell and tube counterpart; however, the helical coil unit would require cleaning less often.

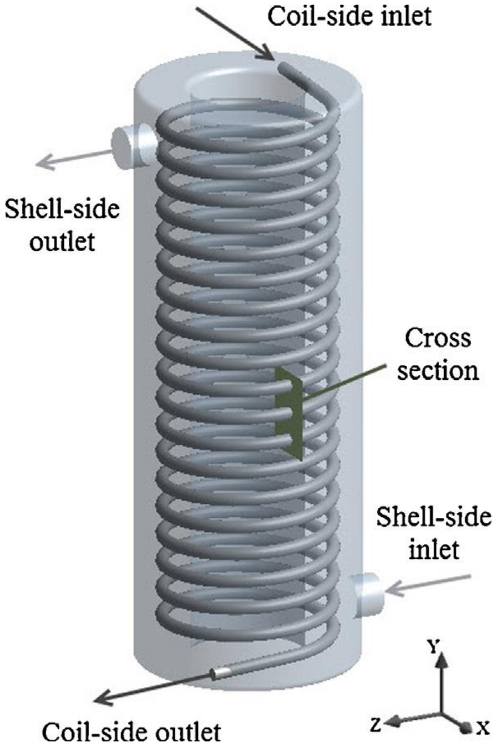


Fig. 1 – Schema of a shell and helical tube heat exchanger

e) Characteristics of helical coil and shell

Helical coil heat exchanger has many benefits that make it a good choice:

- Highly efficient use of space, especially when it's limited and not enough straight pipe can be laid.
- Under conditions of low flowrates, such that that the typical shell-and-tube exchangers have low heat-transfer coefficients and becoming uneconomical.
- When there is low pressure in one of the fluids.
- When one of the fluids has components in multiple phases (solids, liquids, and gases), which tends to create mechanical problems during operations, such as plugging of small-diameter tubes. Cleaning of helical coils for these multiple-phase fluids can prove to be more difficult than its shell and tube counterpart; however, the helical coil unit would require cleaning less often.

15.5.1 2) <u>Material of Helical Coil Heat Exchanger</u>

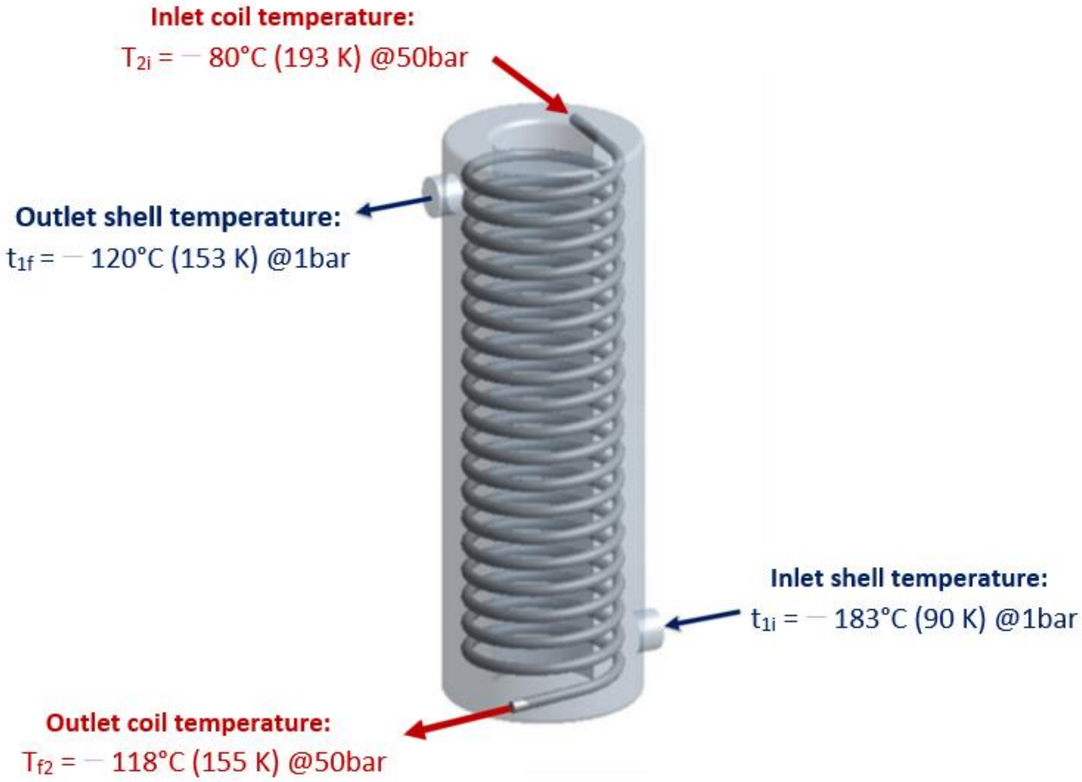
When designing the helical coil heat exchanger, the first thing you need to consider is what material you should use. Copper tube and Stainless-Steel tube are two most common choices. Copper tube have relatively higher heat exchange rate, because copper tube is softer. Stainless steel tube doesn't react with water, which make it last longer, especially when one of the heats transferring fluid is water.

In our case, we will use the copper tube, because stainless steel tubes are not easily available in Lebanon.

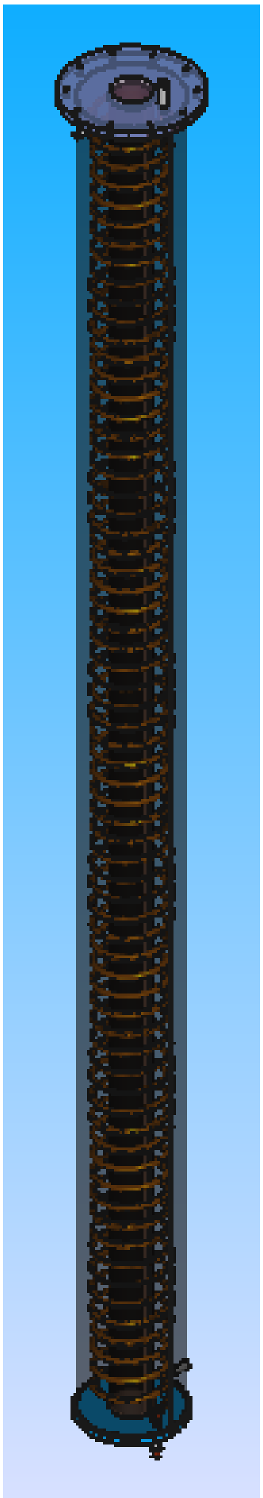
Note:

The flow has been adjusted from 0.1 Kg/s to 0.00094854 Kg/s in respect of the accepted flow rate of the solenoid valve (K_V= 0.6 L/min). Because the flow is reduced, this will not negatively affect the work of the system, but rather it will give it more time for an ideal heat exchange.

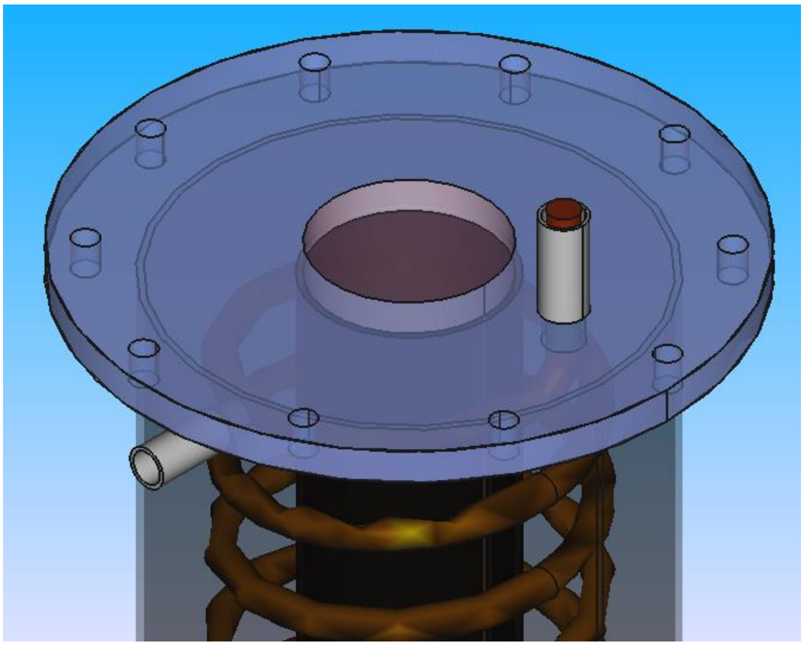
1) Design of heat exchanger

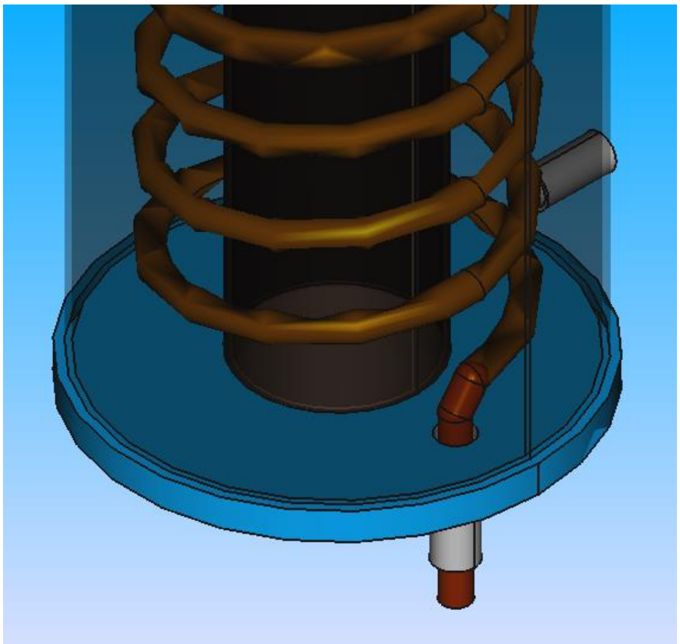


2) HX FreeCAD design and size (v0.17)



Helical Coil Heat exchanger.FCStd

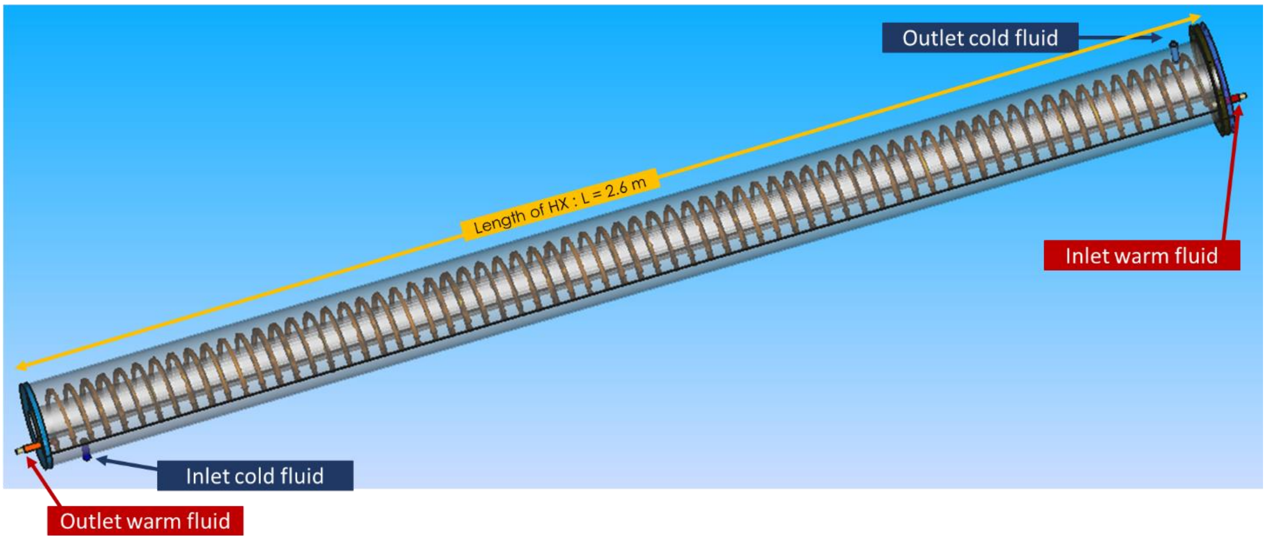


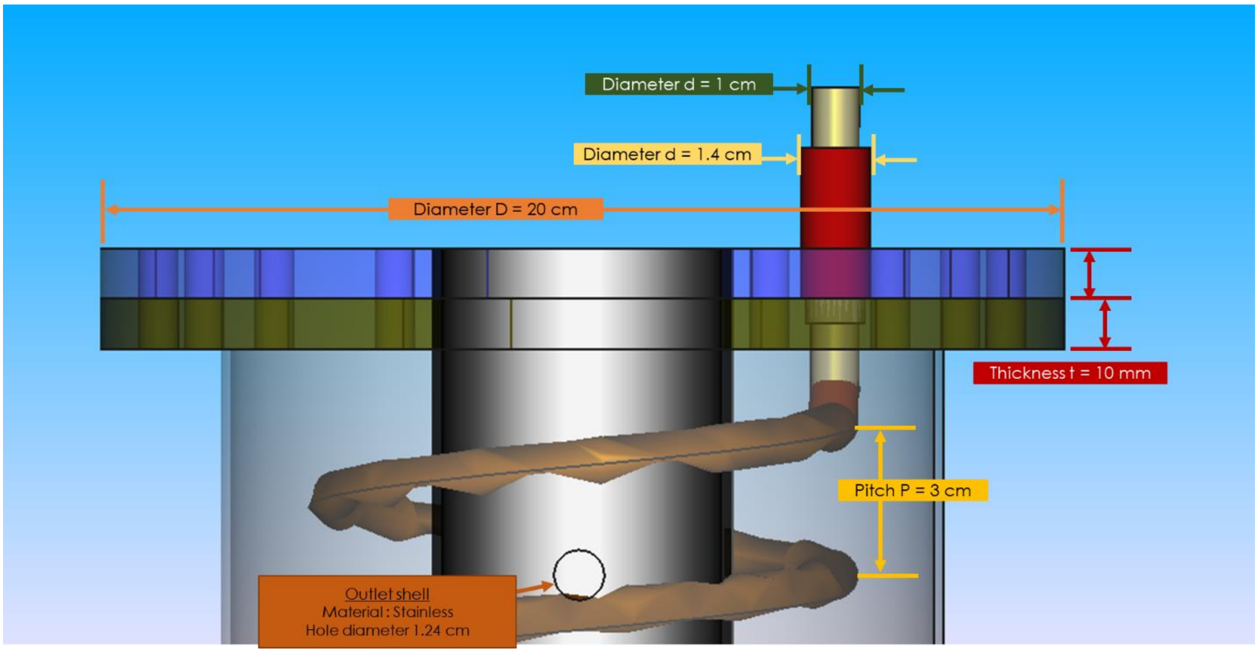


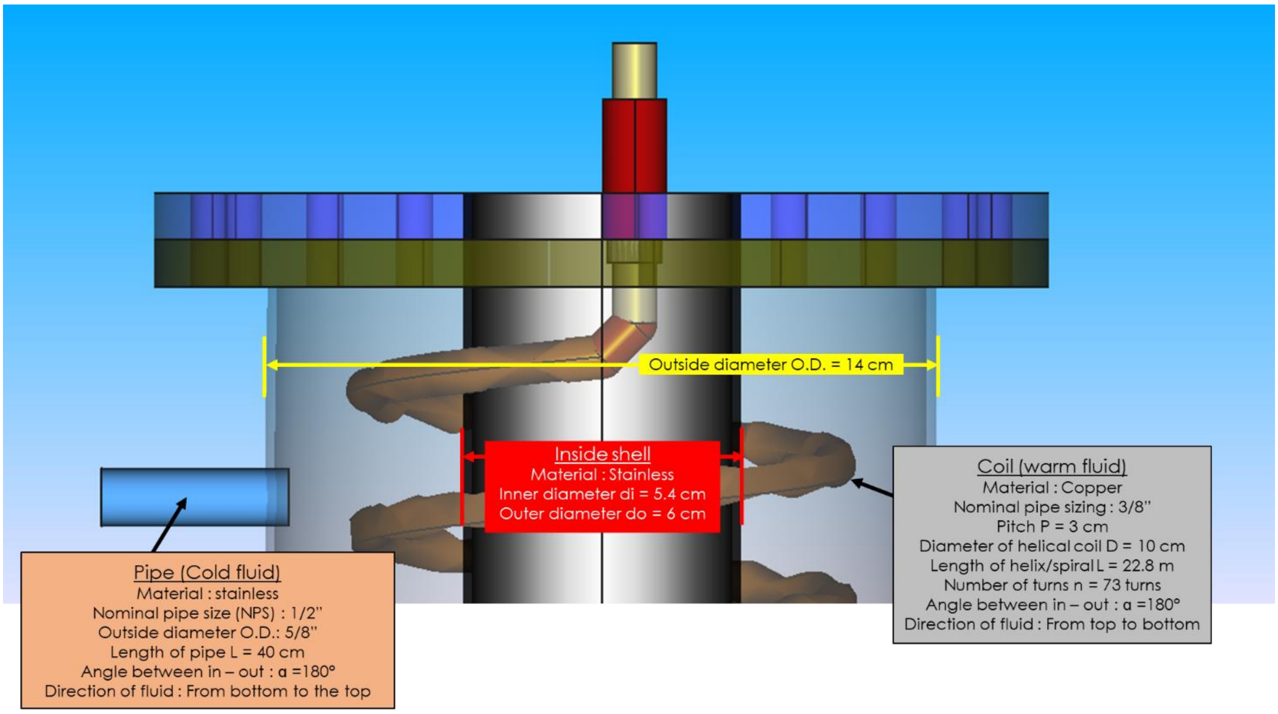
Sizing of helical coil heat exchanger (.pptx)

13092022_ Sizing of helical coil HX.pptx

Project D 22 Liquefaction of Oxygen (ICPT - LOX)



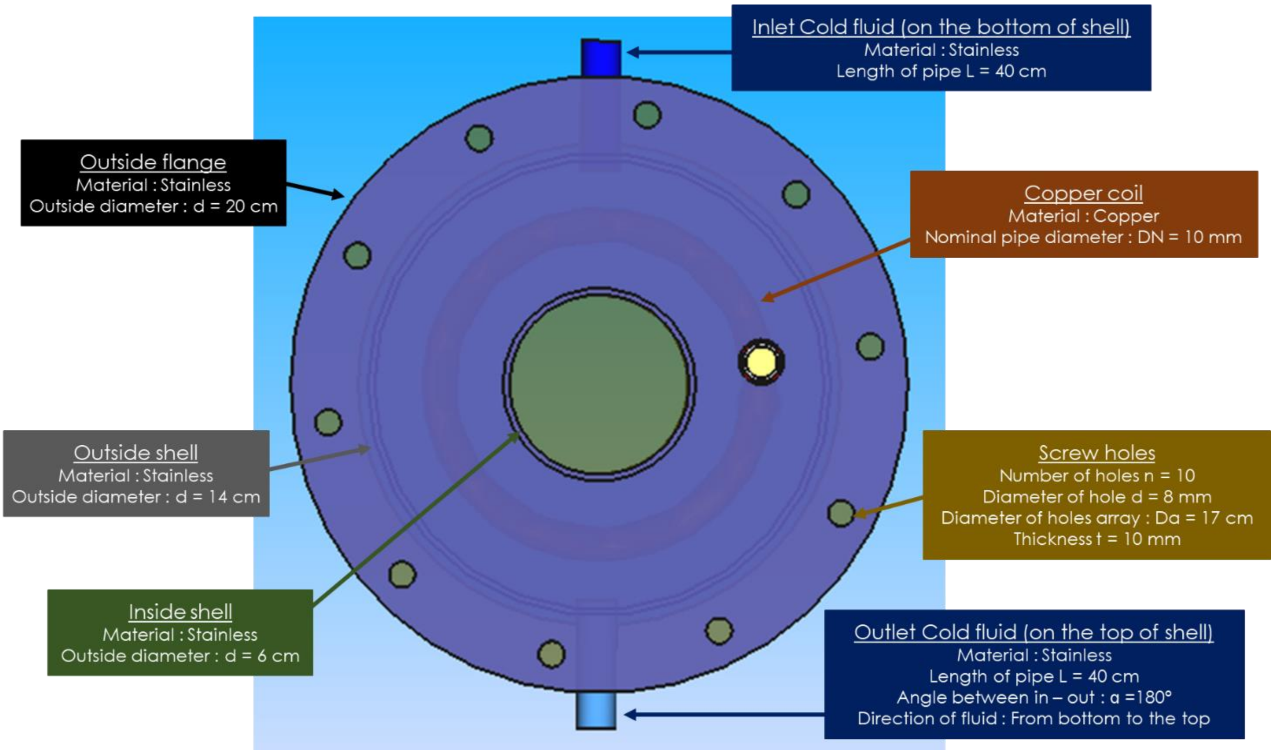




Inside shell
Material : Stainless
Inner diameter di = 5.4 cm
Outer diameter do = 6 cm

Coil (warm fluid)
Material : Copper
Nominal pipe sizing : 3/8''
Pitch P = 3 cm
Diameter of helical coil D = 10 cm
Length of helix/spiral L = 22.8 m
Number of turns n = 73 turns
Angle between in – out : α =180°
Direction of fluid : From top to bottom

Pipe (Cold fluid)
Material : stainless
Nominal pipe size (NPS) : 1/2''
Outside diameter O.D.: 5/8''
Length of pipe L = 40 cm
Angle between in – out : α =180°
Direction of fluid : From bottom to the top


Inlet Cold fluid (on the bottom of shell)
Material : Stainless
Length of pipe L = 40 cm

Outside flange
Material : Stainless
Outside diameter : d = 20 cm

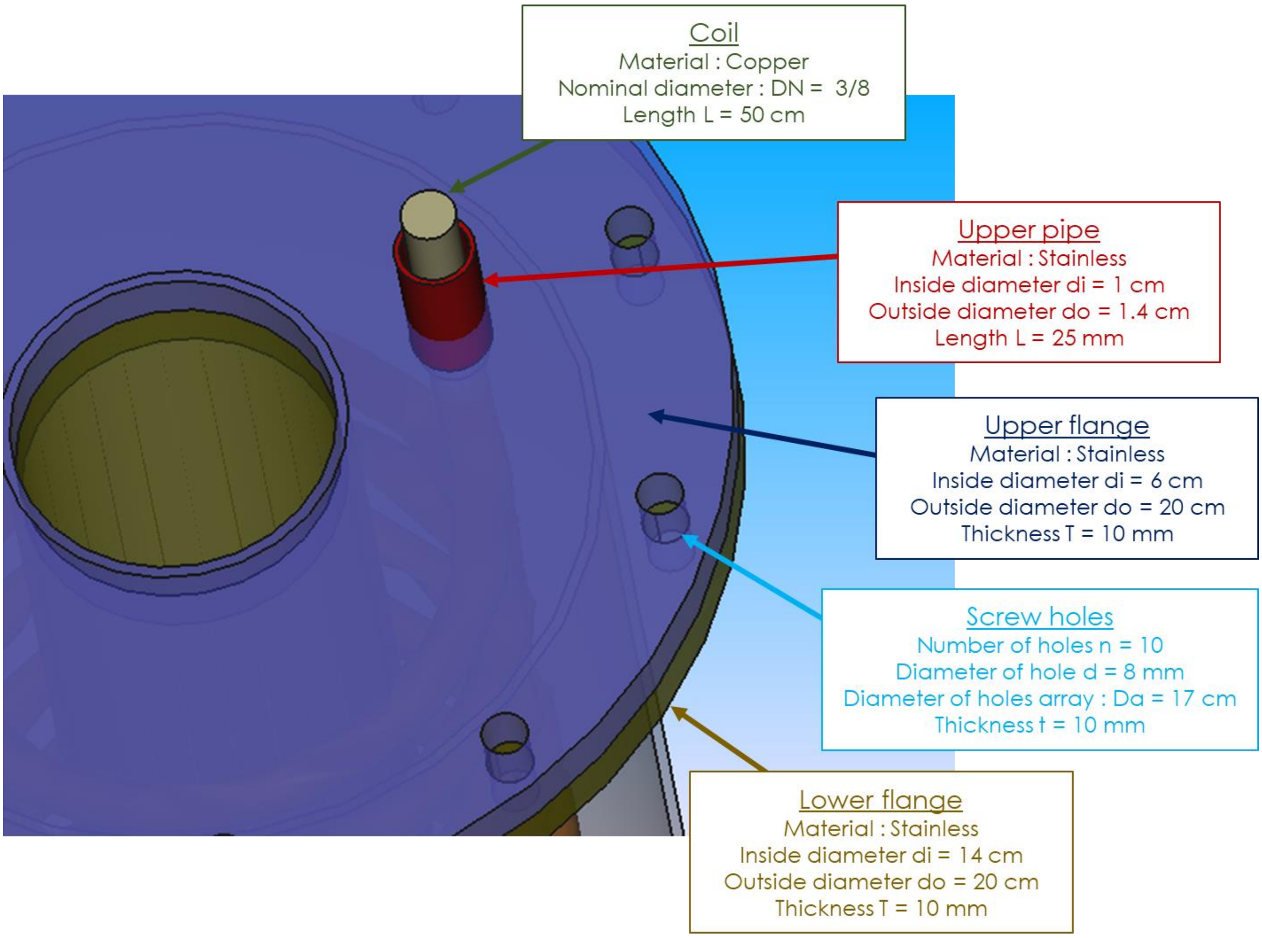
Copper coil
Material : Copper
Nominal pipe diameter : DN = 10 mm

Outside shell
Material : Stainless
Outside diameter : d = 14 cm

Screw holes
Number of holes n = 10
Diameter of hole d = 8 mm
Diameter of holes array : Da = 17 cm
Thickness t = 10 mm

Inside shell
Material : Stainless
Outside diameter : d = 6 cm

Outlet Cold fluid (on the top of shell)
Material : Stainless
Length of pipe L = 40 cm
Angle between in – out : α =180°
Direction of fluid : From bottom to the top



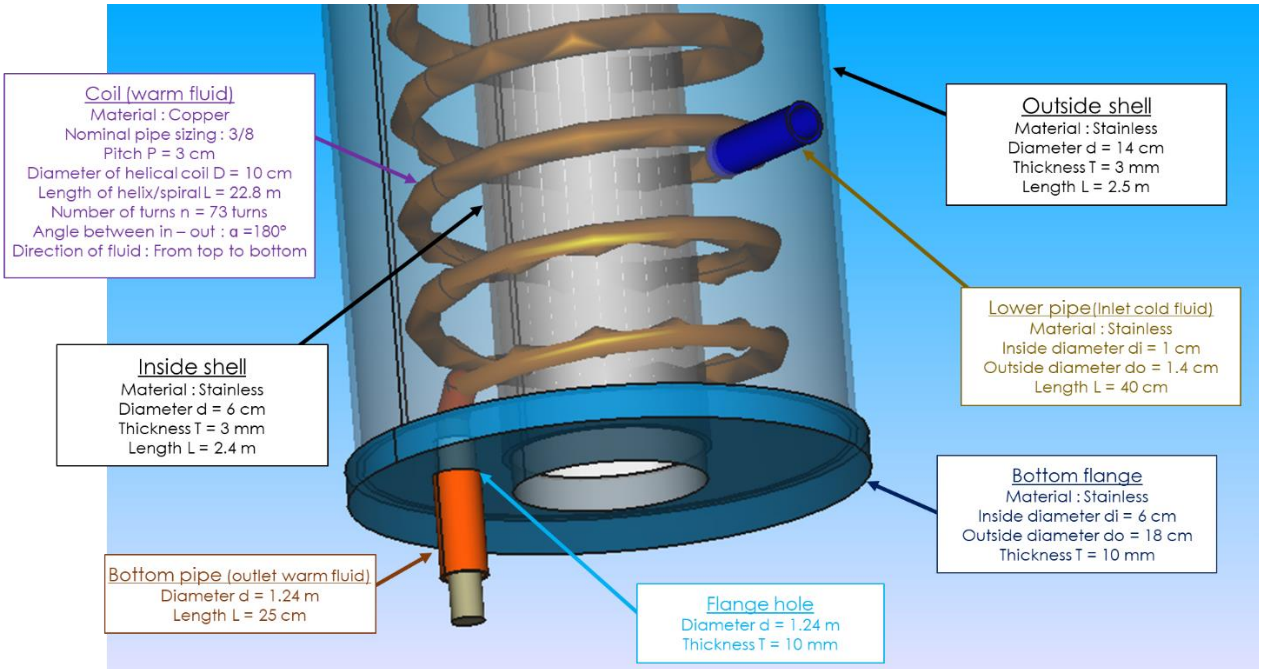
Coil
Material : Copper
Nominal diameter : DN = 3/8
Length L = 50 cm

Upper pipe
Material : Stainless
Inside diameter di = 1 cm
Outside diameter do = 1.4 cm
Length L = 25 mm

Upper flange
Material : Stainless
Inside diameter di = 6 cm
Outside diameter do = 20 cm
Thickness T = 10 mm

Screw holes
Number of holes n = 10
Diameter of hole d = 8 mm
Diameter of holes array : Da = 17 cm
Thickness t = 10 mm

Lower flange
Material : Stainless
Inside diameter di = 14 cm
Outside diameter do = 20 cm
Thickness T = 10 mm



Coil (warm fluid)
Material : Copper
Nominal pipe sizing : 3/8
Pitch P = 3 cm
Diameter of helical coil D = 10 cm
Length of helix/spiral L = 22.8 m
Number of turns n = 73 turns
Angle between in – out : α =180°
Direction of fluid : From top to bottom

Outside shell
Material : Stainless
Diameter d = 14 cm
Thickness T = 3 mm
Length L = 2.5 m

Lower pipe (Inlet cold fluid)
Material : Stainless
Inside diameter di = 1 cm
Outside diameter do = 1.4 cm
Length L = 40 cm

Inside shell
Material : Stainless
Diameter d = 6 cm
Thickness T = 3 mm
Length L = 2.4 m

Bottom flange
Material : Stainless
Inside diameter di = 6 cm
Outside diameter do = 18 cm
Thickness T = 10 mm

Bottom pipe (outlet warm fluid)
Diameter d = 1.24 m
Length L = 25 cm

Flange hole
Diameter d = 1.24 m
Thickness T = 10 mm

5) Heat exchanger - Thermal calculation

a) Average temperature LMTD △tm =?

We have:

Warm side: Temperature In = 195 K
Temperature Out = 155 K
Cold side: Temperature In = 90 K
Temperature Out = 153 K

$\text{LMTD} = (\triangle T_1 - \triangle T_2) / \ln(\triangle T_1/\triangle T_2)$

For counter current:

△ T1 = T warm in – T cold out = 195 – 153 = 42

△ T2 = T warm out – T cold in = 155 – 90 = 65

LMTD = 52.67

- Heat flux Q=?

We estimate G = 0.1 Kg/sec with $\mathbf{Q_{hot} = G.C.(t_{2i} - t_{2f})}$

Where:

Q – quantity of heat transferred or received by the heat transfer medium [W],

G – hot and cold heat transfer medium flow rates [kg/sec],

C – heat capacity of hot and cold heat transfer media at (50 bar, 195 K) and (50 bar, 150 K) [kJ/Kg.deg], C= 1.4 kJ/Kg.K

t_{2f} – final temperature of cold heat transfer media [°C or K],

t_{2i} – initial temperature of cold heat transfer media [°C or K].

$$\Rightarrow \quad \mathbf{Q =} 0.1*1.4*(193-155) = \mathbf{5.32\ kW}$$

6) Design calculation

a) Heat exchange surface A=?

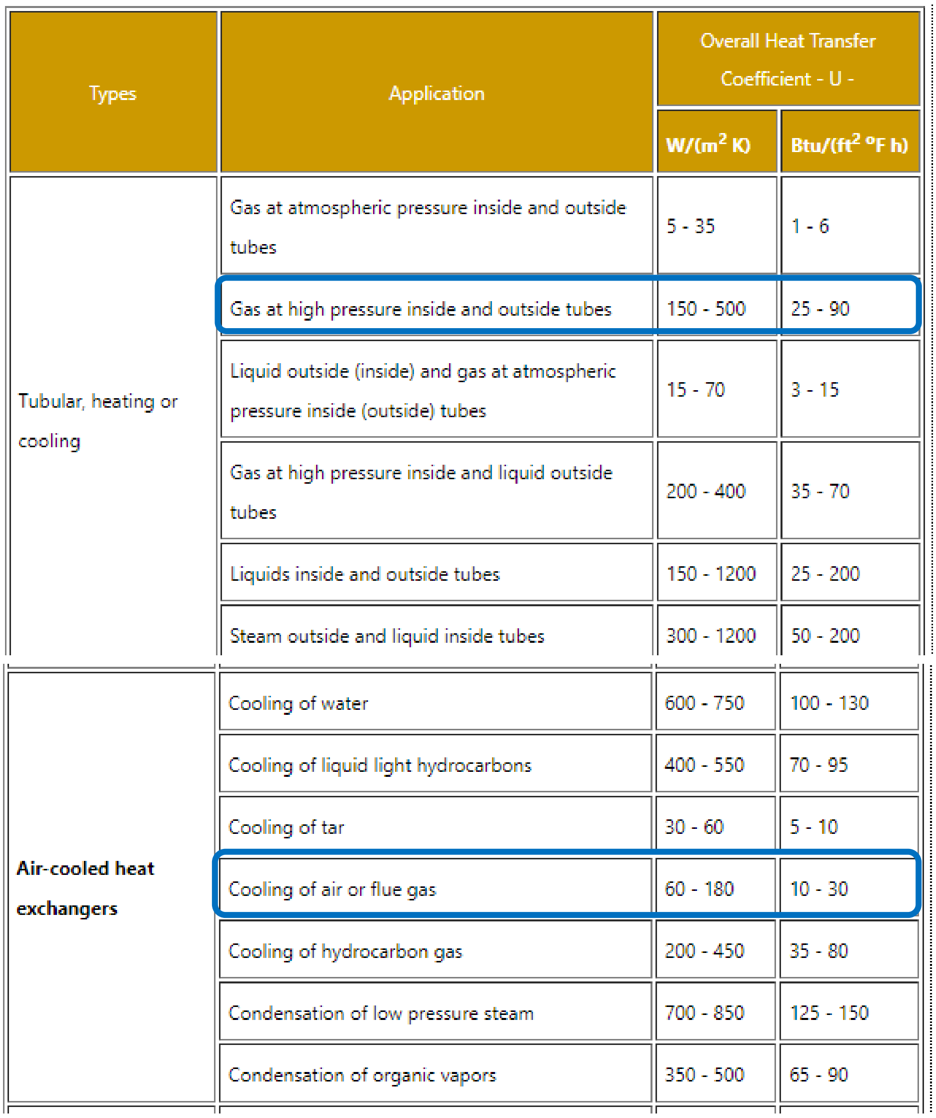
The approximate heat exchange surface is calculated as follows:

$$\mathbf{Q = U \times A \times LMTD}$$

Where:

A: Surface area [m^2];

U: the overall heat transfer coefficient [$W/m^2.K$], by estimation based on tables below U = 150 $W/m^2.K$;



Types	Application	Overall Heat Transfer Coefficient - U -	
		$W/(m^2 K)$	$Btu/(ft^2 \, {}^oF \, h)$
Tubular, heating or cooling	Gas at atmospheric pressure inside and outside tubes	5 - 35	1 - 6
	Gas at high pressure inside and outside tubes	150 - 500	25 - 90
	Liquid outside (inside) and gas at atmospheric pressure inside (outside) tubes	15 - 70	3 - 15
	Gas at high pressure inside and liquid outside tubes	200 - 400	35 - 70
	Liquids inside and outside tubes	150 - 1200	25 - 200
	Steam outside and liquid inside tubes	300 - 1200	50 - 200
Air-cooled heat exchangers	Cooling of water	600 - 750	100 - 130
	Cooling of liquid light hydrocarbons	400 - 550	70 - 95
	Cooling of tar	30 - 60	5 - 10
	Cooling of air or flue gas	60 - 180	10 - 30
	Cooling of hydrocarbon gas	200 - 450	35 - 80
	Condensation of low pressure steam	700 - 850	125 - 150
	Condensation of organic vapors	350 - 500	65 - 90

$$\Rightarrow A = \frac{Q}{U \times LMTD} = \frac{5320\ W}{150\left(\frac{W}{m2.K}\right) \times 52.67} = 0.6733\ m^2 \approx 0.68\ m^2$$

b) Length of tube L=?

During the design calculation of coil heat exchangers, the total length of the coil as well as the number of turns and sections are determined.

$$L = A/\pi d_p$$

With :

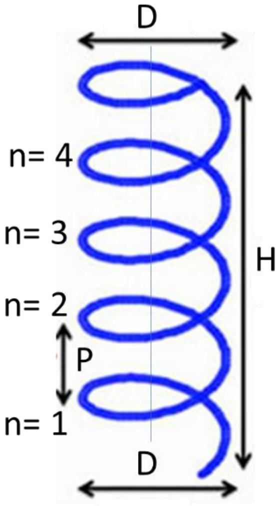
L – total length of the coil [m],

A = 0.68 m^2,

d_p – design diameter of the coil tube [m]; d_p = 9.5 mm = 0.0095 m

⇒ $\mathbf{L} = \frac{0.68}{\pi \times 0.0095}$ **=** 22.78 m **≈ 22.8 m**

c) Number of turns n=?



n – Number of turns

P – Pitch

H – Height

D – Diameter

C – Circumference of spiral

We have L = 22.8 m
We estimate D = 10 cm & P = 3 cm

Circumference **C = π × D**

D = 10 cm = 0.10 m ↠ C = 0.3142 ↠ $C^2 = 0.0987\ m^2$

P = 3 cm = 0.03 m ↠ $P^2 = 0.0009\ m^2$

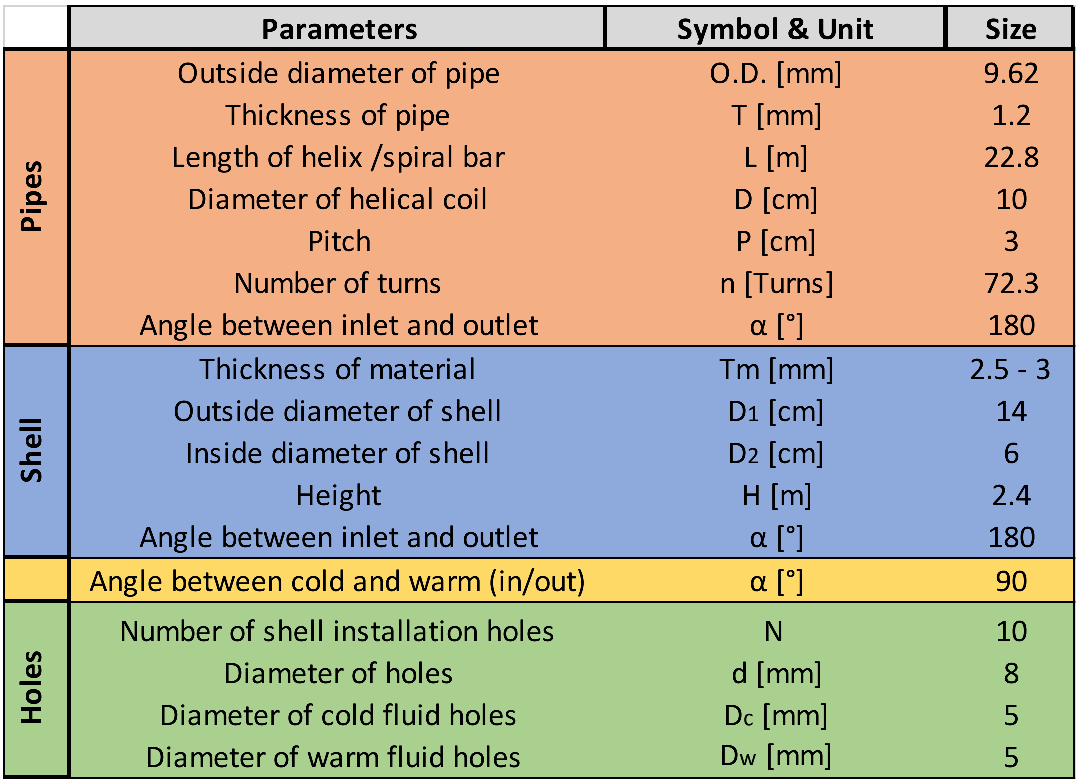
Length of helix: **L = n**$\sqrt{\boldsymbol{C}^2 + \boldsymbol{P}^2}$

⇒ $\mathbf{n} = \frac{\boldsymbol{L}}{\sqrt{\boldsymbol{C}^2+\boldsymbol{P}^2}} = \frac{\mathbf{22.8}}{\sqrt{(\mathbf{0.3142})^2+(\mathbf{0.03})^2}}$ **= 72.243 turns**

⇒ n ≈ 72.3 turns

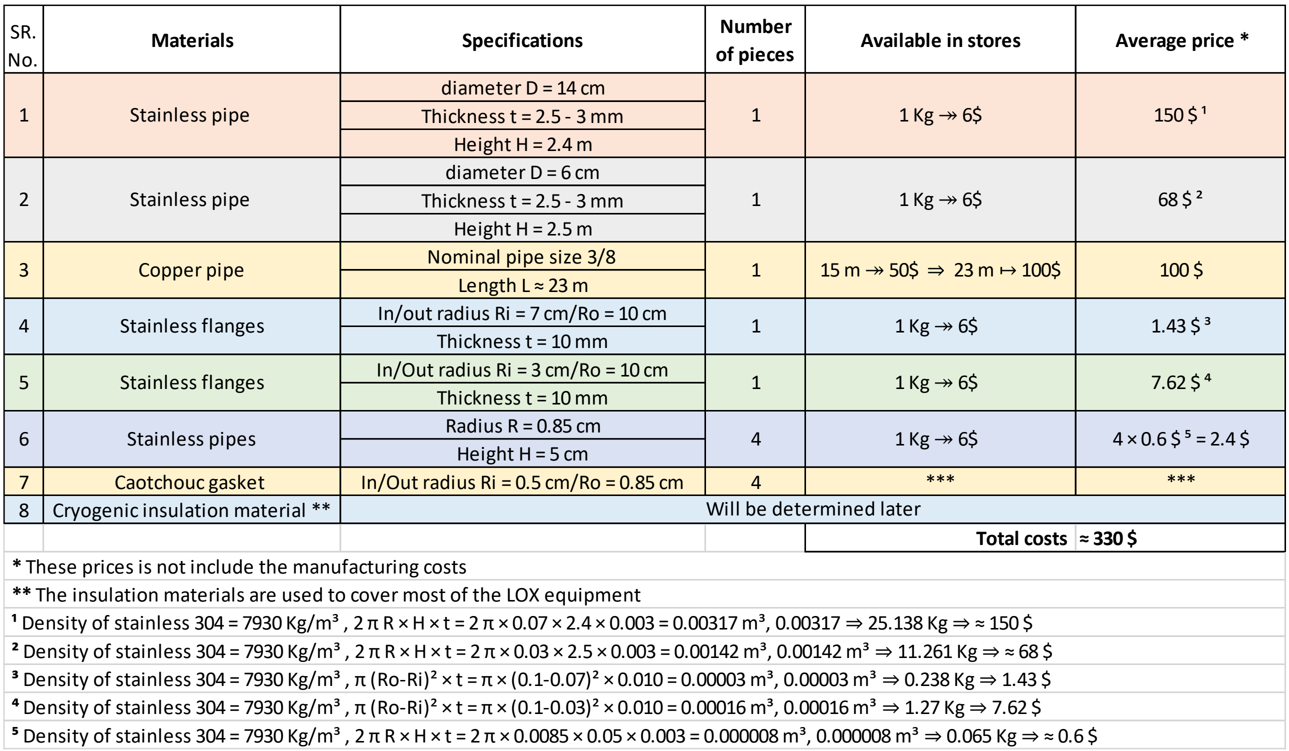
With $\mathbf{n} = \frac{\boldsymbol{H}}{\boldsymbol{P}}$ ⇒ **H =** n × P = 72.3 × 0.03 = 2.169 m **≈ 2.2 m**

7) <u>Measurement summary of the Helical coil heat exchanger</u>



	Parameters	Symbol & Unit	Size
Pipes	Outside diameter of pipe	O.D. [mm]	9.62
	Thickness of pipe	T [mm]	1.2
	Length of helix /spiral bar	L [m]	22.8
	Diameter of helical coil	D [cm]	10
	Pitch	P [cm]	3
	Number of turns	n [Turns]	72.3
	Angle between inlet and outlet	α [°]	180
Shell	Thickness of material	Tm [mm]	2.5 - 3
	Outside diameter of shell	D_1 [cm]	14
	Inside diameter of shell	D_2 [cm]	6
	Height	H [m]	2.4
	Angle between inlet and outlet	α [°]	180
	Angle between cold and warm (in/out)	α [°]	90
Holes	Number of shell installation holes	N	10
	Diameter of holes	d [mm]	8
	Diameter of cold fluid holes	D_c [mm]	5
	Diameter of warm fluid holes	D_w [mm]	5

8) List of HX prices



SR. No.	Materials	Specifications	Number of pieces	Available in stores	Average price *
1	Stainless pipe	diameter D = 14 cm Thickness t = 2.5 - 3 mm Height H = 2.4 m	1	1 Kg ↠ 6$	150 $[1]
2	Stainless pipe	diameter D = 6 cm Thickness t = 2.5 - 3 mm Height H = 2.5 m	1	1 Kg ↠ 6$	68 $[2]
3	Copper pipe	Nominal pipe size 3/8 Length L ≈ 23 m	1	15 m ↠ 50$ ⇒ 23 m ↦ 100$	100 $
4	Stainless flanges	In/out radius Ri = 7 cm/Ro = 10 cm Thickness t = 10 mm	1	1 Kg ↠ 6$	1.43 $[3]
5	Stainless flanges	In/Out radius Ri = 3 cm/Ro = 10 cm Thickness t = 10 mm	1	1 Kg ↠ 6$	7.62 $[4]
6	Stainless pipes	Radius R = 0.85 cm Height H = 5 cm	4	1 Kg ↠ 6$	4 × 0.6 $[5] = 2.4 $
7	Caotchouc gasket	In/Out radius Ri = 0.5 cm/Ro = 0.85 cm	4	***	***
8	Cryogenic insulation material **	Will be determined later			
				Total costs	**≈ 330 $**

* These prices is not include the manufacturing costs

** The insulation materials are used to cover most of the LOX equipment

[1] Density of stainless 304 = 7930 Kg/m^3 , $2\pi R \times H \times t = 2\pi \times 0.07 \times 2.4 \times 0.003 = 0.00317\ m^3$, $0.00317 \Rightarrow 25.138\ Kg \Rightarrow \approx 150\ \$$

[2] Density of stainless 304 = 7930 Kg/m^3 , $2\pi R \times H \times t = 2\pi \times 0.03 \times 2.5 \times 0.003 = 0.00142\ m^3$, $0.00142\ m^3 \Rightarrow 11.261\ Kg \Rightarrow \approx 68\ \$$

[3] Density of stainless 304 = 7930 Kg/m^3 , $\pi (Ro-Ri)^2 \times t = \pi \times (0.1-0.07)^2 \times 0.010 = 0.00003\ m^3$, $0.00003\ m^3 \Rightarrow 0.238\ Kg \Rightarrow 1.43\ \$$

[4] Density of stainless 304 = 7930 Kg/m^3 , $\pi (Ro-Ri)^2 \times t = \pi \times (0.1-0.03)^2 \times 0.010 = 0.00016\ m^3$, $0.00016\ m^3 \Rightarrow 1.27\ Kg \Rightarrow 7.62\ \$$

[5] Density of stainless 304 = 7930 Kg/m^3 , $2\pi R \times H \times t = 2\pi \times 0.0085 \times 0.05 \times 0.003 = 0.000008\ m^3$, $0.000008\ m^3 \Rightarrow 0.065\ Kg \Rightarrow \approx 0.6\ \$$

15.6 Cooling pipes (Inside kelvinator refrigerator)

After the modifications that occurred in the prototype, the most prominent of which was passing oxygen directly into the tubes. This had to change the pipes in the refrigerator. The tubes in the refrigerator are aluminum tubes previously used in automobile radiators, which are contaminated with oil, which makes them liable to explode with oxygen. They will be replaced with 3/8" copper pipping.

1) Sizing calculation

a) Average temperature LMTD △Tm =?

- Warm side:

Temperature In = 263 K

Temperature Out = 195 K

- Cold side :

Temperature In = 193 K

Temperature In = 193 K

b) Heat flux Q=?

$Q_{hot} = G.C.(t_{2i} - t_{2f})$ where G = 0.00094854 Kg/s

$= 0.00094854\ _{kg/s} \times 1.0341\ _{KJ/Kg.K} \times (263\text{-}195)\ _{K}$

$= 0.667$ KW ≈ 667 W

c) Length of tube L=?

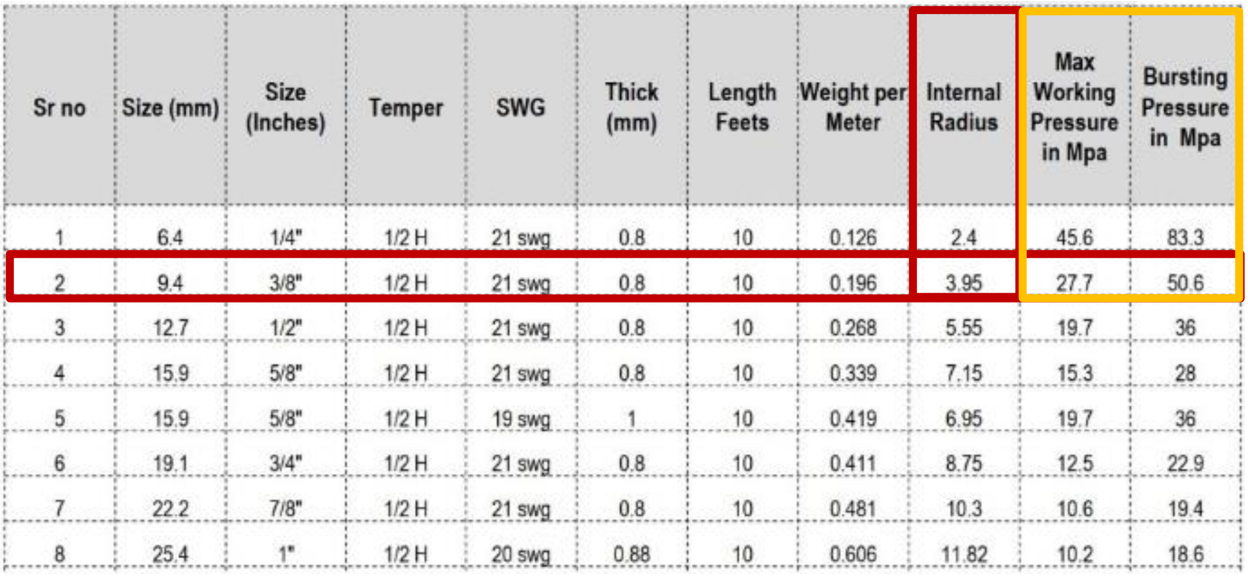
Q = U × A × LMTD

$$\Rightarrow A = \frac{Q}{U \times LMTD} = \frac{667\ W}{50\left(\frac{W}{m2.K}\right) \times 19.13} = 0.6974\ m^2 \approx 0.7\ m^2$$

$L = A/\,\pi\, d_p$ where d_p = 7.9 mm = 0.0079 m

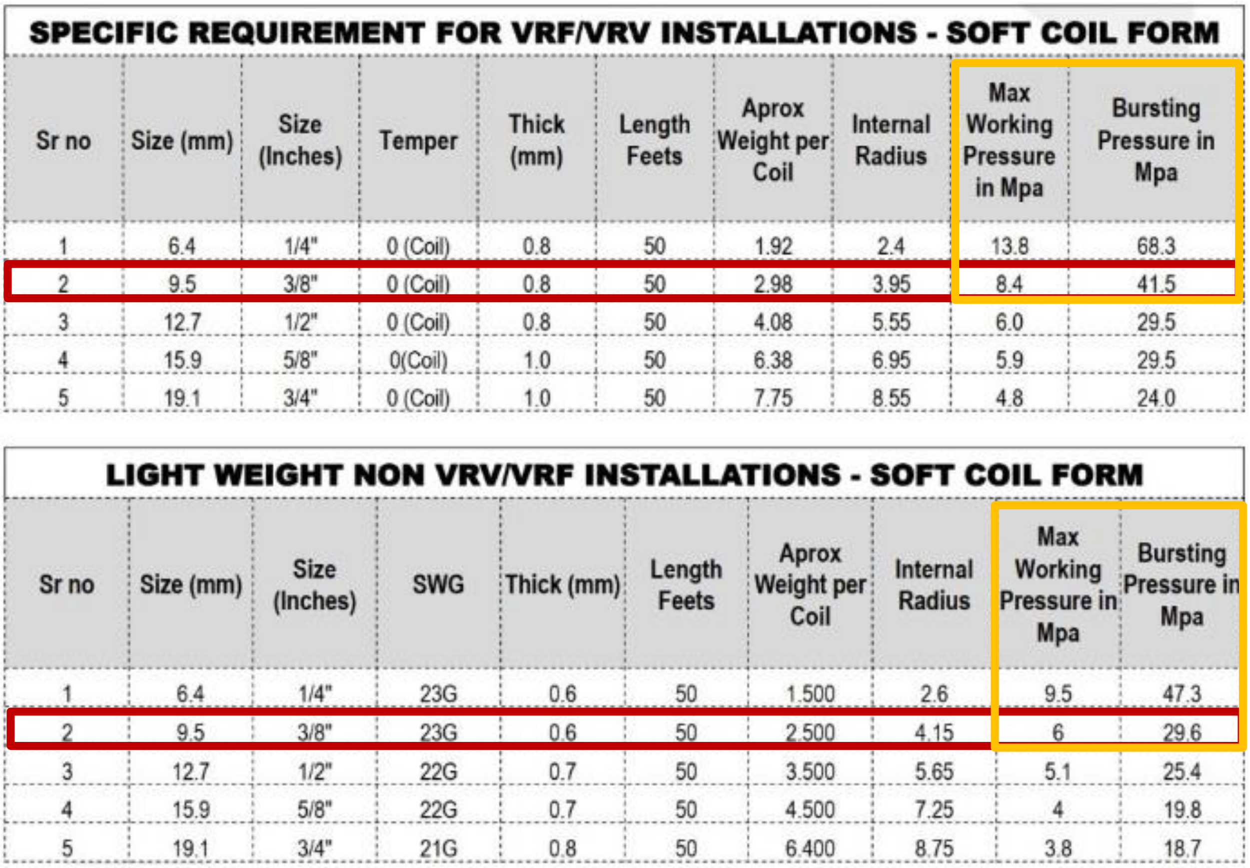
$$\Rightarrow L = \frac{0.7}{\pi \times 0.0079} = 28.205\ m$$

Corrective length: L_c = L × safety factor = 28.205 × 1.05 = 29.615 m ≈ 30 m



Sr no	Size (mm)	Size (Inches)	Temper	SWG	Thick (mm)	Length Feets	Weight per Meter	Internal Radius	Max Working Pressure in Mpa	Bursting Pressure in Mpa
1	6.4	1/4"	1/2 H	21 swg	0.8	10	0.126	2.4	45.6	83.3
2	9.4	3/8"	1/2 H	21 swg	0.8	10	0.196	3.95	27.7	50.6
3	12.7	1/2"	1/2 H	21 swg	0.8	10	0.268	5.55	19.7	36
4	15.9	5/8"	1/2 H	21 swg	0.8	10	0.339	7.15	15.3	28
5	15.9	5/8"	1/2 H	19 swg	1	10	0.419	6.95	19.7	36
6	19.1	3/4"	1/2 H	21 swg	0.8	10	0.411	8.75	12.5	22.9
7	22.2	7/8"	1/2 H	21 swg	0.8	10	0.481	10.3	10.6	19.4
8	25.4	1"	1/2 H	20 swg	0.88	10	0.606	11.82	10.2	18.6

Copper Hard Pipes/Tube Weight and Pressure Details as per ASTM B88 in India [4]



SPECIFIC REQUIREMENT FOR VRF/VRV INSTALLATIONS - SOFT COIL FORM

Sr no	Size (mm)	Size (Inches)	Temper	Thick (mm)	Length Feets	Aprox Weight per Coil	Internal Radius	Max Working Pressure in Mpa	Bursting Pressure in Mpa
1	6.4	1/4"	0 (Coil)	0.8	50	1.92	2.4	13.8	68.3
2	9.5	3/8"	0 (Coil)	0.8	50	2.98	3.95	8.4	41.5
3	12.7	1/2"	0 (Coil)	0.8	50	4.08	5.55	6.0	29.5
4	15.9	5/8"	0(Coil)	1.0	50	6.38	6.95	5.9	29.5
5	19.1	3/4"	0 (Coil)	1.0	50	7.75	8.55	4.8	24.0

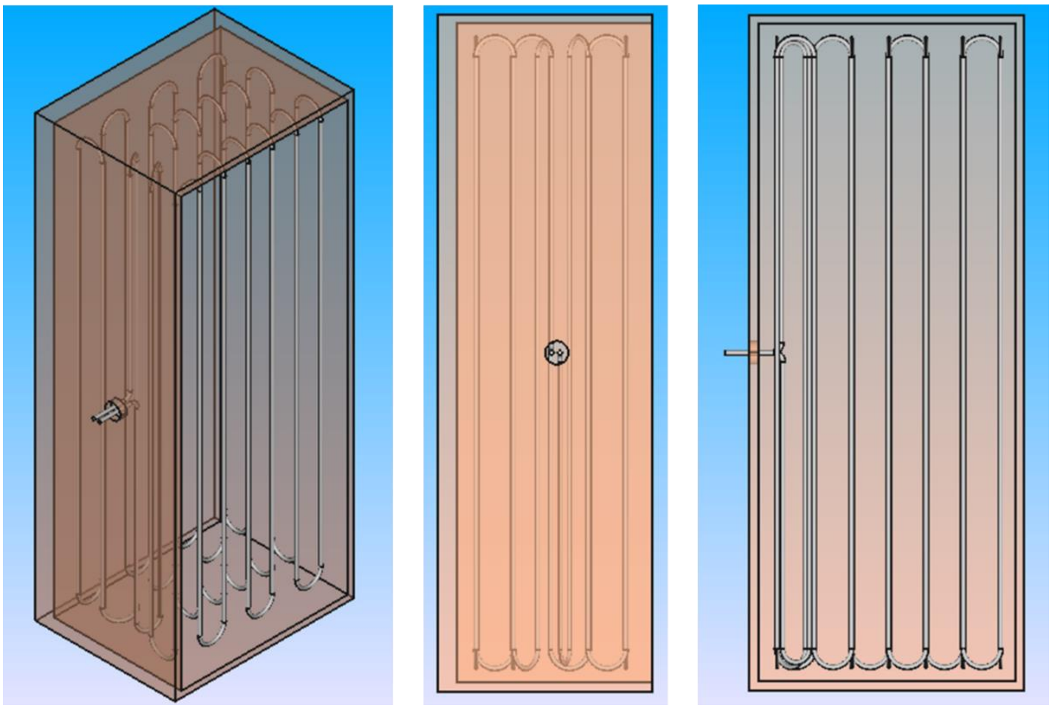
LIGHT WEIGHT NON VRV/VRF INSTALLATIONS - SOFT COIL FORM

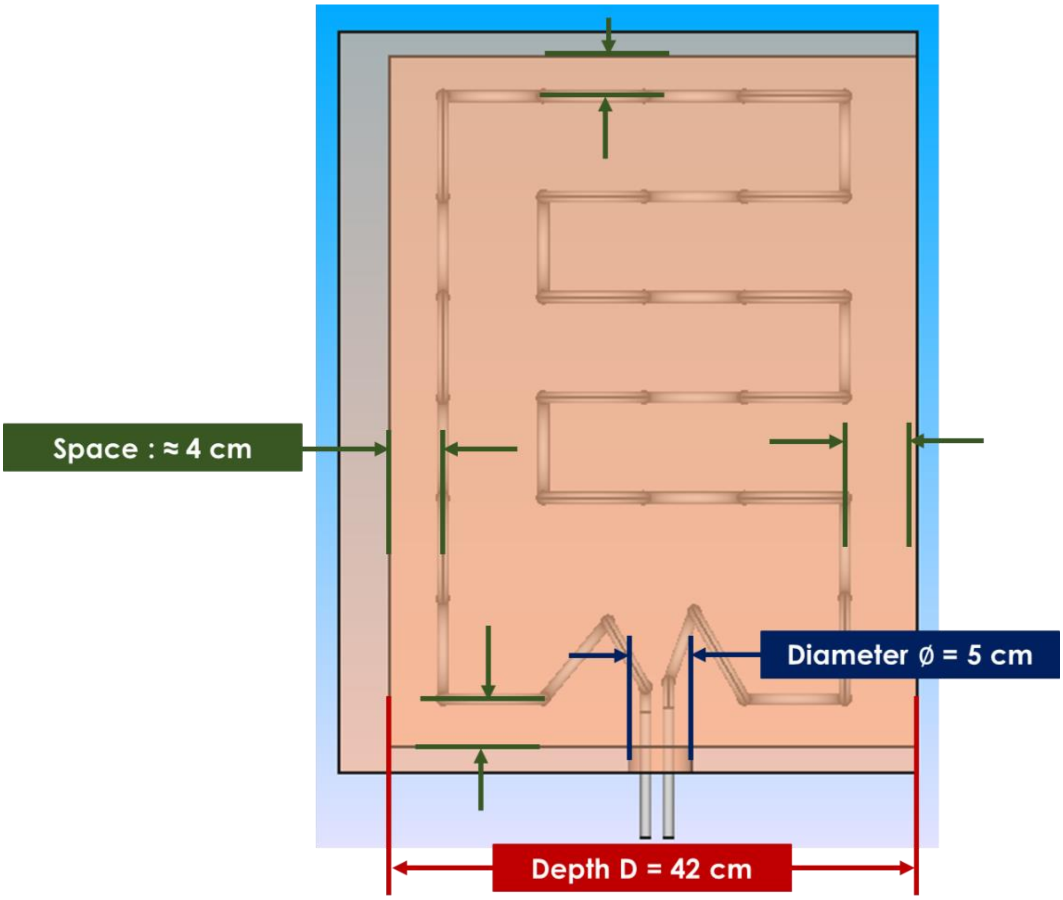
Sr no	Size (mm)	Size (Inches)	SWG	Thick (mm)	Length Feets	Aprox Weight per Coil	Internal Radius	Max Working Pressure in Mpa	Bursting Pressure in Mpa
1	6.4	1/4"	23G	0.6	50	1.500	2.6	9.5	47.3
2	9.5	3/8"	23G	0.6	50	2.500	4.15	6	29.6
3	12.7	1/2"	22G	0.7	50	3.500	5.65	5.1	25.4
4	15.9	5/8"	22G	0.7	50	4.500	7.25	4	19.8
5	19.1	3/4"	21G	0.8	50	6.400	8.75	3.8	18.7

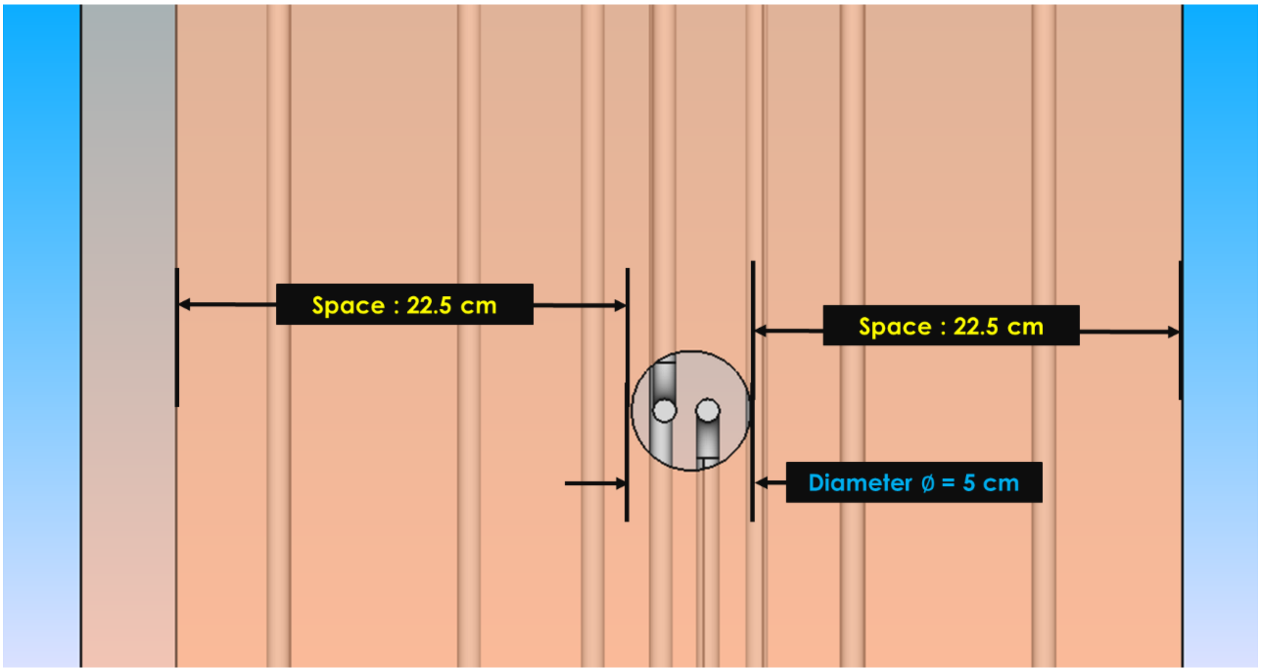
Weight Chart for Copper Non-VRV and VRV/VRF Copper Soft Pipes/ Coils as per Indian Standard [4]

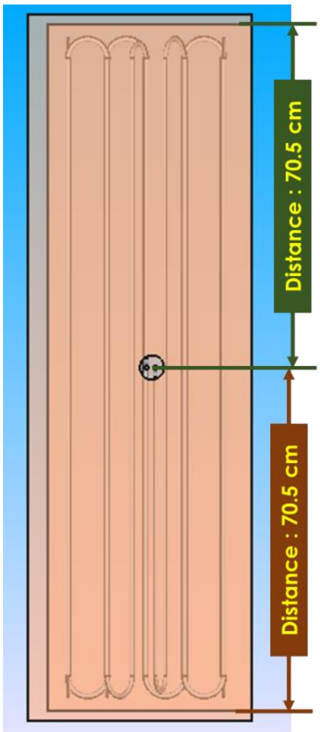
2) Freecad Design

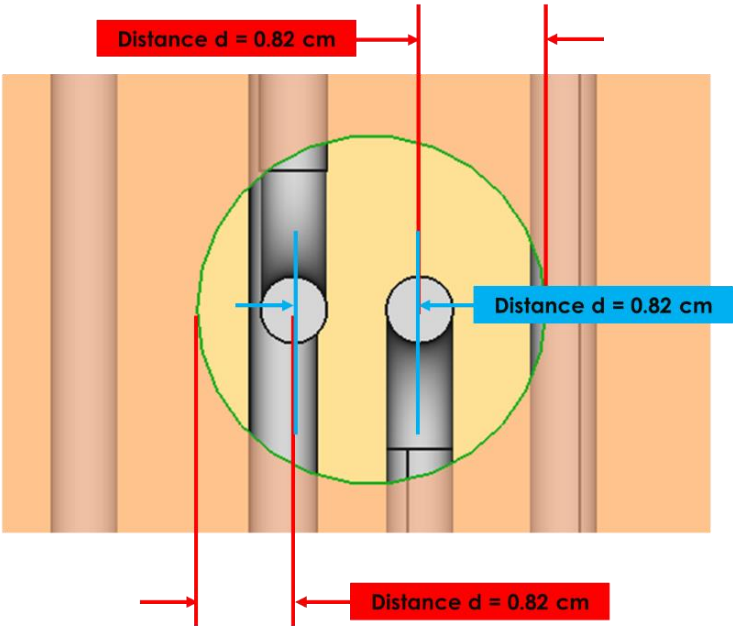
14112022_Cooling
pipe design.FCStd

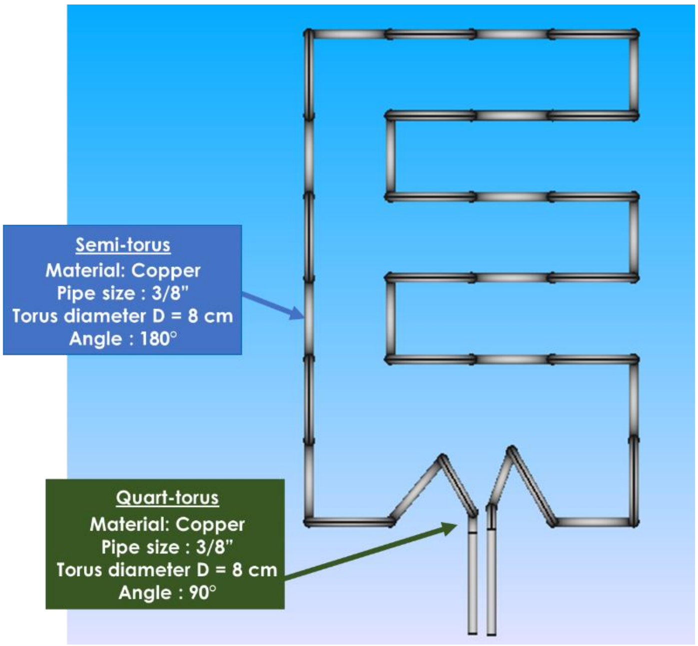


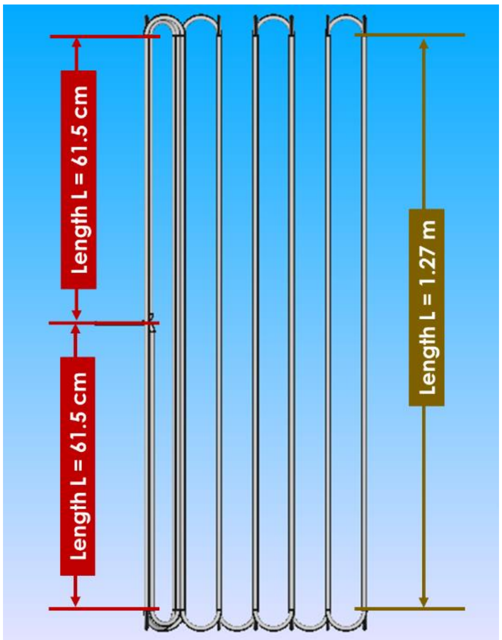

Space : ≈ 4 cm
Diameter ∅ = 5 cm
Depth D = 42 cm


Space : 22.5 cm
Space : 22.5 cm
Diameter ∅ = 5 cm









15.7 Compressor

1) Specifications of compressor

Oil free Oxygen compressor	
Working medium	Dry Oxygen Gas
Rated capacity [Nm³/h]	3 (@inlet pressure 1 bar)
Rated inlet pressure [MPa(G)]	**0.1**
Rated outlet pressure[MPa(G)]	**5**
Inlet temperature [°C]	-10
Outlet temperature [°C]	≈ +5 to +10
Lubricate way shaft and connect rod	Lubricate oil
Lubricate way cylinder	**Oil free lubricate**
Inlet and Outlet [mm]	DN15/DN15

2) <u>Calculation of rated capacity</u>

$$\text{Volumetric flow} = \frac{\text{Mass flow m}\bullet}{Density}$$

Capacity = 3.6*volumetric flow

$$\frac{Kg}{s} \div \frac{Kg}{m^3} = \frac{Kg}{s} \times \frac{m^3}{Kg} = \frac{m^3}{s} = \frac{1000\ L}{s} \Rightarrow \frac{m^3}{s} = 3.6\frac{m^3}{h}$$

15.8 Expansion valve

In this LOx prototype, we need a cryogenic expansion valve, that has the following features:

Specifications of expansion valve	
Media	O2 (Mixture liquid /gas)
Temperature	50°C to -185°C
Pressure	50 bar
Specification	DN10/DN10

A cryogenic expansion valve was not found operating on oxygen gas. therefore, this valve will be replaced by an open-close solenoid valve coupled to a pressure sensor. The solenoid valve, at the request of control, opens when the pressure sensor senses a pressure of 50 bar and closes at 45 bar.

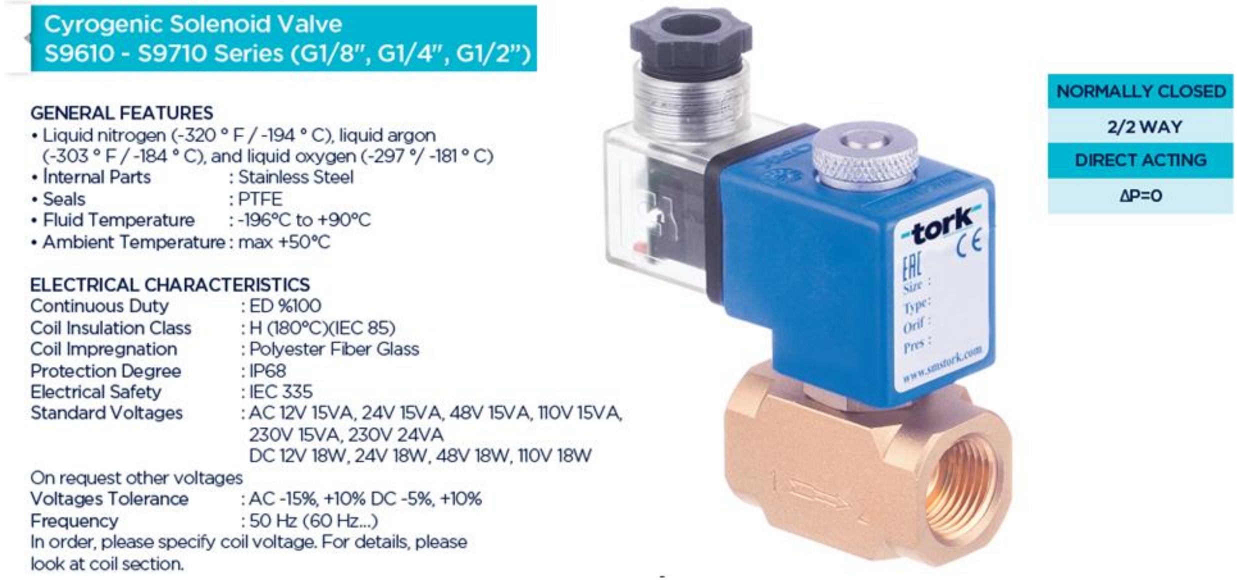
1) <u>Pressure sensor</u>

Detailed will be available in the practical section when it is implemented

2) <u>Solenoid valve</u>

We need a cryogenic solenoid valve that have some specifications:

- Pipe size: 3/8"
- Nominal pressure: 50 bar
- Temperature: 90 K to 320 K



Cyrogenic Solenoid Valve
S9610 - S9710 Series (G1/8", G1/4", G1/2")

GENERAL FEATURES
- Liquid nitrogen (-320 ° F / -194 ° C), liquid argon (-303 ° F / -184 ° C), and liquid oxygen (-297 °/ -181 ° C)
- Internal Parts : Stainless Steel
- Seals : PTFE
- Fluid Temperature : -196°C to +90°C
- Ambient Temperature : max +50°C

ELECTRICAL CHARACTERISTICS

Continuous Duty	: ED %100
Coil Insulation Class	: H (180°C)(IEC 85)
Coil Impregnation	: Polyester Fiber Glass
Protection Degree	: IP68
Electrical Safety	: IEC 335
Standard Voltages	: AC 12V 15VA, 24V 15VA, 48V 15VA, 110V 15VA, 230V 15VA, 230V 24VA DC 12V 18W, 24V 18W, 48V 18W, 110V 18W

On request other voltages

Voltages Tolerance	: AC -15%, +10% DC -5%, +10%
Frequency	: 50 Hz (60 Hz...)

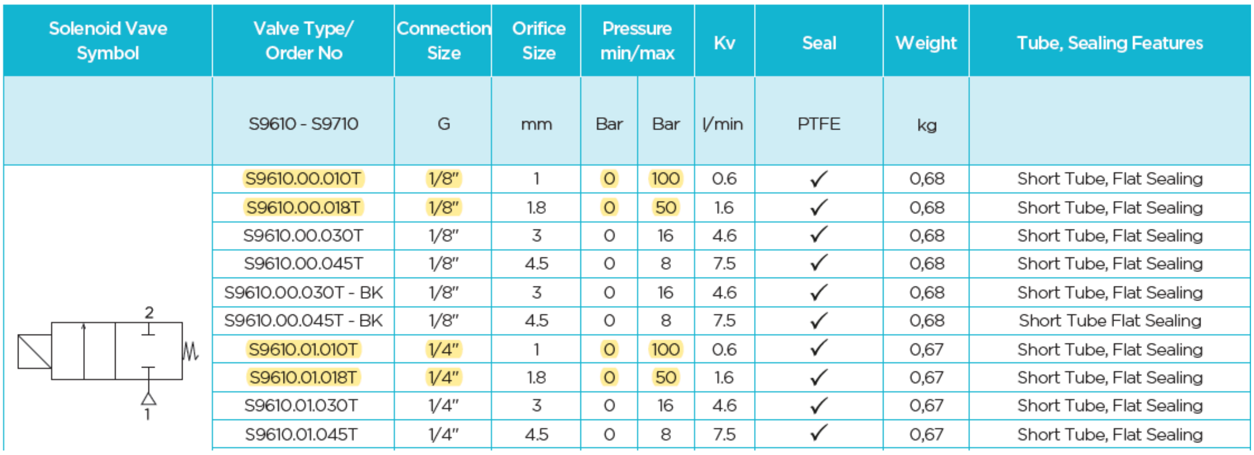
In order, please specify coil voltage. For details, please look at coil section.

NORMALLY CLOSED
2/2 WAY
DIRECT ACTING
ΔP=0

3/8" size not available. 1/4" or 1/8" is accepted as an alternative pipe size, we can choose between 4 valves found in the S9610 series. Available pressure value up to 100 bar.

S9610 - S9710 Series.pdf

[1]



Solenoid Vave Symbol	Valve Type/ Order No	Connection Size	Orifice Size	Pressure min/max		Kv	Seal	Weight	Tube, Sealing Features
	S9610 - S9710	G	mm	Bar	Bar	l/min	PTFE	kg	
	S9610.00.010T	1/8"	1	0	100	0.6	✓	0,68	Short Tube, Flat Sealing
	S9610.00.018T	1/8"	1.8	0	50	1.6	✓	0,68	Short Tube, Flat Sealing
	S9610.00.030T	1/8"	3	0	16	4.6	✓	0,68	Short Tube, Flat Sealing
	S9610.00.045T	1/8"	4.5	0	8	7.5	✓	0,68	Short Tube, Flat Sealing
	S9610.00.030T - BK	1/8"	3	0	16	4.6	✓	0,68	Short Tube, Flat Sealing
	S9610.00.045T - BK	1/8"	4.5	0	8	7.5	✓	0,68	Short Tube Flat Sealing
	S9610.01.010T	1/4"	1	0	100	0.6	✓	0,67	Short Tube, Flat Sealing
	S9610.01.018T	1/4"	1.8	0	50	1.6	✓	0,67	Short Tube, Flat Sealing
	S9610.01.030T	1/4"	3	0	16	4.6	✓	0,67	Short Tube, Flat Sealing
	S9610.01.045T	1/4"	4.5	0	8	7.5	✓	0,67	Short Tube, Flat Sealing

Model	Description	Unit Price(Euro)
S9610.01.018T	1/4", 1.8 mm orif. 0-50 bar	60,00
S9610.01.010T	1/4", 1 mm orif. 0-100 bar	60,00
S9610.00.010T	1/8", 1 mm orif. 0-100 bar	60,00
S9610.00.018T	1/8", 1.8 mm orif. 0-50 bar	60,00

The valve is useful for Cryogenic Fluid, Liquid Oxygen, Hydrogen, Helium, Carbon Dioxide, Nitrogen.

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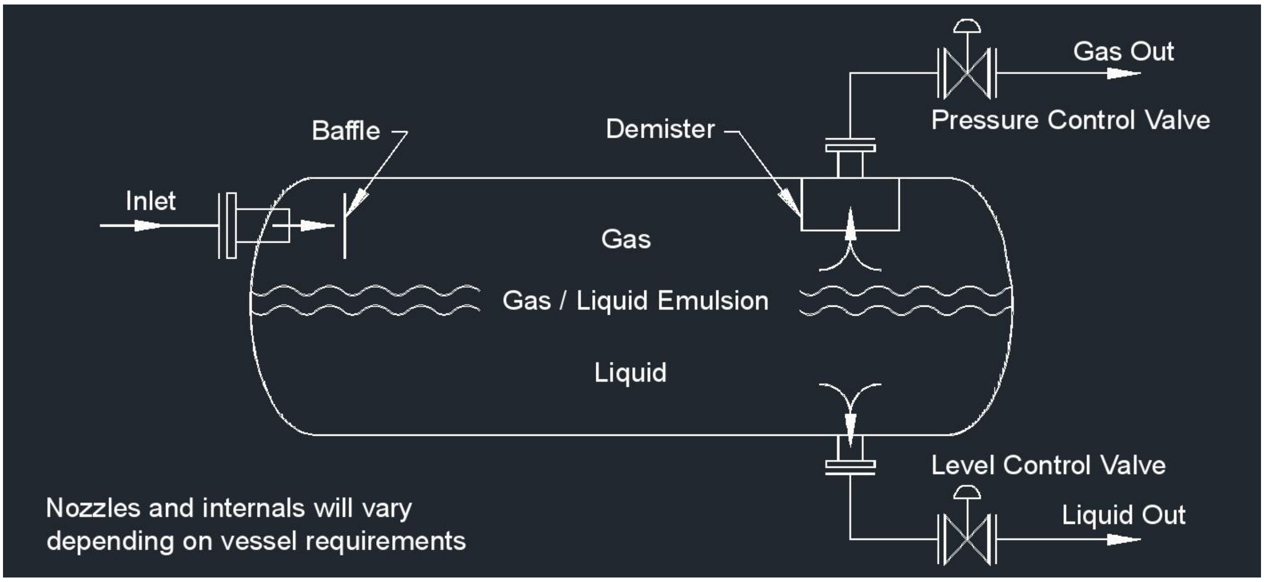
- Causes of leakage of low temperature solenoid operated hydraulic control valve

There are two reasons for the leakage of low temperature solenoid operated hydraulic control valve, firstly the main reasons are the seal deformation in the low temperature state. When the temperature of the medium is decreased, the volume change is caused by the phase change of the material, and the sealing surface with high grinding precision is produced to cause warpage, leading to the bad sealing. Two is the external leakage. It is mainly due to the flange connection between low temperature solenoid valve and pipe, due to the connection pad, connecting bolts, and the connection between the material at low temperature shrinkage caused by the relaxation of the gap and lead to leakage. Therefore, ***the connection mode between the valve body and the pipeline can be changed to the welding structure***, then the low temperature leakage can be avoided. Another is the stem and packing leakage. These are the main reasons for the leakage of low temperature solenoid operated hydraulic control valve.

3) Principle of two phase separator

Separation of the liquid and gas starts when the fluid meets the baffle. At that point, the gas and liquid start to go in different directions. The liquid drops where it is collected at the bottom of the vessel, and the gas rises to the top of the vessel. The gas that is still held in the liquid is in a section called the gas/liquid emulsion, which is in an area at the top of the liquid. In time, the gas is released from the emulsion and rises to the top of the vessel where the rest of the gas resides. Depending on the process, this may contain a mist eliminator or demister. The gas leaves from the top of the vessel, and the liquid leaves from the bottom of the vessel, heading to the next process.



4) Separator calculation

Physically, a decrease in gas pressure corresponds to an expansion in the volume of a gas and a decrease in its temperature. In our case, the purpose of the separator is to provide a place to allow the emergence of a pressure drop difference from 50 bar to 1 bar, which means that oxygen is allowed to expand, which leads to severe coldness of the gas (temperature drop).

- In one hour :

Inlet compressor : 3.229 m³/hr @ 278K (≈ +5°C)
3.402 m³/hr @ 293K (≈ +20°C)
3.634 m³/hr @ 313K (≈ +40°C)

Inlet of solenoid valve: V4• =0.6 L/min =0.036 m³/hr @ 155K, 50 bar

$$\frac{P4.V4}{T4}=\frac{P5.V5}{T5} \Rightarrow V_5=\frac{P4.V4.T5}{T4.P5}=\frac{50\times 0.036\times 90.062}{155\times 1}=1.04588\ \text{m}^3/\text{hr}=V_T{\bullet}$$

$$\left.\begin{array}{l}1.04588\ \text{m}^3 \rightarrow 100\% \\ \quad ? \qquad \leftarrow 0.169\%\end{array}\right\} \Rightarrow V_f{\bullet} = V_L{\bullet} = 0.00177\ \text{m}^3/\text{hr}$$

$= 0.5$ mL/s @90.062K, 1 bar

$V_g{\bullet}= 1.04411$ m³/hr = 0.0123 L/s @90.062K, 1 bar

- Total volume of separator:

In 1 hour: $V_T= 1.04588$ m³

In 20 minutes: V= 0.3486 m³ ≈ 0.35 m³ = $\pi R^2 L$

$= \pi.R^2.\ 1_m$

$$\Rightarrow \quad R = \sqrt{\frac{V}{\pi.L}} = \sqrt{\frac{0.35}{\pi.1}} = 0.3337 \text{ m} \approx 33.5 \text{ cm}$$

5) Sizing of separator

- Specifications:

Horizontal/vertical: Vertical

Material: stainless steel

Pressure: 5MPa

Thickness: 8mm

Volume V [L]	Unit price [$]	Diameter d [mm]	Radius R [mm]
100 L	700 $	377 mm	188.5 mm
170 L	900 $	426 mm	213 mm
350 L	1628 $	550 mm	275 mm

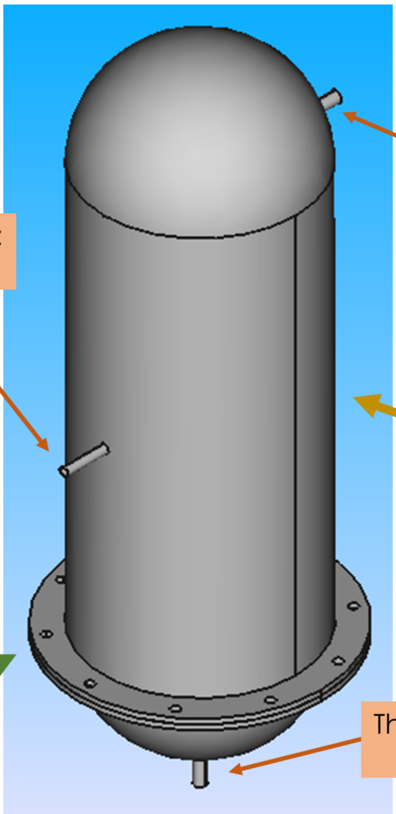
- Sizing details depend on volume

Total volume Vt [m³]	Radius R [m]	Sphere volume Vs [m³]	Cylinder volume Vc [m³]	Length L [m]
0.1	0.18	0.024429024	0.075570976	0.74243792
0.17	0.21	0.038792386	0.131207614	0.947044913
0.35	0.27	0.082447958	0.267552042	1.168236765

N.B.: Changing the volume of the separator does not affect the size of the pipes (inlet/outlet). In other words, the pipe size will remain constant, and it is not related to the volume of the separator.

6) Design of separator

19102022_Separator design.FCStd



Thread 2 (Outlet gas) : 1/2”

Thread 1 (inlet) : 3/8”

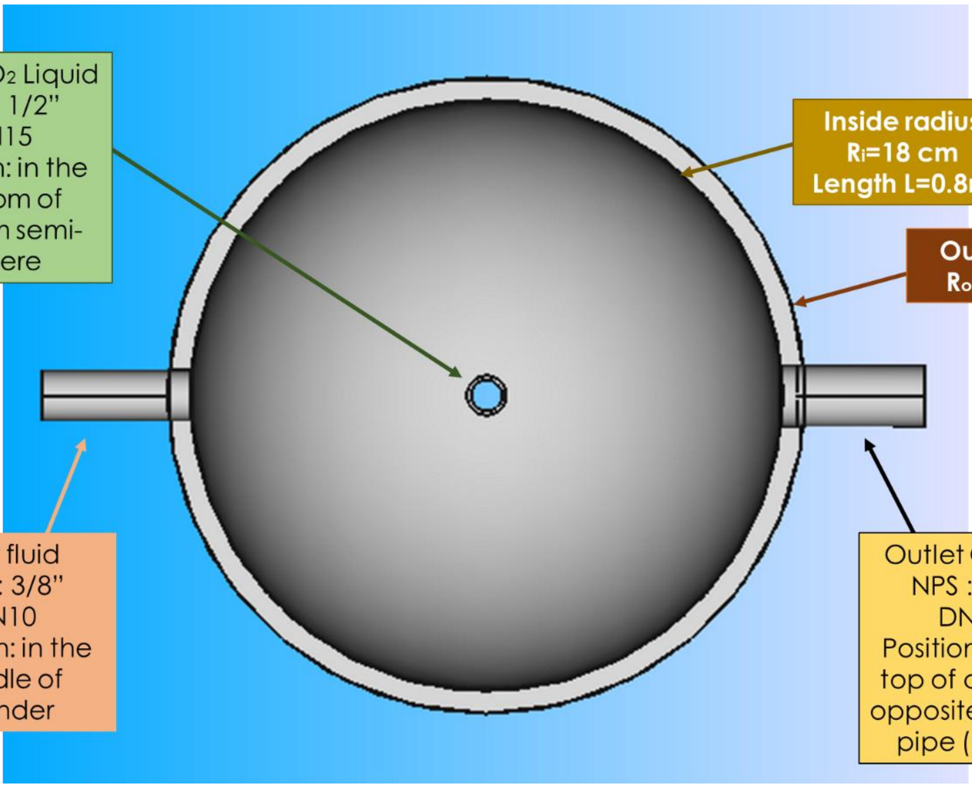
Vertical separator

Material: Stainless steel
Pressure: P= 5 MPa
Thickness: T= 10 mm
Volume: V= 100 L
Radius of separator(cylinder & semi-sphere): R= 18 cm
Length of cylinder: L= 0.8 m

Flange

Material: Stainless steel
Thickness: T= 10 mm
Radius outside R_o= 24 cm
Radius inside R_i= 19 cm
Hole radius R_h= 8 mm
Number of holes : 10 holes

Thread 3 (Outlet liquid) : 1/2”



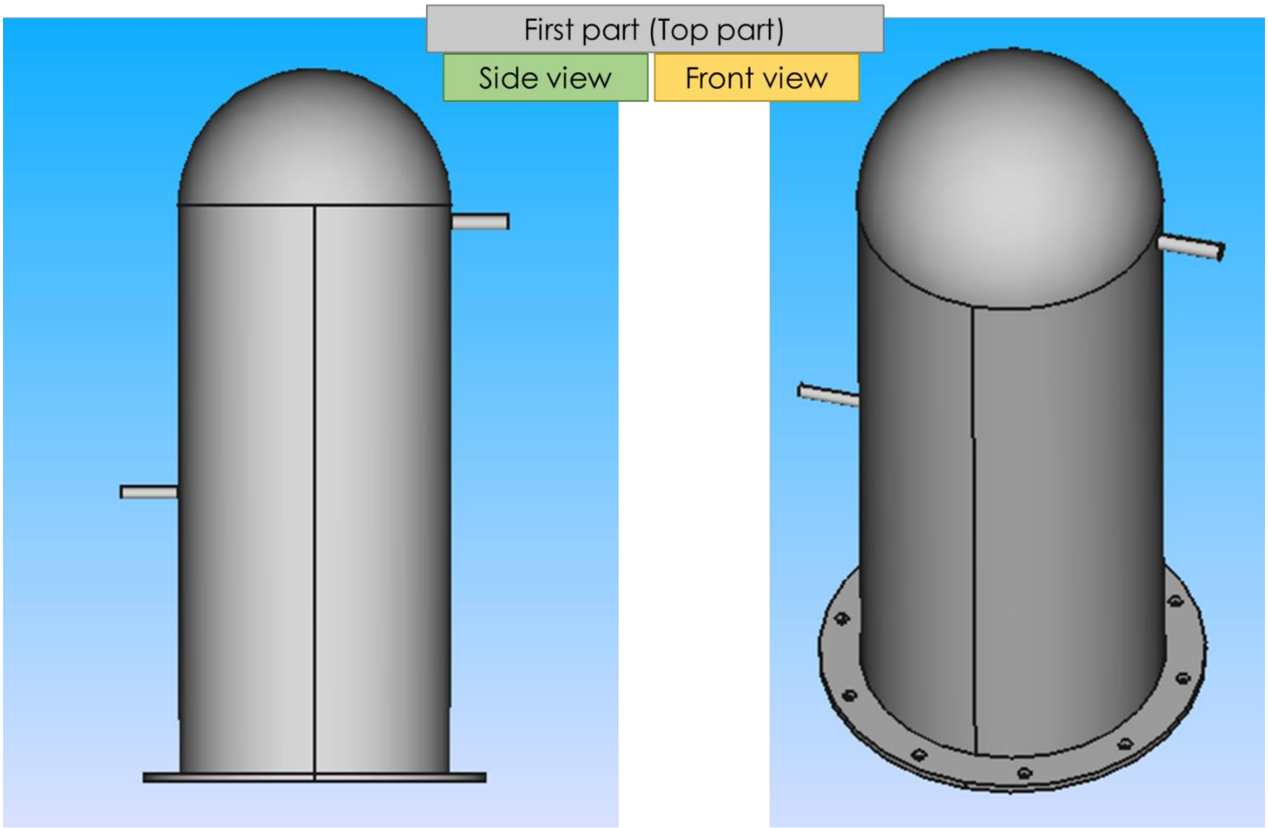
Outlet O_2 Liquid
NPS : 1/2”
DN15
Position: in the bottom of bottom semi-sphere

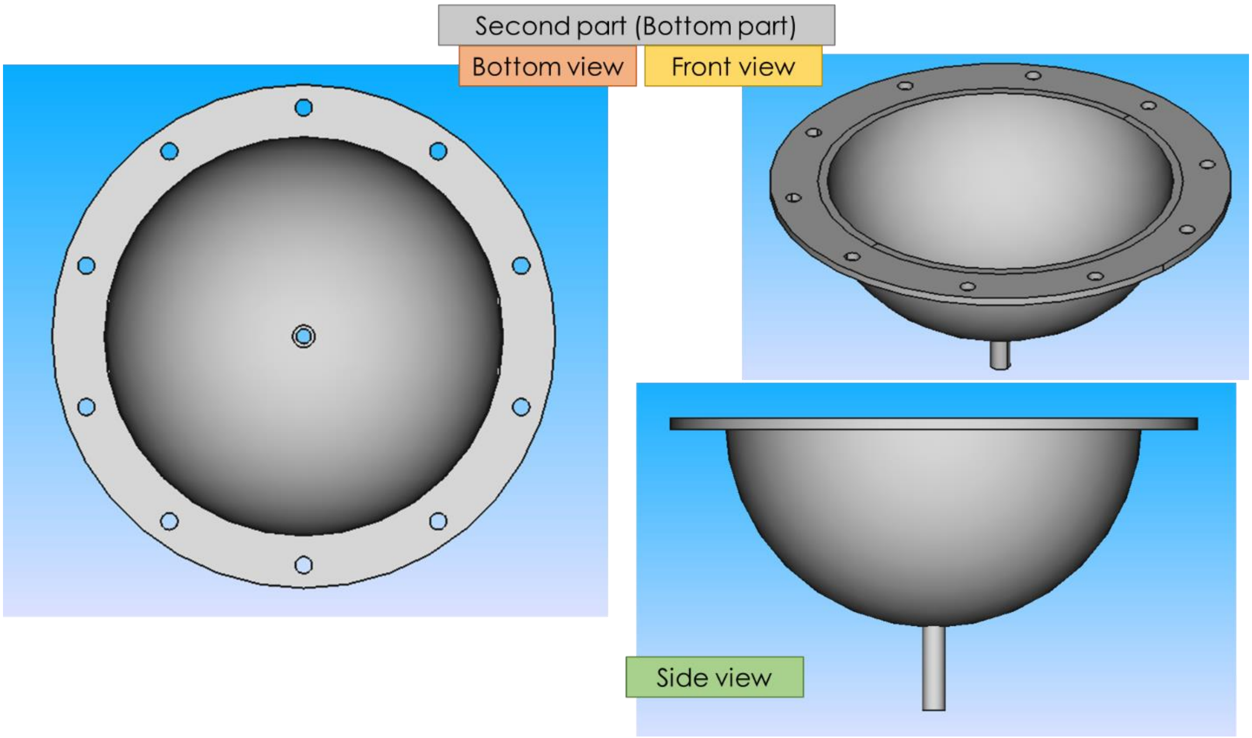
Inside radius
R_i=18 cm
Length L=0.8m

Outer radius
R_o=19.6 cm

Inlet fluid
NPS : 3/8”
DN10
Position: in the middle of cylinder

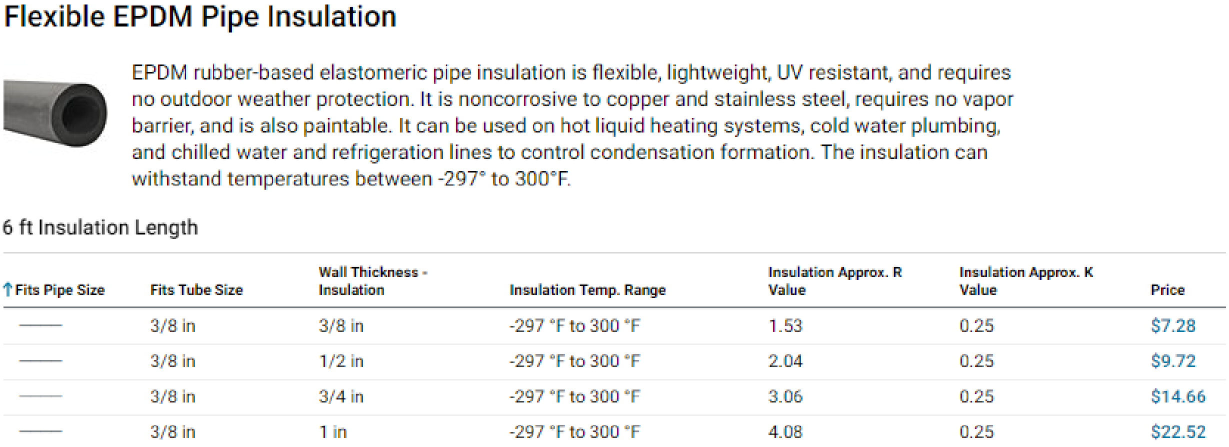
Outlet O2 gas
NPS : 1/2”
DN15
Position: in the top of cylinder opposite to inlet pipe (DN10)





15.9 Cryogenic insulation material for LOx prototype

1) **<u>Flexible EPDM pipe insulation</u>** [5][6]

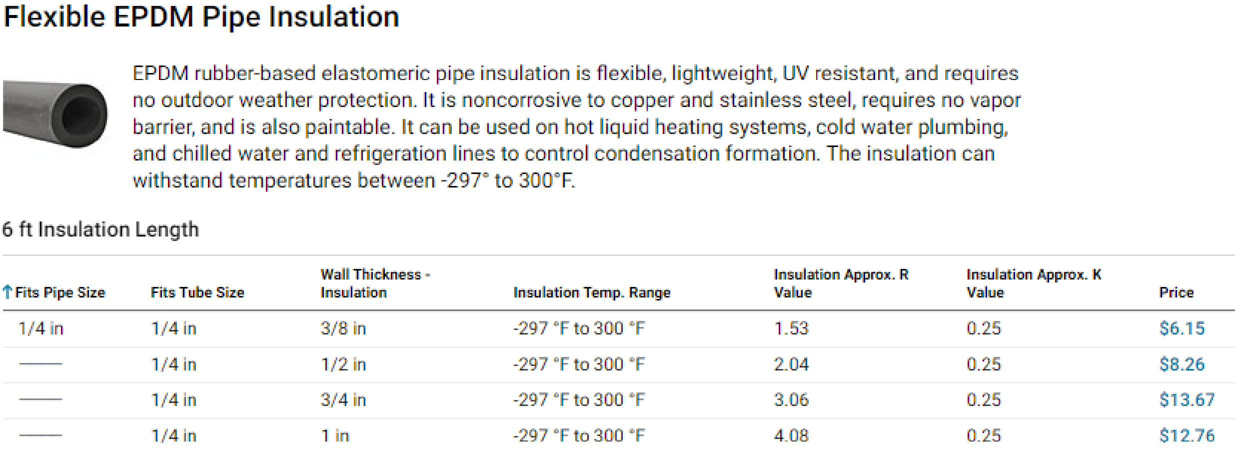


Flexible EPDM Pipe Insulation

EPDM rubber-based elastomeric pipe insulation is flexible, lightweight, UV resistant, and requires no outdoor weather protection. It is noncorrosive to copper and stainless steel, requires no vapor barrier, and is also paintable. It can be used on hot liquid heating systems, cold water plumbing, and chilled water and refrigeration lines to control condensation formation. The insulation can withstand temperatures between -297° to 300°F.

6 ft Insulation Length

↑Fits Pipe Size	Fits Tube Size	Wall Thickness - Insulation	Insulation Temp. Range	Insulation Approx. R Value	Insulation Approx. K Value	Price
—	3/8 in	3/8 in	-297 °F to 300 °F	1.53	0.25	$7.28
—	3/8 in	1/2 in	-297 °F to 300 °F	2.04	0.25	$9.72
—	3/8 in	3/4 in	-297 °F to 300 °F	3.06	0.25	$14.66
—	3/8 in	1 in	-297 °F to 300 °F	4.08	0.25	$22.52



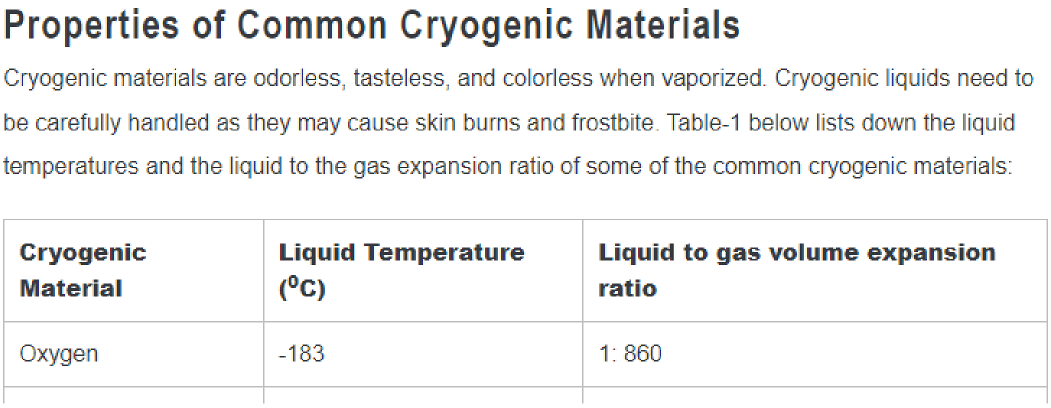
Flexible EPDM Pipe Insulation

EPDM rubber-based elastomeric pipe insulation is flexible, lightweight, UV resistant, and requires no outdoor weather protection. It is noncorrosive to copper and stainless steel, requires no vapor barrier, and is also paintable. It can be used on hot liquid heating systems, cold water plumbing, and chilled water and refrigeration lines to control condensation formation. The insulation can withstand temperatures between -297° to 300°F.

6 ft Insulation Length

↑Fits Pipe Size	Fits Tube Size	Wall Thickness - Insulation	Insulation Temp. Range	Insulation Approx. R Value	Insulation Approx. K Value	Price
1/4 in	1/4 in	3/8 in	-297 °F to 300 °F	1.53	0.25	$6.15
—	1/4 in	1/2 in	-297 °F to 300 °F	2.04	0.25	$8.26
—	1/4 in	3/4 in	-297 °F to 300 °F	3.06	0.25	$13.67
—	1/4 in	1 in	-297 °F to 300 °F	4.08	0.25	$12.76

2) Cryogenic insulation materials [7] [8]



Properties of Common Cryogenic Materials

Cryogenic materials are odorless, tasteless, and colorless when vaporized. Cryogenic liquids need to be carefully handled as they may cause skin burns and frostbite. Table-1 below lists down the liquid temperatures and the liquid to the gas expansion ratio of some of the common cryogenic materials:

Cryogenic Material	Liquid Temperature (^{0}C)	Liquid to gas volume expansion ratio
Oxygen	-183	1: 860

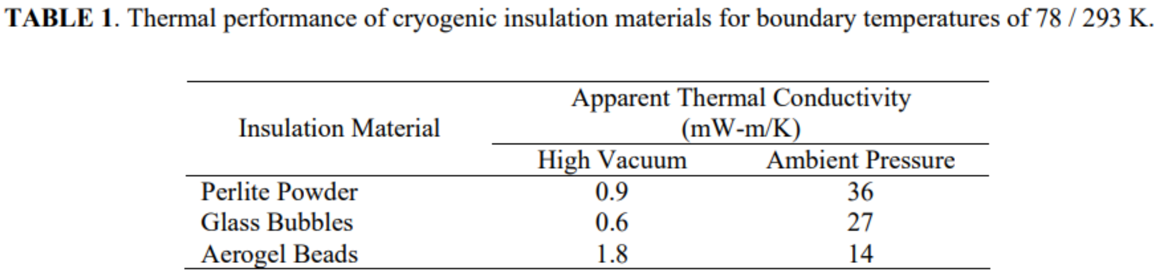


TABLE 1. Thermal performance of cryogenic insulation materials for boundary temperatures of 78 / 293 K.

Insulation Material	Apparent Thermal Conductivity (mW-m/K)	
	High Vacuum	Ambient Pressure
Perlite Powder	0.9	36
Glass Bubbles	0.6	27
Aerogel Beads	1.8	14

15.10 Operating system

1) Preparing the system for operation:

1- Ensure that all components of the system are connected

2- Ensure that the system is free of leaks

3- Ensure that the insulators are placed correctly and in the appropriate places

4- Verify that electrical connections are correct

5- Make sure the valves are working

6- Make sure the oxygen tank is full

7- Fill the system tubes with oxygen

2) Operation system

The first step to operate the system begins with operating the compressor, where the oxygen gas is pumped from the tank at ambient temperature (2 bar) to the pipes by the compressor. Oxygen gas passes through the tubes at a pressure of 50 bar. It is inserted into the Kelvinator refrigerator, which plays the role of a cooler, to cool the oxygen passing through the pipes from +10 °C to -78 °C (283 K to 195 K). The compressed oxygen exits from the cooler and enters the heat exchanger. Compressed oxygen exits from the heat exchanger at -118 °C (155 K) and passes into the solenoid valve, which opens at a pressure of 50 bar and closes at 45 bar. When the pressurized oxygen passes through the solenoid valve and the separator, the oxygen expands and its pressure drops from 50 bar to 1 bar. The fluid temperature also drops from -118 °C to -183 °C (from 155 K to 90 K). At a temperature of -183 °C (90 K, 1 bar), part of the fluid turns into liquid oxygen (1.23%) and collects at the base of the separator, while the other part remains in its gaseous state (98.77%), with a temperature close to the liquefaction temperature (-183 °C (90 K)), where it returns to the exchanger to play the role of a cooling medium for compressed oxygen gas passing through a coil. Oxygen gas comes out of the heat exchanger at a temperature of -120 °C (153 K, 1 bar) to reach the mixer, where the cold gas coming out of the heat exchanger is mixed with a certain amount of oxygen gas in the tank. This quantity is equivalent to the amount of liquid produced, taking into account the difference in pressure and temperature, and therefore the volume. The oxygen gas is then transferred to the heater, where it is heated to -10 °C (263 K) to re-enter the compressor again.

N.B.:

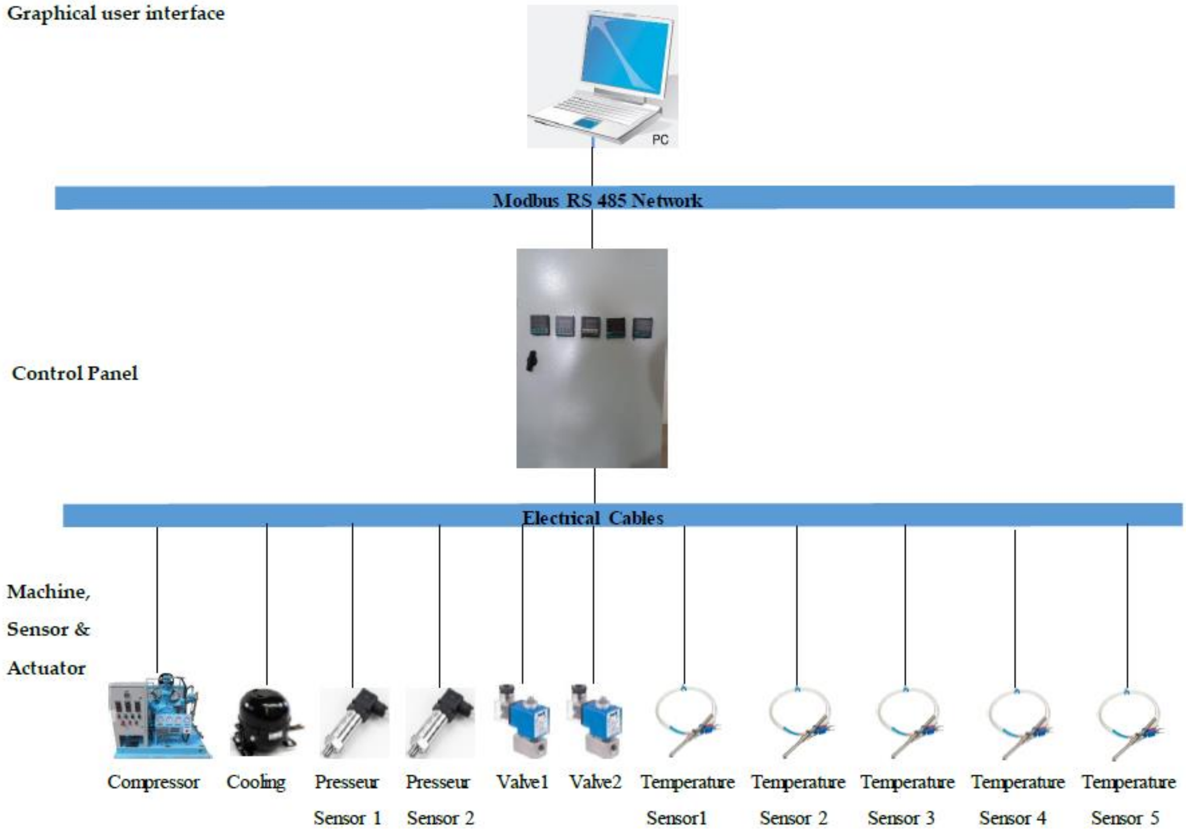
1- The required temperatures will not be obtained from the first pass (cycle #1), but this requires several cycles in order to cool the gas itself and the system.

2- The high pressure and cryogenic temperature may cause fractures (cracks) in the pipes and this may lead to an explosion, so the system must be tested with an upward pressure to reach a high pressure (5 bar, 10 bar, 15 bar, …, up to 50 bar).

3- The safety valve (pressure reducing valve) must be placed at the highest point of the pressure tube in the system, to leak excess pressure in the system, especially after stopping the system from working.

15.11 LOX PCS implementation

1) The process control system for the LOX system



The process control system is the same for the LOX system with/without a heat exchanger (HX) (Version 2021)

LOX system will be controlled via Arduino

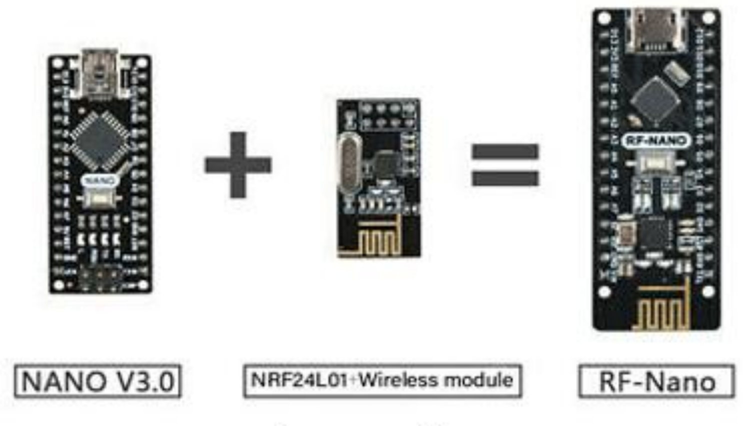
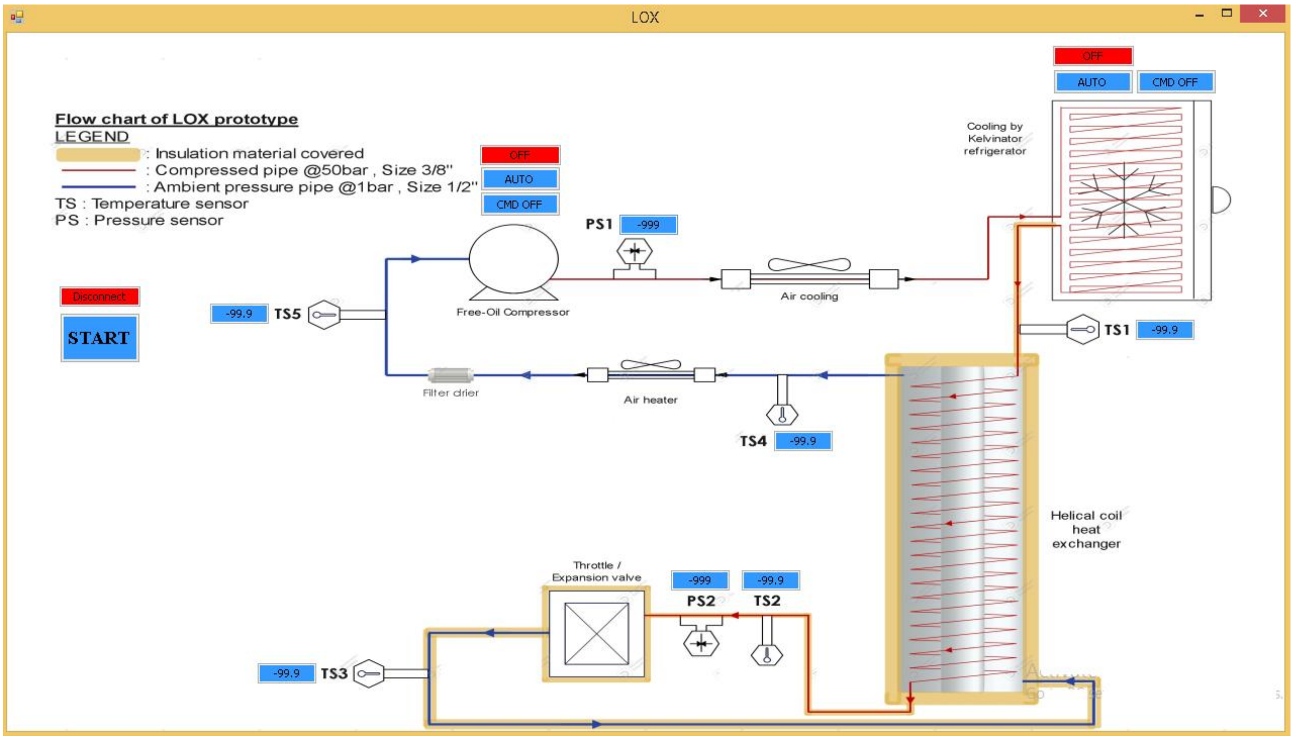


Figure 10. Arduino Nano RF

2) Graphical user interface (Version 2022)



Graphical User Interface code (C#):

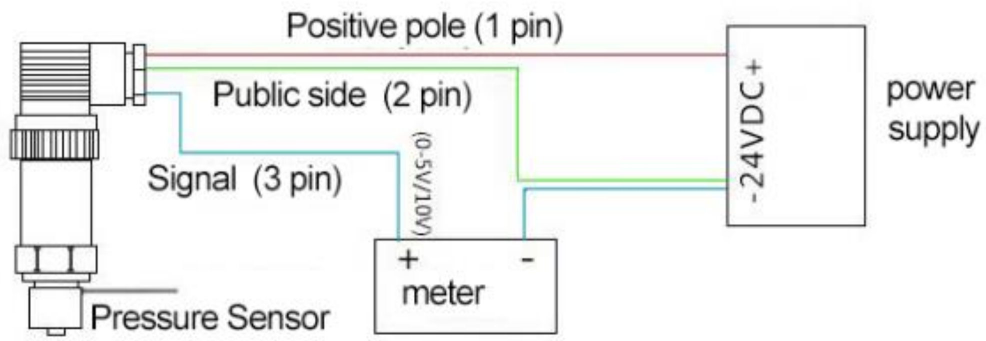
230922_ICPT-LOX_PCS_GUI code.rar

3) The Material Used

1-Temperature Controller TE4-DC18W [9]

2-Temperature sensor PT100

3-Pressure Sensor HDP500 (0-10V Output, 0-10Mpa) [10]

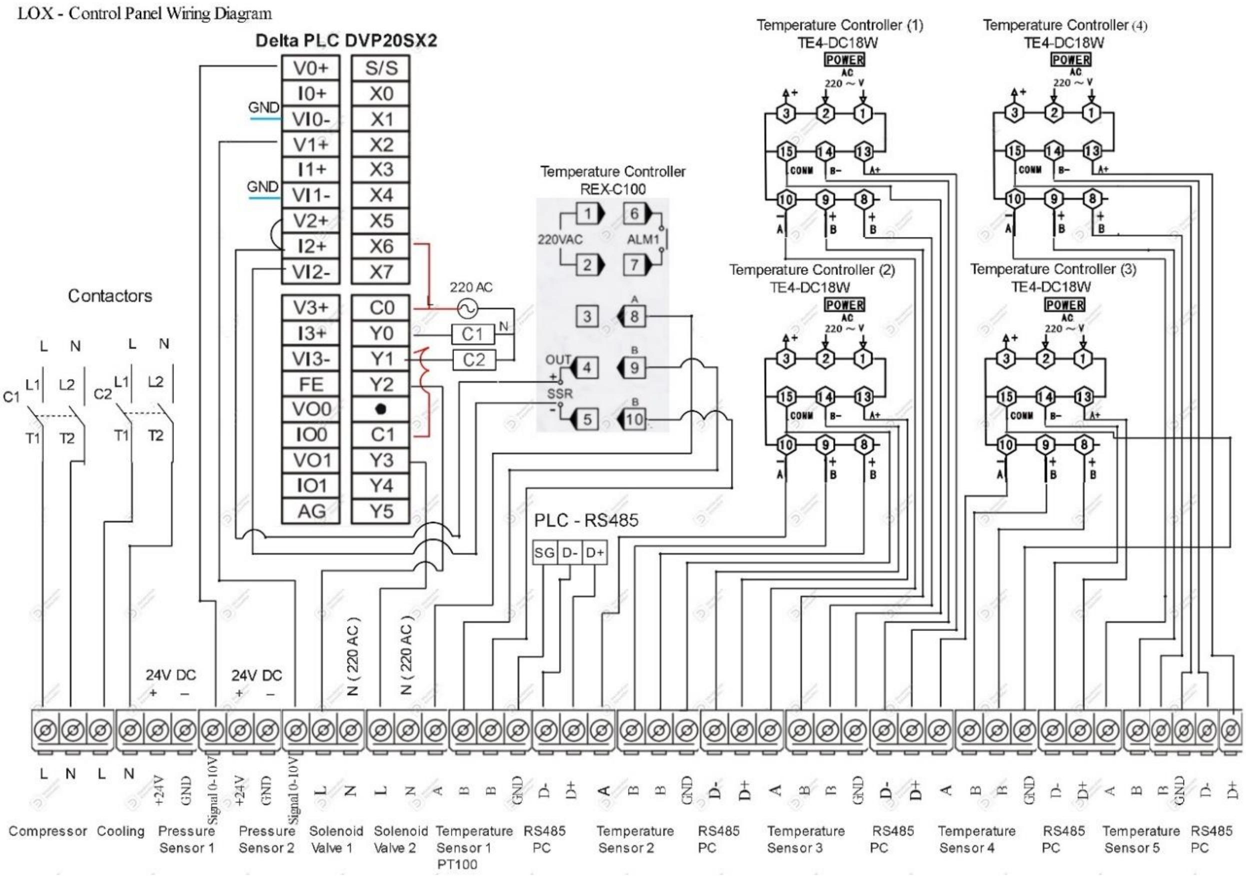


Red line: 24VDC Blue line: voltage output + green line: power supply -

THREE-WIRE VOLTAGE OUTPUT CIRCUIT DIAGRAM

4-Cyrogenic Solenoid Valve [11]

4) Control Panel Wiring Diagram



Control Panel Wiring Diagram:

311022LOX PCS -
Control Panel Wirin

15.12 What‘s next

To complete the practical part of the LOx project, it is necessary to replace the pipes inside the cooling system and to purchase the oil-free compressor and several other equipment. On the basis of compressor selection, features and design of heater, and mixer will be determined, and remote control will be finalized. After completing these steps, we will be ready to perform the first run.

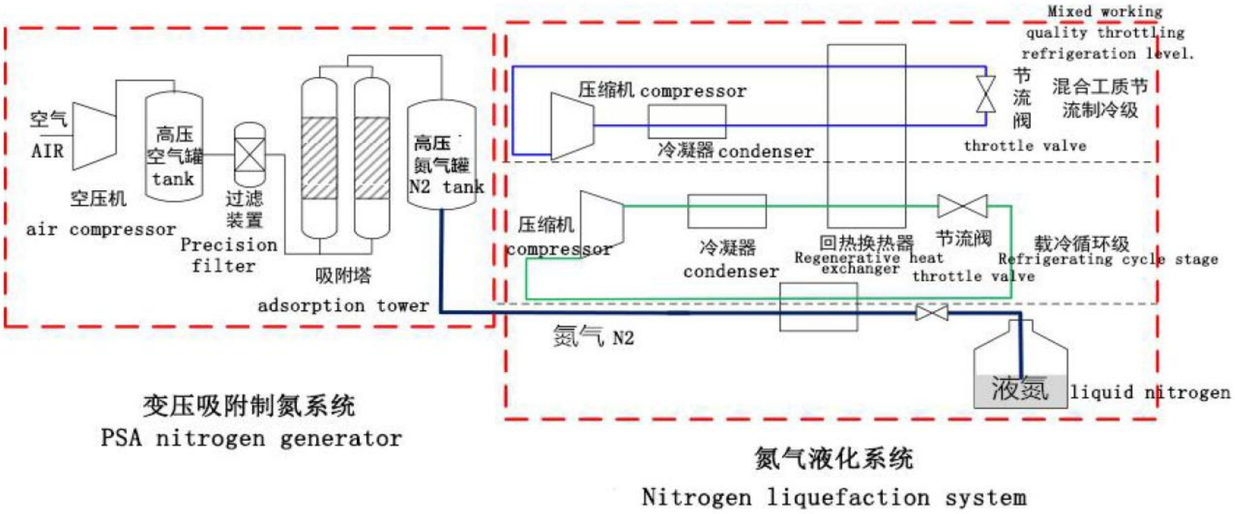
16 Project D 23: Liquefaction of Oxygen (ICPT - LOX), Cooling and Cryogenics

16.1 Position of LOX project

Work on this project began theoretically in the past years. In Jan-March 2025, the focus was on the practical, operational side.

16.2 From NLAP-WEDC Report 2023

16.2.1 Nitrogen Liquefication System Design Apr 2023 (based on Chinese supplier)[47]



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[47] Ref : https://aecenar.com/index.php/institutes/icpt/liquefication-of-air-and-oxygen/icpt-lox-system-concept-design

16.2.2 LOX Mechanical Realization

16.2.2.1 Prototype Location

16.2.2.2 Prototype Installation

16.2.2.3 Compressor:

Figure 4. LR25B Compressor

16.2.2.4 Cooler:

Figure 6. Cooler Tube Implementation

16.2.2.5 Evaporator:

Figure 7. Evaporator

16.2.2.6 Heat exchanger

16.2.3 Liquefication of oxygen System Test Specification[48]

16.2.3.1 First Experiment:

The first experiment (Expr #1) aims to:

1- Compressor operation test with nitrogen gas instead of R-134a,

2- Make sure that the Kelvinator refrigerator is running correctly

3- Ensure that the expansion valve is compatible with the design.

Therefore, the three heat exchangers (HX-N2/N2, HX-N2/O2 main, and HX-N2/O2 2nd) will be excluded from this experiment.

In this experiment, the oxygen will not be liquefied, but only the components will be tested and designed to ensure the proper functioning of the refrigeration cycle.

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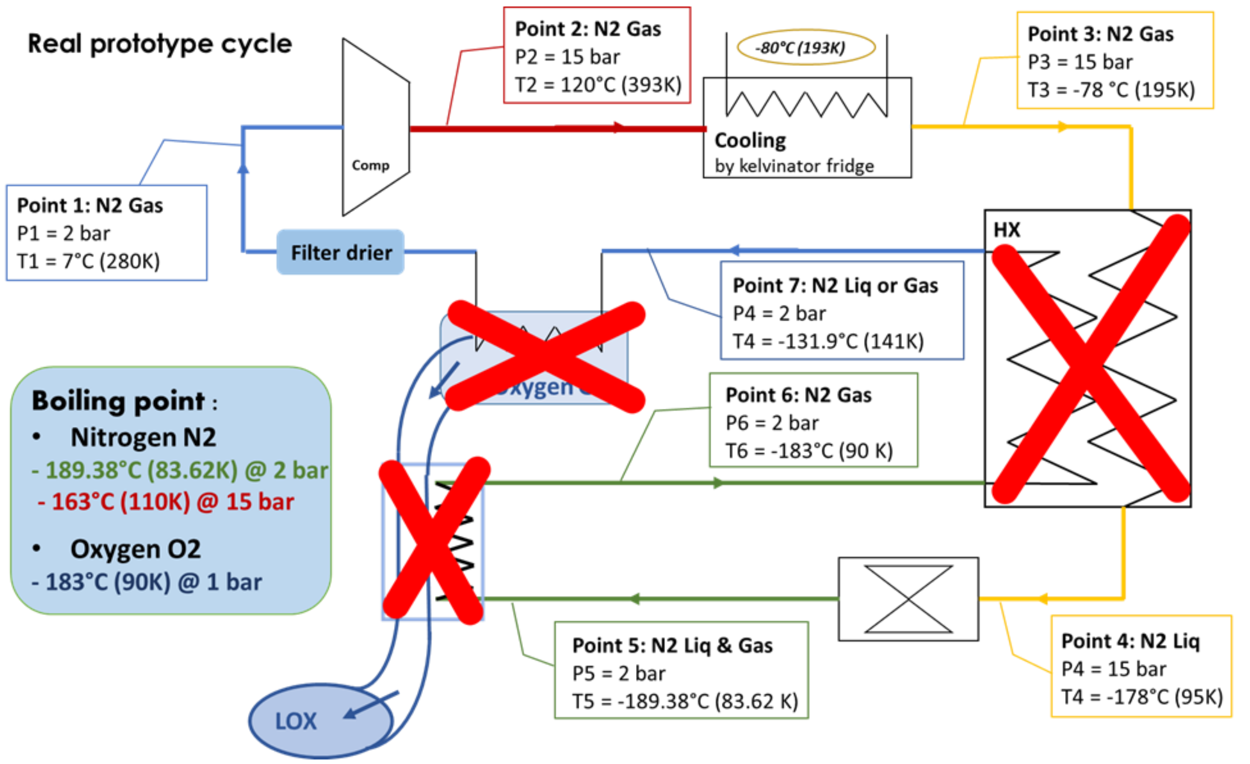
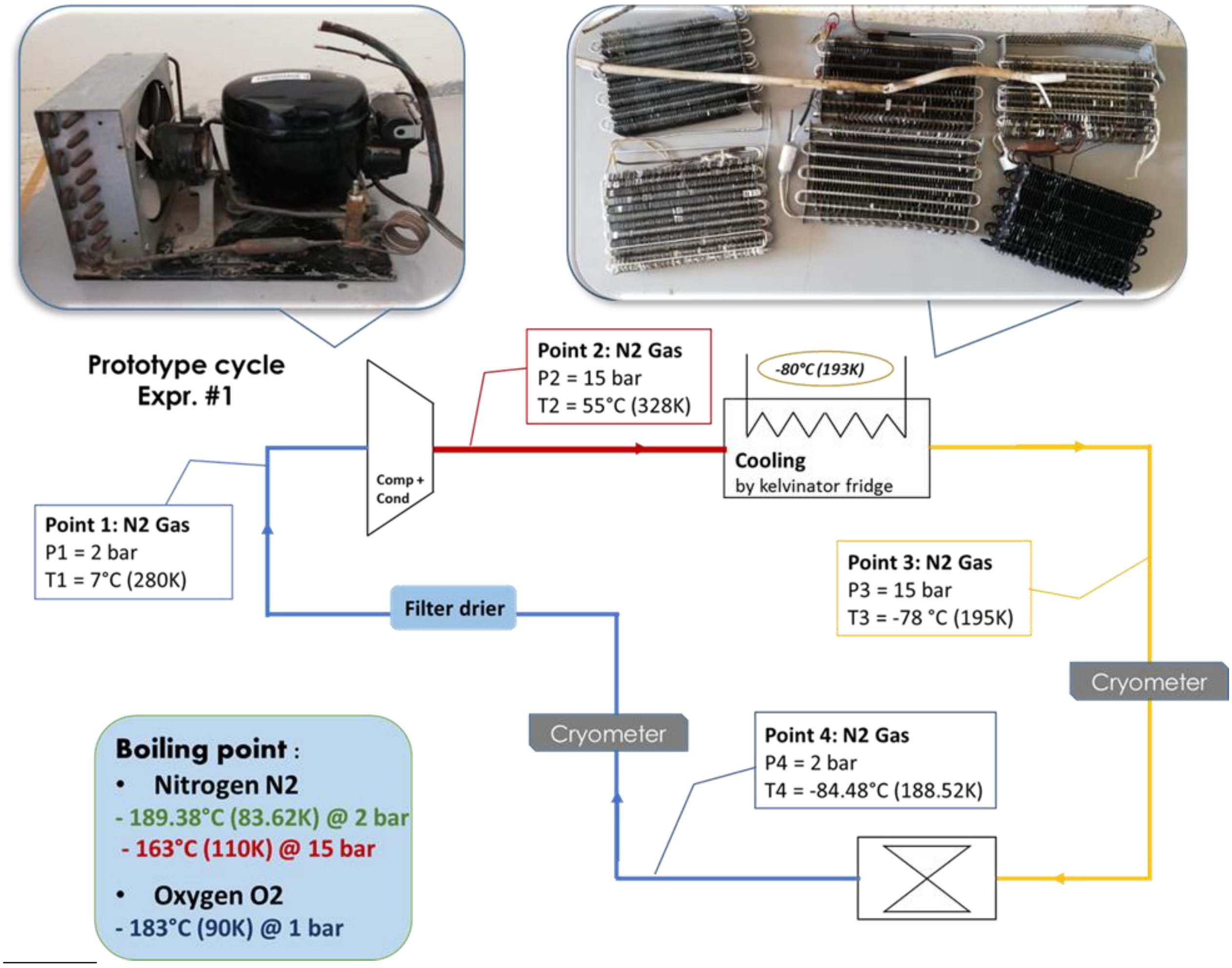
[48] Ref : https://aecenar.com/index.php/institutes/icpt/liquefication-of-air-and-oxygen/icpt-lox-system-test-specification



The first experiment consists of a simple cycle consisting of a compressor (LR25B Laboratory) with a condenser, cooling through a Kelvinator refrigerator, and an expansion valve (taken from an LR25B Laboratory refrigerator).



The components that must be provided to carry out this experiment:

- Filling the design with nitrogen gas, immediately before the pump.
- Covering the design with thermal insulation material to maintain the temperature of the refrigeration cycle,
- The presence of a thermometer (below -100˚C (173 K)) to measure the cooling outlet (an inlet of the expansion valve) and the outlet of the expansion valve,
- Also, a weather thermometer (from -10˚C to 20˚C (263 K to 293 K)) to measure the temperature of the compressor inlet.

For the safety of the compressor:

- In the **first hour of operation**, a 5-minute break must be taken for the compressor every 15 minutes of operation, in order to avoid an explosion of the compressor or one of the designed cables.
- Also, the compressor must **not run for more than two hours** in a row.
- Also, **cold nitrogen gas must be entered into the compressor** to reduce the speed of nitrogen flow, in addition to its role in cooling the compressor.

During this experiment (Expr. #1), the **amount of nitrogen gas filled** in the cycle, the **time of the experiment**, the **temperature reached** by the refrigeration cycle, and the **pressure during operation** will be calculated.

16.2.4 LOX Requirements

16.2.4.1 System requirements

- The LOX system shall be able to liquefy oxygen.

16.2.4.2 Physical requirements

- The pipes shall be able to withstand the temperatures and pressures that exist at the points.

- Temperature that shall be withstood:

- Pressure that shall be withstood:

The different temperatures and pressures are listed in the figures below:

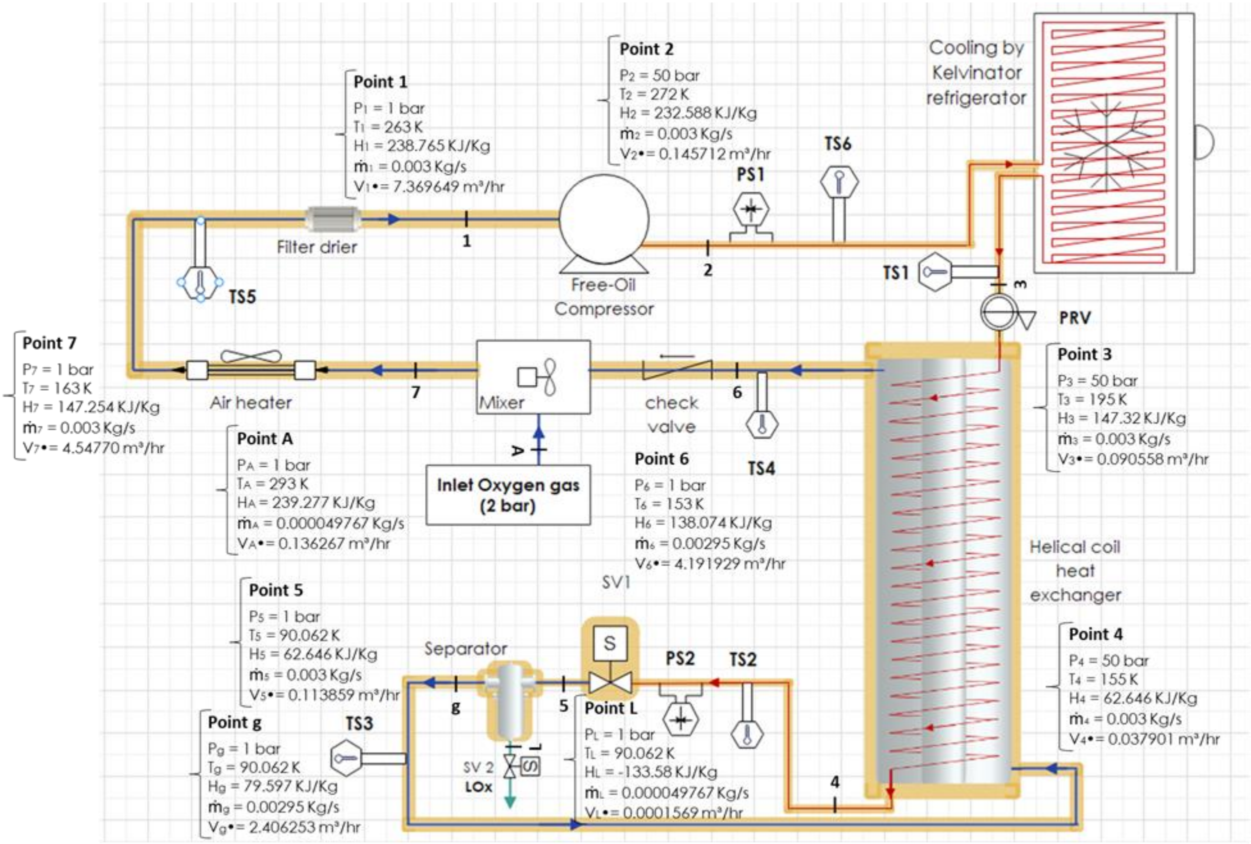
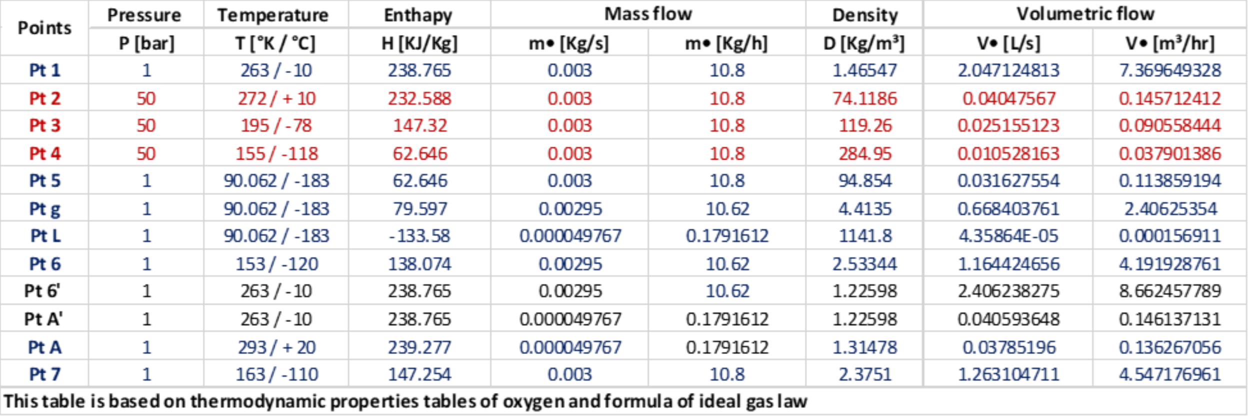


Fig-1-



Points	Pressure	Temperature	Enthapy	Mass flow		Density	Volumetric flow	
	P [bar]	T [°K / °C]	H [KJ/Kg]	m• [Kg/s]	m• [Kg/h]	D [Kg/m³]	V• [L/s]	V• [m³/hr]
Pt 1	1	263 / -10	238.765	0.003	10.8	1.46547	2.047124813	7.369649328
Pt 2	50	272 / + 10	232.588	0.003	10.8	74.1186	0.04047567	0.145712412
Pt 3	50	195 / -78	147.32	0.003	10.8	119.26	0.025155123	0.090558444
Pt 4	50	155 / -118	62.646	0.003	10.8	284.95	0.010528163	0.037901386
Pt 5	1	90.062 / -183	62.646	0.003	10.8	94.854	0.031627554	0.113859194
Pt g	1	90.062 / -183	79.597	0.00295	10.62	4.4135	0.668403761	2.40625354
Pt L	1	90.062 / -183	-133.58	0.000049767	0.1791612	1141.8	4.35864E-05	0.000156911
Pt 6	1	153 / -120	138.074	0.00295	10.62	2.53344	1.164424656	4.191928761
Pt 6'	1	263 / -10	238.765	0.00295	10.62	1.22598	2.406238275	8.662457789
Pt A'	1	263 / -10	238.765	0.000049767	0.1791612	1.22598	0.040593648	0.146137131
Pt A	1	293 / + 20	239.277	0.000049767	0.1791612	1.31478	0.03785196	0.136267056
Pt 7	1	163 / -110	147.254	0.003	10.8	2.3751	1.263104711	4.547176961
This table is based on thermodynamic properties tables of oxygen and formula of ideal gas law								

Table -1-

- The heat exchanger shall be able to decrease the temperature of the oxygen in order to become close to liquefaction temperature at the pressure present.

The temperature that must be reached: -120°C (154 K) @50bar.

- The cooler (Kelvinator refrigerator) shall be able to supply a temperature that is low enough.

The temperature that shall be reached: -80°C (193K).

- The separator shall be sufficient in volume to allow the gas expansion.

- The separator shall be able to separate the oxygen gas from the liquid oxygen.

- The heater shall be able to warm the cryogenic gas, so that their temperature is suitable for entering the compressor.

16.2.4.3 Chemical requirements

- The compressor shall be free of oil (oil-free) to avoid its reaction with oxygen.

16.2.4.4 Mechanical requirements

- The material of the pipes shall be made a Copper (the ideal shall be made a stainless steel)

- The dimensions of the pipes that shall be:

Diameters are listed in the figure below:

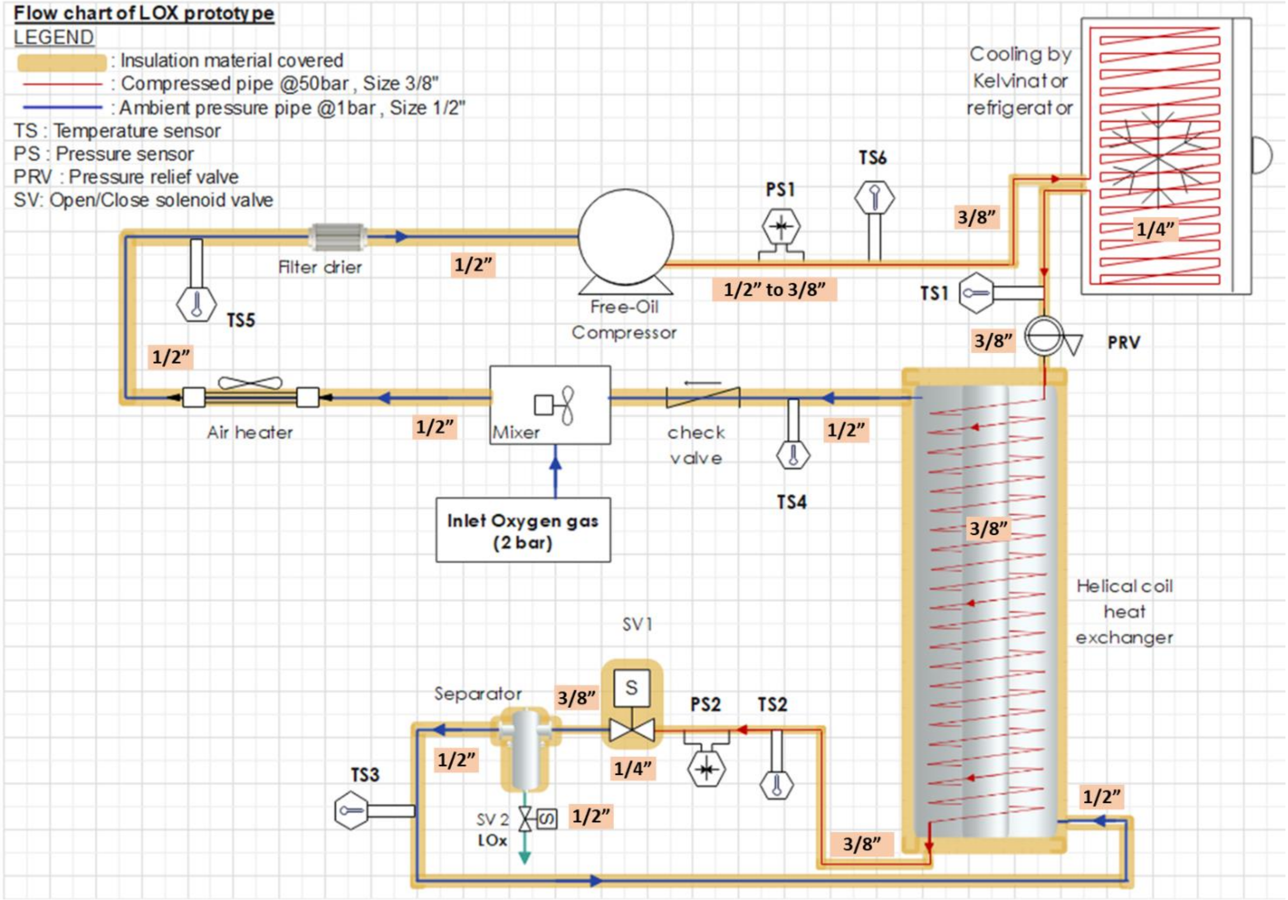


Fig-2-

- The compressor shall be able to increase the pressure of the gas to the required level, from -15°C (258K) @1bar (inlet temperature) - ambient temperature @50bar (outlet pressure).
- The sensors shall be able to measure in the temperature and pressure range, shows in Fig -1-.
- The expansion valve (solenoid valve with separator) shall be able to drop the pressure abruptly, from 50 bar to 1 bar.
- The mixer shall be able to introduce an appropriate amount of fresh oxygen gas into the system; the amount of fresh oxygen gas added shall be equal the amount of liquid oxygen, taking into account the effect of the temperature difference.
- The filter drier shall be able to dry the oxygen gas before entering the compressor.
- The thermal insulation material shall be able to isolate pipes and components from any heat leakage.

- The thermal insulation material shall be made a fiber glass (the ideal thermal insulation shall be made a Flexible EPDM).
- The separator shall be made of stainless steel.
- The LOx system shall be design according to " LOx Mechanical Design ".

16.2.4.5 Automation requirements

- The sensors shall be able to be controlled from the GUI.
- The valves shall be able to be controlled from the GUI.

16.3 Air Liquifecation - Realization

16.3.1 Connections for oxygen liquefaction project

16.4 Heat exchanger (HX) leakage repairing and tests

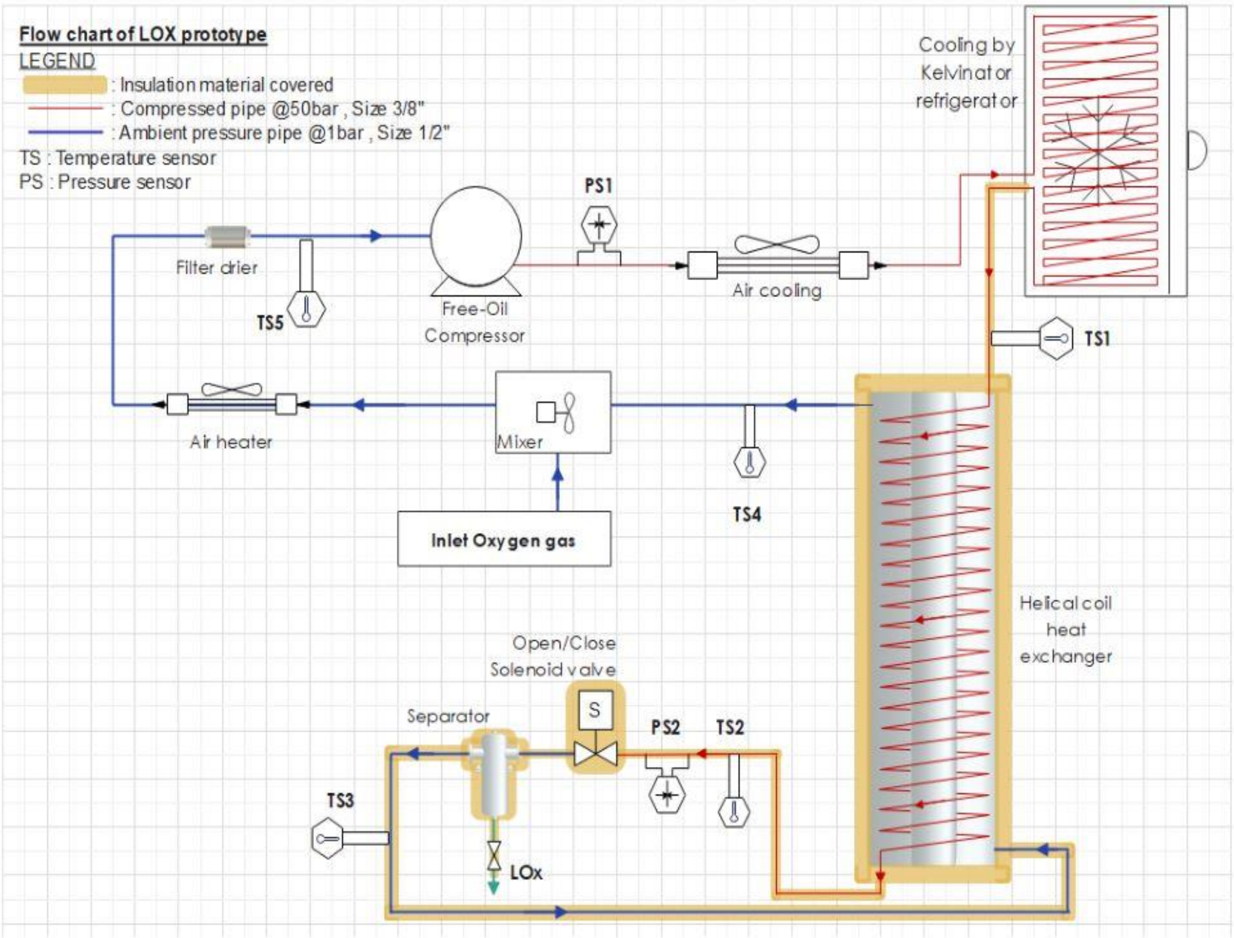
16.4.1 27 Jan 2025

A leakage test was conducted on the heat exchanger to ensure there were no leaks in the system. The test took place on this date and revealed multiple leaks in the heat exchanger's inlets and outlets. The leaks were due to old rubber connections affected by the sun and natural factors and other wrong connections way. These Pictures related to the test above:

16.4.2 30 Jan 2025

On this date new accessories were added to the heat exchanger sealed all the leaks and the system is now fully enclosed.

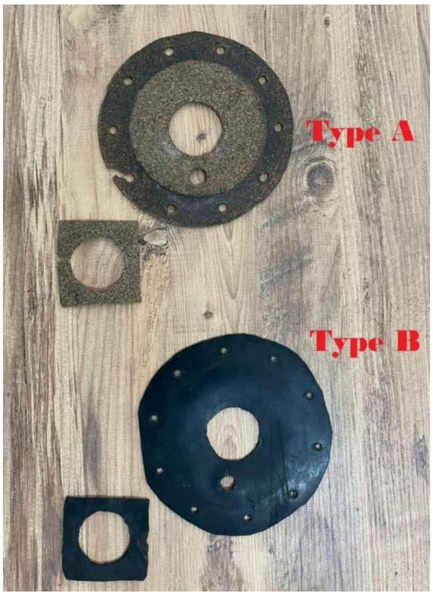
The system was connected depending on the drawing below:



16.4.3 4 Feb 2025

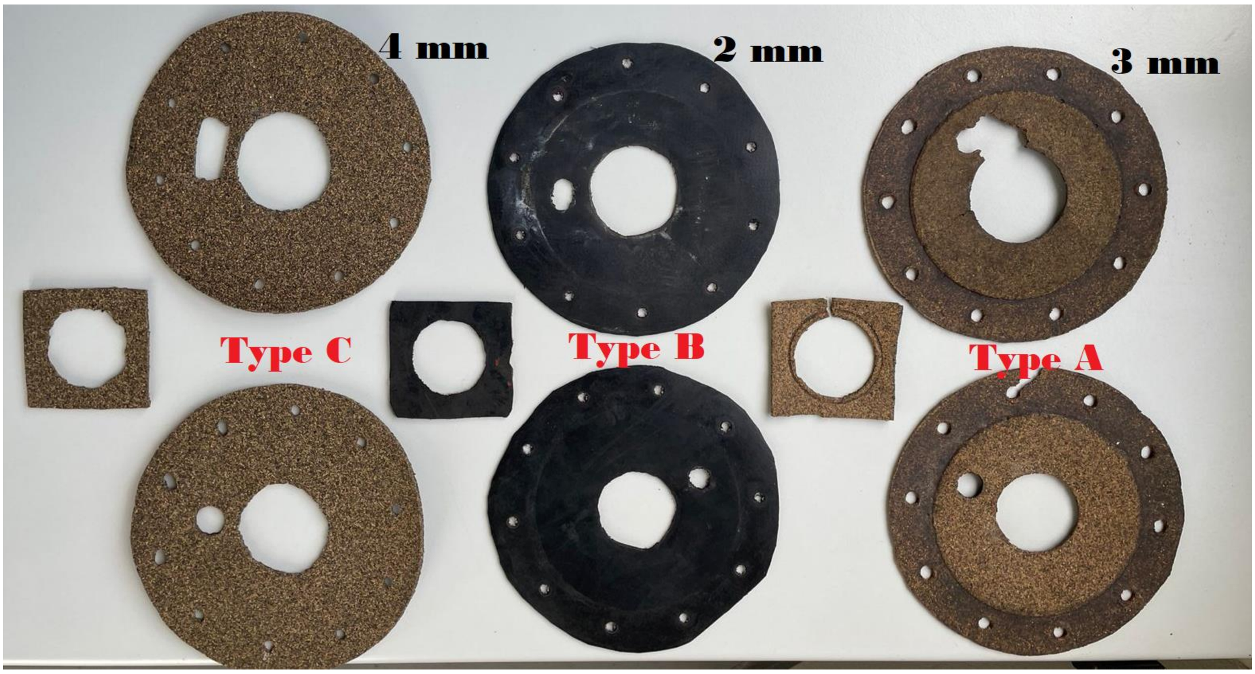
A leakage test was conducted again on the system, revealing leaks in the rubber connection as well as in the stainless-steel components. Due to these issues, the system should be sealed from both the upper and lower openings.

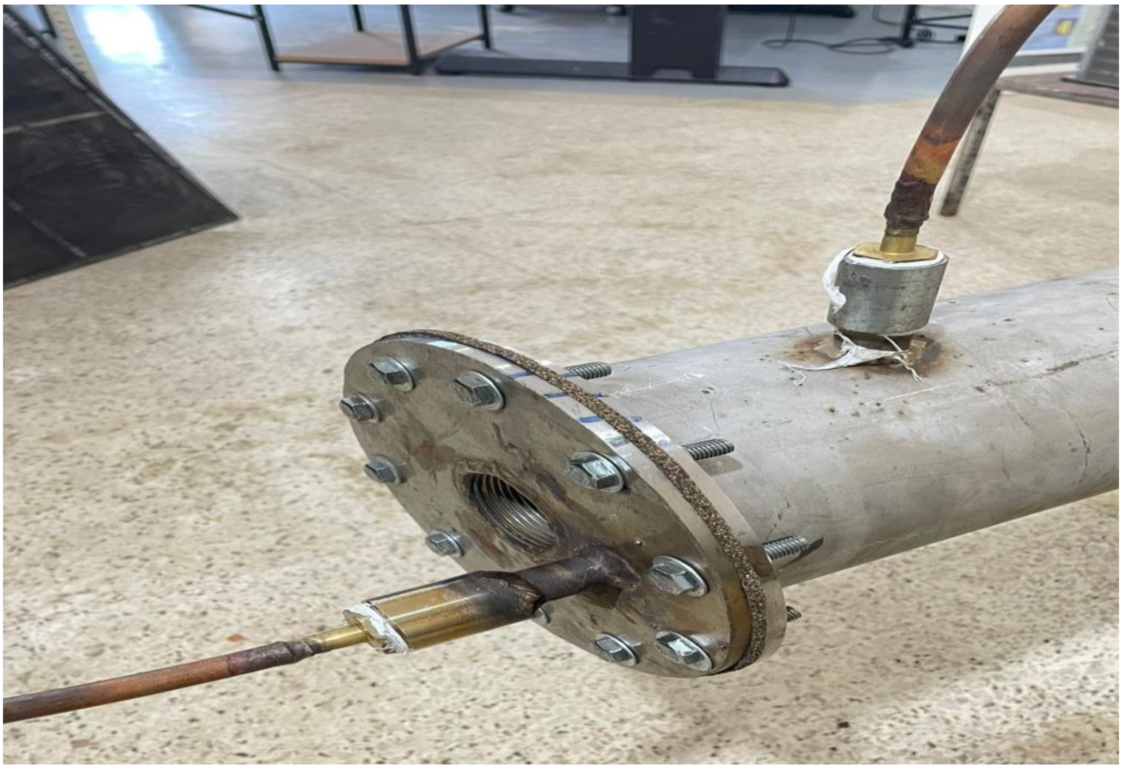
After testing a black rubber (Type B) shown in the picture below, we found that the old rubber (Type A) performed better, as the new one resulted in significant leakage during the test.



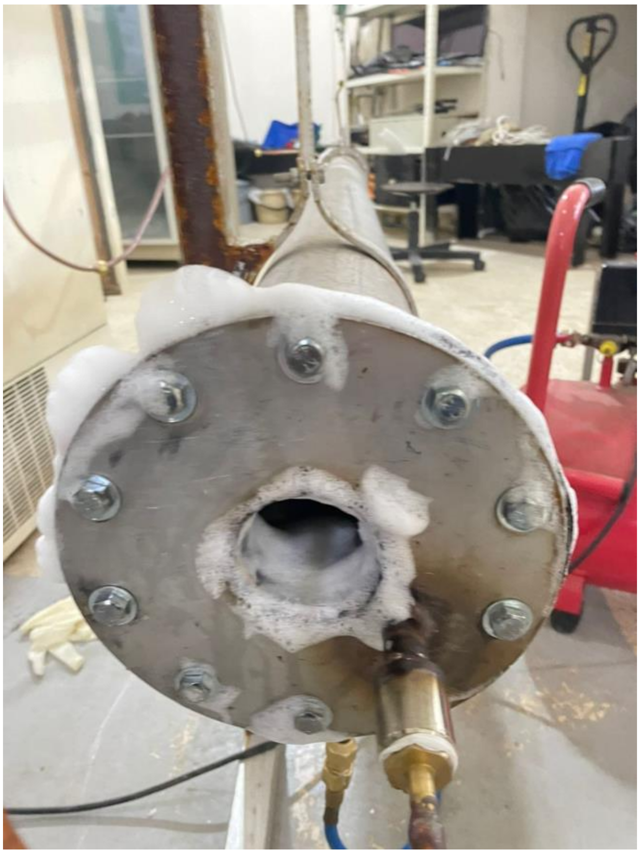
- **10 Feb 2025**

A leakage test was conducted on the heat exchanger after using Type C 4 mm Anti-leakage synthetic rubber when both Type A and B didn’t give good results.


4 mm
2 mm
3 mm
Type C
Type B
Type A



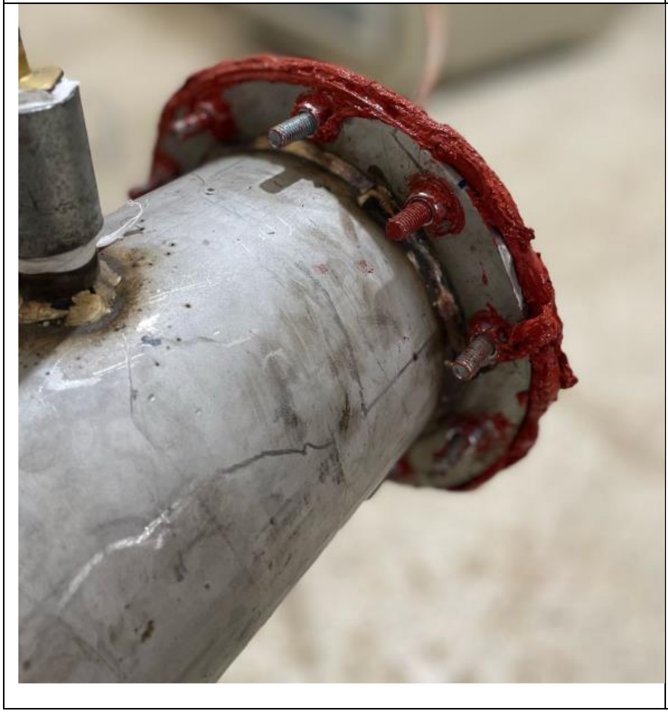
The leaking test started and unfortunately, the third type didn't work due to leakage



16.4.4 12 Feb 2025

On this day, High Temp Silicone Sealant was used instead of the different types of Rubbers used before to make the system sealed

We put the first layer and then a second layer and put the nuts immediately.



Also the 2 holes in the top and bottom were closed with stainless steel because the system was leaking in the middle of the pipe.

16.4.5 15 Feb 2025

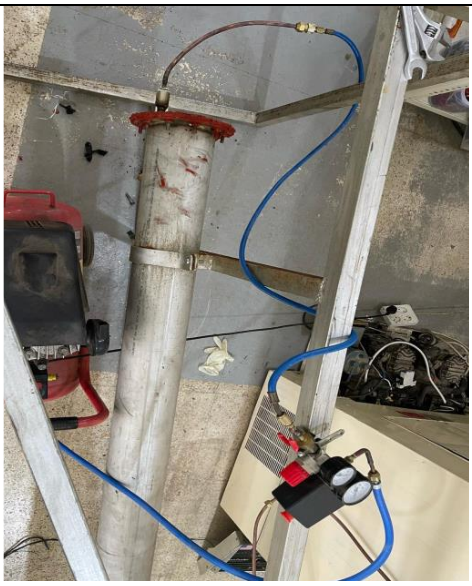
A leakage test was performed on the side part of the heat exchanger, and no leaks were detected, confirming that the red silicone sealant was effective.

A second leakage test was then conducted on the coil sectio Figure above: realization

n of the heat exchanger, specifically in the upper and lower positions.

The results showed a leak in the upper section, as indicated by a significant

pressure drop on the gauge within just half an hour.



When the heat exchanger finally gets into a full leakage test and is tested.

Then we can get into the other step which is the connection of the full process and we will make another leakage test for the full process of the lox and make sure there is no leaking in the system.

16.5 Pilot Plant with air as working fluid: Integration and System Test

16.5.1 System Integration

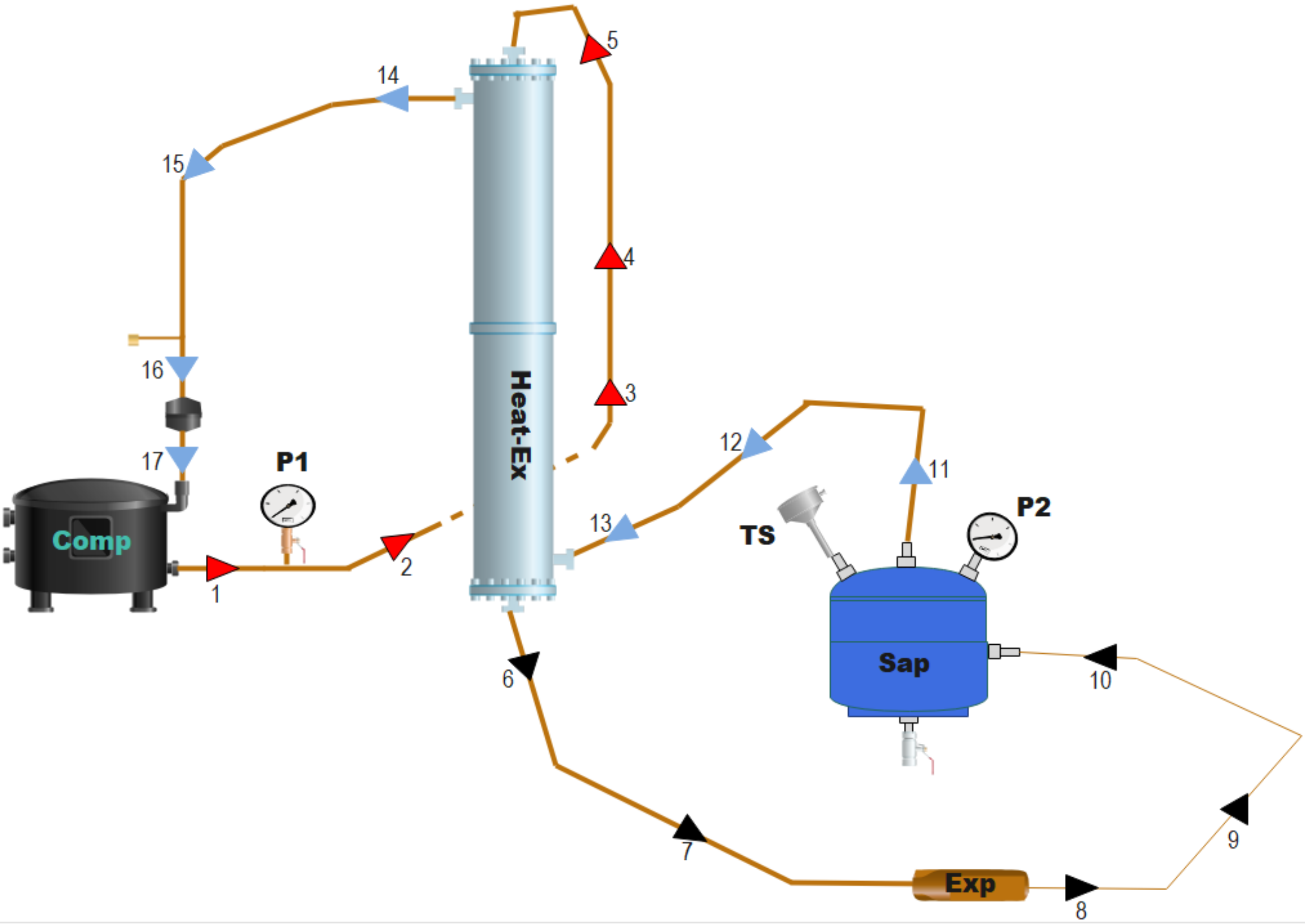
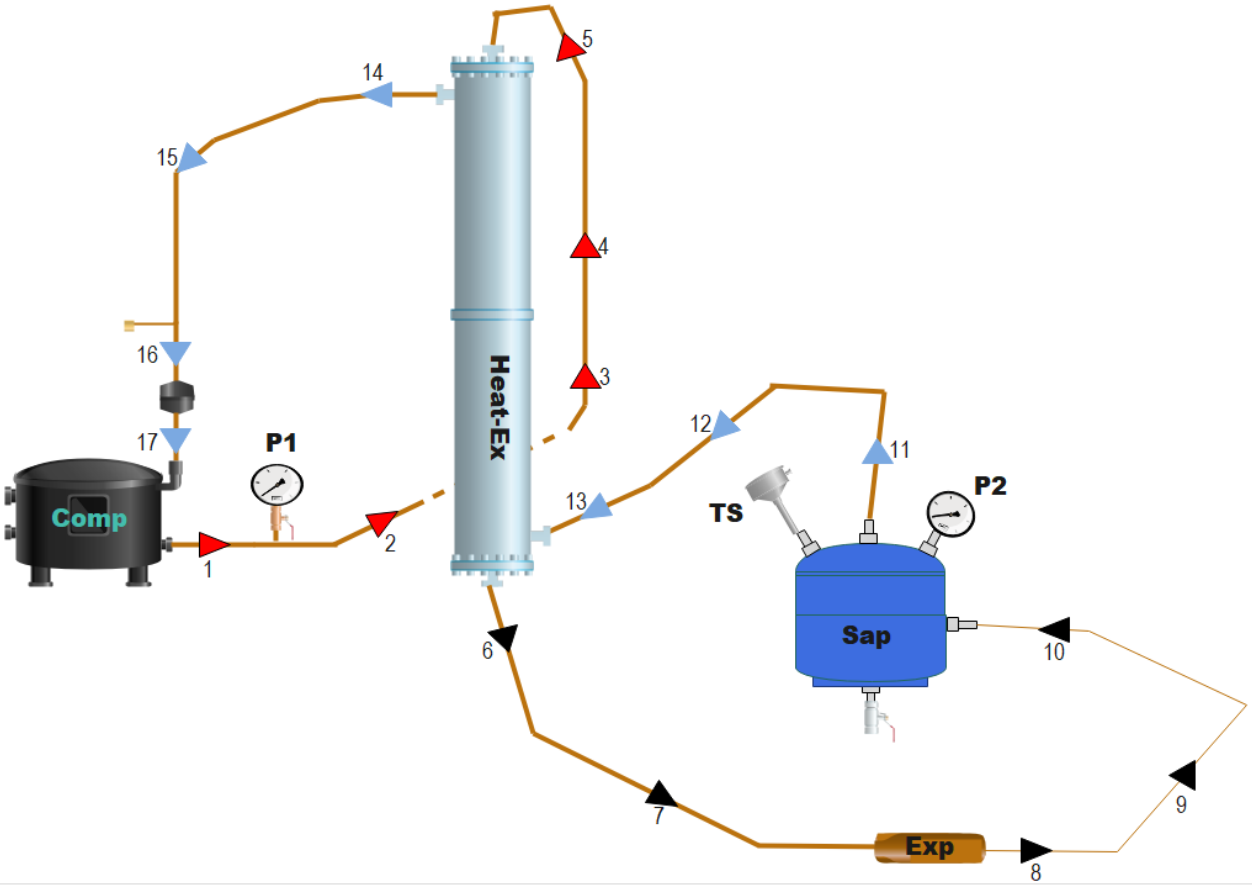


Figure above: Scheme

Figure left: realization

in green cycle: expansion valve

16.5.2 How does the new cycle Actually work?



The cycle begins with the compressor, which compresses the air from 2 bar to a pressure between 8 and 12 bar.

The compressed air then travels through points 1, 2, 3, 4, and 5, entering the heat exchanger, where it loses some heat.

After exiting the heat exchanger at point 6, it moves through point 7, where the pipe diameter decreases, followed by points 8 and 9, eventually reaching point 10, where it enters the separator. Inside the separator, the gas undergoes sudden heat loss, causing the liquid portion to settle at the bottom while the remaining gas continues in the cycle.

The gaseous phase moves through points 11, 12, and 13, re-entering the heat exchanger. Here, it helps cool the incoming compressed gas from the compressor before proceeding through points 14, 15, 16, and 17, finally returning to the compressor to restart the cycle.

16.5.2.1 Remarks

والexpansion valve بتعمل فعالية لما يكون لي refrigerant داخل عليها صار سائل وهيدي مش الحالة لي عنا لأن استخدمنا الهواء

الthrottle valve بتعمل فرق ضغط مفاجئ للrefrigerant قبل وبعد

الseparator هي المكان لي بينفصل فيه الغاز عن السائل بعد ما خسر ضغطه

Throttle valve: ما وضعناها لأنها غالية ومخصصة لحسب نوع الغاز

وضعنا بدلها والexpansion valve

والexpansion valve هو الcapillary pipe لي على شكل spring

وتابع له الfilter drier لي موجود قبله

16.5.3 System Test 14 March 2025

We disconnected the heat exchanger of the refrigerator, which operates at -80°C, due to a malfunction in one of its compressors and an incorrect connection of the 9 heat exchangers inside it. This error occurred because the expansion valves for each cycle were not removed before welding them together. The system was then reconnected according to the scheme above.

The test was conducted using 2 bar of air instead of the refrigerants R-134, R-290, or R-744. During the test, we observed a cooling effect of 1°C.

However, after a few seconds, the compressor began to overheat.

This below is the high pressure side of the compressor:

When we open the system, the high pressure side gets pressurized.

The low-pressure side was kept at 2 bar pressure, and it didn’t change.

16.5.4 System test 19.3.25 (Video)

WhatsApp Video
2025-03-19 at 15.11.3

		 Exit of separator

	 22 °C

Starting the compressor: 	
	 21.5 °C


0
2
4
6
8
10
12
14
16
18
20
0
50
100
150
200
250
300
psi
bar

12 bar


INTELLIGENT METER
PV
21.6
SV
10.0

21.6 °C

16.6 What‘s next

16.6.1 Testing with butane as working fluid

TODOs:

Changing compressor: integration of compressor which was used for biogas(methan) compression

16.6.2 Repairing -80 °C refrigator

- Actual malfunction in one of its compressors
- and an actually incorrect connection of the 9 heat exchangers inside it (9 expansion valves inside to be deleted).

16.6.3 ICPT LOX Compressor Development[49]

to be done:

- Specification of Oil Free Compressor for LOX Testrig (M. El Rez)

- Design of Oil Free Compressor for LOX Testrig (M. El Rez/J.Bachir)

- Manufactoring Oil Free Compressor for LOX Testrig (J. Bachir)

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[49] Ref : https://aecenar.com/index.php/institutes/icpt/liquefication-of-air-and-oxygen/icpt-lox-compressor-development

16.6.4 Further

To complete the practical part of the LOX project, it is necessary to replace the pipes inside the cooling system and to purchase the oil-free compressor and several other equipment. Based on compressor selection, the features and design of the heater, and mixer will be determined, and the remote control will be finalized. After completing these steps, we will be ready to perform the first run.

17 Project F 22: Ammonia production (ICPT - AP)

17.1 Position of AP project

This project starts in September 19, 2022 in an aim to store Hydrogen gas as a fuel. It is based on the reaction between Hydrogen gas and Nitrogen gas to produce Ammonia gas in specific reaction conditions.

17.2 Introduction

17.2.1 General Introduction

Nitrogen and hydrogen combine to generate the inorganic substance ammonia, which has the formula NH_3. Ammonia is an odorless, colorless gas with a characteristic unpleasant odor. It is a stable binary hydride and the simplest pnictogen hydride. It contributes considerably to the nutritional demands of terrestrial creatures by serving as a precursor to 45 percent of the world's food and fertilizers. Biologically, it is a common nitrogenous waste, especially among aquatic animals. About 70% of ammonia is used to create fertilizers, including urea and diammonium phosphate, in a variety of shapes and compositions. Additionally, pure ammonia is sprayed straight onto the ground. About 40% of the nitrogen in people is thought to have originated from the manufacturing of industrial ammonia. Its significance can therefore hardly be emphasized.

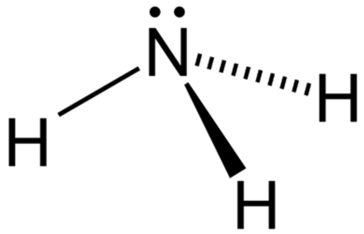


Figure 1 Stereo structural formula of the ammonia molecule.

Ammonia is also a key ingredient in many commercial cleaning solutions and is a building component for the manufacture of numerous medicinal medicines. It is mostly gathered through the displacement of both air and water downward. Although ammonia is widely used and found in nature on Earth and on the outer planets of the Solar System, it is dangerous and caustic when it is concentrated. Facilities that produce, store, or utilize it in sizable amounts are subject to severe reporting requirements in many nations because it is categorized as an exceedingly hazardous material.

A solution of ammonia in water is referred to as ammonia solution, ammonia water, ammonium hydroxide, aqua ammonia, aqueous ammonia, or (inaccurately) ammonia. You can represent it with the symbols NH3 (aq). It is hard to isolate samples of NH4OH, despite the term ammonium hydroxide suggesting an alkali with composition [NH4+][OH]. Except in extremely diluted solutions, the ions NH4+ and OH do not contribute significantly to the total quantity of ammonia.

The creation of ammonia from the elements hydrogen and nitrogen is challenging for fundamental reasons, requiring high pressures and high temperatures. At the start of the twentieth century, the Haber process—which made industrial production possible—revolutionized agriculture.

NH3 must be stored under pressure or at a low temperature because it boils at 33.34 °C (or 28.012 °F) at a pressure of one atmosphere. NH3 is dissolved in water to form household ammonia, also known as ammonium hydroxide. The density of such solutions is measured in units of the Baumé scale, with 26 degrees Baumé being the usual high-concentration commercial product (about 30% (by weight) ammonia at 15.5 °C or 59.9 °F).

17.2.2 Properties

Ammonia is a colourless gas with a characteristically pungent smell. It is lighter than air, its density being 0.589 times that of air. It is easily liquefied due to the strong hydrogen bonding between molecules; the liquid boils at −33.1 °C (−27.58 °F), and freezes to white crystals[23] at −77.7 °C (−107.86 °F).

a) Solid

The crystal symmetry is cubic, Pearson symbol cP16, space group P213 No.198, lattice constant 0.5125 nm.

b) Liquid

Liquid ammonia possesses strong ionising powers reflecting its high ε of 22. Liquid ammonia has a very high standard enthalpy change of vaporization (23.35 kJ/mol, cf. water 40.65 kJ/mol, methane 8.19 kJ/mol, phosphine 14.6 kJ/mol) and can therefore be used in laboratories in uninsulated vessels without additional refrigeration. See liquid ammonia as a solvent.

c) Solvent properties

Ammonia readily dissolves in water. In an aqueous solution, it can be expelled by boiling. The aqueous solution of ammonia is basic. The maximum concentration of ammonia in water (a saturated solution) has a density of 0.880 g/cm3 and is often known as '.880 ammonia'.

d) Combustion

Ammonia does not burn readily or sustain combustion, except under narrow fuel-to-air mixtures of 15–25% air. When mixed with oxygen, it burns with a pale yellowish-green flame. Ignition occurs when chlorine is passed into ammonia, forming nitrogen and hydrogen chloride; if chlorine is present in excess, then the highly explosive nitrogen trichloride (NCl3) is also formed.

e) Decomposition

At high temperature and in the presence of a suitable catalyst or in a pressurized vessel with constant volume and high temperature (e.g. 1,100 °C (2,010 °F)), ammonia is decomposed into its constituent elements. Decomposition of ammonia is a slightly endothermic process requiring 23 kJ/mol (5.5 kcal/mol) of ammonia, and yields hydrogen and nitrogen gas. Ammonia can also be used as a source of hydrogen for acid fuel cells if the unreacted ammonia can be removed. Ruthenium and platinum catalysts were found to be the most active, whereas supported Ni catalysts were less active.

17.2.3 Structure

The ammonia molecule has a trigonal pyramidal shape as predicted by the valence shell electron pair repulsion theory (VSEPR theory) with an experimentally determined bond angle of 106.7°. The central nitrogen atom has five outer electrons with an additional electron from each hydrogen atom. This gives a total of eight electrons, or four electron pairs that are arranged tetrahedrally. Three of these electron pairs are used as bond pairs, which leaves one lone pair of electrons. The lone pair repels more strongly than bond pairs, therefore the bond angle is not 109.5°, as expected for a regular tetrahedral arrangement, but 106.8°. This shape gives the molecule a dipole moment and makes it polar. The molecule's polarity, and especially, its ability to form hydrogen bonds, makes ammonia highly miscible with water. The lone pair makes ammonia a base, a proton acceptor. Ammonia is moderately basic; a 1.0 M aqueous solution has a pH of 11.6, and if a strong acid is added to such a solution until the solution is neutral (pH = 7), 99.4% of the ammonia molecules are protonated. Temperature and salinity also affect the proportion of NH4+. The latter has the shape of a regular tetrahedron and is isoelectronic with methane.

The ammonia molecule readily undergoes nitrogen inversion at room temperature; a useful analogy is an umbrella turning itself inside out in a strong wind. The energy barrier to this inversion is 24.7 kJ/mol, and the resonance frequency is 23.79 GHz, corresponding to microwave radiation of a wavelength of 1.260 cm. The absorption at this frequency was the first microwave spectrum to be observed [30] and was used in the first maser.

17.3 Amphotericity

One of the most characteristic properties of ammonia is its basicity. Ammonia is considered to be a weak base. It combines with acids to form salts; thus with hydrochloric acid it forms ammonium chloride (sal ammoniac); with nitric acid, ammonium nitrate, etc. Perfectly dry ammonia gas will not combine with perfectly dry hydrogen chloride gas; moisture is necessary to bring about the reaction.

As a demonstration experiment under air with ambient moisture, opened bottles of concentrated ammonia and hydrochloric acid solutions produce a cloud of ammonium chloride, which seems to appear "out of nothing" as the salt aerosol forms where the two diffusing clouds of reagents meet between the two bottles.

$$NH_3 + HCl \rightarrow [NH_4]Cl$$

The salts produced by the action of ammonia on acids are known as the ammonium salts and all contain the ammonium ion (NH+4).

Although ammonia is well known as a weak base, it can also act as an extremely weak acid. It is a protic substance and is capable of formation of amides (which contain the NH−2 ion). For example, lithium dissolves in liquid ammonia to give a blue solution (solvated electron) of lithium amide:

$$2\ Li + 2\ NH_3 \rightarrow 2\ LiNH_2 + H_2$$

17.4 Self-dissociation

Like water, liquid ammonia undergoes molecular auto-ionisation to form its acid and base conjugates:

$$2\ NH_3 \rightleftharpoons NH_4^+ + NH^{2-}$$

Ammonia often functions as a weak base, so it has some buffering ability. Shifts in pH will cause more or fewer ammonium cations (NH4+) and amide anions (NH2-) to be present in solution. At standard pressure and temperature,

$K = [NH_4^+] \times [NH_2^-] = 10^{-30}$.

17.5 Combustion

The combustion of ammonia to form nitrogen and water is exothermic:

$4\ NH_3 + 3\ O_2 \rightarrow 2\ N_2 + 6\ H_2O(g)$, $\Delta H°_r = -1267.20$ kJ (or −316.8 kJ/mol if expressed per mol of NH_3)

The standard enthalpy change of combustion, ΔH°c, expressed per mole of ammonia and with condensation of the water formed, is −382.81 kJ/mol. Dinitrogen is the thermodynamic product of combustion: all nitrogen oxides are unstable with respect to N2 and O2, which is the principle behind the catalytic converter. Nitrogen oxides can be formed as kinetic products in the presence of appropriate catalysts, a reaction of great industrial importance in the production of nitric acid:

$$4\ NH_3 + 5\ O_2 \rightarrow 4\ NO + 6\ H_2O$$

A subsequent reaction leads to NO2:

$$2\ NO + O_2 \rightarrow 2\ NO_2$$

The combustion of ammonia in air is very difficult in the absence of a catalyst (such as platinum gauze or warm chromium(III) oxide), due to the relatively low heat of combustion, a lower laminar burning velocity, high auto-ignition temperature, high heat of vaporization, and a narrow flammability range. However, recent studies have shown that efficient and stable combustion of ammonia can be achieved using swirl combustors, thereby rekindling research interest in ammonia as a fuel for thermal power production. The flammable range of ammonia in dry air is 15.15–27.35% and in 100% relative humidity air is 15.95–26.55%. For studying the kinetics of ammonia combustion, knowledge of a detailed reliable reaction mechanism is required, but this has been challenging to obtain.

17.6 Formation of other compounds

Ammonia is a direct or indirect precursor to most manufactured nitrogen-containing compounds.

In organic chemistry, ammonia can act as a nucleophile in substitution reactions. Amines can be formed by the reaction of ammonia with alkyl halides or with alcohols. The resulting −NH2 group is also nucleophilic so secondary and tertiary amines are often formed. When such multiple substitution is not desired, an excess of ammonia helps minimise it. For example, methylamine is prepared by the reaction of ammonia with chloromethane or with methanol. In both cases, dimethylamine and trimethylamine are co-produced. Ethanolamine is prepared by a ring-opening reaction with ethylene oxide, and when the reaction is allowed to go further it produces diethanolamine and triethanolamine. The reaction of ammonia with 2-bromopropanoic acid has been used to prepare racemic alanine in 70% yield.

Amides can be prepared by the reaction of ammonia with carboxylic acid derivatives. For example, ammonia reacts with formic acid (HCOOH) to yield formamide (HCONH2) when heated. Acyl chlorides are the most reactive, but the ammonia must be present in at least a twofold excess to neutralise the hydrogen chloride formed. Esters and anhydrides also react with ammonia to form amides. Ammonium salts of carboxylic acids can be dehydrated to amides by heating to 150–200 °C as long as no thermally sensitive groups are present.

The hydrogen in ammonia is susceptible to replacement by a myriad of substituents. When dry ammonia gas is heated with metallic sodium it converts to sodamide, NaNH2.[31] With chlorine, monochloramine is formed.

Pentavalent ammonia is known as λ5-amine or, more commonly, ammonium hydride. This crystalline solid is only stable under high pressure and decomposes back into trivalent ammonia and hydrogen gas at normal conditions. This substance was once investigated as a possible solid rocket fuel in 1966.

17.7 History

The ancient Greek historian Herodotus mentioned that there were outcrops of salt in an area of Libya that was inhabited by a people called the "Ammonians" (now: the Siwa oasis in northwestern Egypt, where salt lakes still exist). The Greek geographer Strabo also mentioned the salt from this region. However, the ancient authors Dioscorides, Apicius, Arrian, Synesius, and Aëtius of Amida described this salt as forming clear crystals that could be used for cooking and that were essentially rock salt.[44] Hammoniacus sal appears in the writings of Pliny, although it is not known whether the term is identical with the more modern sal ammoniac (ammonium chloride).

The fermentation of urine by bacteria produces a solution of ammonia; hence fermented urine was used in Classical Antiquity to wash cloth and clothing, to remove hair from hides in preparation for tanning, to serve as a mordant in dying cloth, and to remove rust from iron. It was also used by ancient dentists to wash teeth.

In the form of sal ammoniac (نشادر, nushadir), ammonia was important to the Muslim alchemists.

It was mentioned in the Book of Stones, likely written in the 9th century and attributed to Jābir ibn Hayyān. It was also important to the European alchemists of the 13th century, being mentioned by Albertus Magnus. It was also used by dyers in the Middle Ages in the form of fermented urine to alter the colour of vegetable dyes. In the 15th century, Basilius Valentinus showed that ammonia could be obtained by the action of alkalis on sal ammoniac. At a later period, when sal ammoniac was obtained by distilling the hooves and horns of oxen and neutralizing the resulting carbonate with hydrochloric acid, the name "spirit of hartshorn" was applied to ammonia.

Gaseous ammonia was first isolated by Joseph Black in 1756 by reacting sal ammoniac (ammonium chloride) with calcined magnesia (magnesium oxide). It was isolated again by Peter Woulfe in 1767, by Carl Wilhelm Scheele in 1770 and by Joseph Priestley in 1773 and was termed by him "alkaline air". Eleven years later in 1785, Claude Louis Berthollet ascertained its composition.

The Haber–Bosch process to produce ammonia from the nitrogen in the air was developed by Fritz Haber and Carl Bosch in 1909 and patented in 1910. It was first used on an industrial scale in Germany during World War I, following the allied blockade that cut off the supply of nitrates from Chile. The ammonia was used to produce explosives to sustain war efforts.

Before the availability of natural gas, hydrogen as a precursor to ammonia production was produced via the electrolysis of water or using the chloralkali process.

With the advent of the steel industry in the 20th century, ammonia became a byproduct of the production of coking coal.

17.8 Applications

17.8.1 Fertilizer

In the US as of 2019, approximately 88% of ammonia was used as fertilizers either as its salts, solutions or anhydrously. When applied to soil, it helps provide increased yields of crops such as maize and wheat. 30% of agricultural nitrogen applied in the US is in the form of anhydrous ammonia and worldwide 110 million tonnes are applied each year.

17.8.2 Precursor to nitrogenous compounds

Ammonia is directly or indirectly the precursor to most nitrogen-containing compounds. Virtually all synthetic nitrogen compounds are derived from ammonia. An important derivative is nitric acid. This key material is generated via the Ostwald process by oxidation of ammonia with air over a platinum catalyst at 700–850 °C (1,292–1,562 °F), ≈9 atm. Nitric oxide is an intermediate in this conversion:

$$NH_3 + 2\,O_2 \rightarrow HNO_3 + H_2O$$

Nitric acid is used for the production of fertilizers, explosives, and many organonitrogen compounds.

Ammonia is also used to make the following compounds:

- Hydrazine, in the Olin Raschig process and the peroxide process
- Hydrogen cyanide, in the BMA process and the Andrussow process
- Hydroxylamine and ammonium carbonate, in the Raschig process
- Phenol, in the Raschig–Hooker process
- Urea, in the Bosch–Meiser urea process and in Wöhler synthesis
- Amino acids, using Strecker amino-acid synthesis
- Acrylonitrile, in the Sohio process

Ammonia can also be used to make compounds in reactions which are not specifically named. Examples of such compounds include: ammonium perchlorate, ammonium ______nitrate, formamide, dinitrogen tetroxide, alprazolam, ethanolamine, ethyl carbamate, hexamethylenetetramine, and ammonium bicarbonate.

17.8.3 Fuel

The raw energy density of liquid ammonia is 11.5 MJ/L, which is about a third that of diesel. There is the opportunity to convert ammonia back to hydrogen, where it can be used to power hydrogen fuel cells, or it may be used directly within high-temperature solid oxide direct ammonia fuel cells to provide efficient power sources that do not emit greenhouse gases.

The conversion of ammonia to hydrogen via the sodium amide process, either for combustion or as fuel for a proton exchange membrane fuel cell, is possible. Another method is the catalytic decomposition of ammonia using solid catalysts. Conversion to hydrogen would allow the storage of hydrogen at nearly 18 wt% compared to ≈5% for gaseous hydrogen under pressure.

Ammonia engines or ammonia motors, using ammonia as a working fluid, have been proposed and occasionally used. The principle is similar to that used in a fireless locomotive, but with ammonia as the working fluid, instead of steam or compressed air. Ammonia engines were used experimentally in the 19th century by Goldsworthy Gurney in the UK and the St. Charles Avenue Streetcar line in New Orleans in the 1870s and 1880s, and during World War II ammonia was used to power buses in Belgium.

Figure 2 Ammoniacal Gas Engine Streetcar in New Orleans drawn by Alfred Waud in 1871.

Ammonia is sometimes proposed as a practical alternative to fossil fuel for internal combustion engines.

Its high octane rating of 120 and low flame temperature allows the use of high compression ratios without a penalty of high NOx production. Since ammonia contains no carbon, its combustion cannot produce carbon dioxide, carbon monoxide, hydrocarbons, or soot.

Ammonia production currently creates 1.8% of global CO2 emissions. "Green ammonia" is ammonia produced by using green hydrogen (hydrogen produced by electrolysis), whereas "blue ammonia" is ammonia produced using blue hydrogen (hydrogen produced by steam methane reforming where the carbon dioxide has been captured and stored).

However, ammonia cannot be easily used in existing Otto cycle engines because of its very narrow flammability range, and there are also other barriers to widespread automobile usage. In terms of raw ammonia supplies, plants would have to be built to increase production levels, requiring significant capital and energy sources. Although it is the second most produced chemical (after sulfuric acid), the scale of ammonia production is a small fraction of world petroleum usage. It could be manufactured from renewable energy sources, as well as coal or nuclear power. The 60 MW Rjukan dam in Telemark, Norway, produced ammonia for many years from 1913, providing fertilizer for much of Europe.

Despite this, several tests have been run. In 1981, a Canadian company converted a 1981 Chevrolet Impala to operate using ammonia as fuel. In 2007, a University of Michigan pickup powered by ammonia drove from Detroit to San Francisco as part of a demonstration, requiring only one fill-up in Wyoming.

Compared to hydrogen as a fuel, ammonia is much more energy efficient, and could be produced, stored, and delivered at a much lower cost than hydrogen, which must be kept compressed or as a cryogenic liquid.

Rocket engines have also been fueled by ammonia. The Reaction Motors XLR99 rocket engine that powered the X-15 hypersonic research aircraft used liquid ammonia. Although not as powerful as other fuels, it left no soot in the reusable rocket engine, and its density approximately matches the density of the oxidizer, liquid oxygen, which simplified the aircraft's design.

In early August 2018, scientists from Australia's Commonwealth Scientific and Industrial Research Organisation (CSIRO) announced the success of developing a process to release hydrogen from ammonia and harvest that at ultra-high purity as a fuel for cars. This uses a special membrane. Two demonstration fuel cell vehicles have the technology, a Hyundai Nexo and Toyota Mirai.

In 2020, Saudi Arabia shipped forty metric tons of liquid "blue ammonia" to Japan for use as a fuel. It was produced as a by-product by petrochemical industries, and can be burned without giving off greenhouse gases. Its energy density by volume is nearly double that of liquid hydrogen. If the process of creating it can be scaled up via purely renewable resources, producing green ammonia, it could make a major difference in avoiding climate change. The company ACWA Power and the city of Neom have announced the construction of a green hydrogen and ammonia plant in 2020.

Green ammonia is considered as a potential fuel for future container ships. In 2020, the companies DSME and MAN Energy Solutions announced the construction of an ammonia-based ship, DSME plans to commercialize it by 2025. The use of ammonia as a potential alternative fuel for aircraft jet engines is also being explored.

Japan is targeting to bring forward a plan to develop ammonia co-firing technology that can increase the use of ammonia in power generation, as part of efforts to assist domestic and other Asian utilities to accelerate their transition to carbon neutrality. In October 2021, the first International Conference on Fuel Ammonia (ICFA2021) was held.

In June 2022, IHI Corporation succeeded in reducing greenhouse gases by over 99% during combustion of liquid ammonia in a 2,000-kilowatt-class gas turbine achieving truly CO_2-free power generation. In July 2022, Quad nations of Japan, the U.S., Australia and India agreed to promote technological development for clean-burning hydrogen and ammonia as fuels at the security grouping's first energy meeting.

17.8.4 Solvent

Liquid ammonia is the best-known and most widely studied nonaqueous ionising solvent. Its most conspicuous property is its ability to dissolve alkali metals to form highly coloured, electrically conductive solutions containing solvated electrons. Apart from these remarkable solutions, much of the chemistry in liquid ammonia can be classified by analogy with related reactions in aqueous solutions. Comparison of the physical properties of NH_3 with those of water shows NH_3 has the lower melting point, boiling point, density, viscosity, dielectric constant and electrical conductivity; this is due at least in part to the weaker hydrogen bonding in NH_3 and because such bonding cannot form cross-linked networks, since each NH_3 molecule has only one lone pair of electrons compared with two for each H_2O molecule. The ionic self-dissociation constant of liquid NH_3 at −50 °C is about 10^{-33}.

17.8.5 Cleansing agent

Household "ammonia" (or more correctly called ammonium hydroxide) is a solution of NH_3 in water, and is used as a general purpose cleaner for many surfaces. Because ammonia results in a relatively streak-free shine, one of its most common uses is to clean glass, porcelain and stainless steel. It is also frequently used for cleaning ovens and soaking items to loosen baked-on grime. Household ammonia ranges in concentration by weight from 5 to 10% ammonia. United States manufacturers of cleaning products are required to provide the product's material safety data sheet which lists the concentration used.

Solutions of ammonia (5–10% by weight) are used as household cleaners, particularly for glass. These solutions are irritating to the eyes and mucous membranes (respiratory and digestive tracts), and to a lesser extent the skin. Experts advise that caution be used to ensure the substance is not mixed into any liquid containing bleach, due to the danger of toxic gas. Mixing with chlorine-containing products or strong oxidants, such as household bleach, can generate chloramines.

Experts also warn not to use ammonia-based cleaners (such as glass or window cleaners) on car touchscreens, due to the risk of damage to the screen's anti-glare and anti-fingerprint coatings.

17.8.6 Fermentation

Solutions of ammonia ranging from 16% to 25% are used in the fermentation industry as a source of nitrogen for microorganisms and to adjust pH during fermentation.

17.8.7 Antimicrobial agent for food products

As early as in 1895, it was known that ammonia was "strongly antiseptic ... it requires 1.4 grams per litre to preserve beef tea (broth)." In one study, anhydrous ammonia destroyed 99.999% of zoonotic bacteria in 3 types of animal feed, but not silage. Anhydrous ammonia is currently used commercially to reduce or eliminate microbial contamination of beef. Lean finely textured beef (popularly known as "pink slime") in the beef industry is made from fatty beef trimmings (c. 50–70% fat) by removing the fat using heat and centrifugation, then treating it with ammonia to kill *E. coli*. The process was deemed effective and safe by the US Department of Agriculture based on a study that found that the treatment reduces *E. coli* to undetectable levels. There have been safety concerns about the process as well as consumer complaints about the taste and smell of ammonia-treated beef.

What prospects does green ammonia have?

Additional possibilities for the transition to net-zero carbon dioxide emissions may be provided by the manufacture of green ammonia. These consist of:

Ammonia is easily kept in large quantities as a liquid at low pressures (10–15 bar) or chilled to –33 °C. It is therefore the perfect chemical storage system for renewable energy. Ammonia is currently distributed around the world via a network of pipes, road tankers, and ships to transfer it from massive chilled tanks.

Ammonia is a zero-carbon fuel that may be burned in an engine or converted into power in a fuel cell. The only by-products of ammonia use are water and nitrogen. The maritime sector is most likely to replace the use of fuel oil in marine engines as an early adopter.

Hydrogen carrier - although hydrogen gas is employed in some applications (such as PEM fuel cells), it is difficult and expensive to store in large quantities (needing cryogenic tanks or high-pressure cylinders). Ammonia is simpler to store, transport, and purify, and it can easily be "cracked" when needed to produce hydrogen gas.

17.9 Electrochemical Synthesis of Ammonia

1) Electrochemical Production (Electrolysis)

$$N_2 + 3H_2 \leftrightarrow 2NH_3 \qquad (1)$$

The fact that protons and electrons were required for the reaction to be completed suggested that ammonia may be generated electrochemically. To do this, numerous research teams evaluated the performance of aqueous electrochemical cells that generated NH_3 from H_2O and N_2. However, the fact that these cells required to function at low temperatures where reaction kinetics were slow presented a challenge.

Solid state materials with significantly high proton (H^+) conductivity at high temperatures (500–1000 °C) were found in 1981 by Iwahara and colleagues. Experimental evidence of the electrochemical synthesis of ammonia from its constituent parts was presented in 1998 using a high-temperature solid electrolyte cell of this type (Fig. 1).

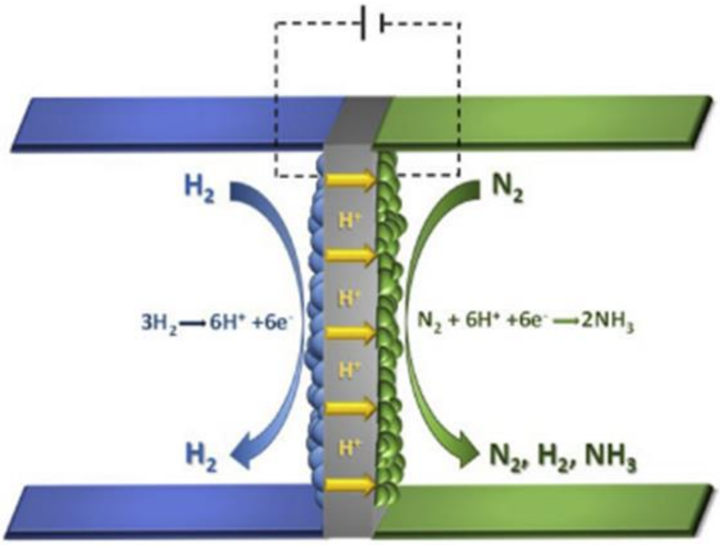


Fig. 1. Schematic diagram of the solid state ammonia synthesis (SSAS) process in a double chamber proton conducting reactor cell.

The procedure was easy. H^+ was created as gaseous hydrogen passed over the proton conducting cell's anodic electrode. The generated protons were electrochemically carried to the cathode by applying the correct voltage, where they interacted with gaseous nitrogen to make ammonia. Because the high-pressure need was balanced by the expenditure of electrical energy, the cell operated at atmospheric pressure.

In an effort to increase reaction rates and reduce electric energy consumption, various research teams have researched the Solid-State Ammonia Synthesis (SSAS) over the past 20 years. Amar et al., Giddey et al., and Garagounis et al. recently examined the key findings from research published prior to 2013.

The current review provides an update on the development of liquid and solid electrolyte cells used in the electrochemical production of ammonia. The experimental studies are separated into three groups based on the operational temperature range: high temperature (T > 500 °C), intermediate temperature (500 °C > T > 100 °C), and low temperature (T 100 °C).

2) Electrochemical Synthesis at High Temperatures

The reported data on the electrochemical synthesis of ammonia at high temperatures (T > 500°C) up until the end of 2015 are listed in Table 1.

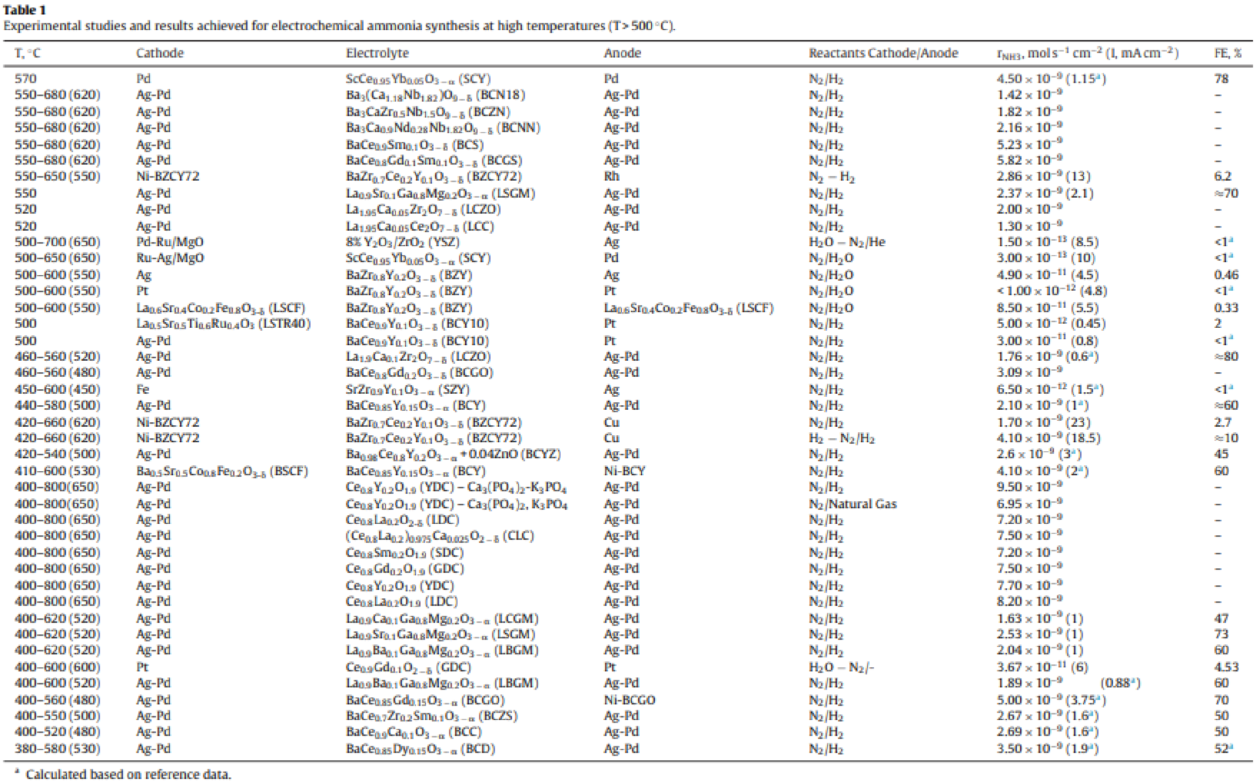


Table 1
Experimental studies and results achieved for electrochemical ammonia synthesis at high temperatures (T > 500 °C).

T, °C	Cathode	Electrolyte	Anode	Reactants Cathode/Anode	r_{NH_3}, mol s^{-1} cm^{-2} (I, mA cm^{-2})	FE, %
570	Pd	$ScCe_{0.95}Yb_{0.05}O_{3-\alpha}$ (SCY)	Pd	N_2/H_2	4.50×10^{-9} (1.15[a])	78
550–680 (620)	Ag-Pd	$Ba_3(Ca_{1.18}Nb_{1.82})O_{9-\delta}$ (BCN18)	Ag-Pd	N_2/H_2	1.42×10^{-9}	–
550–680 (620)	Ag-Pd	$Ba_3CaZr_{0.5}Nb_{1.5}O_{9-\delta}$ (BCZN)	Ag-Pd	N_2/H_2	1.82×10^{-9}	–
550–680 (620)	Ag-Pd	$Ba_3Ca_{0.9}Nd_{0.28}Nb_{1.82}O_{9-\delta}$ (BCNN)	Ag-Pd	N_2/H_2	2.16×10^{-9}	–
550–680 (620)	Ag-Pd	$BaCe_{0.9}Sm_{0.1}O_{3-\delta}$ (BCS)	Ag-Pd	N_2/H_2	5.23×10^{-9}	–
550–680 (620)	Ag-Pd	$BaCe_{0.8}Gd_{0.1}Sm_{0.1}O_{3-\delta}$ (BCGS)	Ag-Pd	N_2/H_2	5.82×10^{-9}	–
550–650 (550)	Ni-BZCY72	$BaZr_{0.7}Ce_{0.2}Y_{0.1}O_{3-\delta}$ (BZCY72)	Rh	$N_2 - H_2$	2.86×10^{-9} (13)	6.2
550	Ag-Pd	$La_{0.9}Sr_{0.1}Ga_{0.8}Mg_{0.2}O_{3-\alpha}$ (LSGM)	Ag-Pd	N_2/H_2	2.37×10^{-9} (2.1)	≈70
520	Ag-Pd	$La_{1.95}Ca_{0.05}Zr_2O_{7-\delta}$ (LCZO)	Ag-Pd	N_2/H_2	2.00×10^{-9}	–
520	Ag-Pd	$La_{1.95}Ca_{0.05}Ce_2O_{7-\delta}$ (LCC)	Ag-Pd	N_2/H_2	1.30×10^{-9}	–
500–700 (650)	Pd-Ru/MgO	8% Y_2O_3/ZrO_2 (YSZ)	Ag	$H_2O - N_2/He$	1.50×10^{-13} (8.5)	<1[a]
500–650 (650)	Ru-Ag/MgO	$ScCe_{0.95}Yb_{0.05}O_{3-\alpha}$ (SCY)	Pd	N_2/H_2O	3.00×10^{-13} (10)	<1[a]
500–600 (550)	Ag	$BaZr_{0.8}Y_{0.2}O_{3-\delta}$ (BZY)	Ag	N_2/H_2O	4.90×10^{-11} (4.5)	0.46
500–600 (550)	Pt	$BaZr_{0.8}Y_{0.2}O_{3-\delta}$ (BZY)	Pt	N_2/H_2O	$< 1.00 \times 10^{-12}$ (4.8)	<1[a]
500–600 (550)	$La_{0.6}Sr_{0.4}Co_{0.2}Fe_{0.8}O_{3-\delta}$ (LSCF)	$BaZr_{0.8}Y_{0.2}O_{3-\delta}$ (BZY)	$La_{0.6}Sr_{0.4}Co_{0.2}Fe_{0.8}O_{3-\delta}$ (LSCF)	N_2/H_2O	8.50×10^{-11} (5.5)	0.33
500	$La_{0.5}Sr_{0.5}Ti_{0.6}Ru_{0.4}O_3$ (LSTR40)	$BaCe_{0.9}Y_{0.1}O_{3-\delta}$ (BCY10)	Pt	N_2/H_2	5.00×10^{-12} (0.45)	2
500	Ag-Pd	$BaCe_{0.9}Y_{0.1}O_{3-\delta}$ (BCY10)	Pt	N_2/H_2	3.00×10^{-11} (0.8)	<1[a]
460–560 (520)	Ag-Pd	$La_{1.9}Ca_{0.1}Zr_2O_{7-\delta}$ (LCZO)	Ag-Pd	N_2/H_2	1.76×10^{-9} (0.6[a])	≈80
460–560 (480)	Ag-Pd	$BaCe_{0.8}Gd_{0.2}O_{3-\delta}$ (BCGO)	Ag-Pd	N_2/H_2	3.09×10^{-9}	–
450–600 (450)	Fe	$SrZr_{0.9}Y_{0.1}O_{3-\alpha}$ (SZY)	Ag	N_2/H_2	6.50×10^{-12} (1.5[a])	<1[a]
440–580 (500)	Ag-Pd	$BaCe_{0.85}Y_{0.15}O_{3-\alpha}$ (BCY)	Ag-Pd	N_2/H_2	2.10×10^{-9} (1[a])	≈60
420–660 (620)	Ni-BZCY72	$BaZr_{0.7}Ce_{0.2}Y_{0.1}O_{3-\delta}$ (BZCY72)	Cu	N_2/H_2	1.70×10^{-9} (23)	2.7
420–660 (620)	Ni-BZCY72	$BaZr_{0.7}Ce_{0.2}Y_{0.1}O_{3-\delta}$ (BZCY72)	Cu	$H_2 - N_2/H_2$	4.10×10^{-9} (18.5)	≈10
420–540 (500)	Ag-Pd	$Ba_{0.98}Ce_{0.8}Y_{0.2}O_{3-\alpha}$ + 0.04ZnO (BCYZ)	Ag-Pd	N_2/H_2	2.6×10^{-9} (3[a])	45
410–600 (530)	$Ba_{0.5}Sr_{0.5}Co_{0.8}Fe_{0.2}O_{3-\delta}$ (BSCF)	$BaCe_{0.85}Y_{0.15}O_{3-\alpha}$ (BCY)	Ni-BCY	N_2/H_2	4.10×10^{-9} (2[a])	60
400–800(650)	Ag-Pd	$Ce_{0.8}Y_{0.2}O_{1.9}$ (YDC) – $Ca_3(PO_4)_2$-K_3PO_4	Ag-Pd	N_2/H_2	9.50×10^{-9}	–
400–800(650)	Ag-Pd	$Ce_{0.8}Y_{0.2}O_{1.9}$ (YDC) – $Ca_3(PO_4)_2$, K_3PO_4	Ag-Pd	N_2/Natural Gas	6.95×10^{-9}	–
400–800 (650)	Ag-Pd	$Ce_{0.8}La_{0.2}O_{2-\delta}$ (LDC)	Ag-Pd	N_2/H_2	7.20×10^{-9}	–
400–800 (650)	Ag-Pd	$(Ce_{0.8}La_{0.2})_{0.975}Ca_{0.025}O_{2-\delta}$ (CLC)	Ag-Pd	N_2/H_2	7.50×10^{-9}	–
400–800 (650)	Ag-Pd	$Ce_{0.8}Sm_{0.2}O_{1.9}$ (SDC)	Ag-Pd	N_2/H_2	7.20×10^{-9}	–
400–800 (650)	Ag-Pd	$Ce_{0.8}Gd_{0.2}O_{1.9}$ (GDC)	Ag-Pd	N_2/H_2	7.50×10^{-9}	–
400–800 (650)	Ag-Pd	$Ce_{0.8}Y_{0.2}O_{1.9}$ (YDC)	Ag-Pd	N_2/H_2	7.70×10^{-9}	–
400–800 (650)	Ag-Pd	$Ce_{0.8}La_{0.2}O_{1.9}$ (LDC)	Ag-Pd	N_2/H_2	8.20×10^{-9}	–
400–620 (520)	Ag-Pd	$La_{0.9}Ca_{0.1}Ga_{0.8}Mg_{0.2}O_{3-\alpha}$ (LCGM)	Ag-Pd	N_2/H_2	1.63×10^{-9} (1)	47
400–620 (520)	Ag-Pd	$La_{0.9}Sr_{0.1}Ga_{0.8}Mg_{0.2}O_{3-\alpha}$ (LSGM)	Ag-Pd	N_2/H_2	2.53×10^{-9} (1)	73
400–620 (520)	Ag-Pd	$La_{0.9}Ba_{0.1}Ga_{0.8}Mg_{0.2}O_{3-\alpha}$ (LBGM)	Ag-Pd	N_2/H_2	2.04×10^{-9} (1)	60
400–600 (600)	Pt	$Ce_{0.9}Gd_{0.1}O_{2-\delta}$ (GDC)	Pt	$H_2O - N_2$/-	3.67×10^{-11} (6)	4.53
400–600 (520)	Ag-Pd	$La_{0.9}Ba_{0.1}Ga_{0.8}Mg_{0.2}O_{3-\alpha}$ (LBGM)	Ag-Pd	N_2/H_2	1.89×10^{-9} (0.88[a])	60
400–560 (480)	Ag-Pd	$BaCe_{0.85}Gd_{0.15}O_{3-\alpha}$ (BCGO)	Ni-BCGO	N_2/H_2	5.00×10^{-9} (3.75[a])	70
400–550 (500)	Ag-Pd	$BaCe_{0.7}Zr_{0.2}Sm_{0.1}O_{3-\alpha}$ (BCZS)	Ag-Pd	N_2/H_2	2.67×10^{-9} (1.6[a])	50
400–520 (480)	Ag-Pd	$BaCe_{0.9}Ca_{0.1}O_{3-\alpha}$ (BCC)	Ag-Pd	N_2/H_2	2.69×10^{-9} (1.6[a])	50
380–580 (530)	Ag-Pd	$BaCe_{0.85}Dy_{0.15}O_{3-\alpha}$ (BCD)	Ag-Pd	N_2/H_2	3.50×10^{-9} (1.9[a])	52[a]

[a] Calculated based on reference data.

The maximal ammonia synthesis (and current density at which it was reached) and Faradaic Efficiency (FE) values attained while employing these materials are shown in this table together with the electrolytes and electrodes employed by various research organizations. Asterisks are used to indicate certain current density or FE values. These numbers were derived using the data provided in the specified reference even though they were not reported there. Additionally, in other instances no exact value is supplied because these works lacked the necessary details to enable its calculation. Similar tables have been created for research carried out at low and moderate temperatures (Tables 2 and 3, respectively)

In a reactor-cell architecture similar to that shown in Fig. 1, solid electrolytes were used in the majority of the research described in Table 1. The electrolyte substance used in the majority of these instances was perovskite. There have also been reports of materials with fluorite or pyrochlore structures being used as electrolytes. One group observed surprisingly high ammonia rates using a composite electrolyte made of calcium-potassium phosphate and YDC. The electrochemical processes at the two electrodes can be expressed as follows when, as in Fig. 1, the electrolyte is a proton conductor:

$$\textit{Anode}: 3H_2 \rightarrow 6H^+ + 6e^- \quad (3)$$

$$\textit{Cathode}: N_2 + 6H^+ + 6e^- \rightarrow 2NH_3 \quad (4)$$

Together, reactions (3) and (4) provide an overall reaction that is identical to reaction (1). The most frequent reactants at the anode and cathode, as shown in Table 1, were gaseous H_2 and N_2, respectively.

The highest rates have been noted over catalysts containing Pd. The cathodic electrode (catalyst) used in the initial SSAS experiments was Pd, and the greatest reaction rate recorded there was $4.5*10^{-9}$ mol s^{-1} cm^{-2}, while the highest FE was 78%.

Numerous researchers have examined Ag-activities Pd's over the last ten years. Li et al. observed reaction rates as high as $5.82*10^{-9}$ mol s^{-1} cm^{-2} using barium cerates (BCS, BCGS) as electrolytes.

Liu et al. achieved a reaction rate of $8.2*10^{-9}$ mol s^{-1} cm^{-2} using a lanthanum-doped cerium oxide electrolyte (LDC). The highest Faradaic Efficiencies have been produced using Ag-Pd electrodes in addition to having high reaction speeds. The FEs obtained by Zhang et al., Chen et al., and Xie et al. when utilizing lanthanum gallate and lanthanum zirconate electrolytes were 70%, 73%, and 80%, respectively.

The protonic conductivity of perovskite electrolytes has been shown to increase in the presence of water vapor (steam). In order to do this, the introduction of humidified hydrogen as opposed to dry hydrogen has also been tested on a variety of materials. Table 1 shows that greater reaction rates and FEs are produced with wet hydrogen over the anode when using barium cerate-based electrolytes.

The industrial process's preparation of the hydrogen input gas, more specifically its purification, accounts for a sizeable portion of the entire cost. Natural gas is the main source of hydrogen production. The latter contains substances that can contaminate the industrial catalyst even in minute concentrations. H_2 must therefore undergo substantial purification.

This prerequisite is not met by the electrochemical synthesis (Fig. 1) because only protons (H^+) are transported through the solid electrolyte. Furthermore, using gaseous H_2 is not required. Evidently, any substance containing hydrogen might be utilized.

Thus, the viability of SSAS from steam and nitrogen was demonstrated in 2009 utilizing the solid electrolyte cell of Fig. 2 and an Ag-Ru/MgO catalyst (cathode).

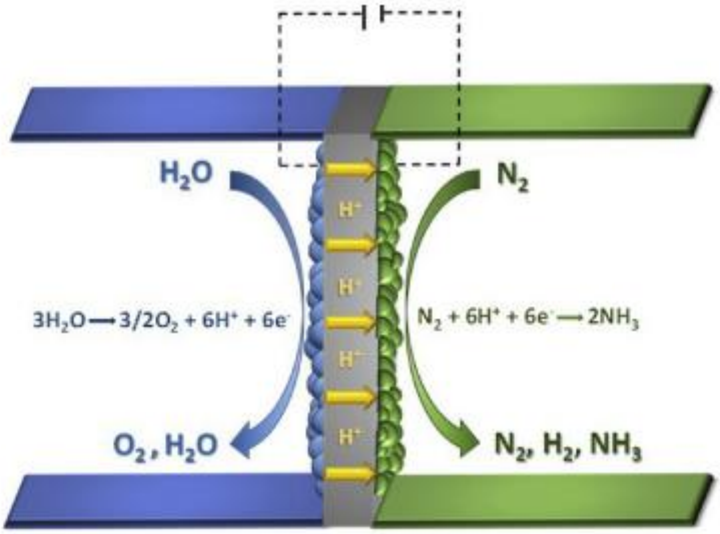


Fig. 2. A schematic of the SSAS process in a double chamber proton conducting cell with steam instead of molecular hydrogen as the source of protons.

Similar investigations using Pt and Ag electrodes came after. Using natural gas (CH_4) as the hydrogen source, Wang et al. examined the reaction at 650°C on an Ag-Pd cathode with a composite electrolyte made of YDC-$Ca_3(PO_4)_2$, K_3PO_4. One of the highest ammonia rates at these temperatures was $6.95*10^{-9}$ mol s^{-1} cm^{-2} that they could measure.

The usage of an oxygen-ion (O^{2-}) conductor for SSAS is schematically depicted in Fig. 3. The following processes result in ammonia when gaseous nitrogen and steam are combined:

$$\textit{Anode}: 3O^{2-} \rightarrow 3/2O_2 + 6e^- \quad (5)$$

$$\textit{Cathode}: N_2 + 3H_2O + 6e^- \rightarrow 2NH_3 + 3O^{2-} \quad (6)$$

$$\textit{Overall}: N_2 + 3H_2O \rightarrow 2NH_3 + 3/2O_2 \quad (7)$$

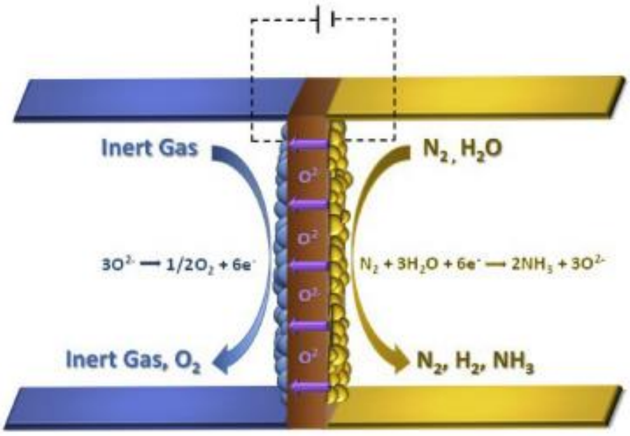


Fig. 3. A schematic of the SSAS process where an oxygen ion (O^{2-}) conductor is employed as the electrolyte.

In this instance, the cathode serves as the site for both steam electrolysis and ammonia production. Table 1 demonstrates that compared to the cells in Figure 1, the response rates in these O_2 cells were one to three orders of magnitude lower.

This is explained by the oxygen-containing molecules (H_2O) that are present near the cathode. Such a setup allows for the supply of gaseous fuel rather than inert gas to the anode. The oxygen pumped away from the cathode could oxidize this fuel, which could lower the energy needed for the in-situ synthesis of hydrogen (steam electrolysis). The entire process might even become spontaneous, fully negating the requirement for an electrical energy source, depending on the fuel and the operating temperature.

3) Electrochemical Synthesis at Intermediate Temperatures

The findings from tests carried out at intermediate temperatures, or between 100°C and 500°C, are presented in Table 2. Molten salts and composite materials were the two types of electrolytes used in these investigations.

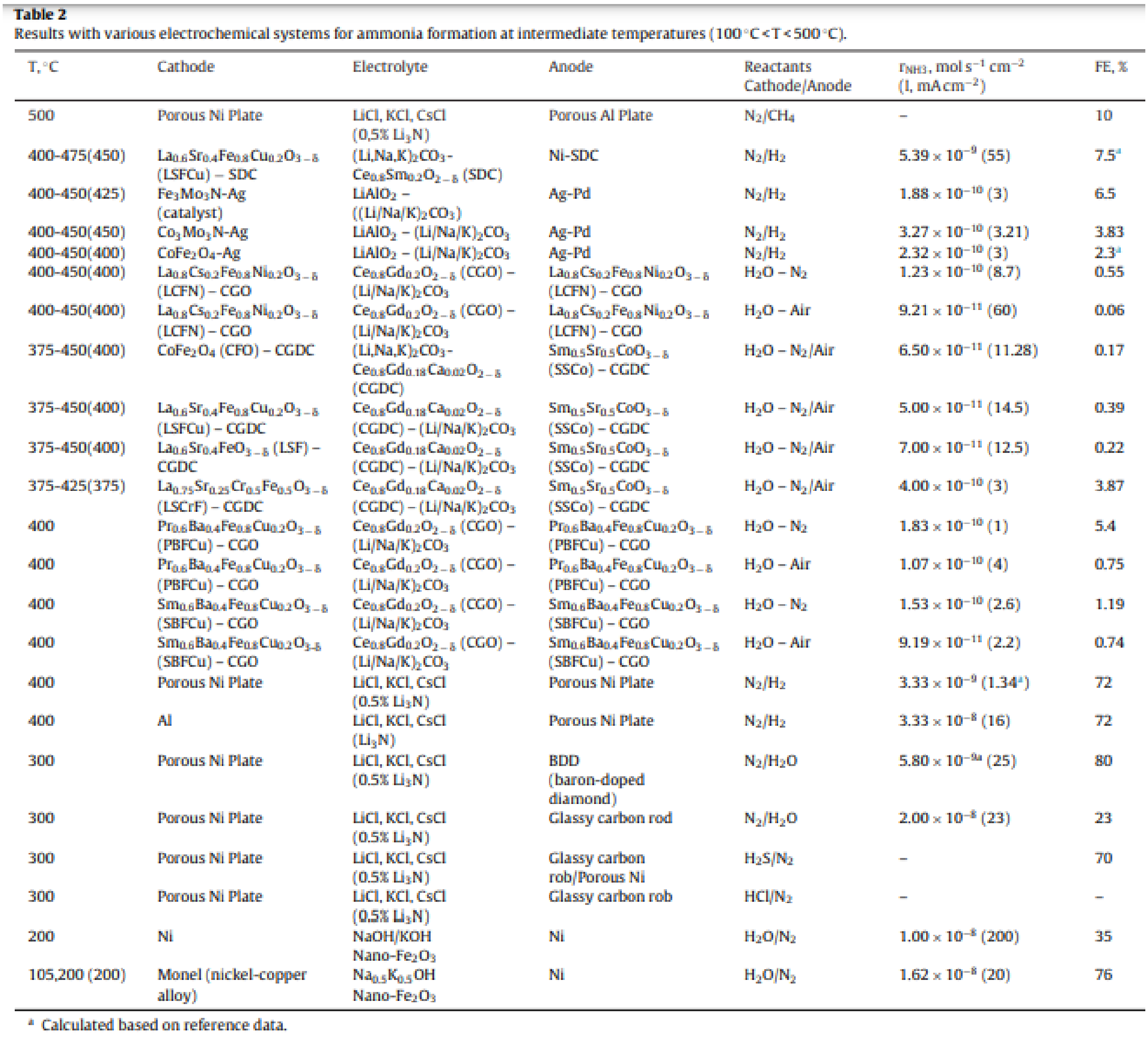


Table 2
Results with various electrochemical systems for ammonia formation at intermediate temperatures (100 °C < T < 500 °C).

T, °C	Cathode	Electrolyte	Anode	Reactants Cathode/Anode	r_{NH_3}, mol s^{-1} cm^{-2} (I, mA cm^{-2})	FE, %
500	Porous Ni Plate	LiCl, KCl, CsCl (0,5% Li_3N)	Porous Al Plate	N_2/CH_4	–	10
400-475(450)	$La_{0.6}Sr_{0.4}Fe_{0.8}Cu_{0.2}O_{3-\delta}$ (LSFCu) – SDC	$(Li,Na,K)_2CO_3$- $Ce_{0.8}Sm_{0.2}O_{2-\delta}$ (SDC)	Ni-SDC	N_2/H_2	5.39×10^{-9} (55)	7.5[a]
400-450(425)	Fe_3Mo_3N-Ag (catalyst)	$LiAlO_2$ – $((Li/Na/K)_2CO_3)$	Ag-Pd	N_2/H_2	1.88×10^{-10} (3)	6.5
400-450(450)	Co_3Mo_3N-Ag	$LiAlO_2$ – $(Li/Na/K)_2CO_3$	Ag-Pd	N_2/H_2	3.27×10^{-10} (3.21)	3.83
400-450(400)	$CoFe_2O_4$-Ag	$LiAlO_2$ – $(Li/Na/K)_2CO_3$	Ag-Pd	N_2/H_2	2.32×10^{-10} (3)	2.3[a]
400-450(400)	$La_{0.8}Cs_{0.2}Fe_{0.8}Ni_{0.2}O_{3-\delta}$ (LCFN) – CGO	$Ce_{0.8}Gd_{0.2}O_{2-\delta}$ (CGO) – $(Li/Na/K)_2CO_3$	$La_{0.8}Cs_{0.2}Fe_{0.8}Ni_{0.2}O_{3-\delta}$ (LCFN) – CGO	H_2O – N_2	1.23×10^{-10} (8.7)	0.55
400-450(400)	$La_{0.8}Cs_{0.2}Fe_{0.8}Ni_{0.2}O_{3-\delta}$ (LCFN) – CGO	$Ce_{0.8}Gd_{0.2}O_{2-\delta}$ (CGO) – $(Li/Na/K)_2CO_3$	$La_{0.8}Cs_{0.2}Fe_{0.8}Ni_{0.2}O_{3-\delta}$ (LCFN) – CGO	H_2O – Air	9.21×10^{-11} (60)	0.06
375-450(400)	$CoFe_2O_4$ (CFO) – CGDC	$(Li,Na,K)_2CO_3$- $Ce_{0.8}Gd_{0.18}Ca_{0.02}O_{2-\delta}$ (CGDC)	$Sm_{0.5}Sr_{0.5}CoO_{3-\delta}$ (SSCo) – CGDC	H_2O – N_2/Air	6.50×10^{-11} (11.28)	0.17
375-450(400)	$La_{0.6}Sr_{0.4}Fe_{0.8}Cu_{0.2}O_{3-\delta}$ (LSFCu) – CGDC	$Ce_{0.8}Gd_{0.18}Ca_{0.02}O_{2-\delta}$ (CGDC) – $(Li/Na/K)_2CO_3$	$Sm_{0.5}Sr_{0.5}CoO_{3-\delta}$ (SSCo) – CGDC	H_2O – N_2/Air	5.00×10^{-11} (14.5)	0.39
375-450(400)	$La_{0.6}Sr_{0.4}FeO_{3-\delta}$ (LSF) – CGDC	$Ce_{0.8}Gd_{0.18}Ca_{0.02}O_{2-\delta}$ (CGDC) – $(Li/Na/K)_2CO_3$	$Sm_{0.5}Sr_{0.5}CoO_{3-\delta}$ (SSCo) – CGDC	H_2O – N_2/Air	7.00×10^{-11} (12.5)	0.22
375-425(375)	$La_{0.75}Sr_{0.25}Cr_{0.5}Fe_{0.5}O_{3-\delta}$ (LSCrF) – CGDC	$Ce_{0.8}Gd_{0.18}Ca_{0.02}O_{2-\delta}$ (CGDC) – $(Li/Na/K)_2CO_3$	$Sm_{0.5}Sr_{0.5}CoO_{3-\delta}$ (SSCo) – CGDC	H_2O – N_2/Air	4.00×10^{-10} (3)	3.87
400	$Pr_{0.6}Ba_{0.4}Fe_{0.8}Cu_{0.2}O_{3-\delta}$ (PBFCu) – CGO	$Ce_{0.8}Gd_{0.2}O_{2-\delta}$ (CGO) – $(Li/Na/K)_2CO_3$	$Pr_{0.6}Ba_{0.4}Fe_{0.8}Cu_{0.2}O_{3-\delta}$ (PBFCu) – CGO	H_2O – N_2	1.83×10^{-10} (1)	5.4
400	$Pr_{0.6}Ba_{0.4}Fe_{0.8}Cu_{0.2}O_{3-\delta}$ (PBFCu) – CGO	$Ce_{0.8}Gd_{0.2}O_{2-\delta}$ (CGO) – $(Li/Na/K)_2CO_3$	$Pr_{0.6}Ba_{0.4}Fe_{0.8}Cu_{0.2}O_{3-\delta}$ (PBFCu) – CGO	H_2O – Air	1.07×10^{-10} (4)	0.75
400	$Sm_{0.6}Ba_{0.4}Fe_{0.8}Cu_{0.2}O_{3-\delta}$ (SBFCu) – CGO	$Ce_{0.8}Gd_{0.2}O_{2-\delta}$ (CGO) – $(Li/Na/K)_2CO_3$	$Sm_{0.6}Ba_{0.4}Fe_{0.8}Cu_{0.2}O_{3-\delta}$ (SBFCu) – CGO	H_2O – N_2	1.53×10^{-10} (2.6)	1.19
400	$Sm_{0.6}Ba_{0.4}Fe_{0.8}Cu_{0.2}O_{3-\delta}$ (SBFCu) – CGO	$Ce_{0.8}Gd_{0.2}O_{2-\delta}$ (CGO) – $(Li/Na/K)_2CO_3$	$Sm_{0.6}Ba_{0.4}Fe_{0.8}Cu_{0.2}O_{3-\delta}$ (SBFCu) – CGO	H_2O – Air	9.19×10^{-11} (2.2)	0.74
400	Porous Ni Plate	LiCl, KCl, CsCl (0.5% Li_3N)	Porous Ni Plate	N_2/H_2	3.33×10^{-9} (1.34[a])	72
400	Al	LiCl, KCl, CsCl (Li_3N)	Porous Ni Plate	N_2/H_2	3.33×10^{-8} (16)	72
300	Porous Ni Plate	LiCl, KCl, CsCl (0.5% Li_3N)	BDD (baron-doped diamond)	N_2/H_2O	5.80×10^{-9a} (25)	80
300	Porous Ni Plate	LiCl, KCl, CsCl (0.5% Li_3N)	Glassy carbon rod	N_2/H_2O	2.00×10^{-8} (23)	23
300	Porous Ni Plate	LiCl, KCl, CsCl (0.5% Li_3N)	Glassy carbon rob/Porous Ni	H_2S/N_2	–	70
300	Porous Ni Plate	LiCl, KCl, CsCl (0.5% Li_3N)	Glassy carbon rob	HCl/N_2	–	–
200	Ni	NaOH/KOH Nano-Fe_2O_3	Ni	H_2O/N_2	1.00×10^{-8} (200)	35
105,200 (200)	Monel (nickel-copper alloy)	$Na_{0.5}K_{0.5}OH$ Nano-Fe_2O_3	Ni	H_2O/N_2	1.62×10^{-8} (20)	76

[a] Calculated based on reference data.

Temperatures between 200 and 500 °C have been used to operate the cells with molten salt electrolytes. Murakami et al. first investigated ammonia synthesis in the schematically depicted cell in Fig. 4. The electrodes were porous nickel, and the electrolyte was a eutectic mixture of LiCl, KCl, and CsCl. The electrolyte included 0.5 mol% Li_3N, which was the source of the nitride ions (N3). The cathode-supplied nitrogen was converted to N^{3-}, which moved through the electrolyte and interacted with hydrogen at the anode to make ammonia:

$$N^{3-} + 3/2H_2 \rightarrow NH_3 + 3e^- \qquad (8)$$

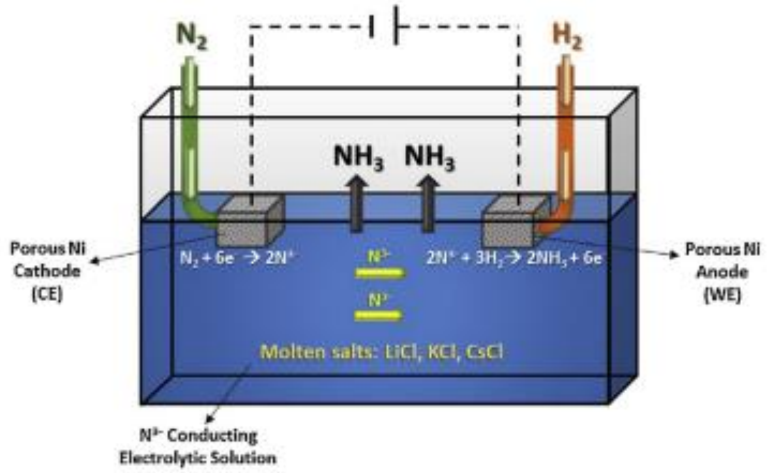


Fig. 4. Apparatus used by Murakami et al. [55]. The electrolyte was a N^{3-} conducting molten salt mixture (57.5LiCl, 13.3KCl, 29.2CsCl mol%) and nitrogen was reduced on a porous Ni cathode.

A certain combination of at least two solid components called a eutectic mixture causes a shift in phase from solid to liquid at a particular temperature. The minimum melting point of the various potential compositions is at this temperature, which is also known as the eutectic point temperature.

The greatest rate they recorded had a FE of 72% and was $3.33*10^{-9}$ mol s^{-1} cm^{-2} at 400 °C and 0.7 volts vs the Li+/Li electrode. The same cell also briefly functioned with methane, hydrogen sulfide, and hydrogen chloride as sources of hydrogen. Similar research looked at how substituting hydrogen with steam affected the rate of ammonia production. A glassy carbon rod that functioned as the anode was fed steam into the reactor. In this instance, the anode reaction was:

$$N^{3-} + 3/2H_2O \rightarrow NH_3 + 3/2O^{2-} \qquad (9)$$

The FE was much lower (23%), but the reaction rate was higher when H2O was employed in place of H2 ($2*10^{-8}$ mol s^{-1} cm^{-2} at 2.9V vs. the Li^+/Li electrode). The carbon electrode and the oxygen ions produced by reaction (9) combined to form carbon dioxide. The glassy carbon anode was swapped out for boron-doped diamond to improve cell stability. As a result, O_2 rather than CO_2 was created at the anode. With the inert anode, the reaction yield was substantially reduced, perhaps as a result of the NH_3 and O_2 reaction. Murphy et al. elaborated on the aforementioned and proposed additional ways to enhance the system. Suggested improvements include, changing the electrolyte (e.g. with bromides in place of chlorides, or organic salts) or the electrodes and the use of multiple cathodes. But these suggestions have not been implemented by any researchers to date.

More recently, a similar setup was presented by Licht et al., however this time the molten electrolyte also contained a nano-particle catalyst. The catalyst was a nano powder of Fe_2O_3, and the electrolyte was a molten combination of NaOH and KOH (1:1 molar ratio). The maximal ammonia generation rate was $1*10^{-8}$ mol s^{-1} cm^{-2} at a 1.45% FE with the application of 2.4V vs. the counter electrode. The gas supplies were nitrogen and steam at the cathode and anode, respectively (CE). The authors reported FEs up to 76% and indicated that the performance of the cell might be enhanced by passing a high current for 15–30 minutes prior to applying the operational current. The catalyst's particle size was important because anything larger than 40 microns was completely inert.

Composite electrolytes have been tested during the past ten years in hydrogen fuel cells that operate between 400 and 800 °C. These electrolytes are composed of a solid oxide and a second phase that modifies the material's overall electrical, thermal, or mechanical properties. This extra phase is often a eutectic mixture of alkali metal salts such as carbonates, halides, sulphates or hydroxides. The electrolyte's working temperature is lowered and the ionic conductivity is improved when the molten phase is present.

Similar to those shown in Figs. 1 and 2, Amar et al. investigated these composite electrolytes for SSAS in cell topologies. $LiAlO_2$ was mixed with $(Li/Na/K)_2CO_3$ at a mass ratio of 1:1 to create a eutectic salt solution. Fe_3MO_3N, Co_3MO_3N, and $CoFe_2O_4$ were three distinct catalysts/cathodes that were evaluated under pure nitrogen with wet hydrogen on the anode side (Table 2). The best of these materials, Co_3Mo_3N, was discovered to have a maximum rate of $3.27*10^{-10}$ mol s^{-1} cm^{-2} at 450 ^{o}C and 0.8V applied versus the CE. At 0.4V versus CE, the maximum faradaic efficiency (3.83%) was found, however at a slightly lower production rate (0.75 1010 mol s1 cm2). It was determined that the quick hydrogen evolution process at this temperature was to blame for the low efficiency in all situations. When the electrolyte was changed to $(Li, Na, K)_2CO^{3-}$ SDC (30:70%wt), the same research team observed a reaction rate 10 times faster than the above (5.39 109 mol s1 cm^2 at 0.8V vs the CE), using a cathodic electrode made up of a 70:30 mixture (by weight) of LSFCu and SDC.

Furthermore, Amar et al. have also tested ammonia synthesis in an oxygen-ion conducting composite electrolyte (see Fig. 3). Using (Li,Na,K)2CO3-CGdC (30:70 wt%) as the electrolyte they studied three different cathodes: CoFe2O4, LSF [51] and LSCrF. The most efficient of them was the LSCrF electrode mixed, with CGdC at a 70:30% wt ratio. The anode was SSCo-CGdC (30:70%wt) and was exposed to the atmosphere, while wet air was fed to the cathode. With this configuration, the researchers observed an ammonia rate equal to 4×10^{-10} mol s^{-1} cm^{-2} with a FE of 3.87% at 375 ◦C at an applied voltage of 1.4V vs CE. The higher voltage used in these studies compared to those of the same group with proton conductors, is dictated by the need to electrolyze steam which was the hydrogen source.

The same group have also studied the ammonia synthesis in a symmetrical single chamber reactor configuration, using $(Li,Na,K)_2CO_3$-(CGO) (70:30 wt%) as the electrolyte. This setup is similar to that shown in Fig. 3, but with both electrodes exposed to the same atmosphere. This means that, not only the ammonia synthesis electrode is exposed to steam which is a potential poison, but also the produced ammonia can react with gaseous oxygen generated by the electrolysis. Nevertheless, they tested three different perovskite type catalysts achieving a maximum ammonia rate of 1.83×10^{-10} mol s^{-1} cm^{-2} with a FE of 4.8% at 400 ◦C and 1.4V vs the CE with PBFCu.

An interesting approach, though not strictly electrochemical, was investigated by Itoh et al. The apparatus is shown in Fig. 5. An Ag-Pd membrane was used to separate hydrogen, generated in situ by water electrolysis.

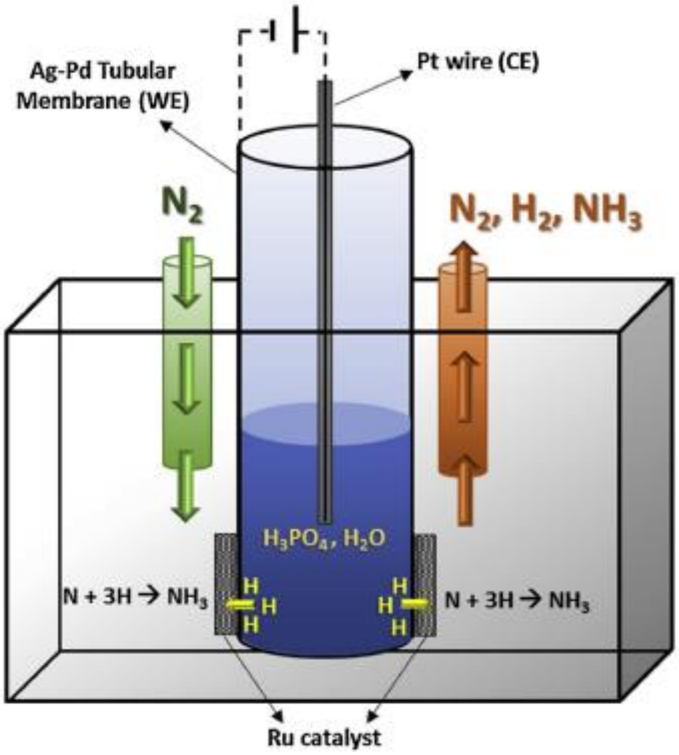


Fig. 5. Schematic representation of the apparatus used by Itoh et al. [64]. Hydrogen is produced in situ from the electrolysis of water.

The membrane was shaped like a closed-ended tube and contained a phosphoric acid solution which served as electrolyte and water source. A Pt-wire was used as the anode, while the membrane also functioned as the cathode. The produced hydrogen, permeated through the membrane in atomic form, to react on a Ru catalyst deposited on its outer surface, over which gaseous nitrogen was flowing. Thus, hydrogen was produced electrochemically, while ammonia was produced catalytically. The highest ammonia synthesis rate measured in this study was 2.22×10^{-6} mol s^{-1} cm^{-2} at 150 ◦C but it was not stable. To improve stability, the authors introduced a porous Al_2O_3 layer on the ruthenium side of the membrane by a surface coating method. In this way they achieved much better stability but at the cost of catalytic activity (2.7×10^{-8} mol s^{-1} g_{cat}^{-1} at 100 ◦C).

4) Electrochemical Synthesis at Low Temperatures

Table 3 contains the results from studies conducted at low temperatures, i.e. T < 100 ◦C.

Table 3
Experimental studies on electrochemical ammonia synthesis at low temperatures (T < 100 °C).

T, °C	Cathode	Electrolyte	Anode	Reactants Cathode/Anode	r_{NH3}, mol s^{-1} cm^{-2}(I, mA cm^{-2})	FE, %
80–110 (105)	13.2% Ru – Fe	Nafion	–	N_2/H_2	1.10×10^{-10} (1200)	<1[a]
80	Fe_2O_3	AEM	Pt	$H_2O - N_2$/-	2.50×10^{-10} (1500)	<1[a]
50	Fe	AEM	–	$H_2O - N_2$/-	3.80×10^{-12}	41
25–95 (80)	$SmBaCuFeO_{5+\delta}$ (SBCF)	Nafion	Ni-$Ce_{0.8}Sm_{0.2}O_{2-\delta}$ (SDC)	N_2/H_2	6.90×10^{-9}	–
25–95 (80)	$SmBaCuCoO_{5+\delta}$ (SBCC)	Nafion	Ni-$Ce_{0.8}Sm_{0.2}O_{2-\delta}$ (SDC)	N_2/H_2	7.20×10^{-9}	–
25–95 (80)	$SmBaCuNiO_{5+\delta}$ (SBCN)	Nafion	Ni-$Ce_{0.8}Sm_{0.2}O_{2-\delta}$ (SDC)	N_2/H_2	8.70×10^{-9}	–
25	Pt	Nafion	Pt	N_2/H_2	3.13×10^{-9} (40)	2.2
25	Pt	Nafion	Pt	Air/H_2	3.50×10^{-9} (150)	0.7
25	Pt	Nafion	Pt	Air/H_2O	1.14×10^{-9} (72)	0.55
20–100 (90)	Ru	Nafion	Pt	$H_2O - N_2$	2.12×10^{-11} (2.6[a])	0.92
20–100 (80)	$Sm_{0.5}Sr_{0.5}CoO_{3-\delta}$ (SSC)	SPSF	Ni-$Ce_{0.8}Sm_{0.2}O_{2-\delta}$ (SDC)	N_2/H_2	6.50×10^{-9}	–
20–100 (80)	NiO – $Ce_{0.8}Sm_{0.2}O_{2-\delta}$ (SDC)	SPSF	Ni-$Ce_{0.8}Sm_{0.2}O_{2-\delta}$ (SDC)	N_2/H_2	2.40×10^{-9}	–
20–100 (80)	$Sm_{1.5}Sr_{0.5}NiO_4$	Nafion	Ni-$Ce_{0.8}Sm_{0.2}O_{2-\delta}$ (SDC)	N_2/H_2	1.05×10^{-8}	–
20–100 (80)	$Sm_{1.5}Sr_{0.5}NiO_4$	SPSF	Ni-$Ce_{0.8}Sm_{0.2}O_{2-\delta}$ (SDC)	N_2/H_2	1.03×10^{-8}	–
20–100 (25)	$SmFe_{0.7}Cu_{0.1}Ni_{0.2}O_3$ (SFCN)	Nafion	Ni-$Ce_{0.8}Sm_{0.2}O_{2-\delta}$ (SDC)	N_2/H_2	1.13×10^{-8} (3.5)	90.4
20–80 (80)	Pt	Nafion	Pt	H_2O – Air	9.37×10^{-10} (10)	0.83

[a] Calculated based on reference data.

The proton conducting electrolytes used in these studies were Nafion and sulfonated polysulfone (SPSF). Operation at low temperatures provides two advantages.

- Firstly, reaction (1) is spontaneous
- secondly, the proton conductivity of low-temperature electrolytes, such as Nafion, is much higher than of those which operate at intermediate and high temperatures.

On the other hand, reaction kinetics are quite slow at low temperatures.

In 2000, the first low temperature ammonia synthesis was reported. Kordali et al. using a Nafion electrolyte combined with an alkaline solution and produced ammonia from water and nitrogen at temperatures up to 100 ◦C. Fig. 6 is a schematic diagram of their cell.

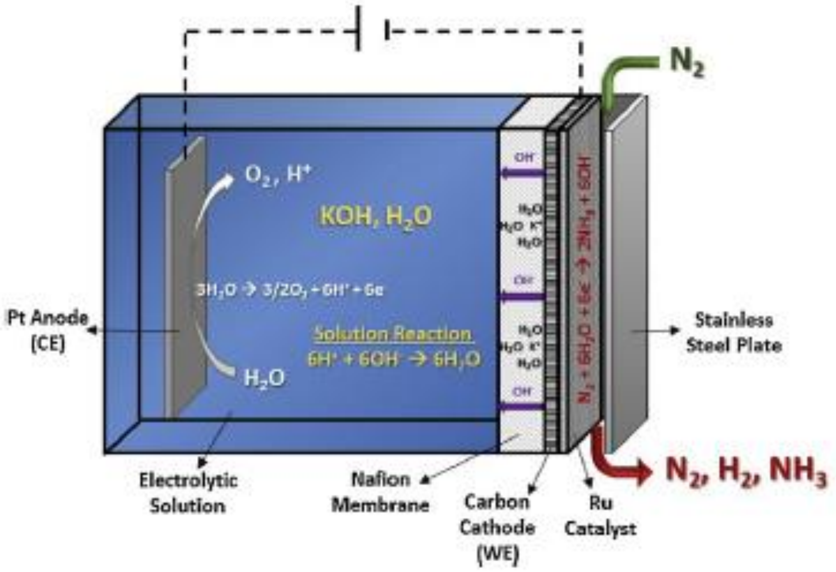


Fig. 6. Illustration of the electrochemical synthesis of ammonia from nitrogen and water at low temperatures as implemented by Kordali et al. [69].

The anodic electrode was Pt, immersed in a KOH solution. The latter was in contact with a Nafion membrane. The cathode was a carbon cloth, on which the Ru catalyst was deposited. Gaseous N_2 was introduced at the cathode side. The reactions at the two electrodes and in the KOH solution can be written as:

$$\textit{Anode}: 3H_2O \rightarrow 6H^+ + 3/2O_2 + 6e^- \qquad (10)$$

$$\textit{Cathode}: N_2 + 6H_2O + 6e^- \rightarrow 2NH_3 + 6OH^- \qquad (11)$$

$$\textit{Solution}: 6H^+ + 6OH^- \rightarrow 6H_2O \qquad (12)$$

The above reactions combine to produce the overall reaction (7):

$$N_2 + 3H_2O \rightarrow 2NH_3 + 3/2O_2 \qquad (7)$$

The hydrogen source for ammonia synthesis in the low temperature experiments was either gaseous H_2 or H_2O. The reactor cell configuration in these two cases were similar to those of Fig. 1 and Fig. 2, respectively. Using a SFCN electrode, Xu et al. reported the highest rate of 1.13×10^{-8} mol s^{-1} cm^{-2} and the highest FE of 90.4%. In general, high reaction rates of the order of 10^{-8} mol s^{-1} cm^{-2} were observed on mixed oxide (e.g. SSN) and perovskite (e.g. SBCN) cathodes. Lan et al. used Pt electrodes and operated their cell at 25 ◦C. The reaction rate and FE achieved were not among the highest (1.14×10^{-9} mol s^{-1} cm^{-2} and 0.55, respectively) but this work is a significant contribution to the promotion of the electrochemical synthesis of ammonia because the most abundant substances were used as reactants (water and air) and the reaction was carried out at ambient conditions (25 ◦C and atmospheric pressure).

5) Factors that affect the production

Today, the Haber-Bosch process is a mature technology. Due to its tremendous industrial importance, the catalytic reaction of ammonia synthesis from its elements has been studied in detail in the past hundred years. The reaction is equilibrium limited and the catalyst accelerates both the forward and the reverse reaction. The composition of the effluent mixture of NH_3, H_2 and N_2 is very close to that predicted by the equilibrium of reaction (1).

The yield to ammonia is a function of:

a) the reactant feed flowrate
b) the reactant composition
c) the reaction temperature
d) the pressure of operation
e) and (primarily) the catalyst used.

The effect of the operating temperature on X_{NH3}, the equilibrium-predicted molar fraction of ammonia, for stoichiometric reactant mixture ($PH_2/PN_2 = 3$) and for various operating pressures, is depicted in Fig. 7a.

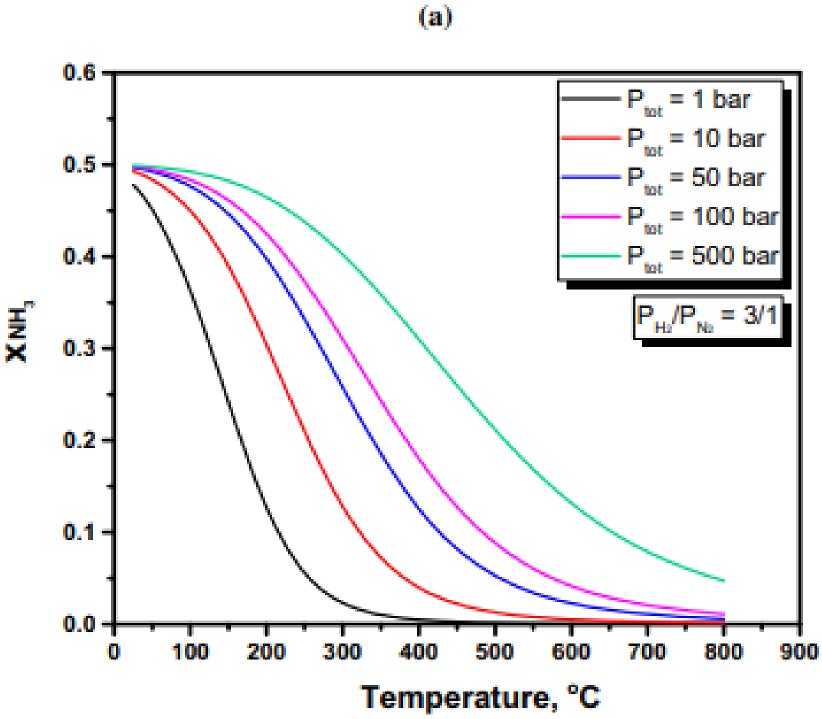


Fig. 7a. Equilibrium mole fraction of ammonia versus temperature (a) under various (total) pressures for the stoichiometric feed ratio

It can be seen that for temperatures between 400 ◦C and 500 ◦C, an industrially acceptable conversion (15-20%) is attainable at pressures between 50 and 100 bar.

In Fig. 7b, X_{NH3} is plotted vs temperature for atmospheric pressure and for various PH_2/PN_2 ratios.

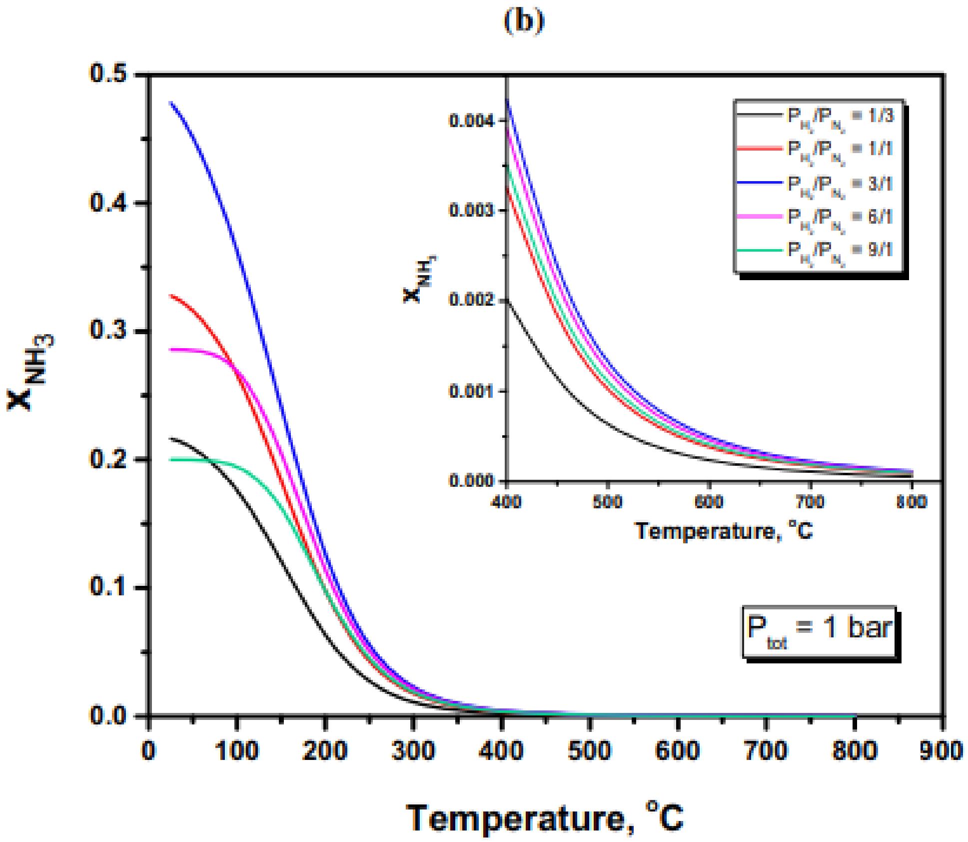


Fig. 7b. Equilibrium mole fraction of ammonia versus temperature (b) for various feed ratios under atmospheric pressure (inset showing temperature effect between 400 and 800 ◦C).

As expected, the stoichiometric PH_2/PN_2 ratio gives the highest conversion to ammonia. It should be pointed out that these are maximum theoretical concentrations and that reaction kinetics, as well as reactor design and operating conditions (e.g flow rate) play an important role in achieving them.

The electrochemical synthesis of ammonia has been studied only in the laboratory and for less than twenty years. Moreover, it is a more complicated system because there are additional factors that affect the reaction rate. The reactants are fed in separately and thus, the inlet flowrate of N_2 and H_2 can be controlled independently of each other. Furthermore, in addition to the effect of temperature and pressure, the rate of the electrochemical synthesis depends on the applied voltage and the generated current. Although the role of these electrochemical parameters has been addressed in previous reviews, a brief summary is presented below in order to include recent experimental findings.

a) Effect of applied potential

Ammonia is not produced unless the voltage becomes more negative (cathodic polarization) than a certain value. This onset value can be calculated from ΔG_R^o, the free energy change of reaction (1):

$$E^{\circ} = -\Delta G_R{}^{\circ}/nF \qquad (19)$$

- where F is Faraday's constant.
- n is the number of electrons (or protons) per molecule of reacting N_2.

Similarly, if ammonia is produced from water and nitrogen, this onset value for E◦ can be calculated from the above equation using the free energy change of reaction (7).

Fig. 8 shows the dependence of the onset potential, V, on the operating temperature.

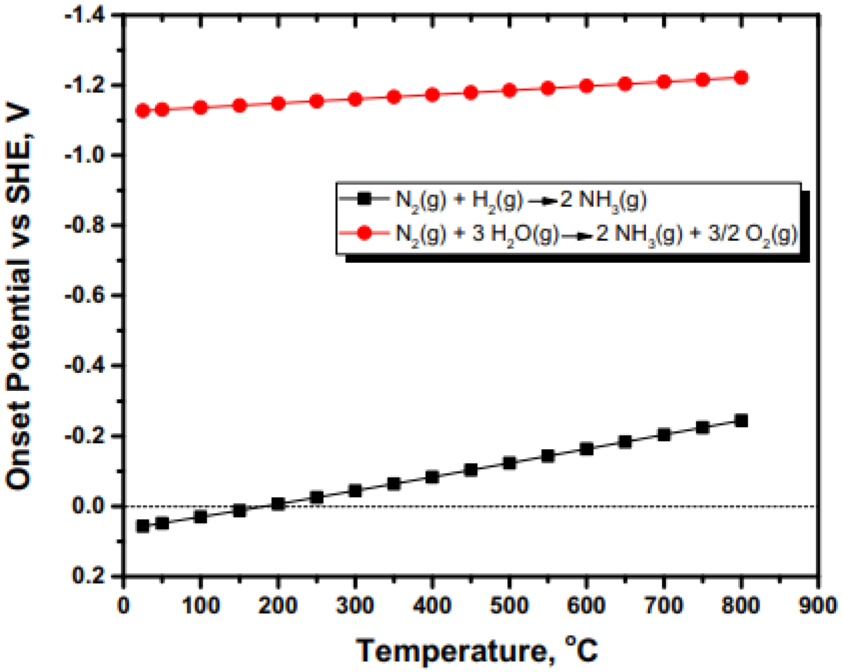


Fig. 8. Dependence of the equilibrium potential (calculated from equation (19)) on the operating temperature for the electrochemical production of ammonia from hydrogen (squares) and steam (circles).

If ammonia is produced from reaction (1), the threshold values of E◦ are 0.057V and −0.123V vs SHE at 25 ◦C and 500 ◦C, respectively. When the hydrogen source is H_2O (equation (7)), the corresponding E◦ values are −1.13V vs SHE at 25 ◦C and −1.21V vs SHE at 500 ◦C.

According to most of the experimental studies, the effect of applied voltage on the rate of NH_3 synthesis follows the behavior shown schematically in Fig. 9.

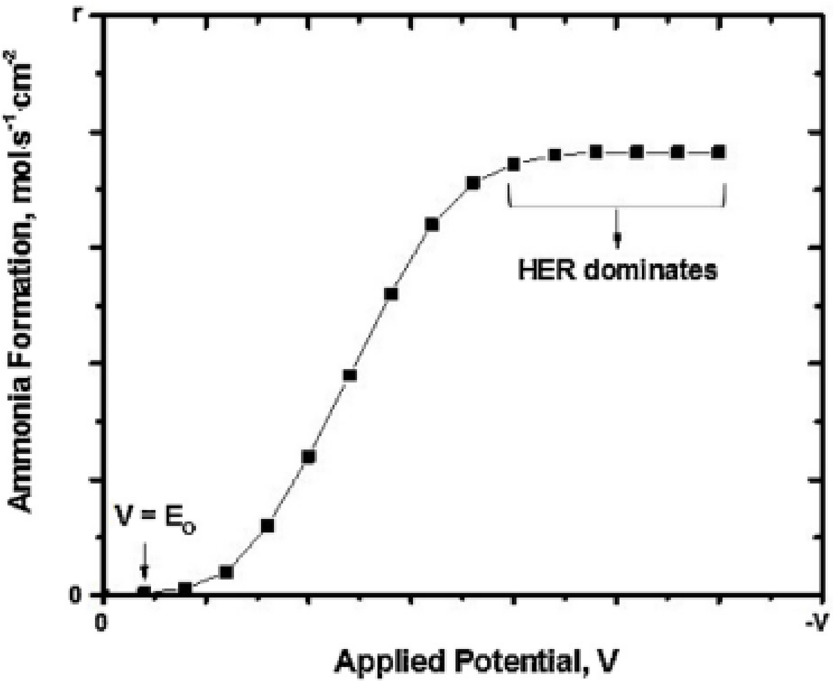


Fig. 9. Dependence of electrocatalytic rate of ammonia synthesis on the applied potential. Eo denotes the onset potential calculated from equation (19).

The production rate, rNH_3, increases with cell potential, −V, up to a certain value, above which the rate levels off. At higher applied potential values, HER is completely dominant.

The above reaction rate-voltage behavior stimulated the search for electrochemical promotion, a phenomenon observed in studies in which the catalyst is the working electrode of a solid electrolyte cell. For SSAS, this phenomenon could be studied in the H^+ cell of Fig. 1. If, instead of pure N_2, a gaseous mixture of N_2 and H_2 is introduced over the cathode, ammonia will be formed under both, open- and closed-circuit conditions. If the reaction rate at open circuit is r_o and a constant current I is imposed, the reaction rate will increase from r_o to r. The rate increase can be correlated with I by means of the dimensionless parameter ʌ:

$$\Lambda = (r - r_o)/(I/3F) \qquad (20)$$

If ʌ = 1, i.e. the rate increase is equal to the rate of H^+ “pumping”, the effect is Faradaic. Since 1981, the phenomenon of Non-Faradaic (ʌ > 1) Electrochemical Modification of Catalytic Activity (NEMCA), also called Electrochemical Promotion of Catalysis (EPOC) has been observed in numerous catalytic reaction systems.

Values of ʌ as high as 3 × 105 have been reported.

In the case of SSAS, however the measured values were very low. On a Pd electrode, the values measured ʌ by Marnellos et al. were as high as 2.0.

Yiokari et al. used an industrial Fe catalyst and were able to increase the open-circuit rate by up to 13 times but only when operating under low conversions, i.e. far from equilibrium.

In a thermodynamic analysis for reactions with limited conversion, Garagounis et al. provided an explanation for the weak NEMCA effect observed in SSAS. Specifically, the thermodynamic analysis indicated that for temperatures between 500 and 600 ◦C, Λ cannot exceed the value of 10. This is because the role of protons in equilibrium limited reaction is both, electrochemical and catalytic. The promotional effect of the H^+ flux is weak because the pumped protons are used not only to modify the catalytic properties of the cathode, but also to carry the electrical power required for ammonia synthesis.

Nevertheless, introducing a H_2-N_2 mixture, rather than N_2 alone, over the cathode, was found to have a positive effect on the electrochemical synthesis rate. Recently, SSAS was studied over a Ni-BZCY72 cathodic electrode, with and without H_2 in the gas phase. Without H_2, the highest rate was 1.7×10^{-9} mol s^{-1} cm^{-2}. When H_2 was present ($PH_2/PN_2 = 1$), an electrochemical reaction rate of 4.1×10^{-9} mol s^{-1} cm^{-2} was obtained, corresponding to a 140% enhancement of the open-circuit rate.

b) Effect of applied current

The effects of current and voltage are not independent of each other. At a given temperature and gas composition, the overall resistance of the cell remains constant. Therefore, the effect of applied current is expected to be similar to that of the potential (Fig. 9).

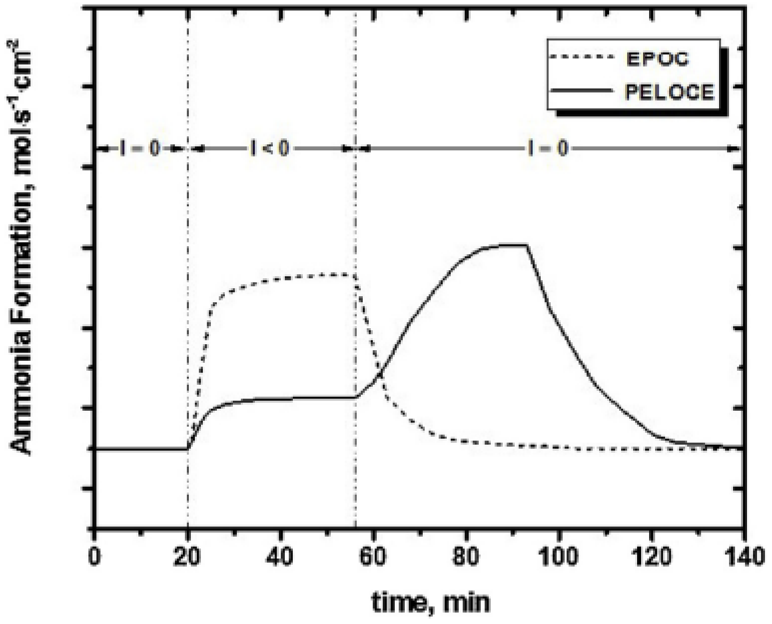


Fig. 10. Ammonia formation rate transients during typical EPOC (dotted line) and PELOCE (continuous line) experiments [89].

In general, the reaction rate will increase up to a certain level above which, it will become current independent. Wang et al. however, observed a negative order dependence of the reaction rate on the imposed current. At low current density values, the rate increased with current. At I = 1 mA, the rate reached a maximum and attained lower values at higher currents. A physical explanation of this behavior is that, at high currents, the catalyst surface is “poisoned” by protons, which combine with electrons and each other, thus forming H_2 rather than NH_3.

Fig. 10 describes the characteristics of a peculiar phenomenon observed in a recent SSAS study. The dotted line, is a typical plot of the electrochemical rate of NH3 synthesis vs. time in an EPOC experiment. The initial rate (I = 0) is enhanced upon closing the circuit. When the circuit is opened again, the rate quickly returns to its original value. The continuous line shows the variation of the reaction rate with time when a $BaZr_{0.7}Ce_{0.2}Y_{0.1}O_{2.9}$ (BZCY72) proton conducting ceramic was used as the electrolyte and a Ni-BZCY72 cermet was used as cathode. At T > 600 ◦C, after establishing a steady state open-circuit operation, the circuit was closed and a new steady state, which corresponded to a moderate increase in the reaction rate, was reached. Upon current interruption, instead of decreasing, the reaction rate increased and reached a maximum. After a period of time, during which it remained essentially unchanged, the rate decreases slowly to reach its open-circuit value. This phenomenon (Post-Electrochemical Open-Circuit Enhancement-PELOCE) was explained assuming that, under closed circuit, a fraction of protons transported to the cathode, is “stored” in the Ni-BZCY72 electrode in the form of a nickel hydride (Fig. 10). Upon current interruption, this hydride reacts with adsorbed N species to form ammonia.

One important difference between catalytic and electrocatalytic ammonia synthesis is that in the latter, one of the reactants (hydrogen) is supplied electrochemically. Hence, the electrolyte conductivity and specifically, the protonic conductivity, is crucial in determining the maximum reaction rate that can be achieved.

The protonic conductivity of low temperature electrolytes, such as Nafion and SPSF, is much higher than that of ceramic high temperature conductors. Thus, there is no need to search for more effective low temperature conductors because the reaction rate is limited by the slow reaction kinetics rather than the supply of protons. This is not the case for high temperature SSAS. The conductivity of a solid electrolyte increases with temperature and is inversely proportional to the thickness of the membrane. With a thin solid electrolyte, significantly higher proton fluxes will be obtained at a given temperature. Alternatively, the thin electrolyte can provide the same proton flux at a lower temperature. Recently, Coors et al. succeeded in fabricating anode supported tubular proton conducting cells with an electrolyte (BZCY72) thickness of only 30 micrometers. This is a considerable step forward in scaling up SSAS at elevated temperatures.

c) The appropriate electro-catalyst

An ideal electro-catalyst should exhibit high catalytic activity and electronic conductivity and at the same time it should suppress HER. Unfortunately, the best Haber-Bosch catalysts often contain large proportions of oxides, which significantly decreases their conductivity. This has led many researchers to explore materials used in typical hydrogenation reactions.

Tables 1–3 show that many materials have been tested as working electrodes (catalysts) in the past fifteen years, including Ru, Fe, Pt, Pd, Ag-Pd, Ni, Ni-Cu as well as conductive oxides and composite materials such as SSN, SBCN, BSCF, SSCO, Ni-BZCY72, etc. The Ag-Pd cathode was used in almost half of the studies and it was the electrode on which the most promising results were obtained.

This is an unexpected result. The Haber-Bosch catalysts are Fe- and Ru-based materials. Ag and Pd are among the worst catalysts for nitrogen dissociative adsorption. Furthermore, under cathodic polarization conditions the surfaces of these two metals are expected to be “flooded” with protons making the side-on nitrogen adsorption difficult.

Table 1, however, shows that on Ag-Pd electrodes, both high reaction rates ($> 10^{-9}$ mol s^{-1} cm^{-2}) and FE (up to 80%), were observed. The work of Skúlason et al. [9], may provide an indirect explanation for the high catalytic activity of the Ag-Pd electrode. This study suggested that early transition metals such as Sc, Y, Ti and Zr could effectively catalyze ammonia synthesis upon imposing a negative voltage, i.e., when used as electrodes. In the studies presented in Table 1, the solid electrolytes contained early transition metals such as Y and Zr. Hence, it is possible that the observed activity of Ag-Pd is due to the presence of these early transition metals at the electrode-electrolyte interphase.

Unfortunately, the experimental studies to date show that cathodic electrodes based on the best known catalysts (Ru and Fe) facilitate HER at the expense of nitrogen hydrogenation. Another important category of ammonia synthesis catalysts which have recently attracted much interest is the transition metal nitrides. Interestingly, only Amar and co-workers tested nitrides in an electrochemical configuration. In particular, Fe_3Mo_3N-Ag and Co_3Mo_3N-Ag were studied at operation temperatures of 400–450 ◦C. The formation rate and FE observed were rather low and reached 3.27×10^{-10} mol s^{-1} cm^{-2} and 6.5%, respectively. This could possibly be attributed to the lack of adequate electronic conductivity of these particular nitrides. On the other hand, theoretical studies based on DFT calculations identified certain nitrides as promising electro-catalysts at ambient conditions. The theoretical analysis of Abghoui et al. predicted stable operation and FEs higher than 75% for V, Cr, Nb and Zr mononitrides at applied bias between 0.5 and 0.76V vs SHE. These results are very promising and further research in this direction could move the electrochemical approach one step forward.

d) Techno-economic considerations

The electrochemical synthesis of ammonia exhibits several advantageous characteristics compared to the catalytic (Haber Bosch) process. The first is that the solid electrolyte is a selective ionic membrane, i.e. protons (H^+) are the only species that can be transported to the cathode. Today, a significant fraction of the overall cost for NH_3 production is due to the extensive purification of hydrogen. This is necessary because hydrogen, which is produced from steam reforming of natural gas, contains carbon monoxide, water vapor, oxygen and sulfur compounds, which, even in trace amounts, may cause poisoning of the catalyst. In SSAS, hydrogen is supplied in the form of protons and therefore the cost of purification is completely eliminated.

Another advantage of the electrochemical method is that the use of gaseous hydrogen can be bypassed. In the Haber-Bosch process, NH_3 is produced exclusively via reaction (1). In the electrochemical synthesis, depending on the temperature of operation, either steam or an aqueous solution can be the hydrogen source. Ammonia can be thus produced via either reaction (1) or (7). In the latter case, the electrical energy consumption will be higher because of the more negative voltage required for water electrolysis. Consequently, the economic feasibility of the electrochemical process will depend strongly on the electrical energy cost. If solar or wind energy is the electricity source, the economics may be favourable, especially when taking into account the environmental effect (use of renewable energy, no CO_2 emissions).

Regardless of the electricity source, scaling up of an electrochemical process requires high FE's to be achieved. Giddey at al. suggested that the industrial promotion of SSAS will require the combination of reaction rates of the order of 10^{-7} mol s^{-1} cm^{-2} with FE's exceeding 50%. Table 3 shows that, with the exception of ref., the FEs at low temperatures are very low (typically <1%) because of the slow reaction kinetics. At high temperatures (Table 1), the FE's are acceptably high, but a large fraction of the produced ammonia is inevitably lost because of the reverse reaction (ammonia decomposition), the rate of which increases with temperature. It is unfortunate that there are no solid state materials exhibiting both, mechanical and chemical strength and high protonic conductivity at temperatures between 250 ◦C and 450 ◦C.

Over the past two decades, a large number of studies worldwide have contributed to the promotion of the electrochemical synthesis of ammonia. New proton conducting materials have been employed and numerous materials have been used as working electrodes. The search for efficient electro-catalysts has been supported by theoretical studies, primarily based on DFT calculations. Reaction rates and Faradaic Efficiencies as high as a 3.3×10^{-8} mol s^{-1} $cm^{-2}$and 90.4%, respectively, have been reported. Also, ceramic proton conductors with a 30 μm thickness, capable of producing NH_3 at rates of the order of 10^{-6} mol H_2 s^{-1} cm^{-2}, have been fabricated and tested [89,90]. Hence, considerable progress has been achieved. Intense collaboration, however, among researchers in the fields of materials science, solid state ionics and heterogeneous catalysis, will be required in order to promote the electrochemical synthesis to the industrial level.

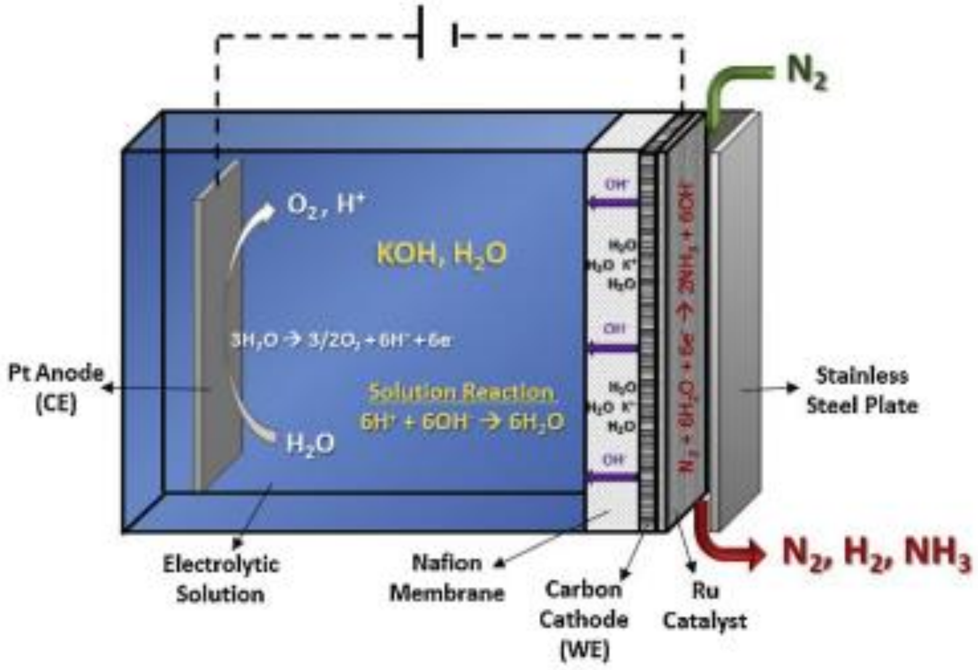


Fig. 6. Illustration of the electrochemical synthesis of ammonia from nitrogen and water at low temperatures as implemented by Kordali et al. [69].

The anodic electrode was Pt, immersed in a KOH solution. The latter was in contact with a Nafion membrane. The cathode was a carbon cloth, on which the Ru catalyst was deposited. Gaseous N_2 was introduced at the cathode side. The reactions at the two electrodes and in the KOH solution can be written as:

$$\textit{Anode}: 3H_2O \rightarrow 6H^+ + 3/2O_2 + 6e^- \qquad (10)$$

$$\textit{Cathode}: N_2 + 6H_2O + 6e^- \rightarrow 2NH_3 + 6OH^- \qquad (11)$$

$$\textit{Solution}: 6H^+ + 6OH^- \rightarrow 6H_2O \qquad (12)$$

The above reactions combine to produce the overall reaction (7):

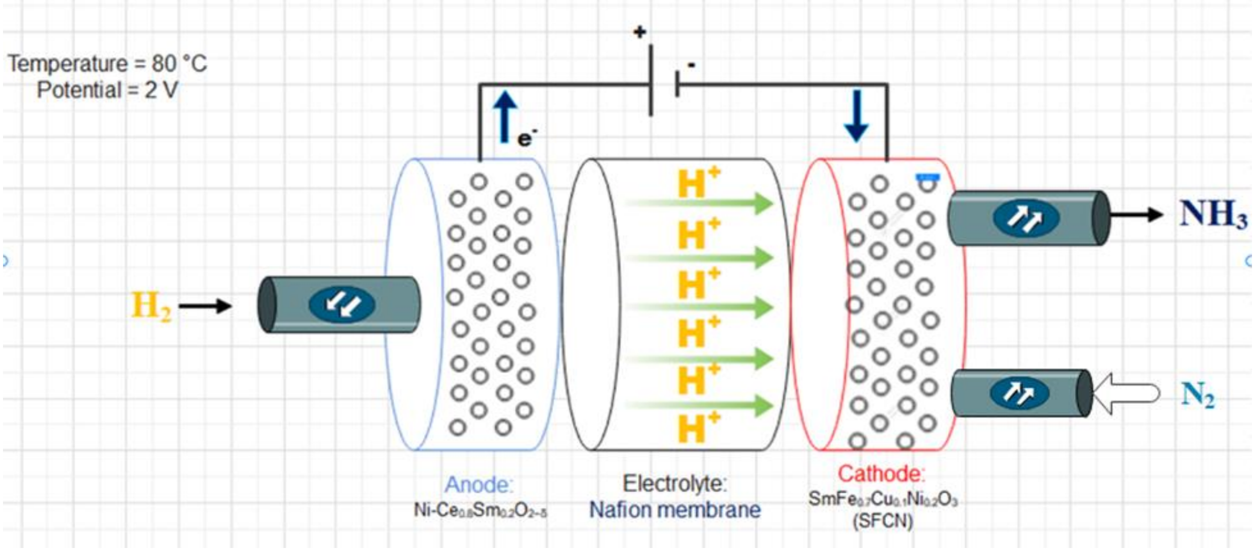
$$N_2 + 3H_2O \rightarrow 2NH_3 + 3/2O_2 \qquad (7)$$

The hydrogen source for ammonia synthesis in the low temperature experiments was either gaseous H_2 or H_2O. The reactor cell configuration in these two cases were similar to those of Fig. 1 and Fig. 2, respectively. Using a SFCN electrode, Xu et al. reported the highest rate of 1.13 × 10^{-8} mol s^{-1} cm^{-2} and the highest FE of 90.4%. In general, high reaction rates of the order of 10^{-8} mol s^{-1} cm^{-2} were observed on mixed oxide (e.g. SSN) and perovskite (e.g. SBCN) cathodes. Lan et al. used Pt electrodes and operated their cell at 25 ◦C. The reaction rate and FE achieved were not among the highest (1.14 × 10^{-9} mol s^{-1} cm^{-2} and 0.55, respectively) but this work is a significant contribution to the promotion of the electrochemical synthesis of ammonia because the most abundant substances were used as reactants (water and air) and the reaction was carried out at ambient conditions (25 ◦C and atmospheric pressure).

17.10 AP system concept

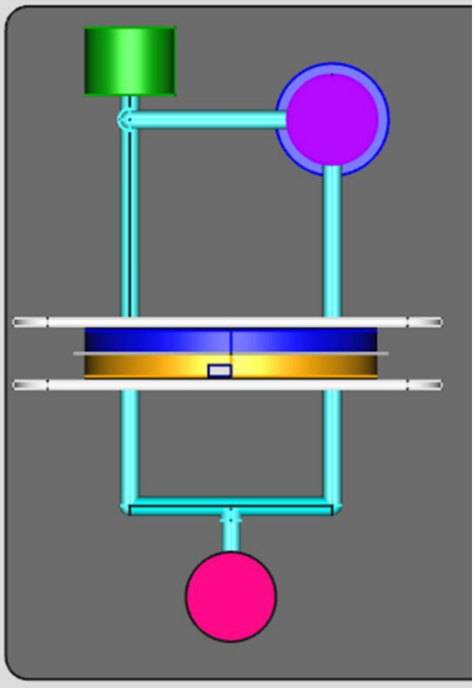
Electrochemical synthesis of ammonia using a cell with a Nafion membrane and $SmFe_{0.7}Cu_{0.1}Ni_{0.2}$ cathode at atmospheric pressure and lower temperature

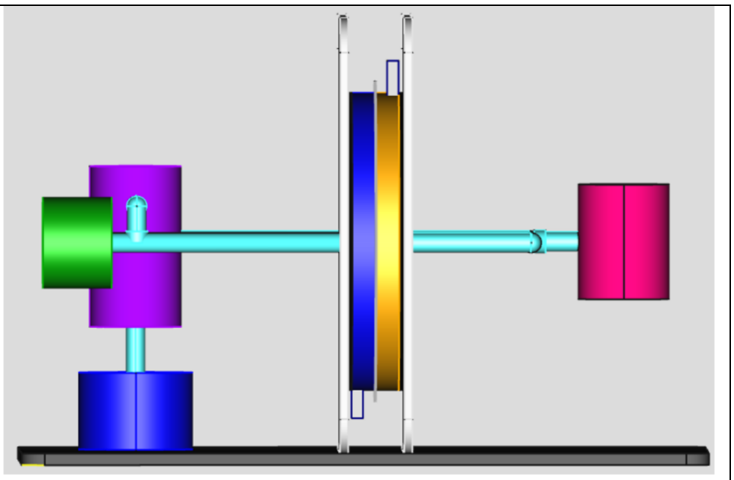
To produce Ammonia from Hydrogen and Nitrogen.



Electrochemical methods of ammonia synthesis have been most widely studied. It is recognized that Nafion is the best polymer proton exchange membrane.

1) <u>FreeCAD design</u>

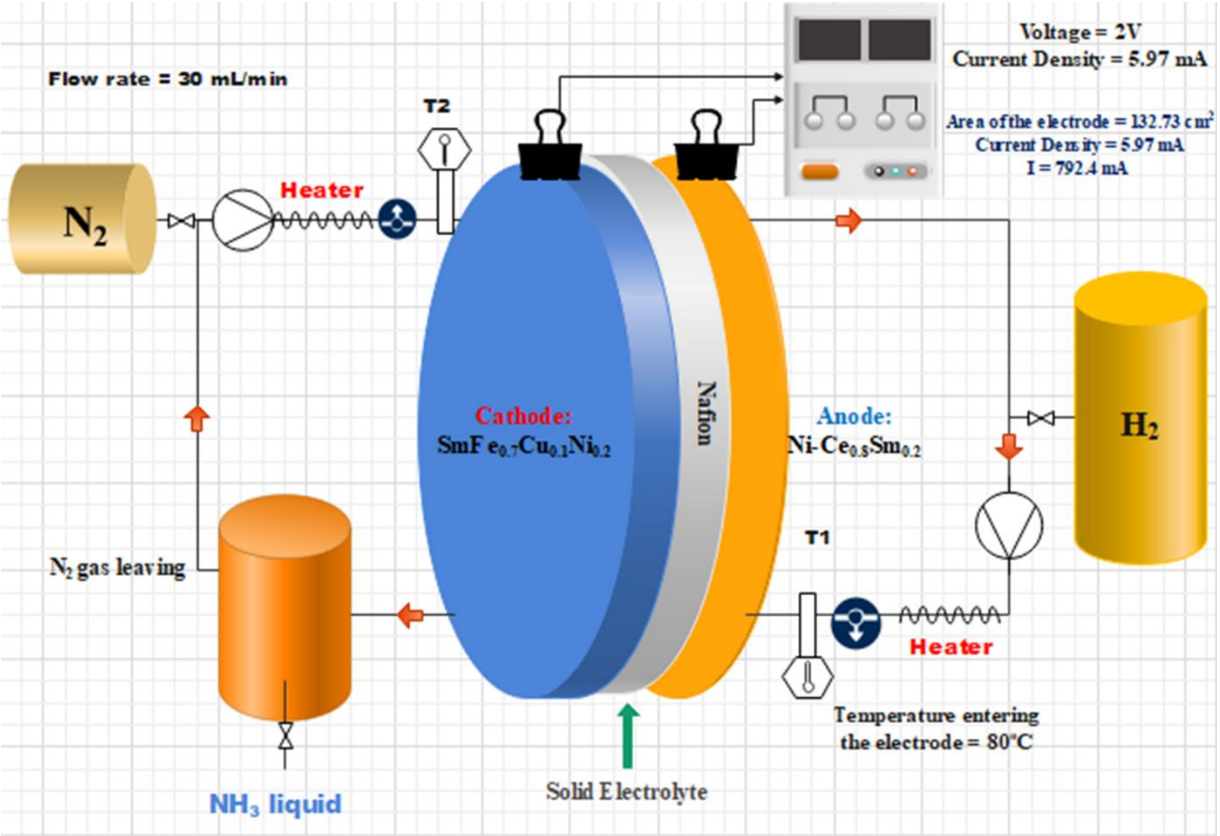


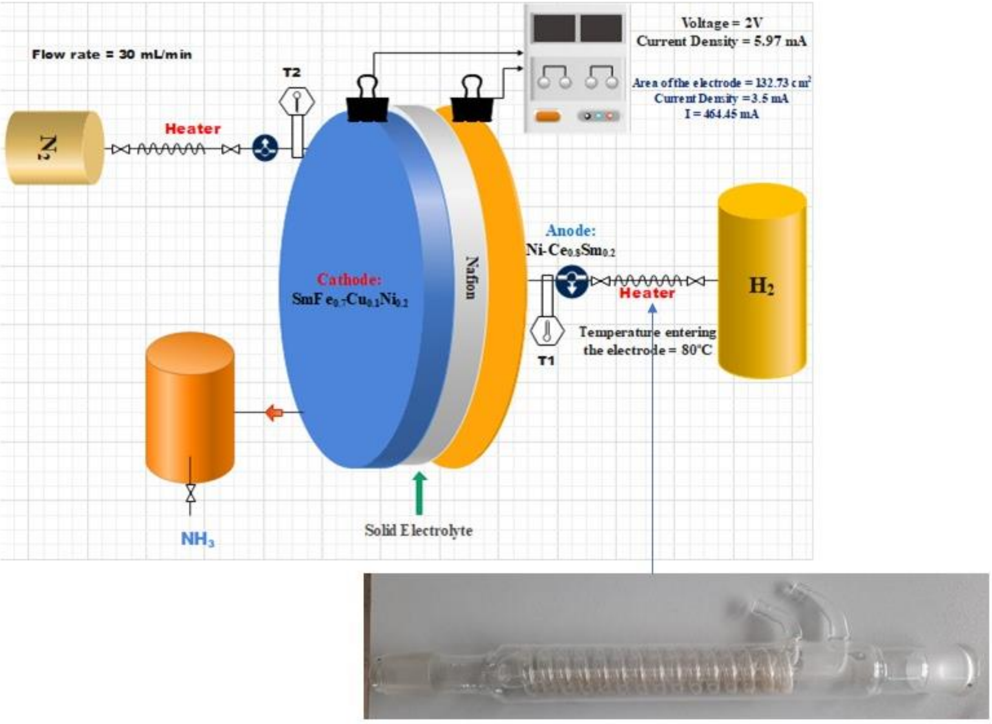


AP 01112022.FCStd

2) Flow chart

Flow chart.eddx





17.11 Characterization: Ammonia synthesis and measurement

Wet H_2 (the gas is bubbled through distilled water at 25℃ before entering the reactor, since water vapour may provide some protons[13] and increase the conductance and the rate of evolution of ammonia) was supplied to the anode, while dry N_2 was supplied to the cathode.

The flow velocities of wet H_2 and dry N_2 are $30\ mL \cdot min^{-1}$. The vent gas from the cathode is absorbed by dilute H_2SO_4 (10 mL, pH 3.85) for 10 min under the closed circuit conditions. When Nessler's reagent was added to the solution, a stable yellow color appeared immediately, which confirmed the presence of NH_4^+ in the solution. The concentration of NH_4^+ in the solution is determined by spectrophotometry[14] using a standard curve method in order to calculate the rate of ammonia synthesis.

NH_3 Detection The amounts of NH_3 trapped in the acid solutions are determined by indophenol and Nessler methods.

For the indophenol method, 1 mL of an aqueous 0.64 M C_6H_5OH, 0.38 M NaOH, and 1.3 mM $C_5FeN_6Na_2O$ solution was mixed with 1 mL of 55 mM NaOCl and 0.75 M NaOH prior to NH_3 Then, 1 mL of either a standard NH_3 solution (a known quantity of NH_4Cl in an aqueous 10 mM H_2SO_4 solution) or the NH_3-containing acid trap solution was added to the indophenol solution after dilution with aqueous 0.1 M KOH. The dissolved NH_4^+ ions were quantified by assessing the absorbance at 633 nm using UV-Vis spectroscopy. The measurements were calibrated by subtracting the background absorbance measured at 875 nm.

In the Nessler method, the acid-trapped-NH_3 solution or the standard NH_4OH solution was diluted in aqueous 90 mM K_2HgI_4 (Nessler reagent, Sigma Aldrich) and 0.1 M KOH before spectroscopic analysis. The absorbance measured at approximately 375 nm (corrected using the background at 700 nm) was used to determine the NH_4^+

For both the indophenol and Nesseler NH_3 detection methods, standard calibration curves were obtained using known amounts of NH_4Cl or NH_4OH, respectively.

17.12 AP System Realization

1) Anode Preparation

Chemical Formula: **$Ni\text{-}Ce_{0.8}Sm_{0.2}$**

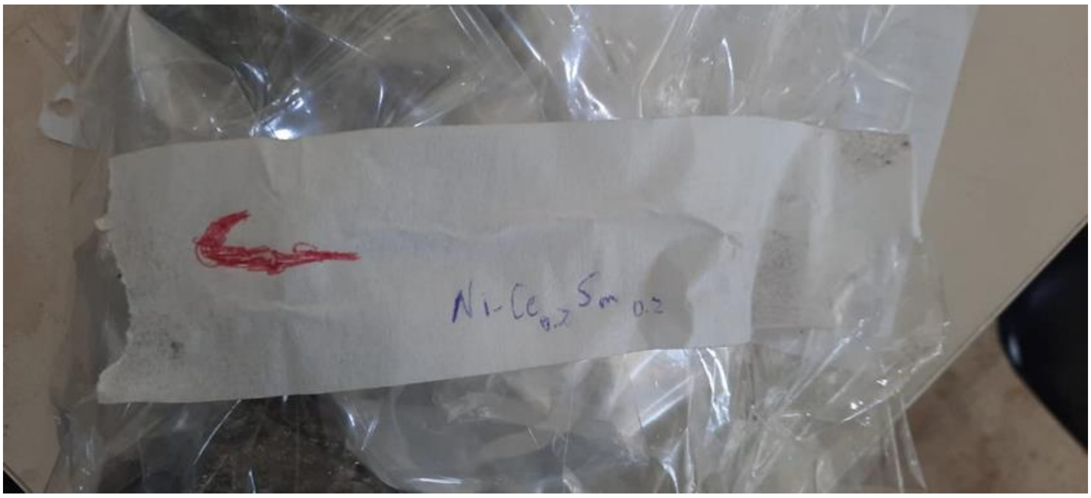
Metal	Melting point	Density (g.cm^{-3})
Nickel	1455 °C	8.902
Cerium	795 °C	6.76
Samarium	1072 °C	7.52

Total volume for 100g mass of this alloy = 13.53 cm^3

Ƥ = 100/14.2 = 7.391 g/cm^3
Volume of the anode (disc shape):
Radius = 6.5 cm; Height = 0.1 cm or more

$V = \pi r^2h = \pi*6.5*0.1 = 13.273\ cm^3 = 13273\ mm^3$
If $h = 1\ mm \rightarrow V = 13273\ mm^3 = 13.273\ cm^3$
M_1 = Ƥ $V = 7.391*13.273 = 98.100743\ g$
$M_{Ni} = 286\ g$
$M_{Ce} = 510\ g$
$M_{Sm} = 147\ g$
$M_{Total} = 286+510+147 = 943\ g$

Metal	Mass (g)	%W	No of moles	X_i
Nickel	286	30.33	4.873	0.5134
Cerium	510	54.08	3.640	0.3835
Samarium	147	15.59	0.978	0.1030
Alloy	943	100	9.491	1



2) Cathode preparation

Chemical Formula: $\mathbf{SmFe_{0.7}Cu_{0.1}Ni_{0.2}}$

Metal	Melting point °C	Density (g.cm^{-3})
Samarium	1072	7.52
Iron	1538	7.874
Copper	1085	8.96
Nickel	1455	8.902

Total volume for 100g mass of this alloy = 13.01 cm^3

Ᵽ = 100/13.01 = 7.69 g/cm^3

Volume of the cathode (disc shape):
Radius = 6.5 cm; Height = 0.1 cm

$V = \pi r^2 h = \pi * 6.5 * 0.1 = 13.273\ cm^3 = 13273\ mm^3$

$\text{If } h = 1\ mm \rightarrow V = 13273\ mm^3 = 13.273\ cm^3$

$M_1 = \rho V = 7.69 * 13.273 = 102.06937\ g$

$M_{Sm} = 740.29\ g$

$M_{Fe} = 192\ g$

$M_{Cu} = 31.5\ g$

$M_{Ni} = 58.5\ g$

$M_{Total} = 740.29 + 192 + 31.5 + 58.5 = 1022.29\ g$

Metal	Mass (g)	%W	No of moles	X_i
Samarium	740.29	72.41	4.9235	0.5
Iron	192	18.78	3.4381	0.35
Copper	31.5	3.08	0.5	0.05
Nickel	58.5	5.72	0.9921	0.1
Alloy	1022.29	100	9.8537	1

17.13 AP Requirements / Experimental

3) Materials and apparatus

1. Solid Electrolyte: Nafion^{TM} NR212
2. 2 Pumps for Hydrogen and Nitrogen. (T=100°C; flow rate= >30mL/min)
3. Sensors

   - 2 Temperature sensors 100°C
   - 2 Flow rate sensors
   - 2 Pressure sensors (1 bar)

4. Hydrogen Peroxide H_2O_2
5. Sulfric acid H_2SO_4
6. Nafion solution **Nafion™ D520CS Alcohol based 1000 EW at 5% weight**
7. Nessler's reagent
8. HDV-7C transistor potentiostat
9. pH meter
10. 7230G visible spectrophotometer
11. The corundum tube reactor and heated reactor with circulating water were made locally.
12. Modified acrylate adhesive
13. Electrodes: We need the following metals for the synthesis of the electrodes: Samarium, Iron, Nickel, Copper, and Cerium.

4) Preparation of cathode and anode and assembly of the single cell

a) Cathode

$SmFe_{0.7}Cu_{0.1}Ni_{0.2}$ (SFCN)
Sm: m= n*M = 1*150.36 = 150.36 g
Fe: m= n*M = 0.7*55.845 = 39.1 g
Cu: m= n*M = 0.1*63.546 = 6.3546 g
Ni: m= n*M = 0.2*58.6934 = 11.73868 g
Total mass = 207.5 g

Metal	Melting point	%W	Density (g.cm^{-3})
Samarium	1072 °C	72.45	7.52
Iron	1538 °C	18.84	7.874
Copper	1085 °C	3.1	8.96
Nickel	1455 °C	5.66	8.902

Total volume for 100g mass of this alloy = 13.01 cm^3
Ƥ = 100/13.01 = 7.69 g/cm^3
Volume of the cathode (disc shape):
Radius = 6.5 cm; Height = 0.1 cm

V = π r^2h = π*6.5*0.1 =13.273 cm^3 = 13273 mm^3
If h = 1 mm → V = 13273 mm^3 = 13.273 cm^3
M_1 = Ƥ V = 7.69*13.273 = 102.06937 g
M_{Sm} = = 73.95 g
M_{Fe} = = 19.23 g
M_{Cu} = = 3.16 g
M_{Ni} = = 5.78 g
If h = 2 mm → V = 26546.46 mm^3 = 26.54646 cm^3
M_2 = Ƥ V = 7.69*26.54646 = 204.1422774 g
→ M_3 = M_1*3 = 102.06937 g *3 = 306.20811 g

b) <u>Anode</u>

Ni-$Ce_{0.8}Sm_{0.2}$
Ni: m= n*M = 1*58.6934 = 58.7 g
Ce: m= n*M = 0.8*140.116 = 112.1 g
Sm: m= n*M = 0.2*150.36 = 30.1 g
Total mass = 200.9 g

Metal	Melting point	%W	Density (g.cm^{-3})
Nickel	1455 °C	29.22	8.902
Cerium	795 °C	55.8	6.76
Samarium	1072 °C	15	7.52

Total volume for 100g mass of this alloy = 13.53 cm^3
Ƥ = 100/14.2 = 7.391 g/cm^3
Volume of the anode (disc shape):
Radius = 6.5 cm; Height = 0.1 cm

V = π r^2h = π*6.5*0.1 = 13.273 cm^3 = 13273 mm^3
If h = 1 mm → V = 13273 mm^3 = 13.273 cm^3
M_1 = Ƥ V = 7.391*13.273 = 98.100743 g
M_{Ni} = = 28.66482 g
M_{Ce} = = 54.74 g
M_{Sm} = = 14.715 g
If h = 2 mm → V = 26546.46 mm^3 = 26.54646 cm^3
→ M_2 = M_1*2 = 98.1 g *2 = 196.2 g

17.14 What's next

After drawing up the initial design of the AP project, the electrodes should be made. After that we will be able to install the whole system. PLC automation should also be worked on.

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18 Project F 23: Electrochemical Ammonia production (ICPT - AP)

18.1 Position of the ICPT-AP project

Work on this project began theoretically in 2022. In this year (2024), the study was followed up.

18.2 AP experimental process

18.2.1 Experimental introduction

SmFe0.7Cu0.1Ni0.2O3 is a mixed metal oxide compound composed of samarium (Sm), iron (Fe), copper (Cu), nickel (Ni), and oxygen (O). The numerical subscripts indicate the atomic ratio of each element in the compound. In this case, it consists of 1 atom of samarium, 0.7 atoms of iron, 0.1 atoms of copper, 0.2 atoms of nickel, and 3 atoms of oxygen.

18.2.2 SmFe0.7Cu0.1Ni0.2O3

To obtain SmFe0.7Cu0.1Ni0.2O3, you can follow these steps:

1. Dissolve Fe (NO3)3, Cu (NO3)2, Ni (NO3)2, and Sm2O3 in water.
2. Add citric acid to the solution with a molar ratio of 2:1.
3. Adjust the pH to 6-7 with NH3·H2O.
4. Evaporate the solution to obtain a viscous sol.
5. Dry the sol in a constant-temperature oven at 170℃.
6. Calcine the dried gel at 700℃ in a muffle furnace.
7. Compress the powder into ceramic discs and sinter at 1150℃ for 10 hours.

The molar ratio of citric acid (C6H8O7) can be calculated based on its molecular formula. Citric acid has a molar mass of approximately 192.12 g/mol.

The molecular formula of citric acid is C6H8O7. This means that in one molecule of citric acid, there are 6 carbon atoms, 8 hydrogen atoms, and 7 oxygen atoms.

Based on the molar ratios you provided in your question, the molar ratio of citric acid to SmFe0.7Cu0.1Ni0.2O3 is indeed 2:1.

Let's calculate the molar ratio for each compound:

1. Citric acid (C6H8O7):

- Carbon (C): 6 moles
- Hydrogen (H): 8 moles
- Oxygen (O): 7 moles

2. $SmFe_{0.7}Cu_{0.1}Ni_{0.2}O_3$:

- Samarium (Sm): 1 mole
- Iron (Fe): 0.7 moles
- Copper (Cu): 0.1 moles
- Nickel (Ni): 0.2 moles
- Oxygen (O): 3 moles

To find the molar ratio of citric acid to $SmFe_{0.7}Cu_{0.1}Ni_{0.2}O_3$, we compare the moles of citric acid to the moles of $SmFe_{0.7}Cu_{0.1}Ni_{0.2}O_3$:

Citric acid ($C_6H_8O_7$):

- Total moles = 6 (C) + 8 (H) + 7 (O) = 21 moles

$SmFe_{0.7}Cu_{0.1}Ni_{0.2}O_3$:

- Total moles = 1 (Sm) + 0.7 (Fe) + 0.1 (Cu) + 0.2 (Ni) + 3 (O) = 5 moles

Therefore, the molar ratio of citric acid to $SmFe_{0.7}Cu_{0.1}Ni_{0.2}O_3$ is 21 moles : 5 moles, which simplifies to 4.2 : 1 or approximately 2 : 1.

18.2.3 Convert Ni metal to $Ni(NO_3)_2$

To convert Ni metal to **$Ni(NO_3)_2$**, you can use nitric acid (HNO_3). Here's the balanced chemical equation for the reaction:

$Ni(s) + 2HNO_3(aq) \rightarrow Ni(NO_3)_2(aq) + H_2(g)$

18.2.3.1 Procedure:

1. **Obtain Ni metal and nitric acid:** Ensure that the Ni metal is clean and free of any oxides or impurities. Nitric acid is a strong oxidizing agent and should be handled with care.
2. **Set up a reaction vessel:** Place the Ni metal in a suitable container, such as a beaker or Erlenmeyer flask.
3. **Add nitric acid:** Slowly pour nitric acid into the container containing the Ni metal. The reaction will be vigorous and may produce heat and nitrogen oxide gas (NOx). Exercise caution and avoid inhaling the fumes.
4. **Stir or heat:** Gently stir the mixture to ensure complete reaction. If necessary, you can apply gentle heat to accelerate the process.
5. **Filter:** Once the reaction is complete, filter the solution to remove any unreacted Ni metal or impurities.
6. **Evaporate:** To obtain solid $Ni(NO_3)_2$, carefully evaporate the water from the filtrate. This can be done by heating the solution gently on a hot plate or in a water bath.

18.2.3.2 Safety precautions:

- Nitric acid is a strong acid and can cause severe burns. Wear appropriate protective equipment, including gloves, eye protection, and a lab coat.
- Work in a well-ventilated area to avoid inhaling nitrogen oxide fumes.
- Avoid direct contact with nitric acid and its solutions.
- If you come into contact with nitric acid, immediately rinse with plenty of water and seek medical attention.

18.2.3.3 Additional considerations:

- The concentration of nitric acid used can affect the reaction rate and the purity of the final product.
- If you need a high-purity Ni(NO3)2, you may need to perform additional purification steps, such as recrystallization.

By following these steps and taking appropriate safety precautions, you can successfully convert Ni metal to Ni(NO3)2.

18.2.4 Recrystallization of Ni(NO3)2

Recrystallization is a technique used to purify substances by dissolving them in a hot solvent, allowing the solution to cool slowly, and then isolating the crystals that form. For Ni(NO3)2, a suitable solvent is **water**.

18.2.4.1 Procedure:

1. **Dissolution:**
   - **Heat water:** Heat a suitable amount of water to boiling in a beaker.
   - **Add Ni(NO3)2:** Gradually add your Ni(NO3)2 powder to the boiling water while stirring continuously. Keep adding until no more Ni(NO3)2 dissolves. This is called saturation.

2. **Filtration (optional):**
   - If there are any insoluble impurities, filter the hot solution while it's still hot to remove them.

3. **Cooling:**
   - **Slow cooling:** Allow the filtered solution to cool slowly to room temperature. This will encourage the formation of larger, purer Ni(NO3)2 crystals. You can cover the beaker with a watch glass to prevent dust from contaminating the solution.

4. **Crystallization:**
   - As the solution cools, Ni(NO3)2 crystals will begin to form.

5. **Filtration:**
    - Once crystallization is complete, filter the solution to isolate the $Ni(NO_3)_2$ crystals. Use a Buchner funnel and filter paper.

6. **Washing:**
    - Wash the crystals with a small amount of cold water to remove any remaining impurities.

7. **Drying:**
    - Allow the crystals to air-dry on a filter paper or in a desiccator. Avoid using heat to dry them, as this can cause decomposition.

18.2.4.2 Additional Tips:

- **Purity check:** After recrystallization, you can check the purity of your $Ni(NO_3)_2$ using techniques like melting point determination or elemental analysis.

By following these steps, you can effectively recrystallize $Ni(NO_3)_2$ to obtain a pure product.

18.2.5 Convert Fe metal to $Fe(NO_3)_3$

18.2.5.1 Reaction:

The reaction between iron metal (Fe) and nitric acid (HNO_3) produces iron(III) nitrate ($Fe(NO_3)_3$) and hydrogen gas (H_2).

18.2.5.2 Balanced Equation:

$Fe(s) + 3HNO_3(aq) \rightarrow Fe(NO_3)_3(aq) + 3H_2(g)$

18.2.5.3 Procedure:

1. **Obtain Materials:**
    - **Iron metal:** Ensure it's clean and free from rust.
    - **Nitric acid:** A concentrated solution is typically used. Handle with care as it's a strong oxidizing agent.
2. **Safety Precautions:**
    - **Ventilation:** Work in a well-ventilated area as nitric acid fumes can be harmful.
    - **Protective Gear:** Wear gloves, eye protection, and a lab coat.
3. **Reaction Setup:**
    - **Container:** Place the iron metal in a suitable container, such as a beaker.
    - **Nitric Acid:** Slowly add the concentrated nitric acid to the container. The reaction will be vigorous and may produce brown fumes of nitrogen dioxide (NO_2).
4. **Observe Reaction:**
    - The iron metal will dissolve, and a solution of iron(III) nitrate will form. Hydrogen gas will be released.
5. **Filtering (Optional):**

   - If there are any unreacted iron particles or impurities, filter the solution to remove them.
6. **Evaporation (Optional):**
   - If you need solid iron(III) nitrate, carefully evaporate the water from the solution. This can be done by heating it gently on a hot plate.

Note: The reaction with nitric acid is a redox reaction. The iron is oxidized to iron(III), while the nitric acid is reduced to nitrogen dioxide.

18.2.5.4 Additional Considerations:

- **Concentrated Nitric Acid:** Using a more dilute solution might result in a slower reaction or the formation of iron(II) nitrate.
- **Temperature:** The reaction rate can be influenced by temperature. A higher temperature might accelerate the reaction.
- **Purity:** If a high-purity iron(III) nitrate is required, additional purification steps like recrystallization might be necessary.

By following these steps and adhering to safety guidelines, you can successfully convert iron metal to iron(III) nitrate.

18.2.6 Convert metal to Cu(NO3)2

18.2.6.1 Reaction:

The reaction between copper metal and nitric acid (HNO3) produces copper nitrate (Cu(NO3)2) and nitrogen dioxide gas (NO2).

$Cu(s) + 4HNO_3(aq) \rightarrow Cu(NO_3)_2(aq) + 2NO_2(g) + 2H_2O(l)$

18.2.6.2 Procedure:

1. **Obtain Materials:**
   - **Copper metal:** Ensure it's clean and free from oxides.
   - **Nitric acid:** A concentrated solution is typically used.
   - **Safety equipment:** Gloves, eye protection, and a lab coat.
2. **Set Up the Reaction:**
   - **Fume hood:** Conduct the reaction in a fume hood due to the toxic nature of nitrogen dioxide gas.
   - **Reaction vessel:** Place the copper metal in a suitable container (e.g., a beaker).
3. **Add Nitric Acid:**
   - **Slowly add:** Pour nitric acid over the copper metal. The reaction will be vigorous, producing brown nitrogen dioxide gas.
   - **Stir:** Gently stir the mixture to ensure complete reaction.

4. **Evaporate:**
   - **Heat:** Heat the solution to evaporate the excess water. This can be done on a hot plate or in a water bath.
   - **Crystallization:** As the water evaporates, copper nitrate crystals will form.

5. **Filter:**
    - **Separate crystals:** Filter the solution to separate the crystals from any remaining liquid.
6. **Dry:**
    - **Air dry:** Allow the crystals to air dry on a filter paper.

18.2.6.3 Safety Precautions:

- **Nitric acid:** It's a strong acid and can cause severe burns. Handle it with care.
- **Nitrogen dioxide:** It's a toxic gas. Work in a well-ventilated area or use a fume hood.
- **Protective equipment:** Wear appropriate safety gear to protect yourself from acid spills and fumes.

Note: The concentration of nitric acid and the reaction conditions can affect the rate of the reaction and the purity of the final product.

18.2.7 Convert Sm metal to Sm_2O_3

18.2.7.1 Reaction:

Samarium metal reacts with oxygen to form samarium oxide.

$4Sm(s) + 3O_2(g) \rightarrow 2Sm_2O_3(s)$

18.2.7.2 Procedure:

1. **Obtain Materials:**
    - **Samarium metal:** Ensure it's clean and free from oxides.
    - **Oxygen:** A source of oxygen, such as a cylinder or oxygen gas generator.
    - **Crucible:** A heat-resistant container to hold the samarium metal.
    - **Furnace:** A high-temperature furnace capable of reaching temperatures above 800°C.
2. **Prepare the Crucible:**
    - **Clean:** Ensure the crucible is clean and free from contaminants.
    - **Place metal:** Place the samarium metal into the crucible.
3. **Heat in Oxygen:**
    - **Furnace:** Place the crucible containing the samarium metal into the furnace.
    - **Oxygen flow:** Introduce a flow of oxygen into the furnace.
    - **Temperature:** Heat the furnace to a temperature above 800°C. The exact temperature may vary depending on the purity and particle size of the samarium metal.
4. **Cool and Collect:**
    - **Cool:** Allow the furnace to cool down naturally.
    - **Remove:** Remove the crucible from the furnace and carefully handle the resulting samarium oxide.

18.2.7.3 Safety Precautions:

- **Oxygen:** Oxygen is a flammable gas. Handle it with care and avoid contact with combustible materials.
- **High temperatures:** The furnace can reach very high temperatures. Use appropriate safety equipment and handle hot materials with caution.

- **Samarium oxide:** Samarium oxide is a rare earth oxide and should be handled with care. Avoid inhaling dust or ingesting the compound.

Note: The specific conditions and equipment required may vary depending on the desired purity and quantity of samarium oxide. It's recommended to consult with a chemist or materials scientist for more specific guidance.

18.2.8 Process to make SmFe0.7Cu0.1Ni0.2O3

The process to make $SmFe_{0.7}Cu_{0.1}Ni_{0.2}O_3$ involves several steps, as outlined in the document. Here's a summary of the preparation method:

1. **Materials Preparation**:
    - The starting materials include Sm_2O_3, $Fe(NO_3)_3$, $Cu(NO_3)_2$, and $Ni(NO_3)_2$, which are analytically pure reagents.
2. **Citrate Method**:
    - A solid citric acid with a molar ratio of citric acid to metal ions of 2:1 is added to a solution containing the metal ions.
    - The solution is stirred until the solid citric acid has completely dissolved.
3. **pH Adjustment**:
    - The pH of the solution is adjusted to between 6 and 7 by adding $NH_3{\cdot}H_2O$.
4. **Evaporation**:
    - The solution is slowly evaporated on a water bath at 70°C until a viscous liquid sol is obtained.
5. **Drying**:
    - The viscous sol is placed in a constant-temperature drying oven at 170°C until a solid mass is formed.
6. **Calcination**:
    - The dried gel is calcined at 700°C in a muffle furnace for 5 hours to form the desired powder.
7. **Sintering**:
    - The powder is then compressed into ceramic discs under a pressure of about 80 MPa.
    - These discs are sintered in air at 1150°C for 10 hours to prepare the final ceramic cathode material.
8. **Final Preparation**:
    - The ceramic discs are polished on both sides to achieve smooth surfaces, and a thick Ag—Pt slurry is applied to one side to act as the current collector.

This method ensures the formation of the $SmFe_{0.7}Cu_{0.1}Ni_{0.2}O_3$ material with the desired properties for use in ammonia synthesis

18.2.9 SmFe0.7Cu0.1Ni0.2O3 is a cathode, what is the anode

In the study, the anode used in the electrochemical synthesis of ammonia is made from NiO-SDC (Nickel Oxide - Samaria-Doped Ceria). The NiO-SDC ceramic flake is prepared using established methods in literature.

18.2.10 Process to make NiO-SDC

The process of making NiO-SDC (Nickel Oxide - Samaria-Doped Ceria) involves several steps, which are typically based on established methods. Here's a typical process:

1. **Materials Preparation**:
    - The starting materials include cerium oxide (CeO_2) and samarium oxide (Sm_2O_3) for the Samaria-doped ceria (SDC) component, along with nickel nitrate ($Ni(NO_3)_2$) for the nickel oxide component.
2. **Doping Process**:
    - The desired amount of Sm_2O_3 is mixed with CeO_2 to achieve the desired doping level (e.g., 20% Sm doping in CeO_2).
3. **Solution Preparation**:
    - Nickel nitrate is dissolved in distilled water to create a solution.
4. **Mixing**:
    - The ceria and samaria powders are mixed with the nickel nitrate solution. This can be done using a ball mill or other mixing techniques to ensure a homogeneous mixture.
5. **Drying**:
    - The mixed solution is dried to remove water, often by evaporating it at a controlled temperature.
6. **Calcination**:
    - The dried mixture is then calcined at a high temperature (typically around 500-700°C) in air or an inert atmosphere for several hours. This step helps to convert the nitrates into oxides and to form the desired NiO-SDC phase.
7. **Reduction**:
    - If the final product is to be NiO-SDC, it may need to be reduced in a hydrogen atmosphere at elevated temperatures (e.g., 500°C) to convert NiO to metallic Ni, depending on the specific application.
8. **Sintering**:
    - The resulting powder can be pressed into pellets or discs and sintered at a higher temperature (e.g., 1150°C) to achieve the desired density and microstructure.

This general method provides a framework for synthesizing NiO-SDC, which is used as the anode material in the electrochemical synthesis of ammonia

18.2.11 Details of the reduction part

The reduction of NiO to metallic Ni is a crucial step in the preparation of NiO-SDC (Nickel Oxide - Samaria-Doped Ceria) when the nickel oxide is intended to be used in its reduced form for enhanced catalytic activity. Here are the detailed steps typically involved in the reduction process:

1. **Preparation of the Sample**:
    - After the calcination step, where the nickel nitrate and ceria-samaria mixture is heated to form NiO-SDC, the resulting material is typically in the form of a powder or ceramic disc.
2. **Setting Up the Reduction Environment**:
    - The reduction is performed in a controlled atmosphere, usually in a tube furnace or a muffle furnace.

   - A hydrogen gas source is required for the reduction process. The hydrogen can be supplied from a gas cylinder or generated in situ.
3. **Temperature Control**:
   - The reduction process is typically carried out at elevated temperatures, commonly around 500°C. This temperature is sufficient to facilitate the reduction of NiO to Ni.
4. **Hydrogen Atmosphere**:
   - The sample is placed in the furnace, and a flow of hydrogen gas is introduced. The flow rate is usually controlled to ensure a consistent atmosphere around the sample.
   - The reduction reaction can be represented as follows: NiO+H2→Ni+H2O
   - This reaction indicates that nickel oxide (NiO) is reduced to metallic nickel (Ni), while hydrogen (H_2) is oxidized to water (H_2O).
5. **Duration of Reduction**:
   - The reduction process typically lasts for about 2 hours, allowing sufficient time for the complete reduction of NiO to Ni. The exact duration may vary depending on the specific material and desired properties.
6. **Cooling**:
   - After the reduction is complete, the furnace is allowed to cool down to room temperature while maintaining a hydrogen atmosphere to prevent oxidation of the reduced nickel.
7. **Post-Reduction Treatment**:
   - Once cooled, the reduced NiO-SDC can be removed from the furnace. It is important to handle the material in an inert atmosphere (e.g., under nitrogen or argon) if it is to be stored, to prevent re-oxidation of the metallic nickel.
8. **Characterization**:
   - After reduction, the material can be characterized using techniques such as X-ray diffraction (XRD) and scanning electron microscopy (SEM) to confirm the successful reduction and to analyze the microstructure.

This reduction step is critical for enhancing the catalytic properties of the NiO-SDC anode material, making it more effective for applications such as electrochemical synthesis of ammonia.

18.2.12 Materials need for cathode preparation

The materials needed for the preparation of the cathode, specifically for the $SmFe_{0.7}Cu_{0.3-x}Ni_xO_3$ (SFCN) cathode used in the electrochemical synthesis of ammonia, include the following:

1. **Metal Nitrates**:

   - **Iron Nitrate ($Fe(NO_3)_3$)**: This serves as a source of iron in the cathode material.
   - **Copper Nitrate ($Cu(NO_3)_2$)**: This provides copper, which is a component of the cathode.
   - **Nickel Nitrate ($Ni(NO_3)_2$)**: This is used for doping the cathode material with nickel.

2. **Samarium Oxide**:

   - **Samarium Oxide (Sm_2O_3)**: This is used as a dopant in the ceria structure to enhance the properties of the cathode.

3. **Citric Acid**:

- **Citric Acid**: This is used as a chelating agent in the preparation process, helping to form a homogeneous solution with the metal ions.

4. **Distilled Water**:

    - **Distilled Water**: Used to dissolve the metal nitrates and to prepare the solution for the citrate method.

5. **Hydrochloric Acid or Ammonia**:

    - **Ammonia ($NH_3 \cdot H_2O$)**: This is used to adjust the pH of the solution during the preparation process.

6. **Solvent for Drying**:

    - **Water**: Used in the initial steps for dissolving and mixing the components.

7. **Additional Materials**:

    - **Ag-Pt Slurry**: This is used as a current collector on the cathode.
    - **Nafion Membrane**: While not part of the cathode itself, it is essential for the assembly of the electrochemical cell.

8. **Equipment**:

    - **Furnace**: For calcination and sintering of the prepared material.
    - **Ball Mill or Mixer**: For mixing the powders and ensuring homogeneity.
    - **Pressing Equipment**: For forming the ceramic discs from the powder.

These materials and equipment are essential for synthesizing the SFCN cathode, which is characterized by its perovskite structure and is used in the electrochemical synthesis of ammonia.

18.2.13 Materials need for anode preparation

The materials needed for the preparation of the anode, specifically for the nickel-doped samaria-doped ceria (Ni-SDC) anode used in the electrochemical synthesis of ammonia, include the following:

18.2.13.1 Nickel Oxide:

- **Nickel Oxide (NiO)**: This serves as the primary source of nickel for the anode material. It is later reduced to metallic nickel during the preparation process.

18.2.13.2 Samaria-Doped Ceria:

- **Ceria (CeO_2)**: This is the base material for the anode, which is doped with samarium to enhance its ionic conductivity.
- **Samarium Oxide (Sm_2O_3)**: This is used to dope ceria, improving its properties for use in solid oxide fuel cells and electrochemical applications.

18.2.13.3 Citric Acid:

- **Citric Acid**: Similar to the cathode preparation, citric acid is used as a chelating agent to help form a homogeneous solution with the metal ions.

18.2.13.4 Distilled Water:

- **Distilled Water**: Used to dissolve the metal nitrates and prepare the solution for the citrate method.

18.2.13.5 Hydrochloric Acid or Ammonia:

- **Ammonia ($NH_3 \cdot H_2O$)**: This is used to adjust the pH of the solution during the preparation process.

18.2.13.6 Additional Materials:

- **Ag-Pt Slurry**: This is used as a current collector on the anode.
- **Nafion Membrane**: While not part of the anode itself, it is essential for the assembly of the electrochemical cell.

18.2.13.7 Equipment:

- **Furnace**: For calcination and sintering of the prepared material.
- **Ball Mill or Mixer**: For mixing the powders and ensuring homogeneity.
- **Pressing Equipment**: For forming the ceramic discs from the powder.
- These materials and equipment are essential for synthesizing the Ni-SDC anode, which plays a critical role in the electrochemical synthesis of ammonia.

18.2.14 Details of Sintering part

The sintering process is a crucial step in the preparation of ceramic materials, including the cathode and anode used in the electrochemical synthesis of ammonia. Here are the details of the sintering part as described in the document:

1. **Preparation of the Precursor**:
   After the citrate precursor is formed by evaporating the solution containing the metal nitrates and citric acid, the dried gel is obtained.
2. **Calcination**:
   The dried gel is calcined at **700°C** in a muffle furnace for **5 hours**. This step is essential for decomposing the organic components and forming the desired metal oxide phases.
3. **Formation of Ceramic Discs**:
   The calcined powder is then compressed into ceramic discs under a pressure of about **80 MPa**. This step ensures that the material has sufficient density and mechanical strength.
4. **Sintering**:
   The ceramic discs are sintered in air at **1150°C** for **10 hours**. Sintering is a process where the ceramic material is heated to a temperature below its melting point, allowing the particles to bond together, reduce porosity, and enhance the mechanical and electrical properties of the material.
5. **Cooling**:

After the sintering process, the discs are allowed to cool down gradually to room temperature. Controlled cooling is important to avoid thermal shock and cracking of the ceramic material.

6. **Polishing**:
   The sintered ceramic discs (both the cathode and anode) are polished on both sides to achieve smooth surfaces. This step is important for ensuring good contact with the Nafion membrane and the current collectors.
7. **Final Assembly**:
   After polishing, a thick Ag-Pt slurry is smeared on one side of each disk to act as the current collector. Platinum wire is then bonded to each disk to serve as a lead. The final assembly involves placing the Ni-SDC and SFCN discs on opposite sides of the Nafion membrane, which is used to bind them together.

These steps ensure that the ceramic materials have the necessary structural integrity and electrochemical properties for effective performance in the ammonia synthesis process.

18.3 Ammonia Production (AP) simulation

18.3.1 Green Hydrogen

Green hydrogen, produced from renewable sources of raw materials and energy, water ($H2O$) can be converted into hydrogen gas ($H2$) and oxygen gas ($O2$) this is represented by equation:

$H2O \rightarrow H2 + ½ O2$

equation of Ammonia synthesis:

$N2+H2 \rightarrow NH3$

water electrolysis is the process whereby water is split into hydrogen and oxygen through the application of electrical energy, the total energy that is needed for water electrolysis is increasing with temperature, while the required electrical energy decreases.

At the cathode: hydrogen ions are converted into hydrogen: $2 H2O + 2e- \to 2 OH- + H2$

anode :oxidation

$2OH- \rightarrow H2O +2e- + ½ O2$

18.3.2 The Electrolysis of water equation

$2H2O$ + electrical energy $\to H2 + 0.5 O2 + H2O$

18.3.2.1 Parameters to be determined before water electrolysis

cell voltage

power requirement of the Electrolysers.

conversion of water into hydrogen gas.

In ICPT there is already a prototype Water Electrolyzer, where system tests where undergone:

18.3.3 The Haber Bosch revolution :

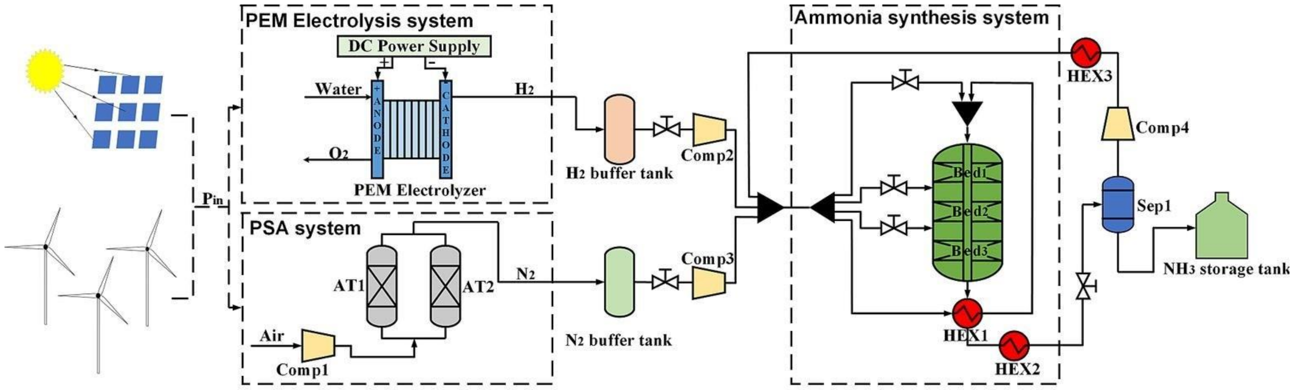
$N_2+3H_2 \rightarrow 2NH_3$

Ammonia is a precursor for fertilizers (ammonium nitrate).

our objective is to storage H2 under ammonia

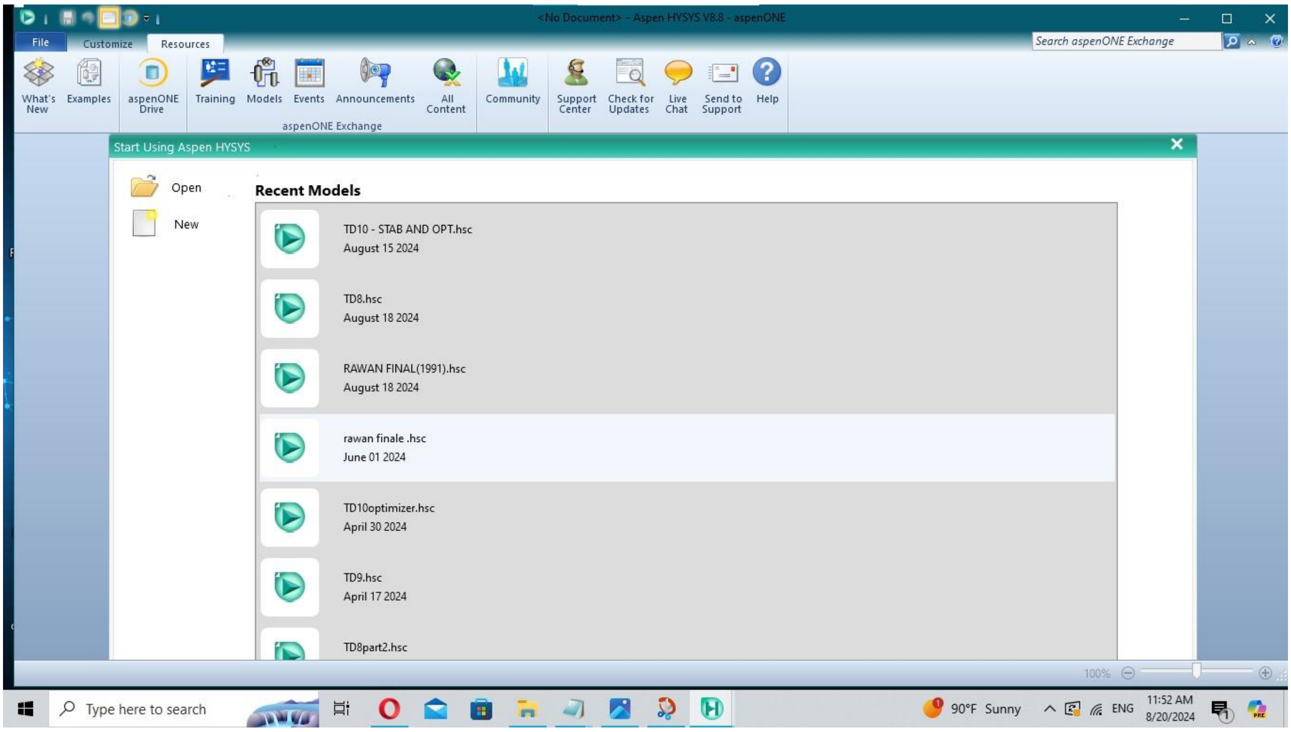
The disadvantage of H2 as an energy carrier is its low volumetric energy density

solution NH3 as energy storage for H2 (H2 should be converted into NH3 using the Haber Bosch process).



18.3.4 Simulation using Aspen Hysys

- **Create new File**



Recent Models

TD10 - STAB AND OPT.hsc
August 15 2024

TD8.hsc
August 18 2024

RAWAN FINAL(1991).hsc
August 18 2024

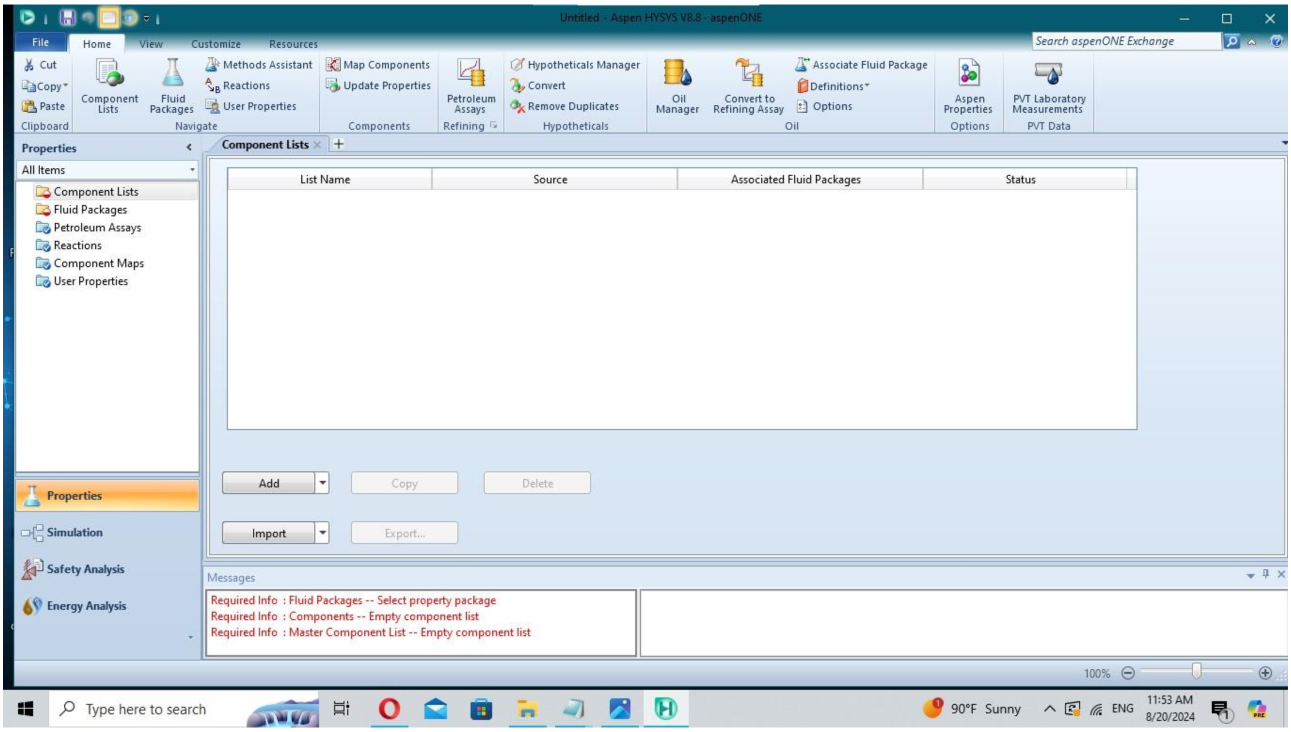
rawan finale .hsc
June 01 2024

TD10optimizer.hsc
April 30 2024

TD9.hsc
April 17 2024

TD8part2.hsc

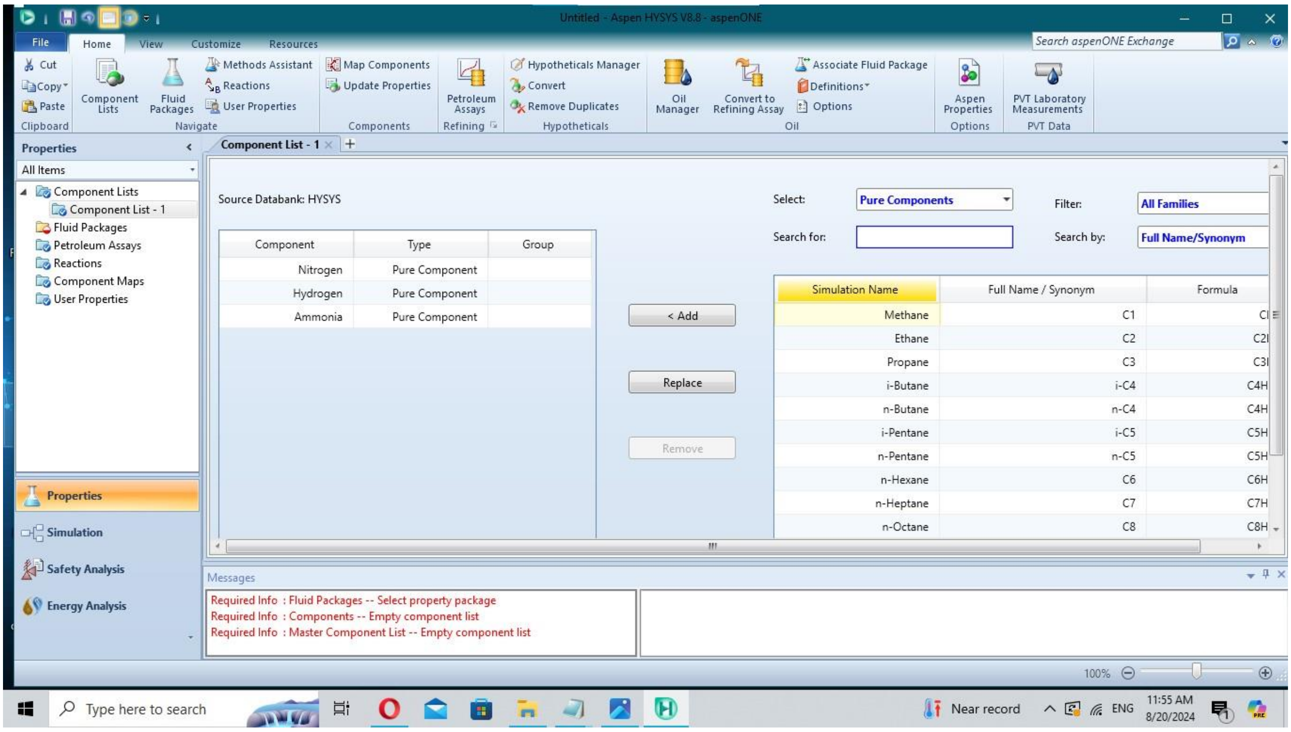
- **Add Component list**



Messages

Required Info : Fluid Packages -- Select property package
Required Info : Components -- Empty component list
Required Info : Master Component List -- Empty component list

- **Add Nitrogen, Hydrogen and Ammonia**



Source Databank: HYSYS

Select: Pure Components

Filter: All Families

Search for:

Search by: Full Name/Synonym

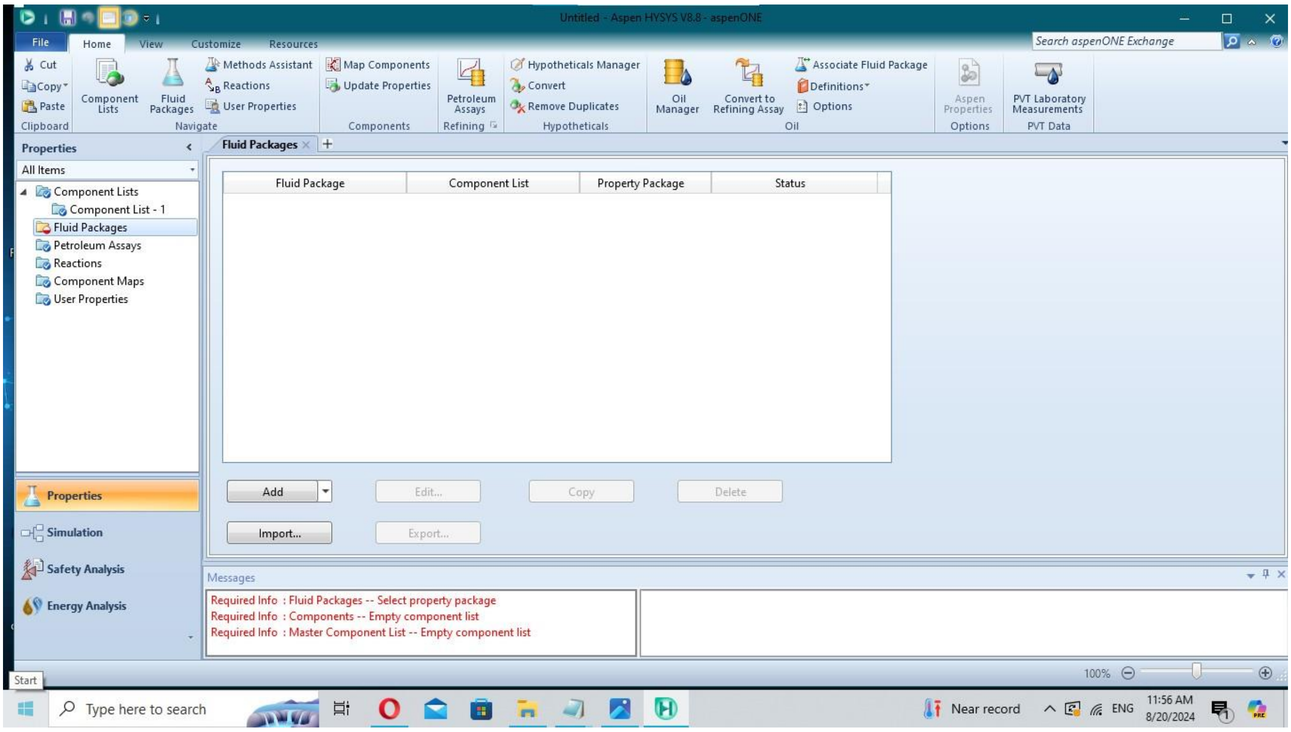
Component	Type	Group
Nitrogen	Pure Component	
Hydrogen	Pure Component	
Ammonia	Pure Component	

Simulation Name	Full Name / Synonym	Formula
Methane	C1	C
Ethane	C2	C2
Propane	C3	C3
i-Butane	i-C4	C4H
n-Butane	n-C4	C4H
i-Pentane	i-C5	C5H
n-Pentane	n-C5	C5H
n-Hexane	C6	C6H
n-Heptane	C7	C7H
n-Octane	C8	C8H

Messages

Required Info : Fluid Packages -- Select property package
Required Info : Components -- Empty component list
Required Info : Master Component List -- Empty component list

- **Add Fluid packages**

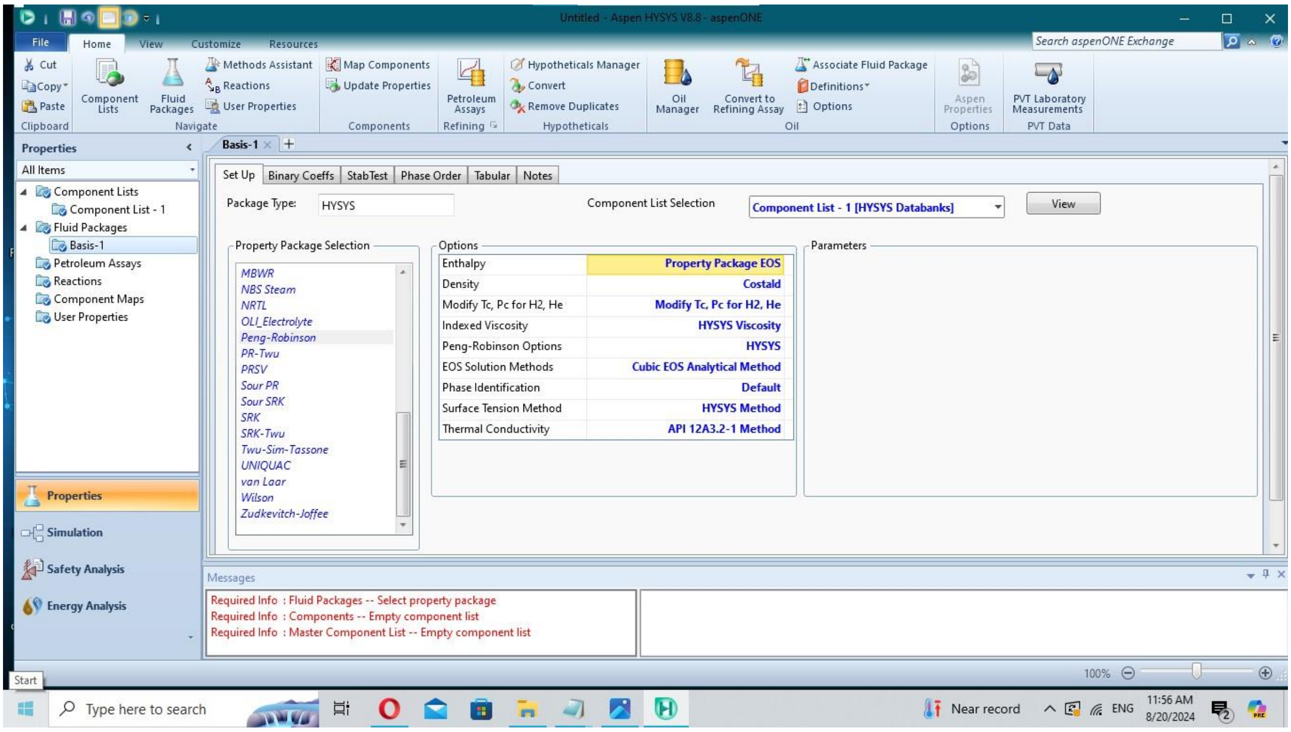


Fluid Package	Component List	Property Package	Status

Messages

Required Info : Fluid Packages -- Select property package
Required Info : Components -- Empty component list
Required Info : Master Component List -- Empty component list

- **search and select Peng Robinson**



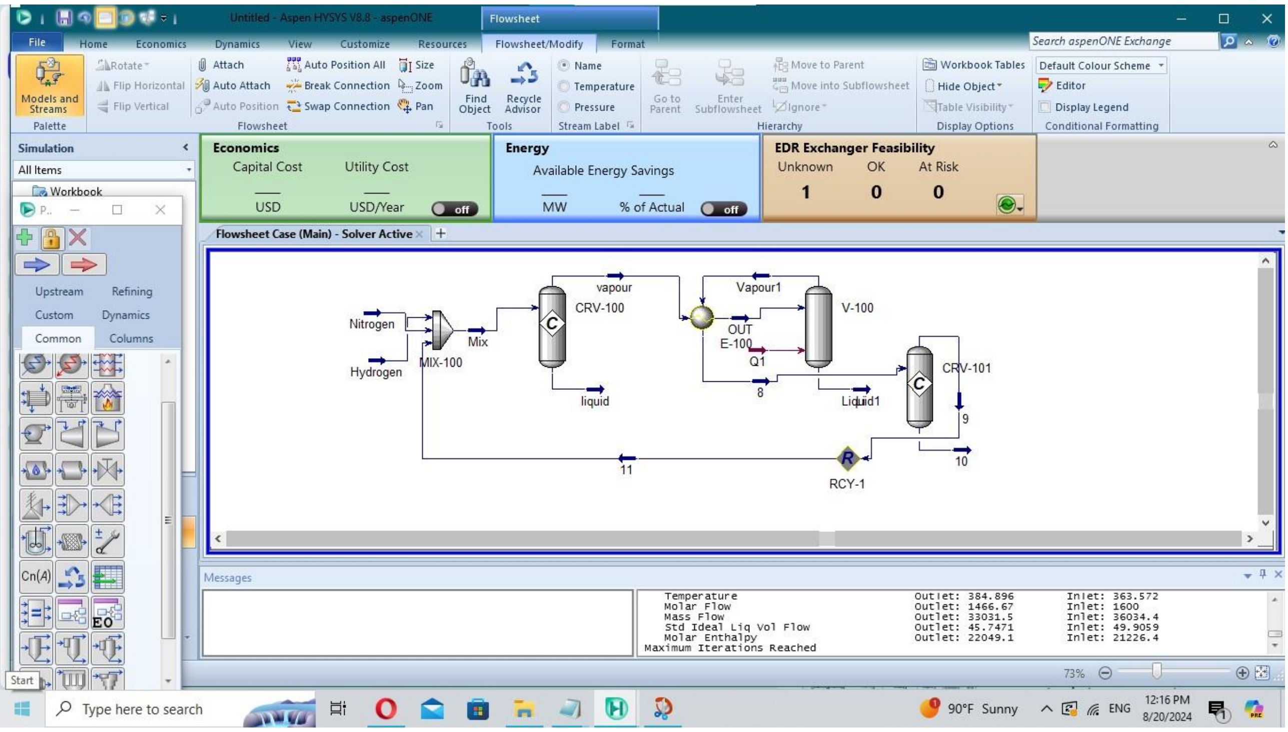
Package Type: HYSYS

Component List Selection: Component List - 1 [HYSYS Databanks]

Options	
Enthalpy	Property Package EOS
Density	Costald
Modify Tc, Pc for H2, He	Modify Tc, Pc for H2, He
Indexed Viscosity	HYSYS Viscosity
Peng-Robinson Options	HYSYS
EOS Solution Methods	Cubic EOS Analytical Method
Phase Identification	Default
Surface Tension Method	HYSYS Method
Thermal Conductivity	API 12A3.2-1 Method

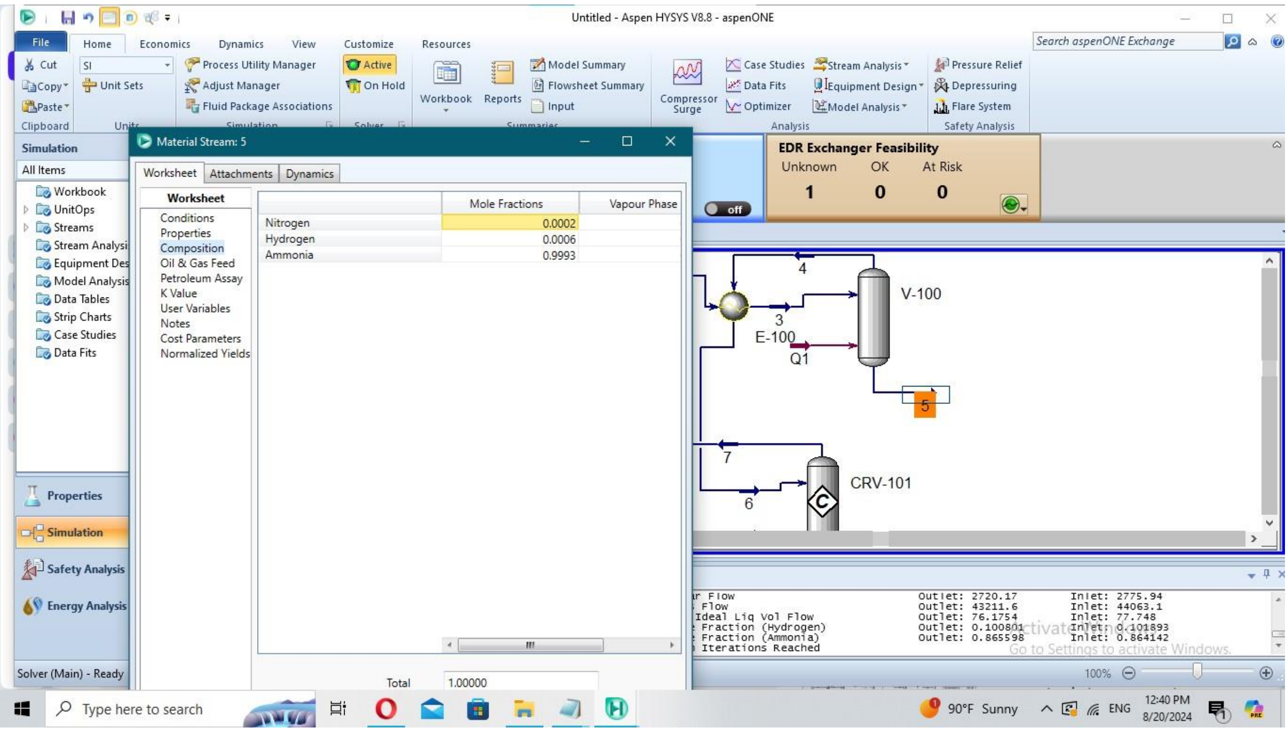
```
Required Info : Fluid Packages -- Select property package
Required Info : Components -- Empty component list
Required Info : Master Component List -- Empty component list
```

- **Start Simulation**



```
   Temperature                          Outlet: 384.896      Inlet: 363.572
   Molar Flow                           Outlet: 1466.67      Inlet: 1600
   Mass Flow                            Outlet: 33031.5      Inlet: 36034.4
   Std Ideal Liq Vol Flow               Outlet: 45.7471      Inlet: 49.9059
   Molar Enthalpy                       Outlet: 22049.1      Inlet: 21226.4
Maximum Iterations Reached
```

- **Result**



	Mole Fractions	Vapour Phase
Nitrogen	0.0002	
Hydrogen	0.0006	
Ammonia	0.9993	
Total	1.00000	

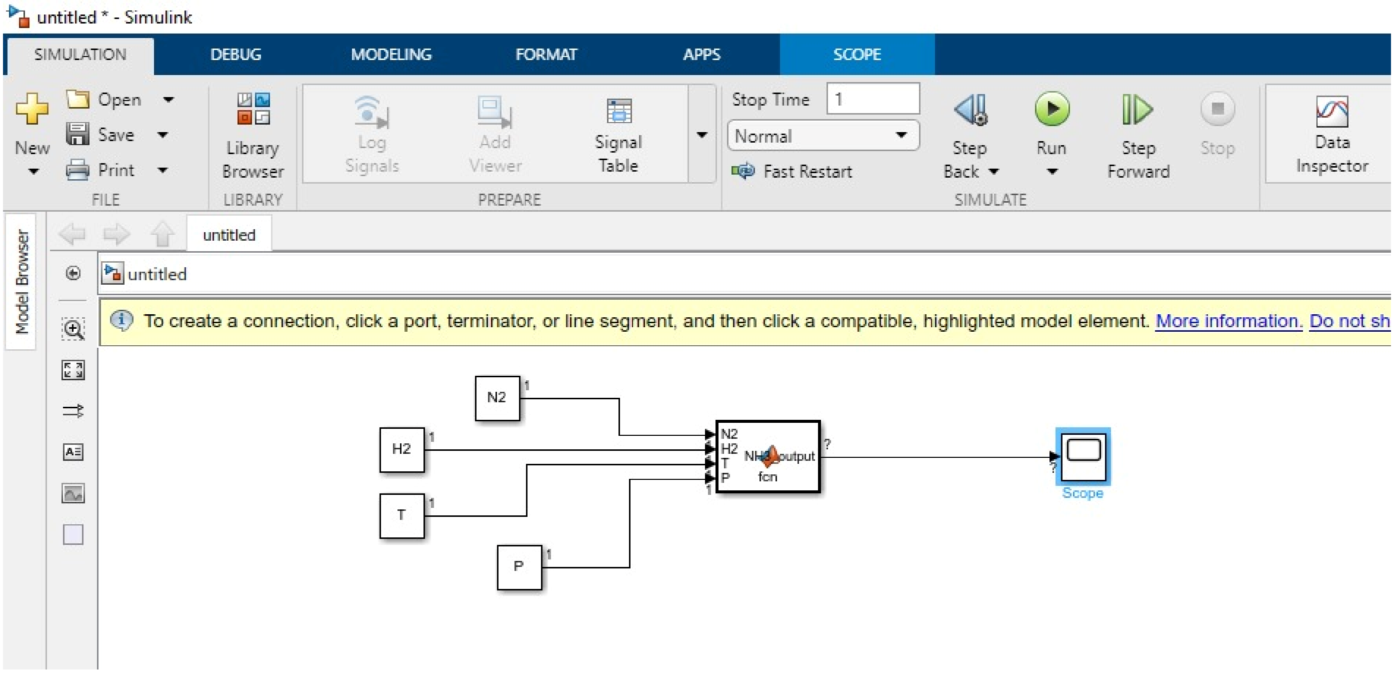
```
r Flow                              Outlet: 2720.17        Inlet: 2775.94
 Flow                               Outlet: 43211.6        Inlet: 44063.1
Ideal Liq Vol Flow                  Outlet: 76.1754        Inlet: 77.748
 Fraction (Hydrogen)                Outlet: 0.100801       Inlet: 0.101893
 Fraction (Ammonia)                 Outlet: 0.865598       Inlet: 0.864142
 Iterations Reached
```

18.3.5 Principal features of Aspen, COCO, and CHEMCAD simulators concerning H2 storage in ammonia

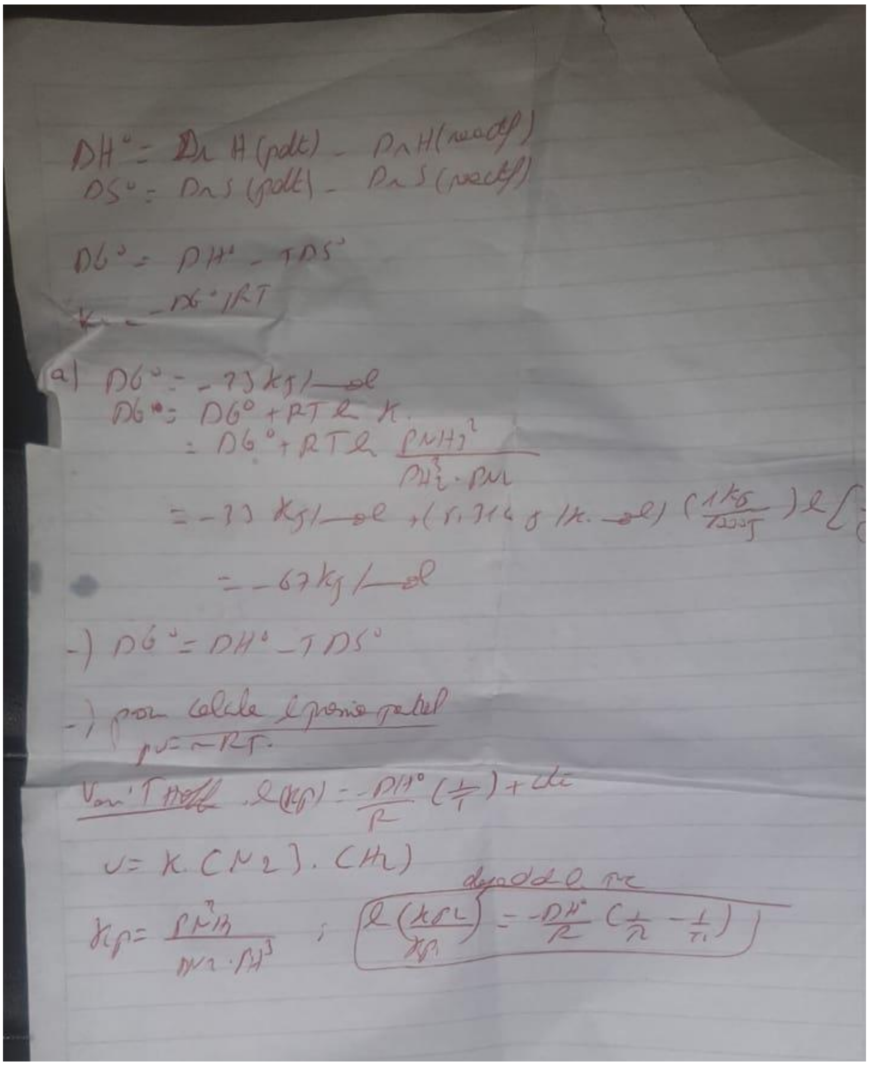
Feature/Aspect	**Aspen**	**Coco**	**CHEMCAD**
process Modeling	Advanced process modeling with extensive thermodynamic and kinetic models	Basic modeling capabilities with customizable units	Good modeling capabilities with a focus on usability
Thermodynamic packages	Wide variety	supports CAPE_OPEN thermodynamic models	Extensive thermodynamic models, user_friendly selection
Reaction Kinetics	Comprehensive Kinetic modeling for reactions, including custom Kinetics	Custom Kinetic modeling is possible with CAPE_open units	Kinetic modeling supported, with a focus on ease of use

custom unit operations	Highly customizable unit operations, including custom coding	customizable through CAPE_open compliant modules	custom unit operations with intuitive interfaces
Simulation Flexibility	High flexibility in process simulation, suitable for complex systems	Flexible but may require manual setup and coding	Flexible, with a balance between complexity and usability
user interface	complex	simple, basic	user friendly
cost	Expensive	Free	Moderate
Industry Application	widely used in chemical petrochemical	More suited for academic and simple industrial application	common in chemical, pharmaceutical, and food industries

18.3.6 Simulation with MATLAB



To create a connection, click a port, terminator, or line segment, and then click a compatible, highlighted model element. More information. Do not sh



$\Delta H^\circ = \Delta_r H(\text{pdt}) - \Delta_r H(\text{reactf})$

$\Delta S^\circ = \Delta_r S(\text{pdt}) - \Delta_r S(\text{reactf})$

$\Delta G^\circ = \Delta H^\circ - T\Delta S^\circ$

$K = {}^{-\Delta G^\circ / RT}$

a) $\Delta G^\circ = -33\ \text{kJ/mol}$

$\Delta G^* = \Delta G^\circ + RT \ln K$

$= \Delta G^\circ + RT \ln \frac{(P_{NH_3})^2}{P_{H_2}^3 \cdot P_{N_2}}$

$= -33\ \text{kJ/mol} + (8.314\ \text{J/K.mol}) \left(\frac{1\ \text{kJ}}{1000\ \text{J}}\right) \ln [$

$= -67\ \text{kJ/mol}$

-) $\Delta G^\circ = \Delta H^\circ - T\Delta S^\circ$

-) pour calcule la pression partiel

$pV = nRT$.

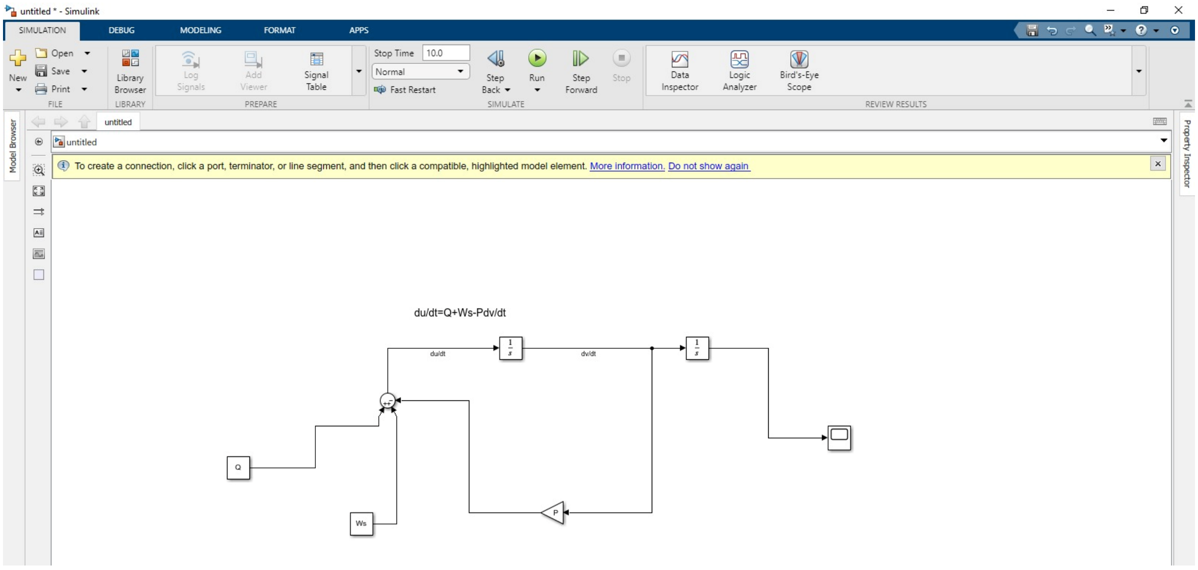
Van't Hoff $\ln(K_p) = -\frac{\Delta H^\circ}{R}\left(\frac{1}{T}\right) + cte$

$v = k \cdot [N_2] \cdot [H_2]$

dépendance de T

$K_p = \frac{P_{NH_3}^2}{P_{N_2} \cdot P_{H_2}^3}$; $\boxed{\ln\left(\frac{K_{p2}}{K_{p1}}\right) = -\frac{\Delta H^\circ}{R}\left(\frac{1}{T_2} - \frac{1}{T_1}\right)}$

18.3.6.1 Differential equation used MATLAB



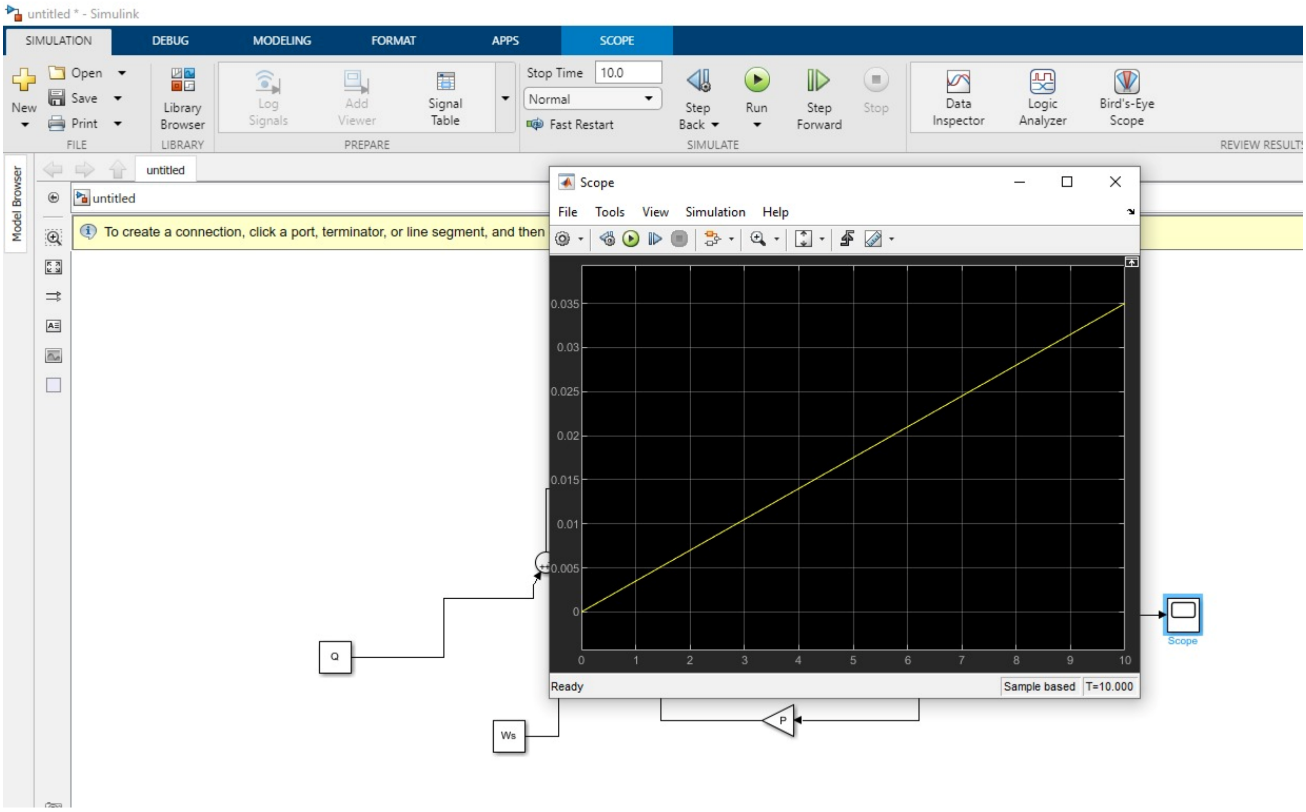
Stop Time 10.0

Normal

To create a connection, click a port, terminator, or line segment, and then click a compatible, highlighted model element. More information. Do not show again

du/dt=Q+Ws-Pdv/dt

18.3.6.2 The result



To create a connection, click a port, terminator, or line segment, and then

>>- $PV=nRT$; $\Delta H=\sum \Delta H_f^\circ(\text{products})-\sum \Delta H_f^\circ(\text{reactants})$ $\Delta S=\sum S^\circ(\text{products})-\sum S^\circ(\text{reactants})$

$\Delta G=\Delta H-T\Delta S$

$\Delta G=-RT\ln K$

A l equilibre

$\Delta G=0$------->$K=e^{-\Delta G/RT}$

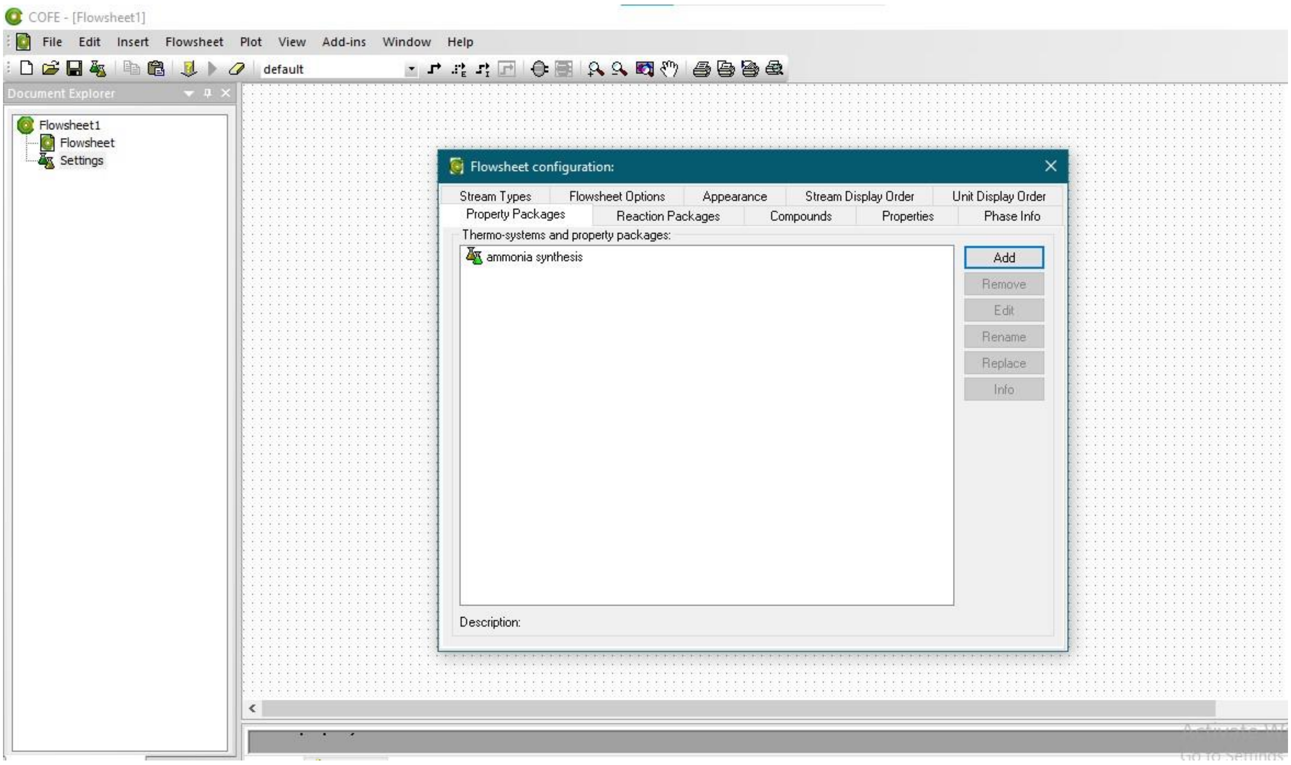
Perfect gas eq.: $PV=nRT$

18.3.7 Simulation with COCO

step 1: Open the program COFE to simulate with coco:

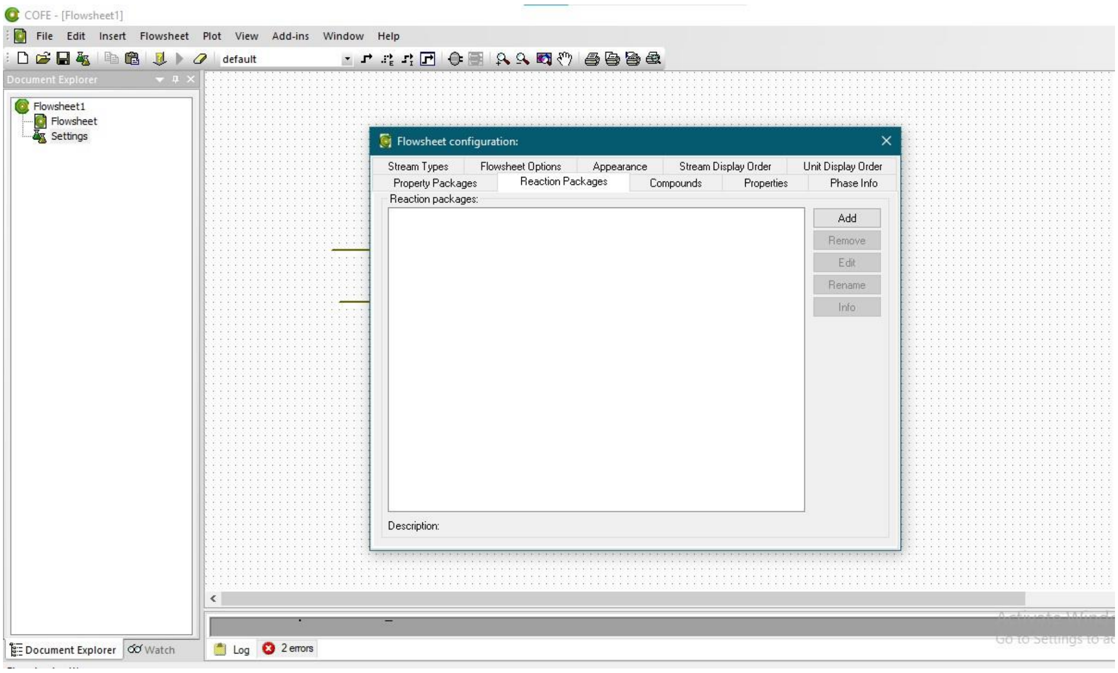
step 2: Click on settings.

- Packages ammonia

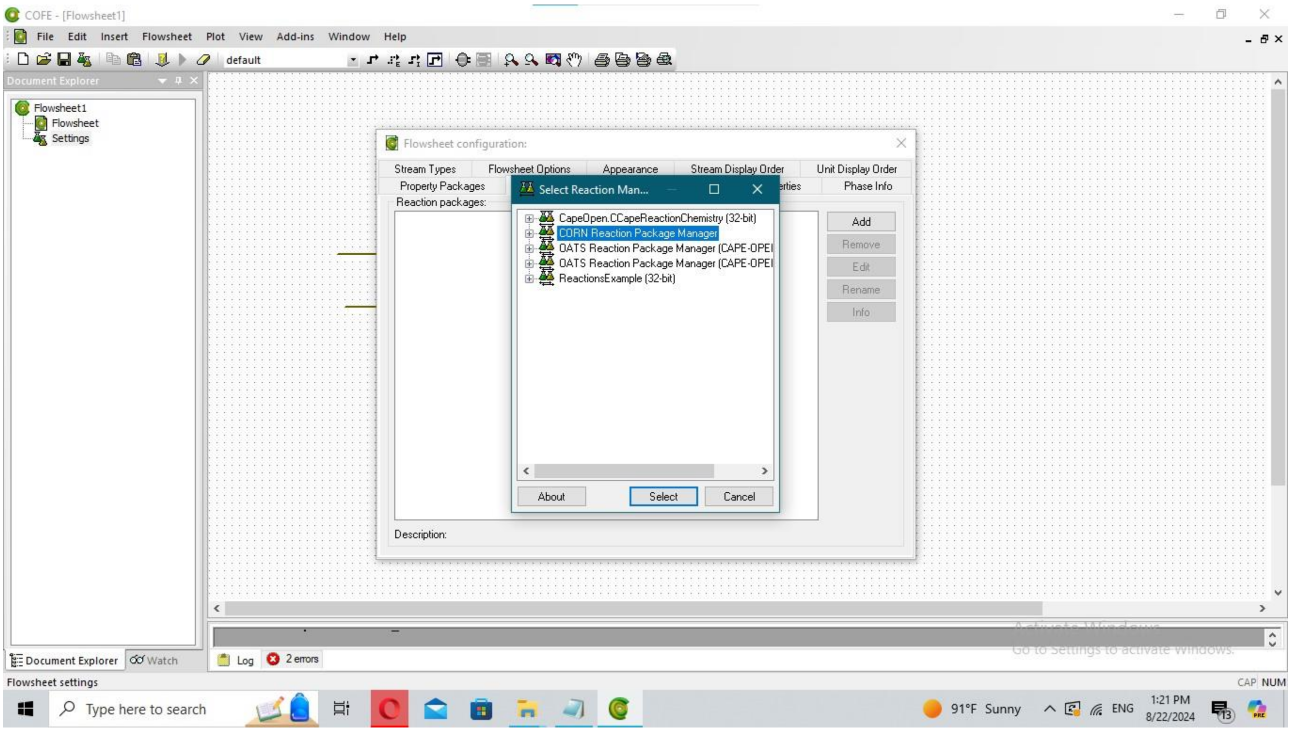


Thermo-systems and property packages:
ammonia synthesis

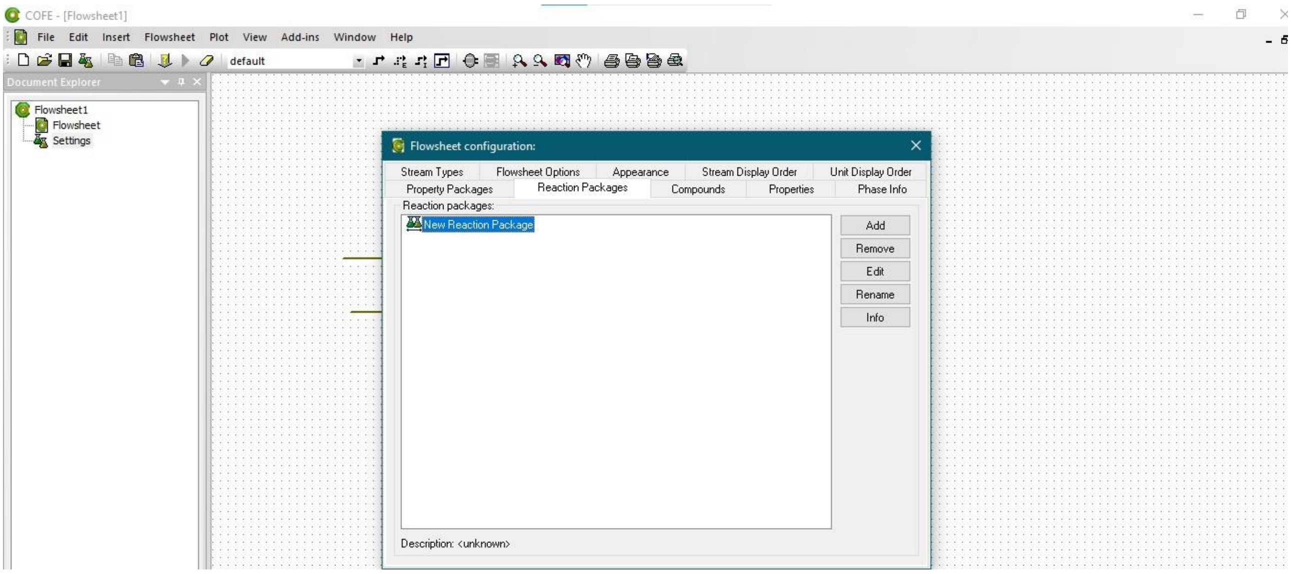
- Add reaction



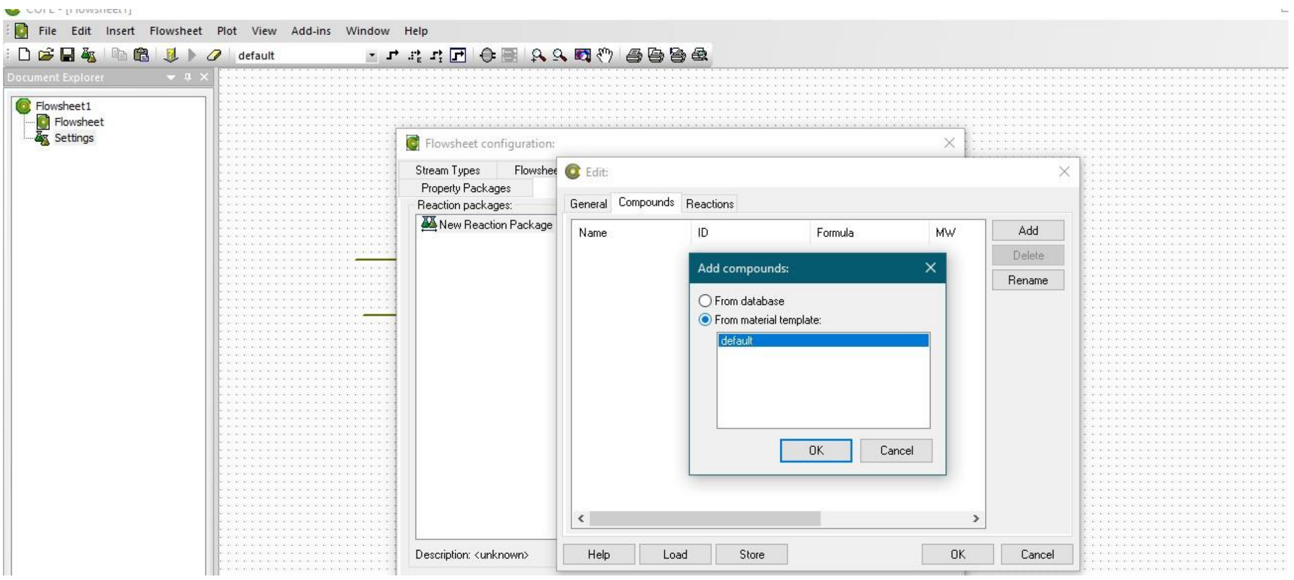
- Add reaction manager



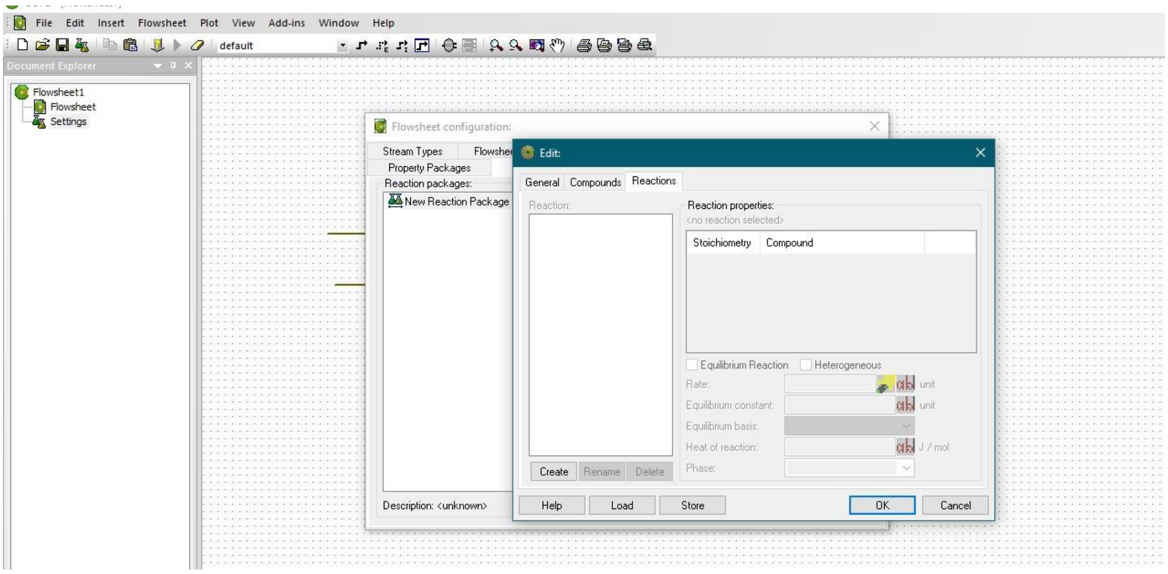
- Edit new reaction



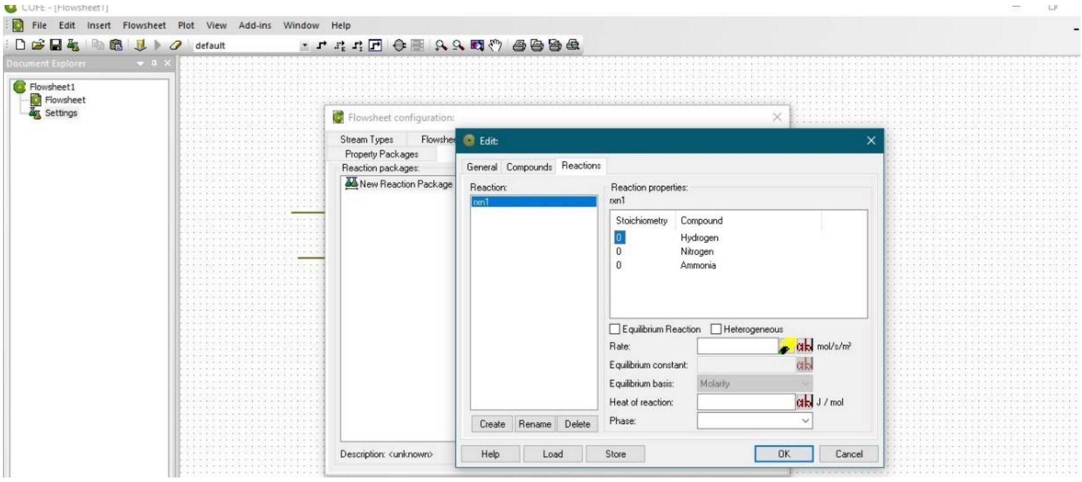
- Add compound of material



- Select reaction



- Stochiometrics



Reaction:
rxn1

Reaction properties:
rxn1

Stoichiometry	Compound
0	Hydrogen
0	Nitrogen
0	Ammonia

☐ Equilibrium Reaction ☐ Heterogeneous

Rate: mol/s/m³

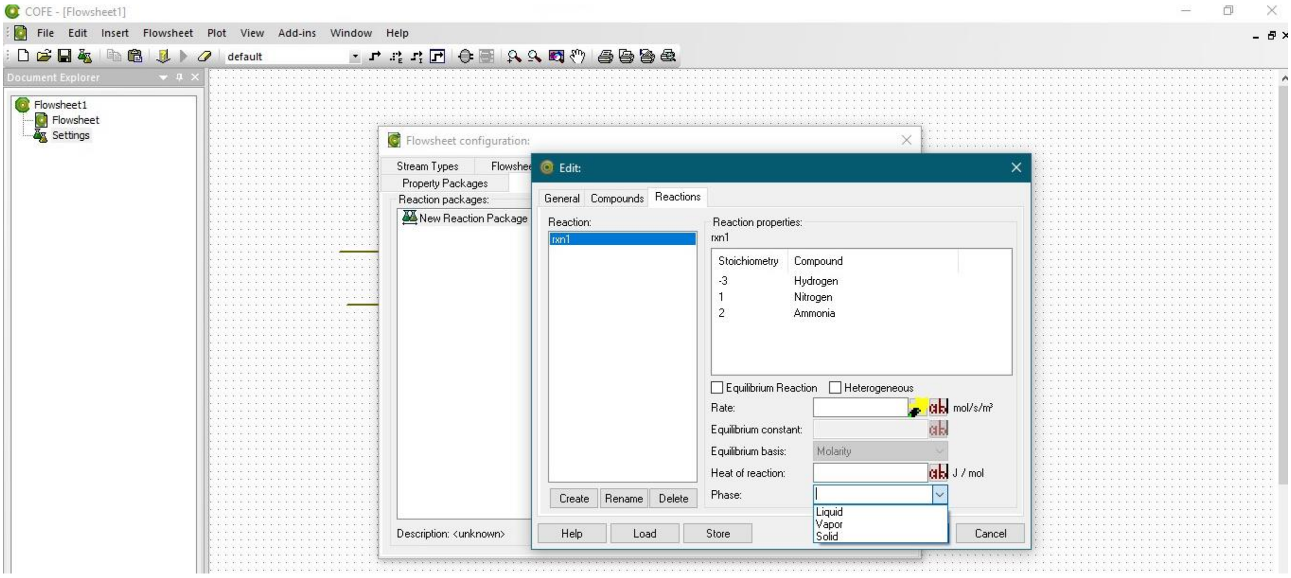
Equilibrium constant:

Equilibrium basis: Molarity

Heat of reaction: J / mol

Phase:

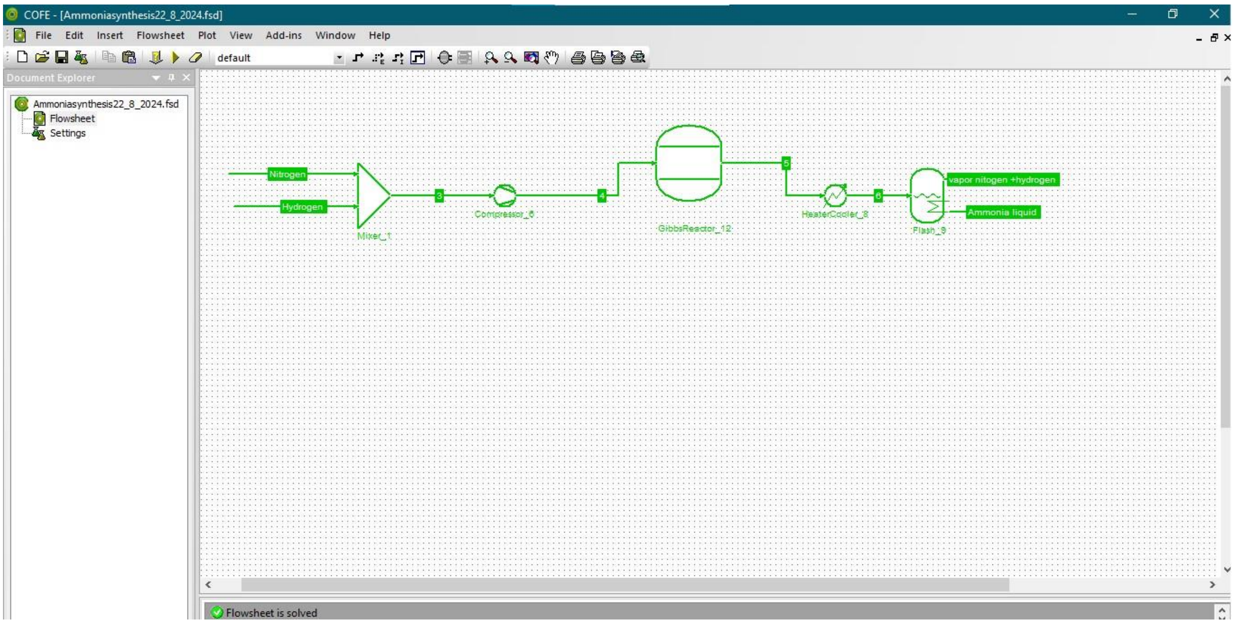
- Select GAS phase



Stoichiometry	Compound
-3	Hydrogen
1	Nitrogen
2	Ammonia

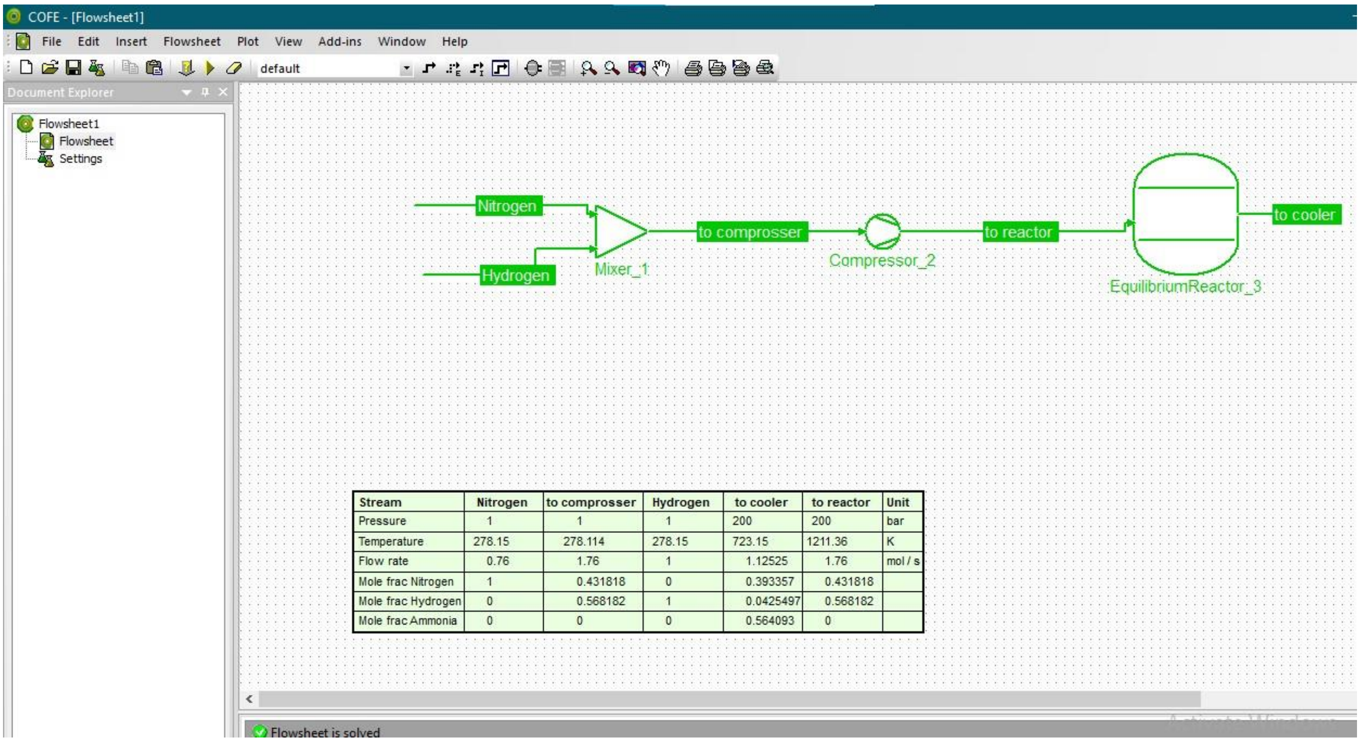
☐ Equilibrium Reaction ☐ Heterogeneous

- The unit operation used



Flowsheet is solved

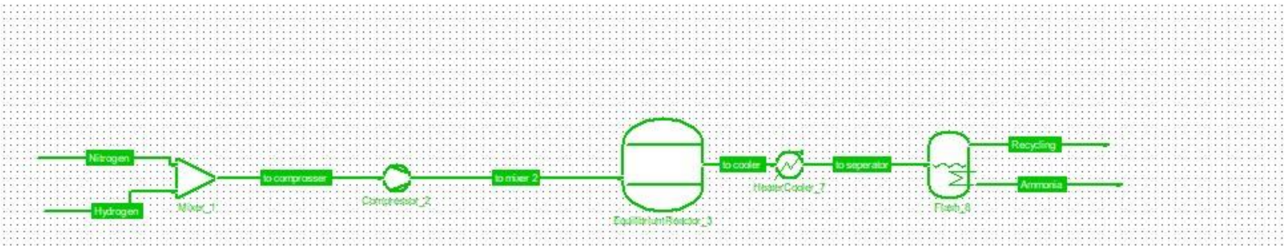
- Streams info



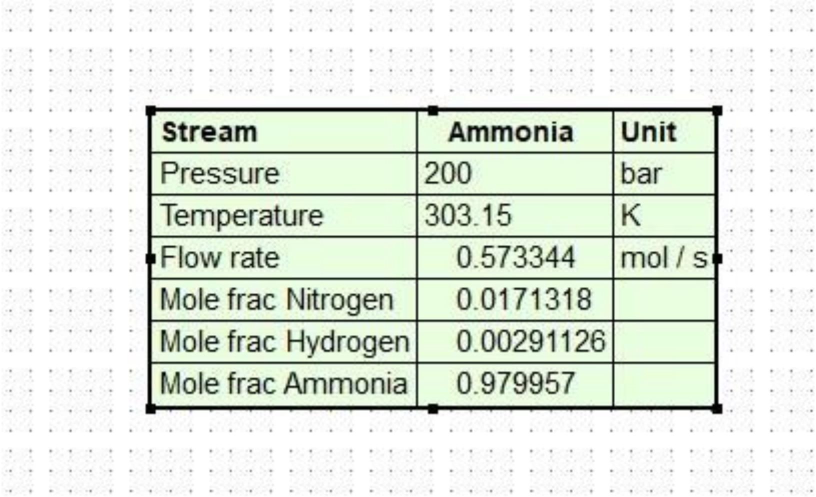
Stream	Nitrogen	to compresser	Hydrogen	to cooler	to reactor	Unit
Pressure	1	1	1	200	200	bar
Temperature	278.15	278.114	278.15	723.15	1211.36	K
Flow rate	0.76	1.76	1	1.12525	1.76	mol / s
Mole frac Nitrogen	1	0.431818	0	0.393357	0.431818	
Mole frac Hydrogen	0	0.568182	1	0.0425497	0.568182	
Mole frac Ammonia	0	0	0	0.564093	0	

Flowsheet is solved

- Simulation



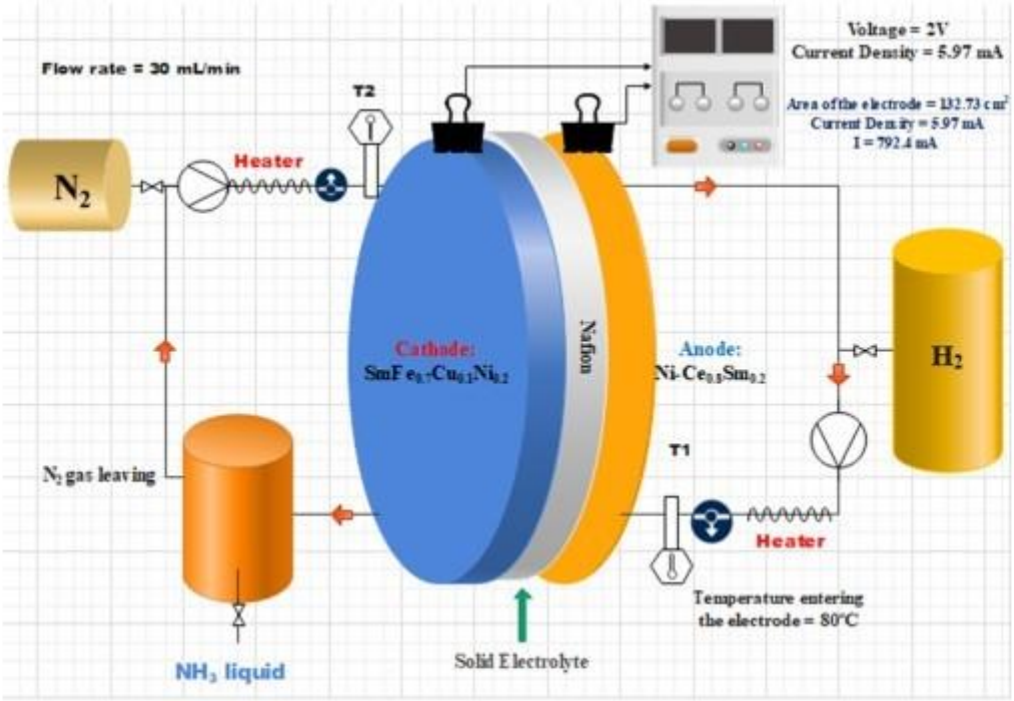
- Result



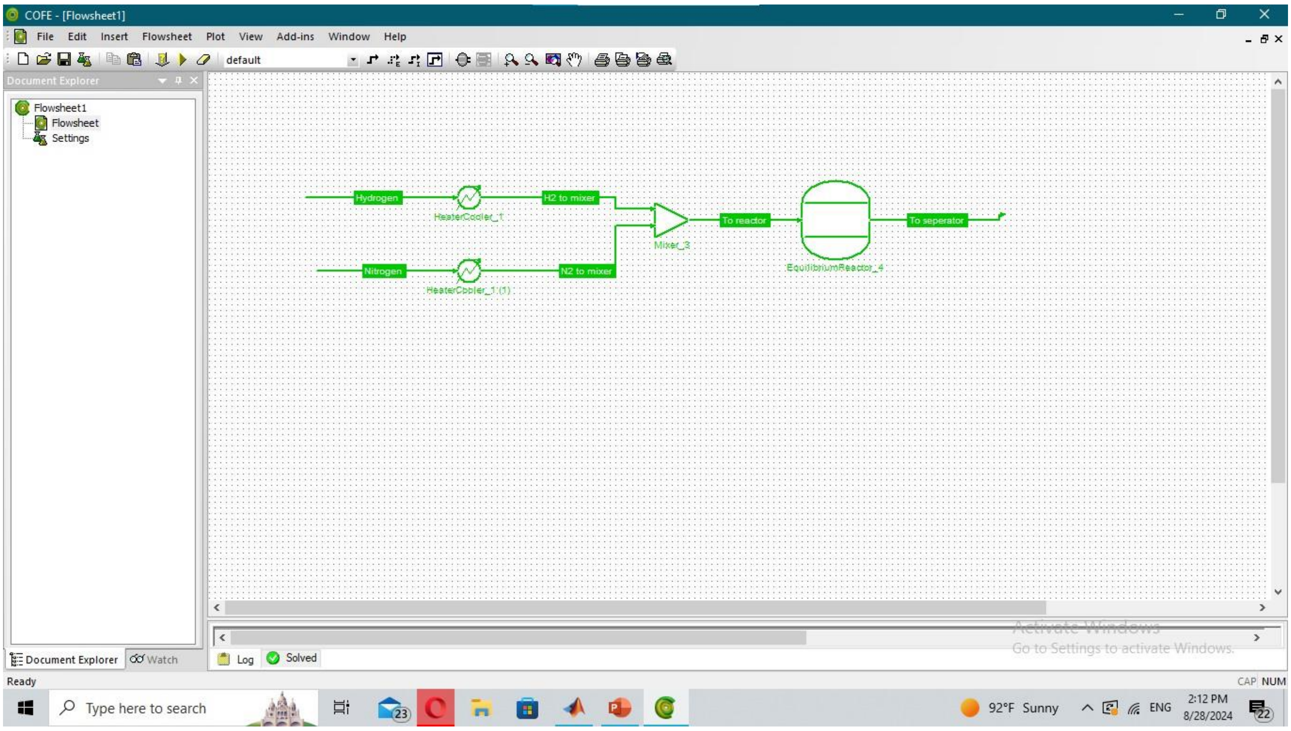
Stream	Ammonia	Unit
Pressure	200	bar
Temperature	303.15	K
Flow rate	0.573344	mol / s
Mole frac Nitrogen	0.0171318	
Mole frac Hydrogen	0.00291126	
Mole frac Ammonia	0.979957	

18.3.8 Electrochemical synthesis Simulation

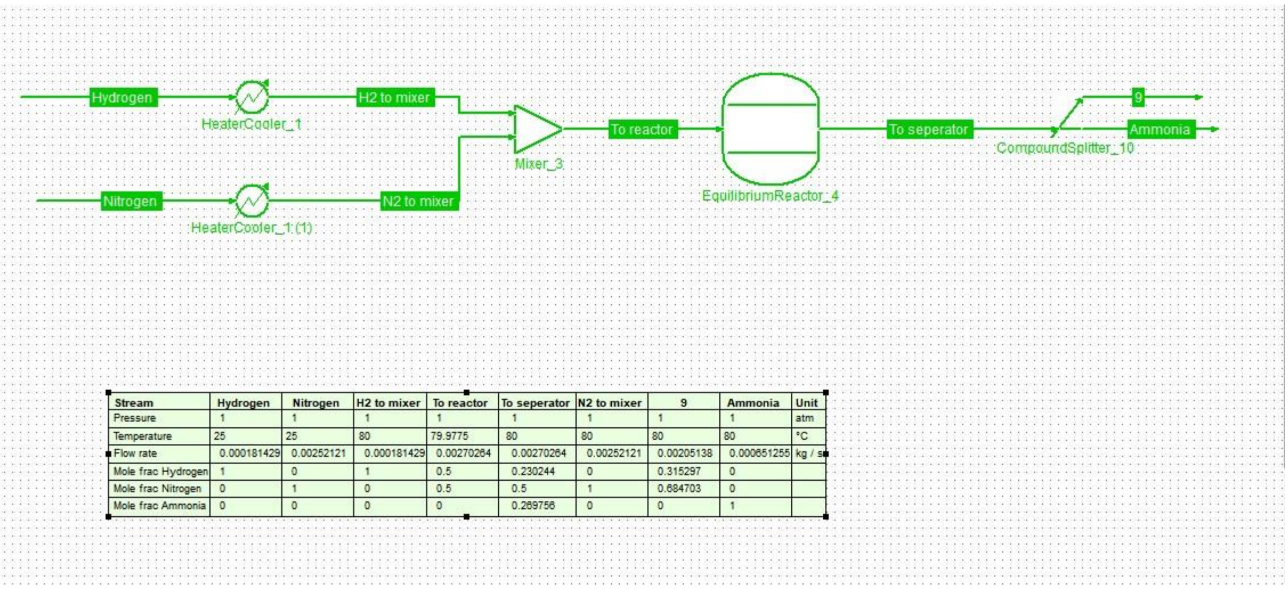
We should simulate this process with coco simulation



- **Electrochemical coco simulation :**



- **FINAL simulation**



Stream	Hydrogen	Nitrogen	H2 to mixer	To reactor	To seperator	N2 to mixer	9	Ammonia	Unit
Pressure	1	1	1	1	1	1	1	1	atm
Temperature	25	25	80	79.9775	80	80	80	80	°C
Flow rate	0.000181429	0.00252121	0.000181429	0.00270264	0.00270264	0.00252121	0.00205138	0.000651255	kg / s
Mole frac Hydrogen	1	0	1	0.5	0.230244	0	0.315297	0	
Mole frac Nitrogen	0	1	0	0.5	0.5	1	0.684703	0	
Mole frac Ammonia	0	0	0	0	0.269756	0	0	1	

18.4 What’s next

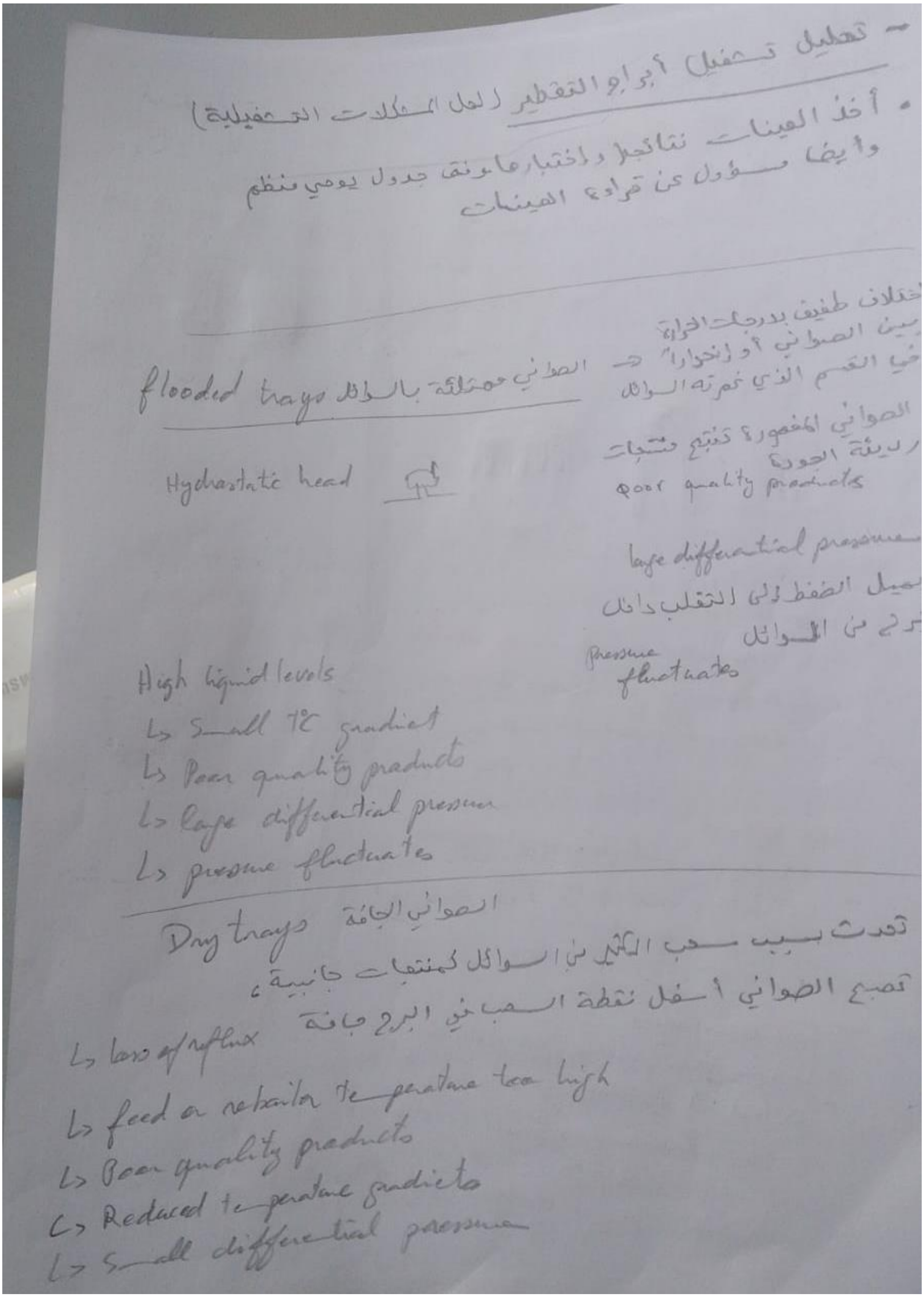
After drawing up the initial design of the AP project, the electrodes should be made – following section 6.2 (AP experimental part)

After that, we will be able to install the whole system.

PLC automation should also be worked on.

19 Project G 23: Air Separation and Distillation Unit

19.1 Air Distillation Concept and Design



- تحليل تشغيل أبراج التقطير (لحل المشكلات التشغيلية)

• أخذ العينات نتائجها واختبارها وفق جدول يومي منظم
وأيضا مسؤول عن قراءة العينات

flooded trays الصواني ممتلئة بالسوائل ⇒ اختلاف طفيف بدرجات الحرارة
بين الصواني أو إنحدارا
في القسم الذي تمر به السوائل

الصواني المغمورة تنتج منتجات
رديئة الجودة
poor quality products

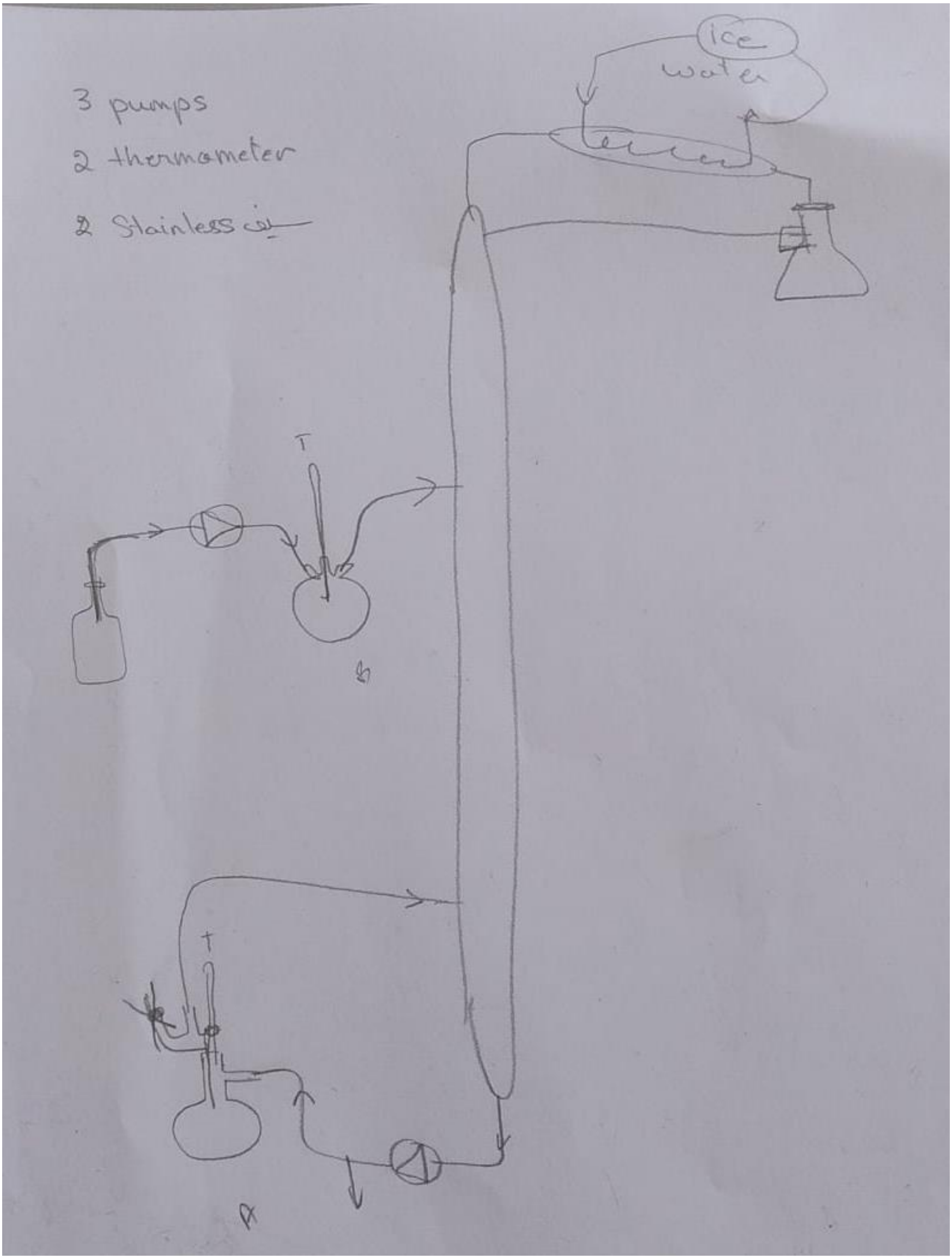
Hydrastatic head

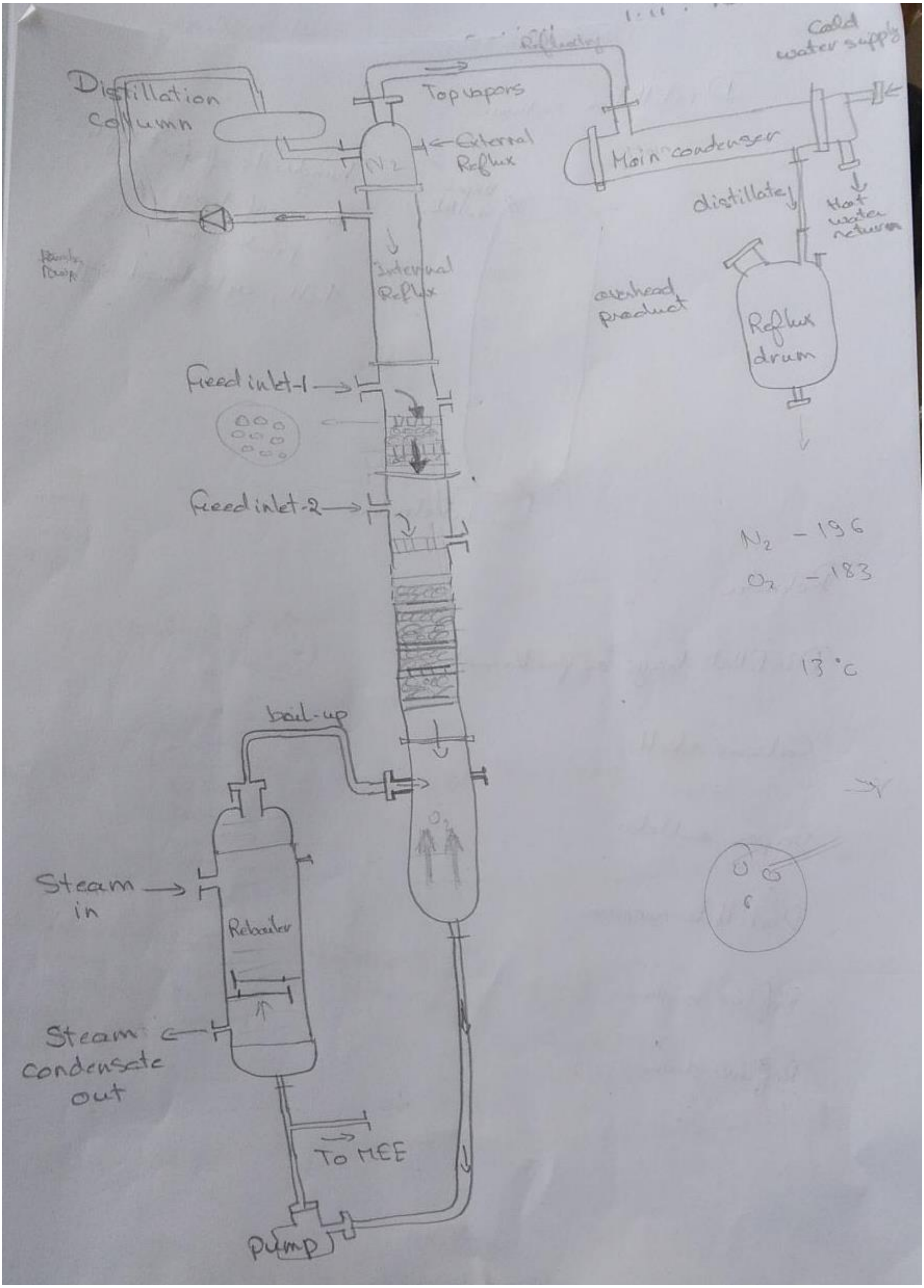
large differential pressure
يميل الضغط إلى التقلب داخل
برج من السوائل

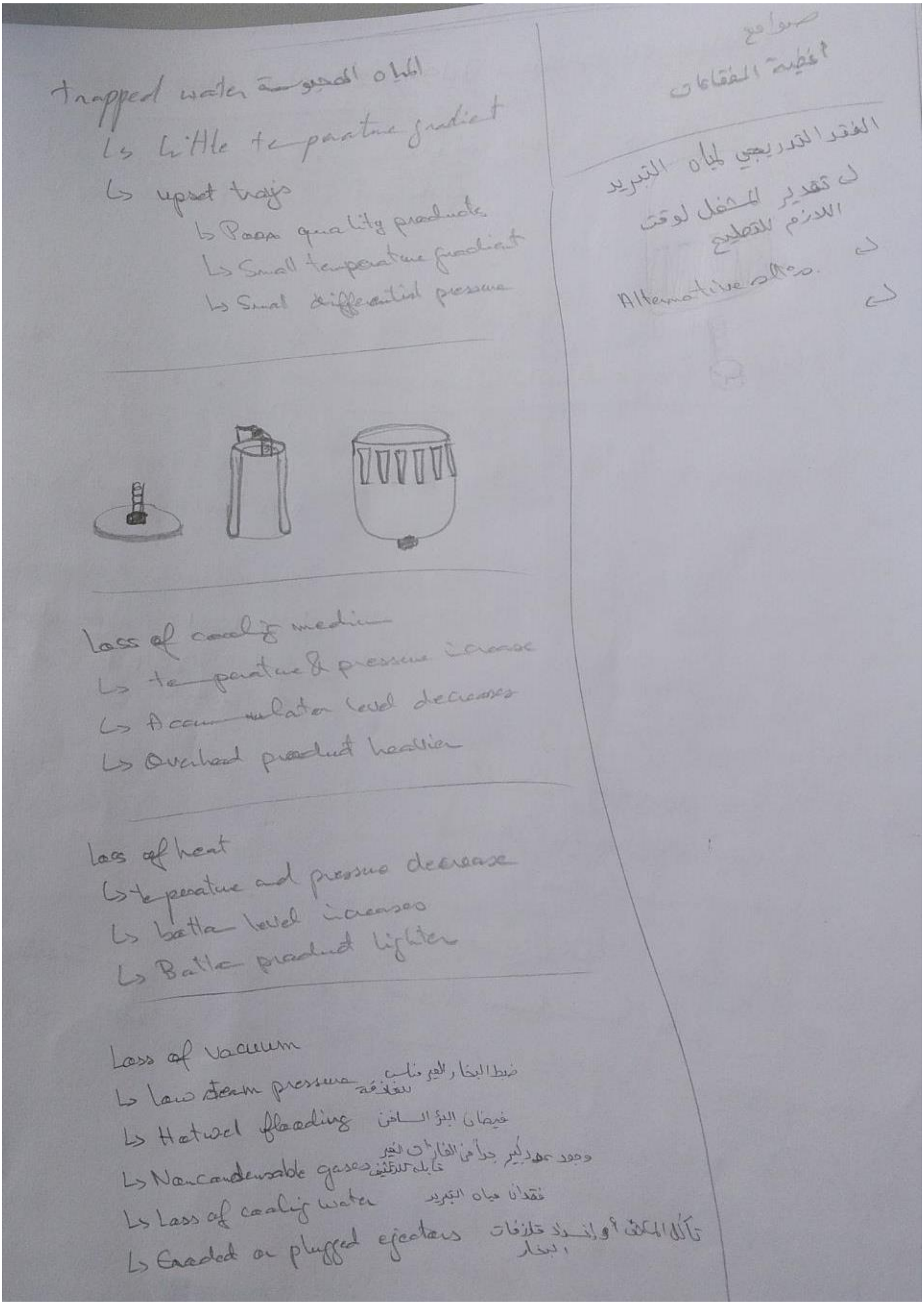
pressure
fluctuates

High liquid levels
↳ Small T°C gradient
↳ Poor quality products
↳ large differential pressure
↳ pressure fluctuates

Dry trays الصواني الجافة
تحدث بسبب سحب الكثير من السوائل كمنتجات جانبية،
تصبح الصواني أسفل نقطة السحب في البرج جافة
↳ loss of reflux
↳ feed or reboiler temperature too high
↳ Poor quality products
↳ Reduced temperature gradients
↳ Small differential pressure


3 pumps
2 thermometer
2 Stainless سين
ice
water
T
B
T
A


Distillation column
Top vapors
Cold water supply
External Reflux
N_2
Main condenser
distillate
Hot water return
Internal Reflux
overhead product
Reflux drum
Feed inlet-1
Feed inlet-2
N_2 −196
O_2 −183
13 °C
boil-up
O_2
Steam in
Reboiler
Steam condensate out
To MEE
Pump



Trapped water المياه المحبوسة
- Little temperature gradient
- upset trays
  - Poor quality products
  - Small temperature gradient
  - Small differential pressure

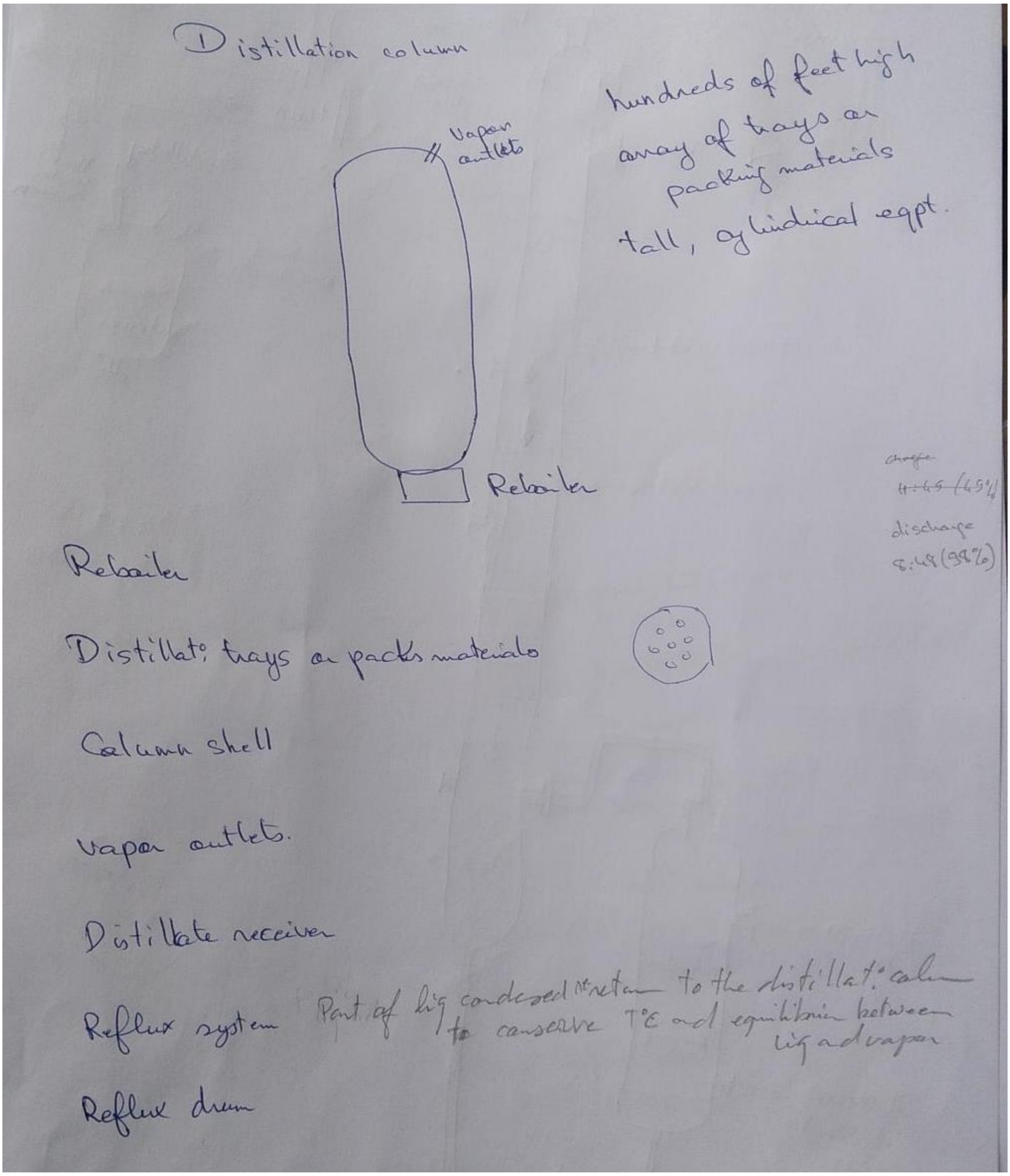
صوامع
أغطية الفقاعات

الفقد التدريجي لمياه التبريد
ل تقدير المحفل لوقت
اللازم للتصليح
ل
Alternative حلول.
ل

Loss of cooling medium
- temperature & pressure increase
- Accumulator level decreases
- Overhead product heavier

Loss of heat
- temperature and pressure decrease
- bottom level increases
- Bottom product lighter

Loss of vacuum
- low steam pressure ضبط البخار، الغير مناسب للغلاية
- Hotwell flooding فيضان البئر الساخن
- Noncondensable gases وجود عدد كبير جداً من الغازات الغير قابلة للتكثيف
- Loss of cooling water فقدان مياه التبريد
- Eroded or plugged ejectors تآكل المكثف أو انسداد قاذفات البخار



Distillation column

hundreds of feet high
array of trays or
packing materials
tall, cylindrical eqpt.

Vapor outlets

Reboiler

~~charge~~
~~4:45 (45%)~~
discharge
8:49 (98%)

Reboiler

Distillat° trays or packs materials

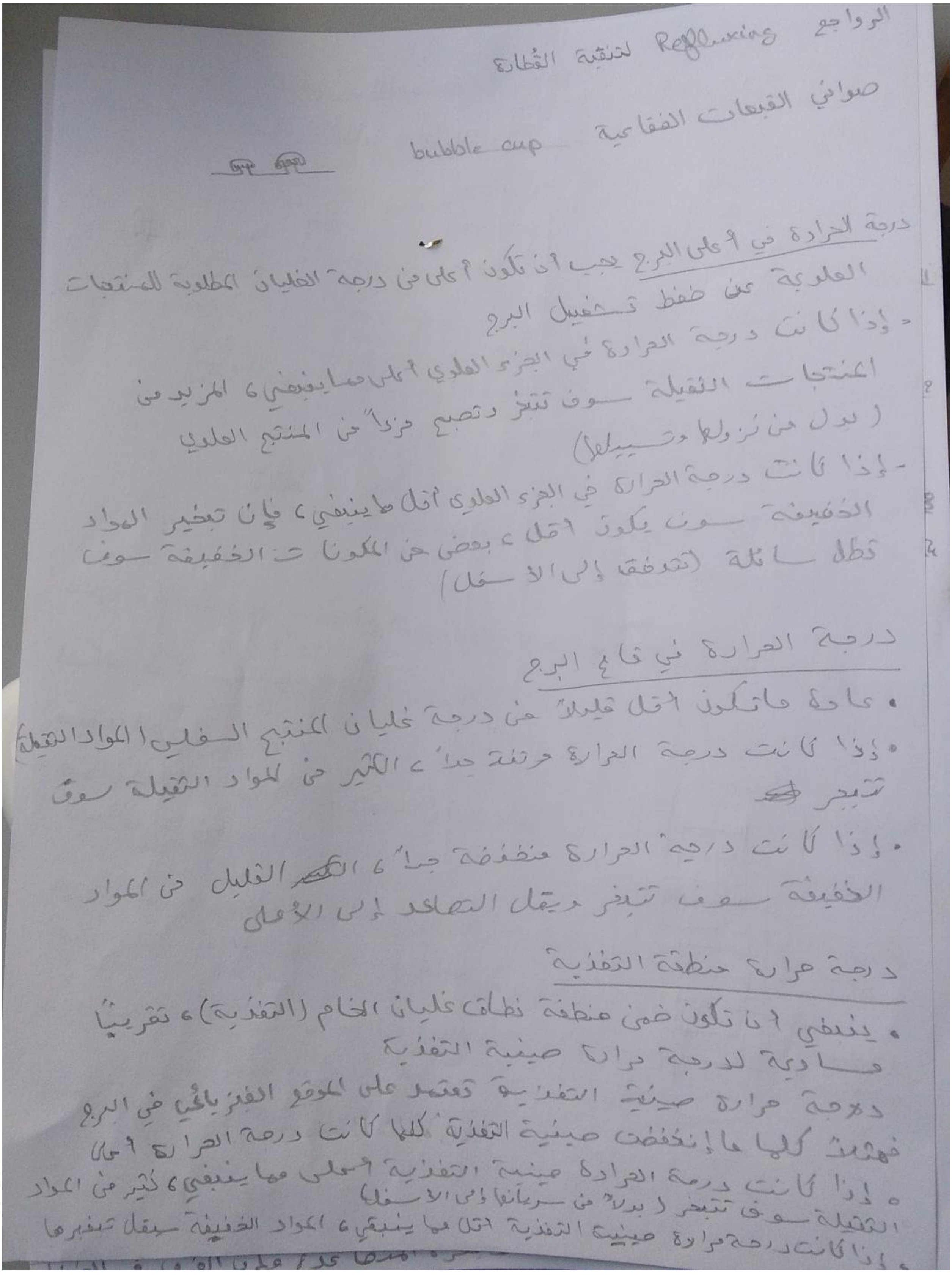
Column shell

vapor outlets.

Distillate receiver

Reflux system Part of liq condensed return to the distillat° colm to conserve T°C and equilibrium between liq and vapor

Reflux drum



الرواجع Refluxing لتنقية القطارة

صواني القبعات الفقاعية bubble cup

درجة الحرارة في أعلى البرج يجب أن تكون أعلى من درجة الغليان المطلوبة للمنتجات العلوية عند ضغط تشغيل البرج

- إذا كانت درجة الحرارة في الجزء العلوي أعلى مما ينبغي، المزيد من المنتجات الثقيلة سوف تتبخر وتصبح جزءاً من المنتج العلوي (بدلاً من نزولها وتسييلها)
- إذا كانت درجة الحرارة في الجزء العلوي أقل مما ينبغي، فإن تبخير المواد الخفيفة سوف يكون أقل، بعض من المكونات الخفيفة سوف تظل سائلة (تتدفق إلى الأسفل)

درجة الحرارة في قاع البرج

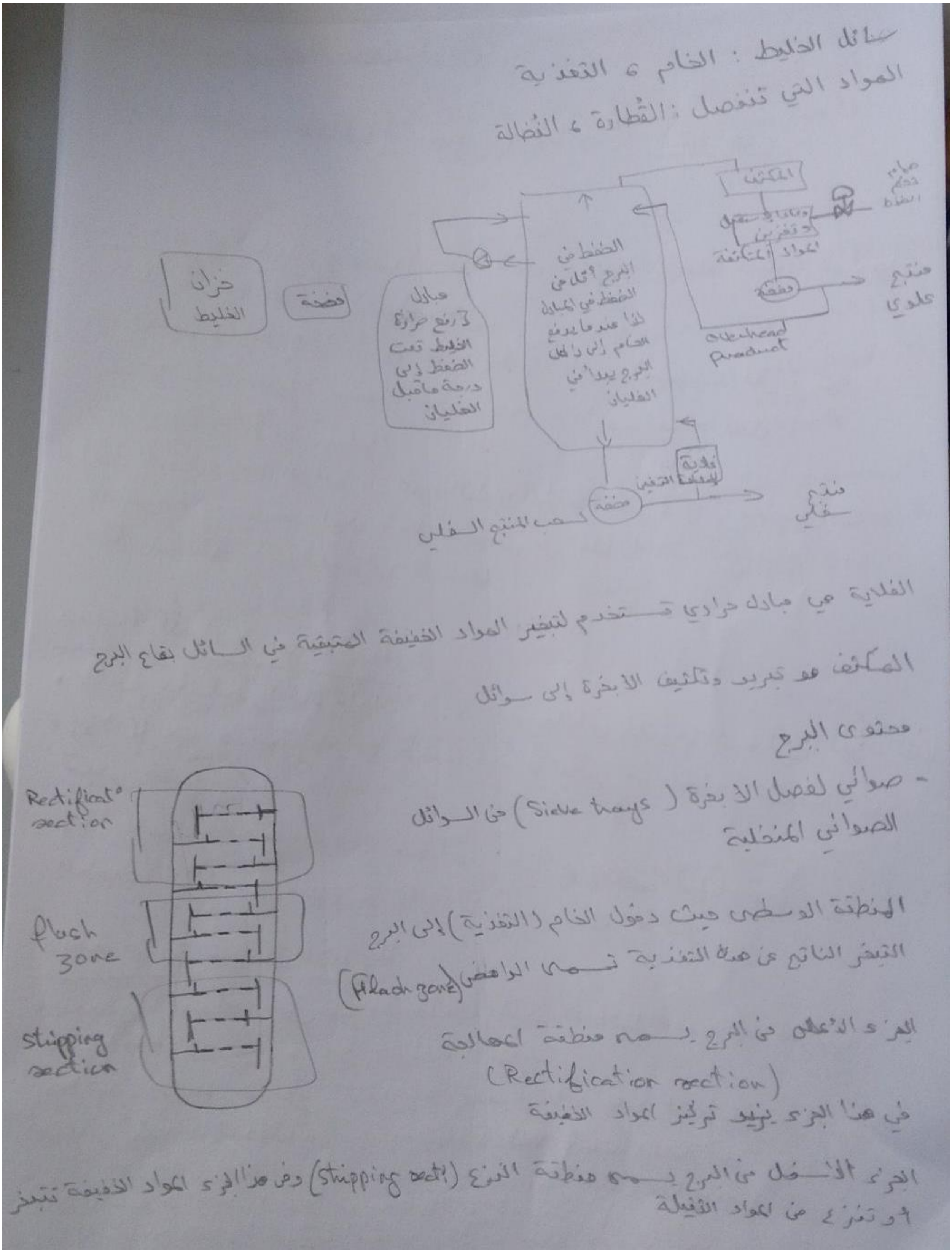
- عادة ماتكون أقل قليلاً من درجة غليان المنتج السفلي المواد الثقيلة
- إذا كانت درجة الحرارة مرتفعة جداً، الكثير من المواد الثقيلة سوف تتبخر
- إذا كانت درجة الحرارة منخفضة جداً، القليل من المواد الخفيفة سوف تتبخر ويقل التصاعد إلى الأعلى

درجة حرارة منطقة التغذية

- ينبغي أن تكون ضمن منطقة نطاق غليان الخام (التغذية)، تقريباً مساوية لدرجة حرارة صينية التغذية

درجة حرارة صينية التغذية تعتمد على الموقع الفيزيائي في البرج فهنا كلما انخفضت صينية التغذية كلما كانت درجة الحرارة أعلى

- إذا كانت درجة الحرارة صينية التغذية أعلى مما ينبغي، كثير من المواد الثقيلة سوف تتبخر (بدلاً من سريانها إلى الأسفل)
- إذا كانت درجة حرارة صينية التغذية أقل مما ينبغي، المواد الخفيفة سيقل تبخيرها



سائل الخليط : الخام ، التغذية
المواد التي تنفصل : القطارة ، النضالة

الغلاية هي مبادل حراري تستخدم لتبخير المواد الخفيفة المتبقية في السائل بقاع البرج

المكثف هو تبريد وتكثيف الأبخرة إلى سوائل

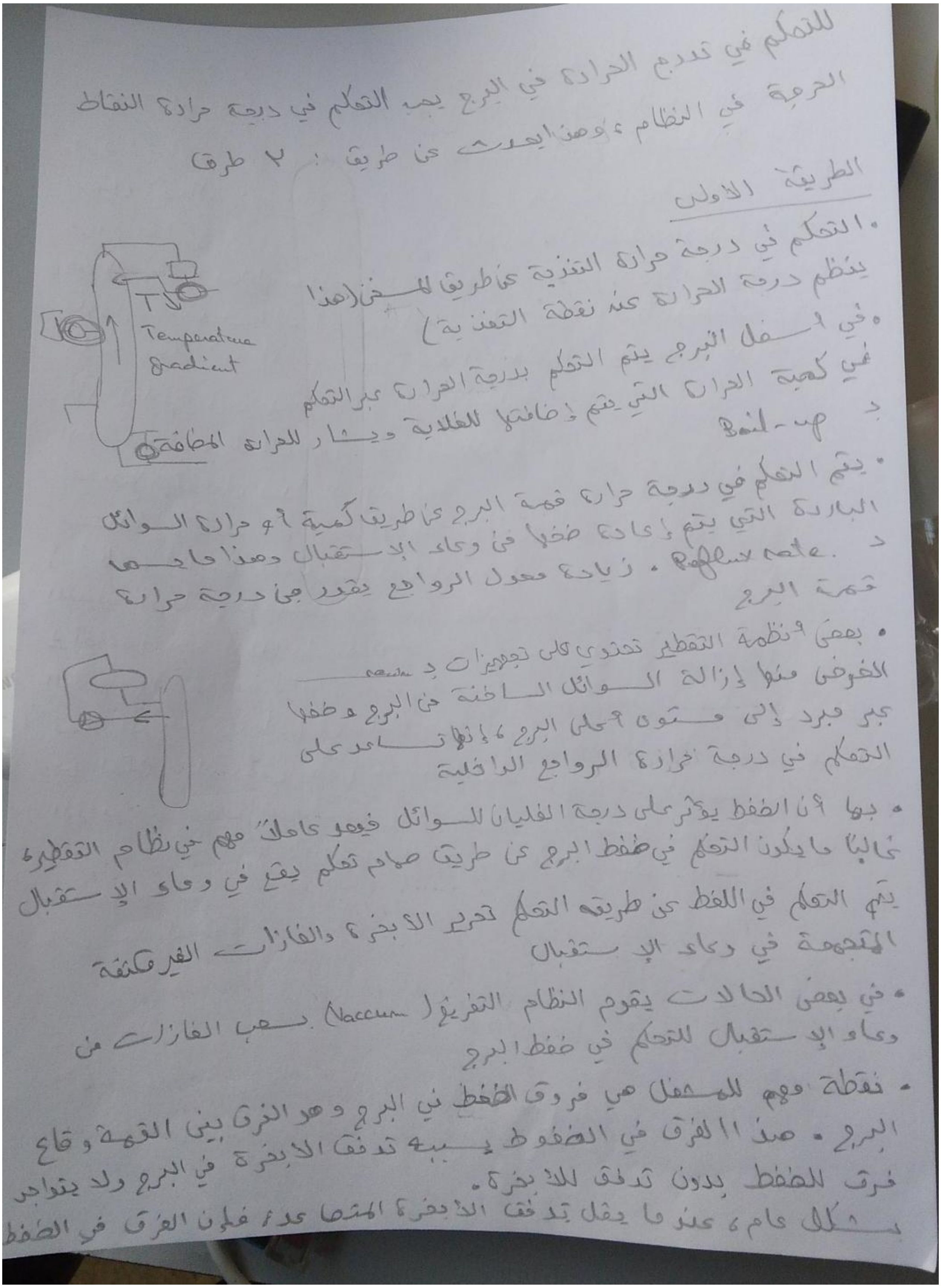
محتوى البرج

- صواني لفصل الأبخرة (Sieve trays) عن السوائل
الصواني المنخلية

المنطقة الوسطى حيث دخول الخام (التغذية) إلى البرج
التبخر الناتج عن هذه التغذية تسمى الوامض (Flash zone)

الجزء الأعلى من البرج يسمى منطقة المعالجة
(Rectification section)
في هذا الجزء يزيد تركيز المواد الخفيفة

الجزء الأسفل من البرج يسمى منطقة النزع (Stripping sect) وفي هذا الجزء المواد الخفيفة تتبخر
و تنزع من المواد الثقيلة



للتحكم في تدرج الحرارة في البرج يجب التحكم في درجة حرارة النقاط الحرجة في النظام، وهذا يحدث عن طريق : ٢ طرق

الطريقة الاولى

١. التحكم في درجة حرارة التغذية عن طريق المسخن (هذا ينظم درجة الحرارة عند نقطة التغذية)

- في أسفل البرج يتم التحكم بدرجة الحرارة عبر التحكم في كمية الحرارة التي يتم إضافتها للغلاية ويشار للحرارة المضافة ب Boil-up

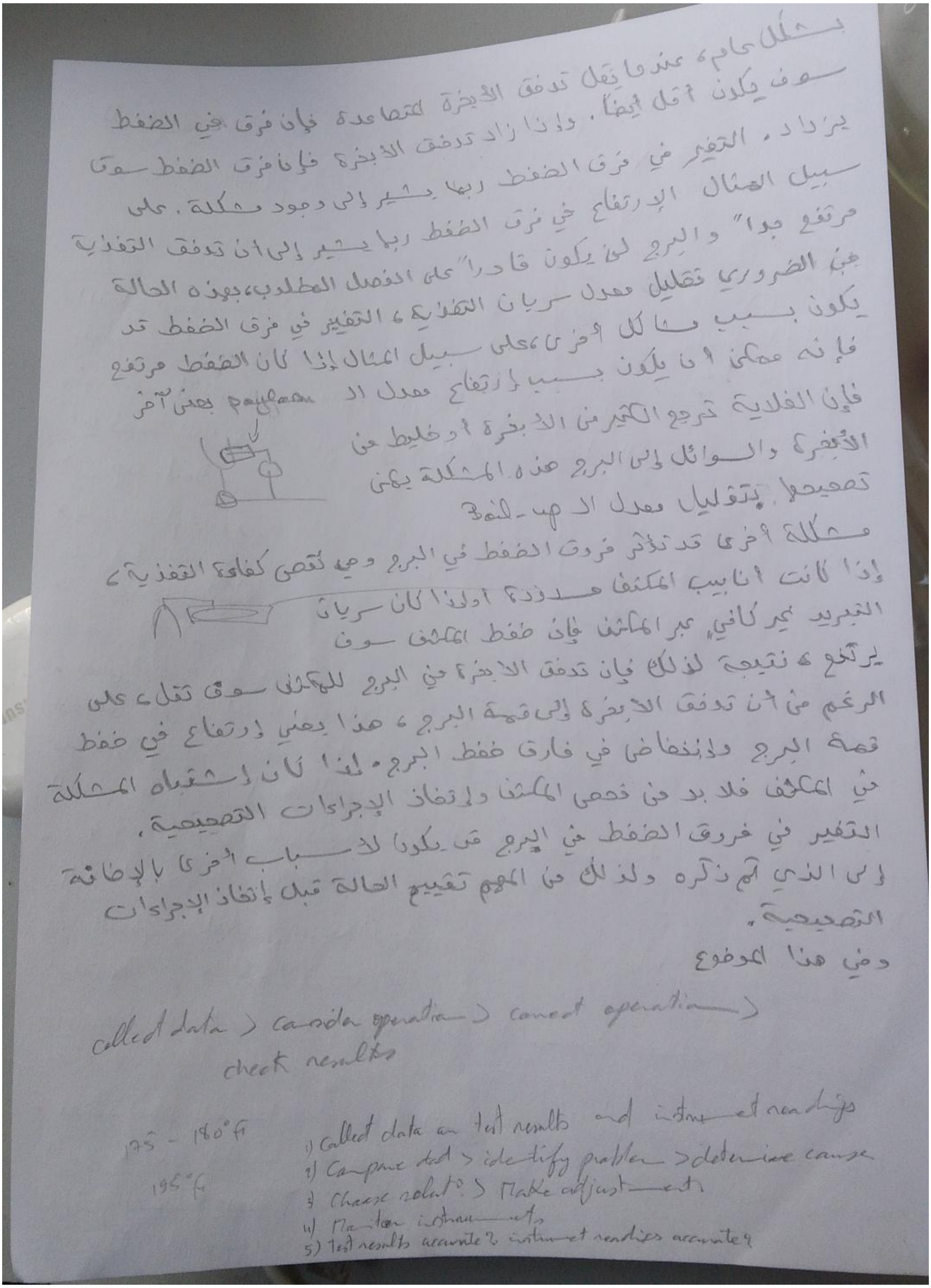
- يتم التحكم في درجة حرارة قمة البرج عن طريق كمية أو حرارة السوائل الباردة التي يتم إعادة ضخها في وعاء الاستقبال وهذا ما يسمى ب Reflux rate. زيادة معدل الرواجع يقلل من درجة حرارة قمة البرج

- بعض أنظمة التقطير تحتوي على تجهيزات ب [illegible] الضخ منها لإزالة السوائل الساخنة من البرج وضخها عبر مبرد إلى مستوى أعلى البرج، إنها تساعد على التحكم في درجة حرارة الرواجع الداخلية

- بما أن الضغط يؤثر على درجة الغليان للسوائل فهو عاملاً مهم في نظام التقطير، غالبا ما يكون التحكم في ضغط البرج عن طريق صمام تحكم يقع في وعاء الاستقبال
يتم التحكم في الضغط عن طريقة التحكم تحرير الأبخرة والغازات الغير مكثفة المتجمعة في وعاء الاستقبال

- في بعض الحالات يقوم النظام التفريغ (Vaccum) بسحب الغازات من وعاء الاستقبال للتحكم في ضغط البرج

- نقطة مهم للمحلل هي فروق الضغط في البرج وهو الفرق بين القمة وقاع البرج. هذا الفرق في الضغوط بسبب تدفق الأبخرة في البرج ولا يتواجد فرق للضغط بدون تدفق للأبخرة.
بشكل عام، عندما يقل تدفق الأبخرة المتصاعدة فإن الفرق في الضغط



بشكل عام، عندما يقل تدفق الأبخرة المتصاعدة فإن فرق في الضغط
سوف يكون أقل أيضاً. وإذا زاد تدفق الأبخرة فإن فرق الضغط سوف
يزداد، التغير في فرق الضغط ربما يشير إلى وجود مشكلة. على
سبيل المثال الإرتفاع في فرق الضغط ربما يشير إلى أن تدفق التغذية
مرتفع جداً" والبرج لن يكون قادراً" على الفصل المطلوب، بهذه الحالة
من الضروري تقليل معدل سريان التغذية، التغير في فرق الضغط قد
يكون بسبب مشاكل أخرى، على سبيل المثال إذا كان الضغط مرتفع
فإنه ممكن أن يكون بسبب إرتفاع معدل ال reboiler بمعنى آخر
فإن الغلاية تخرج الكثير من الأبخرة أو خليط من
الأبخرة والسوائل إلى البرج هذه المشكلة يمكن
تصحيحها بتقليل معدل ال Boil-up
مشكلة أخرى قد تؤثر فروق الضغط في البرج وهي نقص كفاءة التغذية،
إذا كانت أنابيب المكثف مسدودة أو إذا كان سريان
التبريد غير كافي، عبر المكثف فإن ضغط المكثف سوف
يرتفع، نتيجة لذلك فإن تدفق الأبخرة في البرج للمكثف سوف تقل على
الرغم من أن تدفق الأبخرة إلى قمة البرج، هذا يعني إرتفاع في ضغط
قمة البرج وإنخفاض في فارق ضغط البرج. إذا كان إشتباه المشكلة
في المكثف فلا بد من فحص المكثف وإتخاذ الإجراءات التصحيحية.
التغير في فروق الضغط في البرج قد يكون لأسباب أخرى بالإضافة
إلى الذي تم ذكره ولذلك من المهم تقييم الحالة قبل إتخاذ الإجراءات
التصحيحية.
وفي هذا الموضوع

collect data > consider operation > correct operation >
check results

175 - 180°F
195°F

1) Collect data on test results and instrument readings
2) Compare data > identify problem > determine cause
3) Choose solut°. > Make adjustments
4) Monitor instruments
5) Test results accurate? instrument readings accurate?

19.2 Pilot project: Distillation of Ethanol (Ethanol separation)

19.2.1 Equipment and Steps for a Distillation Column Experiment (Water-Ethanol Mixture)

19.2.1.1 Equipment

- Distillation Apparatus:

  - Round-bottom flask (500 mL or 1 L)
  - Fractionating column (packed or unpacked)
  - Condenser (Liebig or water-jacketed)
  - Adapter (to connect the flask to the column)
  - Thermometer adapter
  - Receiving flask (or multiple flasks for collecting fractions)
- Heat Source: Heating mantle or hot plate

- Thermometer: To measure the temperature of the vapor

- Stand and Clamps: To secure the apparatus

- Other Supplies:

  - Water-ethanol mixture (known composition)
  - Boiling chips
  - Ice water bath for the condenser
  - Wash bottle with distilled water
  - Safety glasses and gloves

19.2.1.2 Steps

1 Set up the Apparatus:

* Assemble the distillation apparatus as shown in the diagram, ensuring all connections are secure.

* Insert the thermometer into the thermometer adapter so that the bulb is just below the sidearm of the adapter.

* Place boiling chips in the round-bottom flask to prevent bumping.

2. Add the Mixture:

* Carefully pour the water-ethanol mixture into the round-bottom flask.

3. Heat the Mixture:

* Turn on the heat source and gradually increase the temperature.

* Monitor the temperature closely.

4. Collect the Distillate:

* Once the mixture begins to boil and vapor rises into the column, the temperature will stabilize.

* Collect the distillate in the receiving flask(s).

* You may observe a gradual increase in temperature as the more volatile component (ethanol) is distilled off.

5. Monitor and Adjust:

* Continuously monitor the temperature and adjust the heating rate as needed to maintain a steady distillation rate.

* You can collect different fractions of the distillate at different temperature ranges.

6. 6.Analyze the Results:

* Measure the volume of each fraction collected.

* Determine the ethanol content of each fraction using a refractometer or other analytical methods.

* Compare the composition of the distillate to the original mixture to assess the efficiency of the separation.

Note:

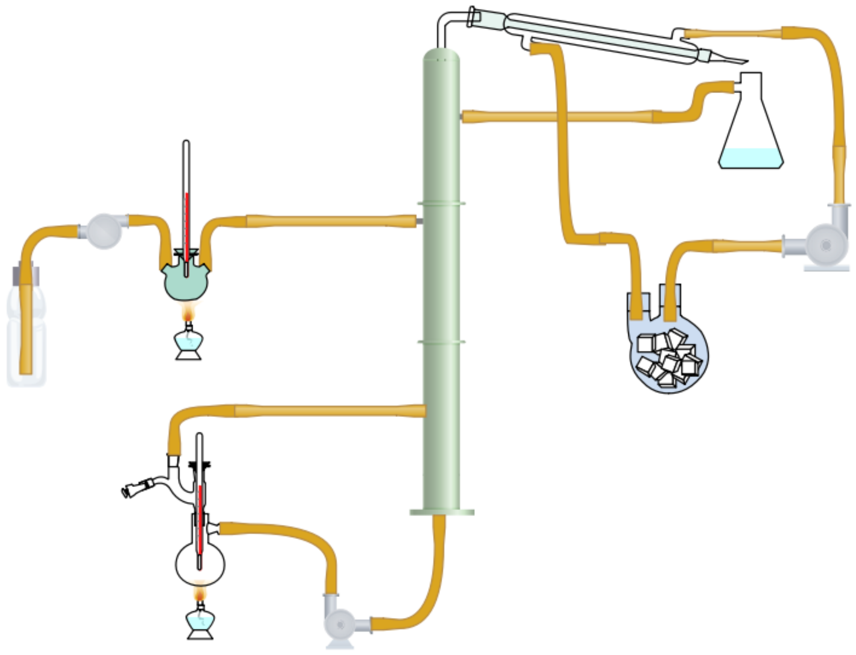
*** This is a simplified procedure. The actual steps and conditions may vary depending on the specific experimental objectives and the complexity of the distillation column.**

*** It's important to follow proper safety procedures and handle chemicals with care.**

*** For a more accurate and efficient separation, you may need to use a more sophisticated distillation column with a greater number of theoretical plates.**

By following these steps and using the appropriate equipment, you can conduct a distillation column experiment to separate a mixture of water and ethanol and gain a better understanding of the principles of dis

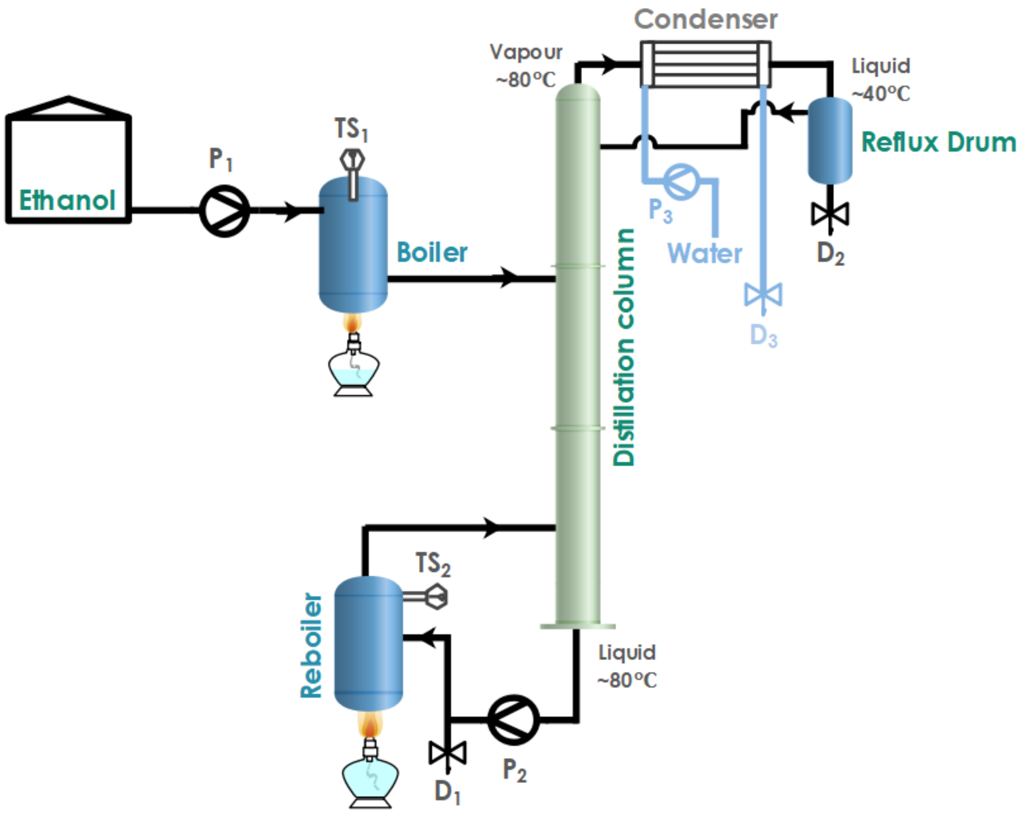
19.2.2 Preliminary design

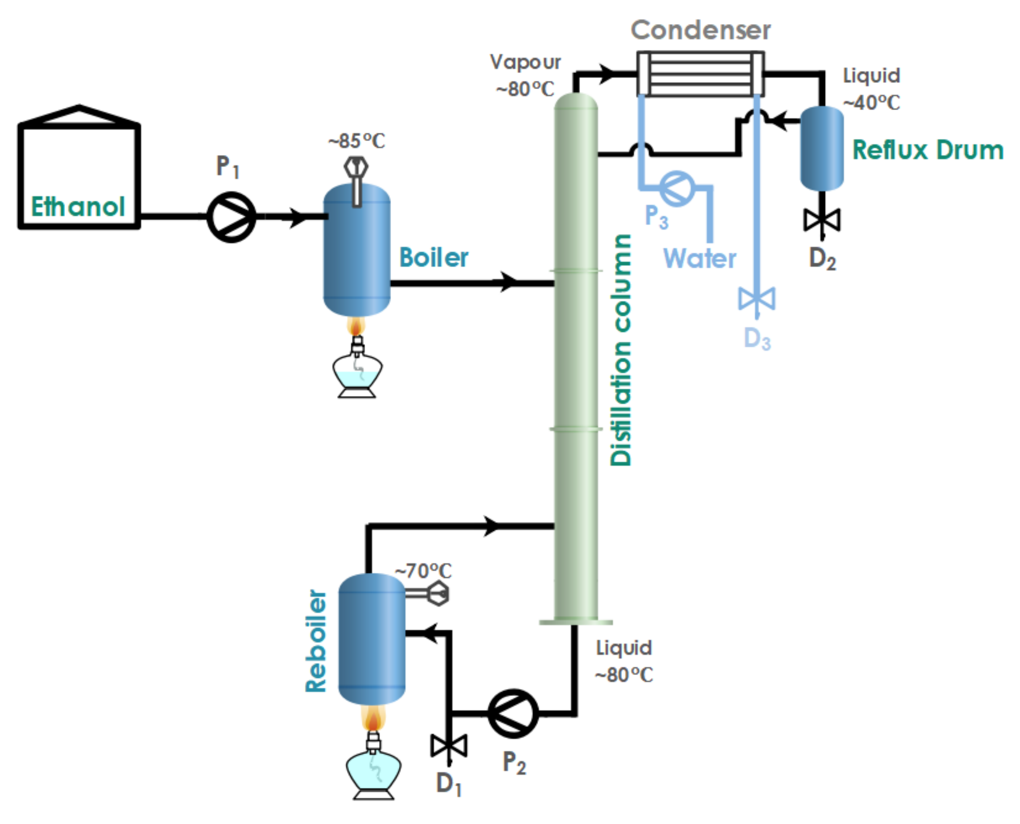


Edraw file :

15012025_premiun design.eddx

19.2.3 Flow Chart of pilot distillation (distillation of ethanol)



	Edraw file (with and without T): 29012025_Ethanol distillation.eddx

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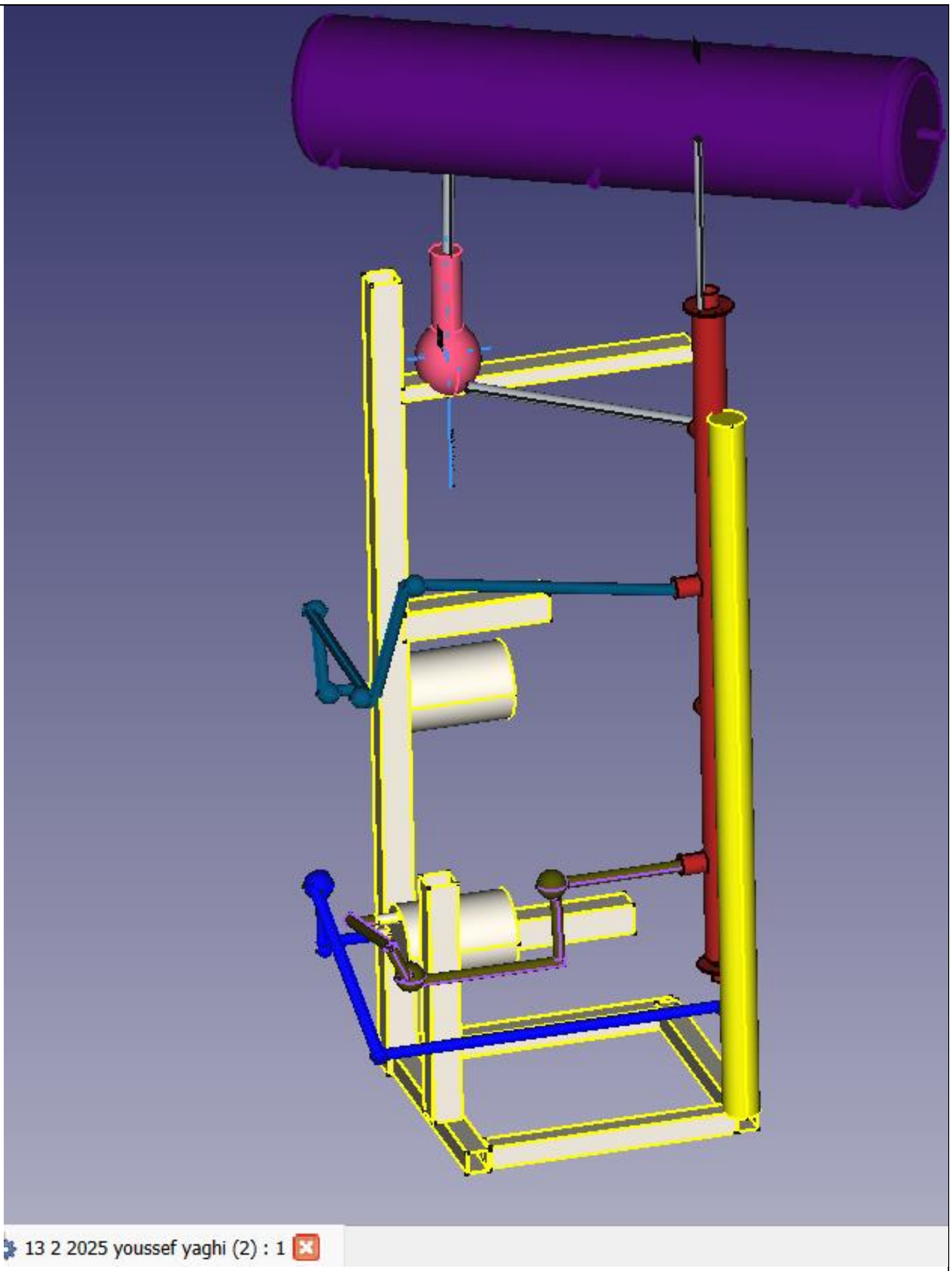
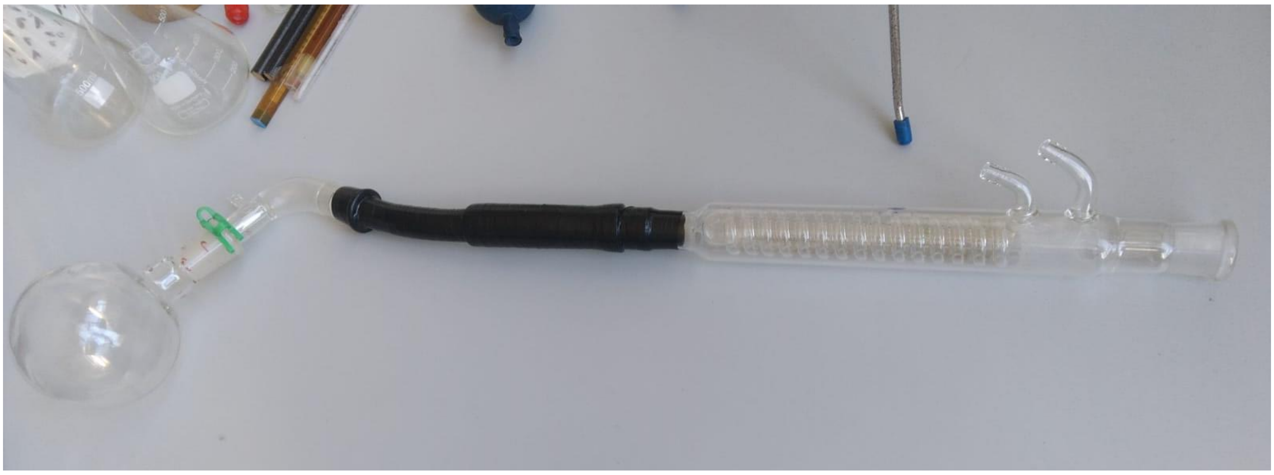
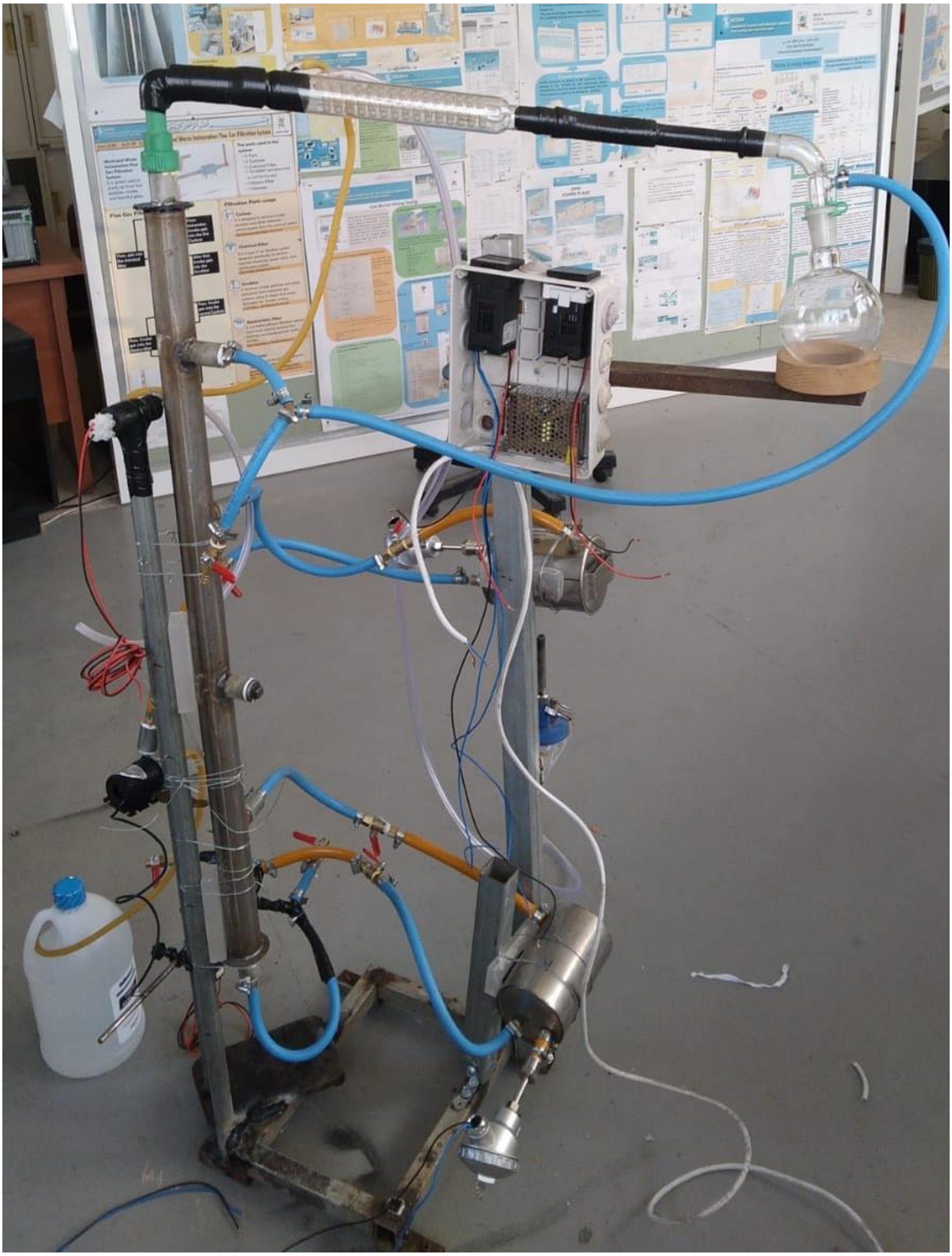
FreeCAD file 13.02.2025: 13 2 2025 youssef yaghi.FCStd	

19.2.4 Distillation of Ethanol – Realization of apparatus



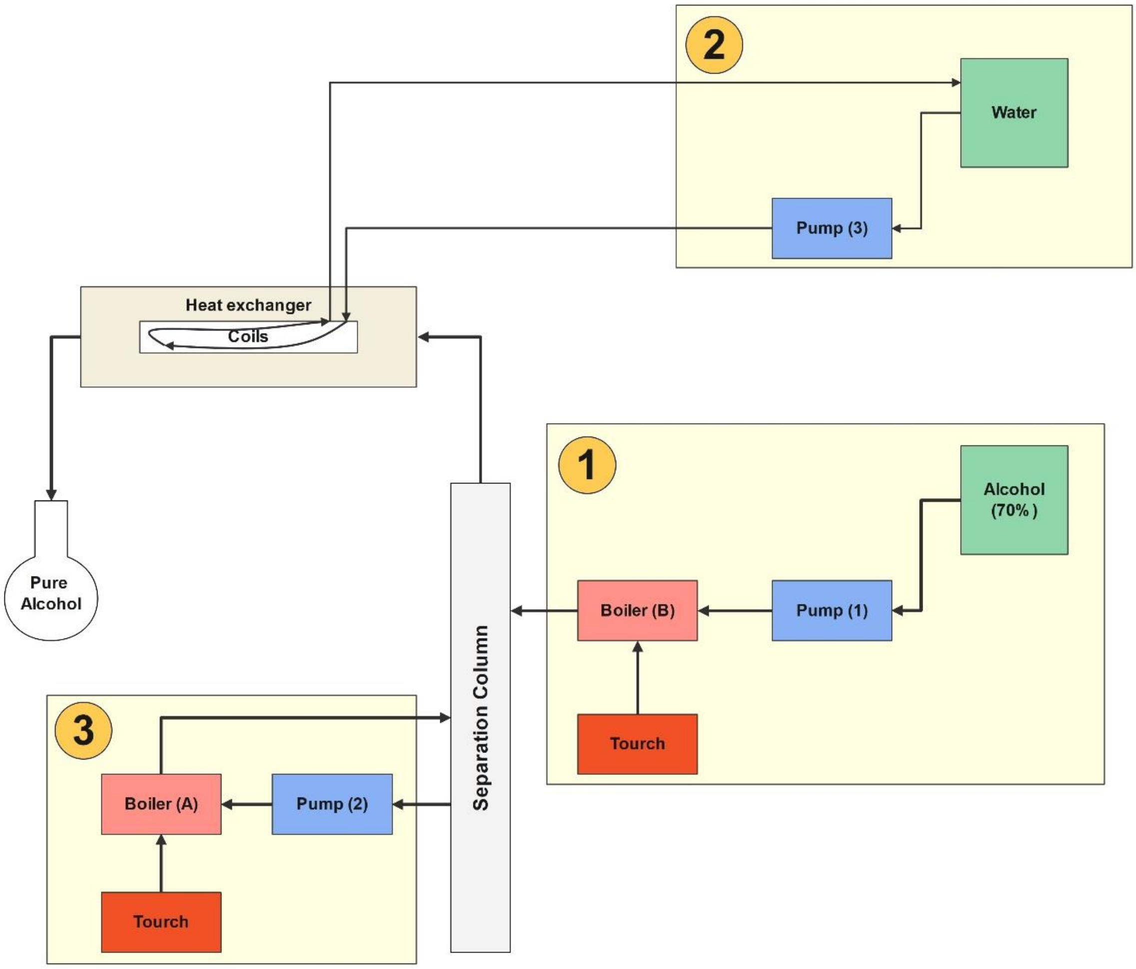
28.1.25:




3
2

Pilot project: Distillation of Ethanol (Ethanol separation)

19.2.5 Ethanol separation - test specification



1. First, the ethanol (70%) is transported via pump (1) to boiler (B). The ethanol in boiler (B) is then heated up until it reaches a temperature of approx. 80-90°C.
   As soon as the temperature is reached, the ethanol begins to evaporate. The steam passes through the tower into the heat exchanger.
2. Now cold Water is transported via pump (3) into the coils of the heat exchanger. This is where the condensation process takes place. Because of the cold water, the steam loses its heat and begins to condense. The condensed ethanol (pure ethanol) now drips into the tube.
3. The ethanol that has not yet evaporated is transported via pump (2) into boiler (A) and heated up there. Once the temperature is reached, the steam passes through the tower so that it can also condense. This process is repeated until only pure ethanol remains.

19.2.6 Ethanol separation - test documentation (test date: 20.02.2025)

	In the lower bottle we have ethanol (70% ethanol) and in the upper bottle we have cold water for the condensation process. The bottles were connected via a rubber hose with the system.	
		The ethanol is heated up in the boiler until it reaches a temperature of approx. 80-90°C.
		Cold water is transported via pump into the heat exchanger. Here the hot steam meets the cold water. Now the condensation process has started. In the right picture you can see the pure liquid ethanol in teardrop form

<table>
<tr>
<td></td>
<td></td>
<td>Now the pure ethanol drips into the tube. After the test we filled the ethanol from the tube in a bottle like you can see in the right picture.</td>
</tr>
<tr>
<td colspan="2"></td>
<td>The ethanol that has not yet evaporated is heated again in the lower boiler and brought back into the system circuit.</td>
</tr>
</table>

---

tillation.

19.2.7 e-test

19.3 Example for Distillation: H2O2 50% to 90% upgrading

Hydrogen peroxide is often referred to as water with one more oxygen atom. It is acidic in nature, and PH is about 4.5. It is a 100 per cent degradable compound.

Hydrogen Peroxide Chemical Formula H_2O_2

Molecular Weight/Molar Mass 4.0147 g/mol

Density 1.05 g/cm3

Boiling Point 150.2 °C

Melting Point -0.43 °C

Properties of Hydrogen Peroxide

Physical Properties

- In the pure state, hydrogen peroxide is an almost colourless (very pale blue) liquid.
- It melts at 272.4 K and has a boiling point of 423 K (extrapolated).
- It is miscible in water in all proportions and forms hydrates.

Chemical Properties

Hydrogen peroxide in both acidic and basic mediums acts as an oxidising as well as a reducing agent. The following reactions will give a clear picture:

Why Is Hydrogen Peroxide Stored in Plastic Containers?

Hydrogen peroxide decomposes when exposed to sunlight, this process is catalysed by traces of alkali metals. Therefore, H_2O_2 is stored in wax-lined glass or plastic containers and kept in the dark.

It should also be kept away from dust particles because dust can induce explosive decomposition of this compound.

================================

Boiling Point Of Hydrogen Peroxide

The boiling point of hydrogen peroxide is 150.2 °C (302.3 °F) at atmospheric pressure (1 atm, which converts to 14.6 PSI). This is approximately 50 °C higher than the boiling point of water, which is 100 °C. This chemical undergoes thermal decomposition (which is decomposition caused by heat) and boils explosively at this temperature, so it is not advisable.

Heat Capacity Of Hydrogen Peroxide

The specific heat capacity of liquid hydrogen peroxide is 2.619 J/(g-K), and in gas form, it is 1.267 J/(g-K). This (specific heat) refers to the amount of energy required to raise the temperature of hydrogen peroxide, not the latent heat. Latent heat refers to heat that results in the chemical's expansion. The latent heat of vaporization for hydrogen peroxide is 542 BTU/pound.

This means it takes 542 BTU of heat to convert 1 pound of H_2O_2 into its gas phase (convert it into a gas).

Density Of Hydrogen Peroxide

The density of hydrogen peroxide is 1.11 g/cm3 (1.11 grams per cubic centimeter), which means that a cubic centimeter of H_2O_2 weighs 1.11 grams.

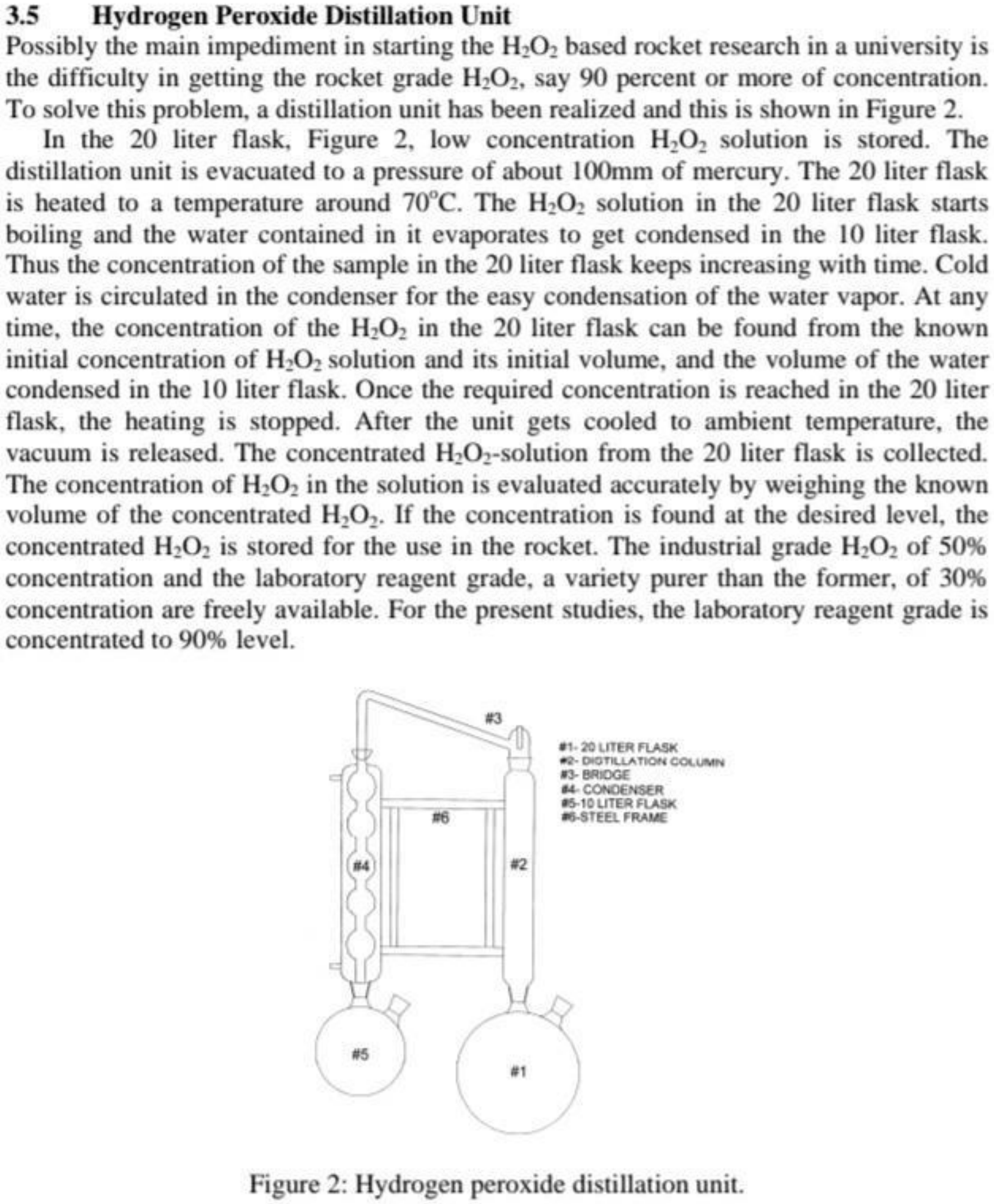
============

Purifying hydrogen peroxide from water is challenging due to several factors:

- Azeotrope Formation: Water and hydrogen peroxide form an azeotrope at a specific concentration. This means that at this point, the vapor phase has the same composition as the liquid phase, making further separation by simple distillation impossible.
- Thermal Decomposition: Hydrogen peroxide is thermally unstable and decomposes into water and oxygen at elevated temperatures, making traditional distillation methods difficult.

Methods for Concentration (but not complete purification):

- Vacuum Distillation: Lowering the pressure reduces the boiling points of both water and hydrogen peroxide, allowing distillation at lower temperatures and minimizing decomposition.
- Extractive Distillation: Using a third component (entrainer) to break the azeotrope.



3.5 Hydrogen Peroxide Distillation Unit

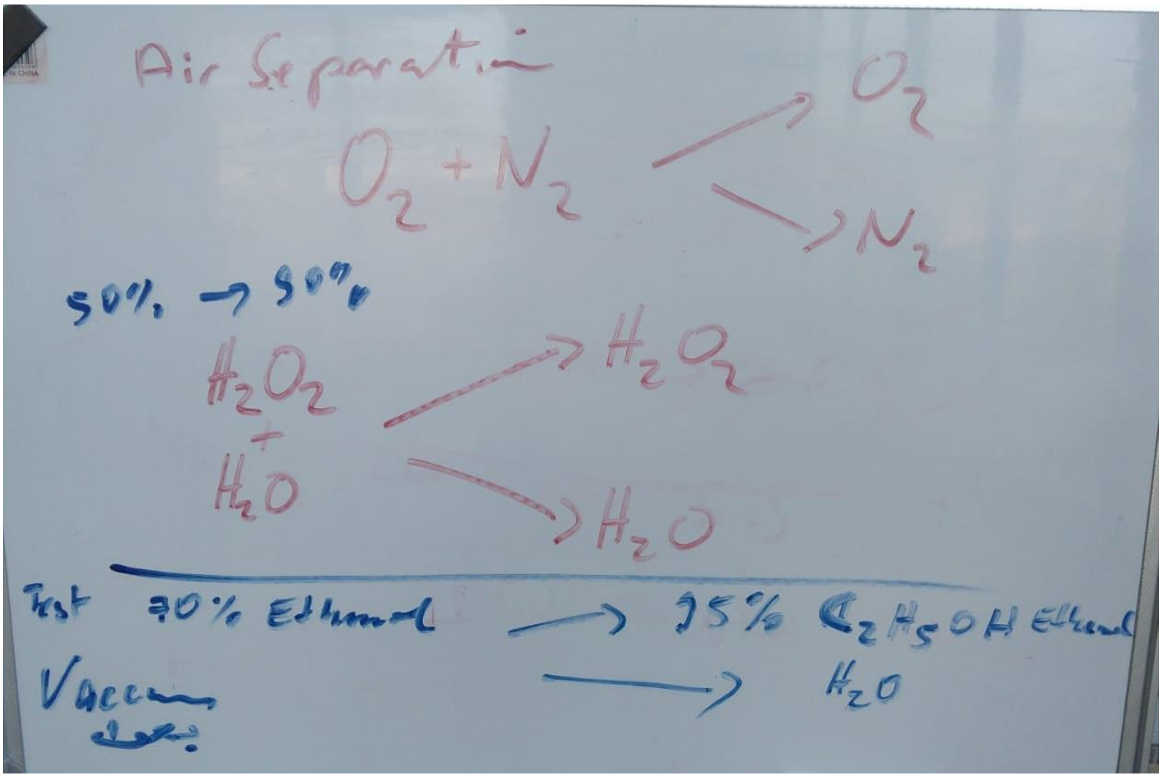
Possibly the main impediment in starting the H_2O_2 based rocket research in a university is the difficulty in getting the rocket grade H_2O_2, say 90 percent or more of concentration. To solve this problem, a distillation unit has been realized and this is shown in Figure 2.

In the 20 liter flask, Figure 2, low concentration H_2O_2 solution is stored. The distillation unit is evacuated to a pressure of about 100mm of mercury. The 20 liter flask is heated to a temperature around 70°C. The H_2O_2 solution in the 20 liter flask starts boiling and the water contained in it evaporates to get condensed in the 10 liter flask. Thus the concentration of the sample in the 20 liter flask keeps increasing with time. Cold water is circulated in the condenser for the easy condensation of the water vapor. At any time, the concentration of the H_2O_2 in the 20 liter flask can be found from the known initial concentration of H_2O_2 solution and its initial volume, and the volume of the water condensed in the 10 liter flask. Once the required concentration is reached in the 20 liter flask, the heating is stopped. After the unit gets cooled to ambient temperature, the vacuum is released. The concentrated H_2O_2-solution from the 20 liter flask is collected. The concentration of H_2O_2 in the solution is evaluated accurately by weighing the known volume of the concentrated H_2O_2. If the concentration is found at the desired level, the concentrated H_2O_2 is stored for the use in the rocket. The industrial grade H_2O_2 of 50% concentration and the laboratory reagent grade, a variety purer than the former, of 30% concentration are freely available. For the present studies, the laboratory reagent grade is concentrated to 90% level.

Figure 2: Hydrogen peroxide distillation unit.

19.4 Liquefication of Oxygen Prototype (ICPT-LOX) and Air Distillation

Distillation/Separation of oxygen, nitrogen, and noble gases from liquid air



20 Project H 21: Fuel Cell

List of figures

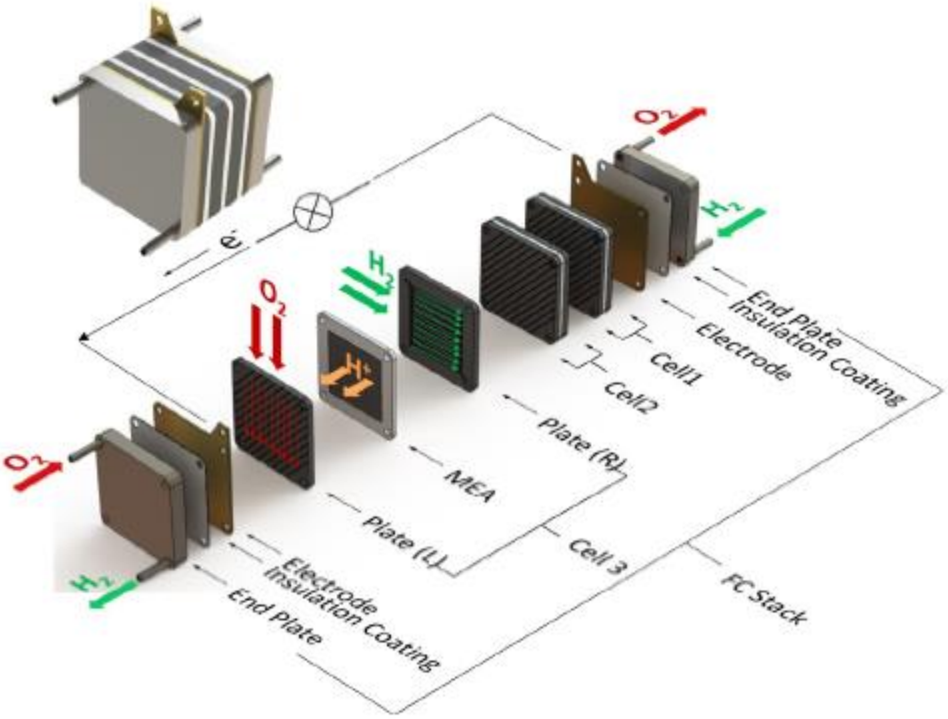


Fig. 1 :Schematics of a fuel cell stack operation and components[50]

An electric generator:

- The fuel cell transforms chemical energy into electrical energy;

- We have a fuel and an oxidizer as in a heat engine;

- Electric power is produced directly without an alternator.

The first fuel cell was demonstrated in the middle of the 19th century by a scientist named William Grove. In a fuel cell a reaction takes place where hydrogen and oxygen recombine into water and thereby releasing electrical energy. The chemical formula of the reaction is seen in equation 1.

$$2H_2 + O_2 \rightarrow 2H_2O + Energy \qquad (1)$$

A fuel cell consists of two electrodes, anode and cathode, with a layer of electrolyte between them, Figure 1. The electrodes are normally made flat and porous to achieve good contact between the electrolyte and the gases. The layer of electrolyte is made thin for the purpose to allow ions to pass through it without too much ohmic losses.

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[50] https://www.researchgate.net/publication/309898224_A_review_on_prognostics_and_health_monitoring_of_proton_exchange_membrane_fuel_cell/download

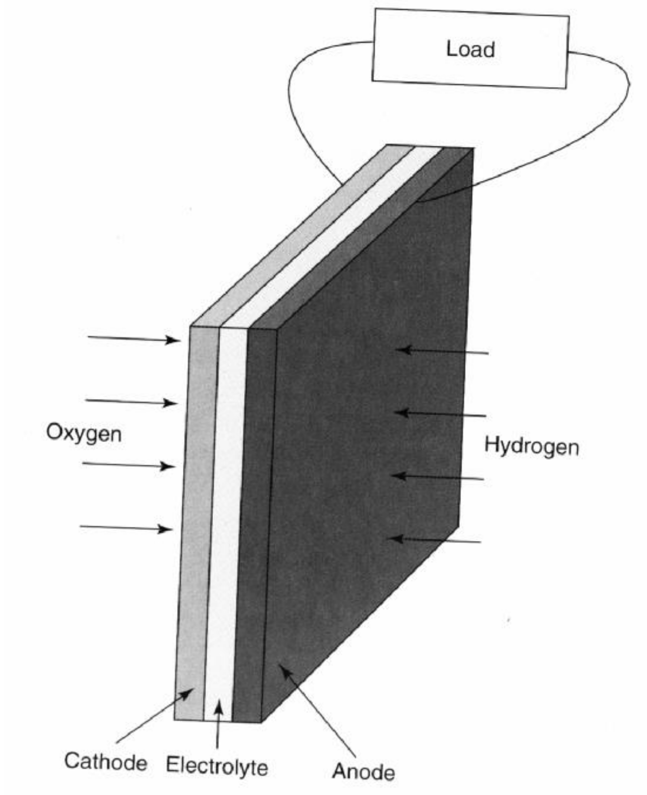


fig. 2 :Basic structure of a fuel cell.

20.1 Types of fuel cell

There are many different fuel cell types. The differences between them are the reactions at the electrodes and the electrolyte used. In the following subparagraghs some of the most common types of fuel cells are explained briefly.

20.1.1 Acid electrolyte fuel cell

The most common type of fuel cell is the acid electrolyte, seen in Fig 3. At the anode the following reaction takes place.

$$2H_2 \rightarrow 4H^+ + 4e^- \qquad \textbf{(2)}$$

Hydrogen gas ionizes into hydrogen ions and electrons, equation (2). The electrons released from the reaction flow through an external load to the cathode, creating a current. The H^+ ions pass through the electrolyte which is possible because an acid is a fluid with mobile H^+ ions. At the cathode the H^+ reacts with oxygen and the electrons forming water, equation (3)

$$O_2 + 4e^- + 4H^+ \rightarrow 2H_2O \qquad \textbf{(3)}$$

The electrons are not allowed to pass through the electrolyte because then no current would flow in the external circuit.

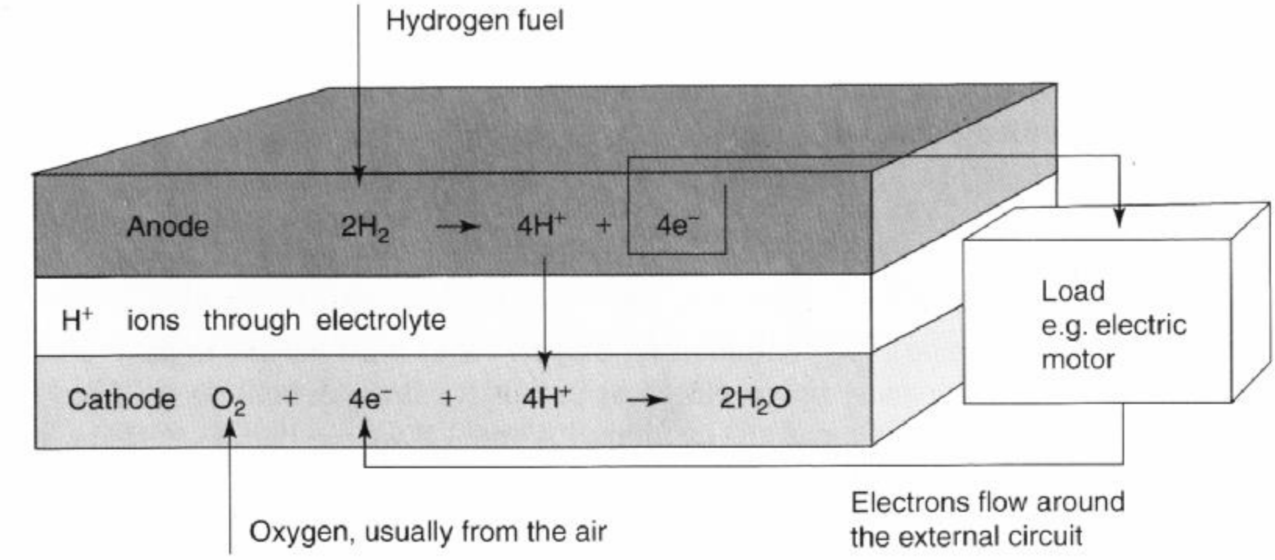


Fig. 3:Electrode reactions and electrical flow for an acid electrolyte fuel cell. The electrons flow from the anode to the cathode via an external circuit.

20.1.2 Alkaline electrolyte fuel cell

In the Alkaline electrolyte the reaction is similar to the acid electrolyte but the reactions at each electrode are different. In this case the mobile ions are hydroxyl ions (OH^-). The hydrogen fuel reacts with OH^- at the anode producing water and releasing electrical energy, equation (4).

$$2H_2 + 4OH^- \rightarrow 4H_2O + 4e^- \qquad \textbf{(4)}$$

At the cathode side the electrons released from the anode reacts with oxygen and water creating new OH^- ions, equation (5). Although water is consumed at the cathode, twice the amount is produced at the anode.

$$O_2 + 4e^- + 2H_2O \rightarrow 4OH^- \quad \textbf{(5)}$$

As for the acid electrolyte there must be an external load so that the electrons can flow from the anode to the cathode, Figure 4.

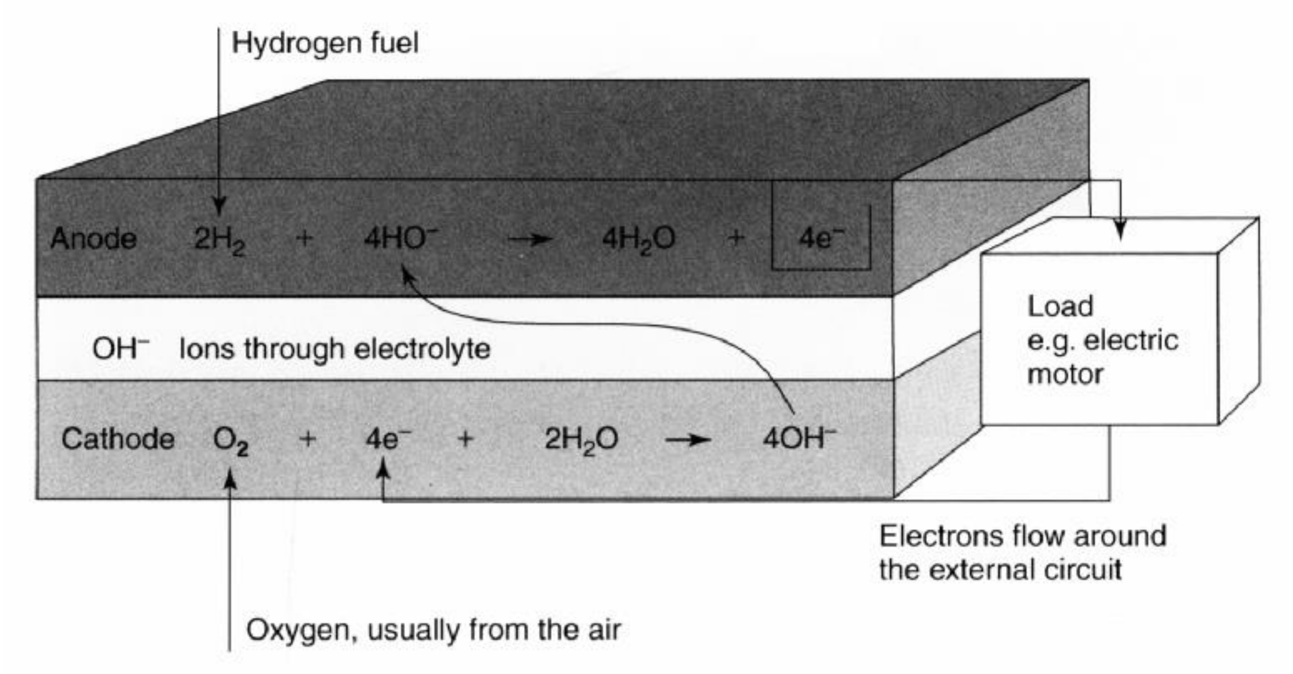


Fig. 4:Electrode reactions and electrical flow for an alkaline electrolyte fuel cell.

Worth mentioning is that for both the acid electrolyte and the alkaline electrolyte twice as many moles of hydrogen as of oxygen are needed in the reaction.

20.1.3 Proton exchange membrane fuel cell

The Proton Exchange Membrane (PEM) fuel cell is the most useful at present time. A solid polymer, in which protons (H^+) are mobile, is used as electrolyte. The fact that the electrolyte is solid and immobile makes this cell very simple. The working temperature of these cells is quite low, around 30 -100°C, which gives a problem of slow reaction rates but at the same time the startup is fast. The problem of slow reaction rates is solved by the use of more effective electrodes and catalysts such as platinum. Another drawback is that the membrane is fragile and breaks easily. The field of application is essentially in vehicles, portable applications and low power CHP (Combined Heat and Power) systems.

➢ There are currently 6 types of fuel cell:

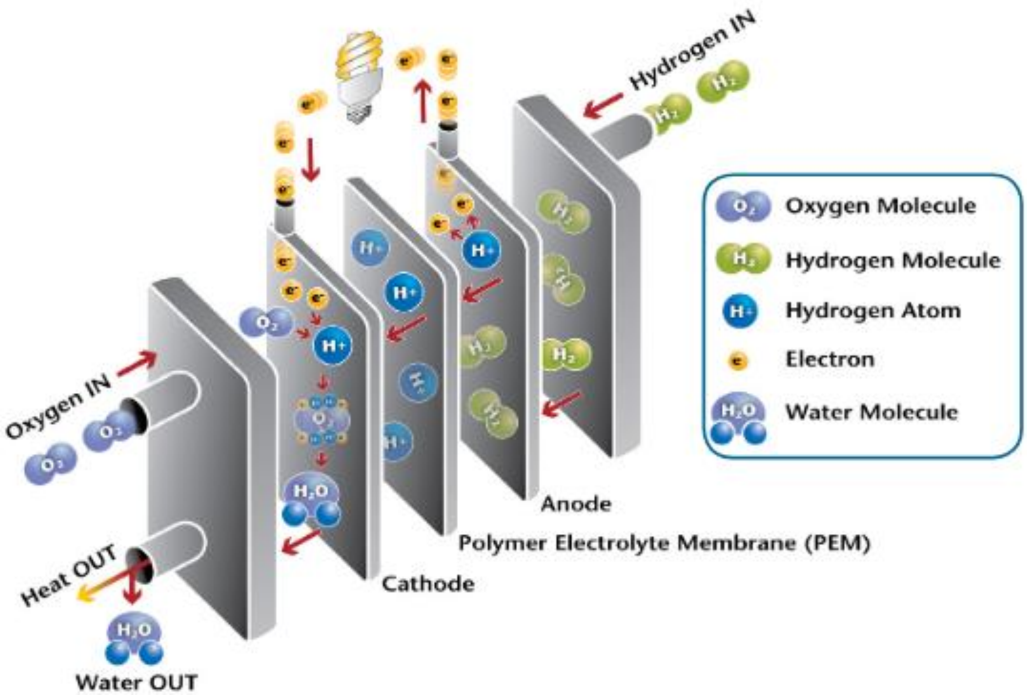
- AFC (Alkaline fuel Cell),
- PEMFC (Proton Exchange Membran Fuel Cell),

- DMFC (Direct Methanol Fuel Cell),
- PAFC (Phosphoric Acid Fuel Cell),

- MCFC (Molten carbonate Fuel Cell),
- SOFC (Solid Oxid Fuel Cell).

✍ **PEMFC**

- Uses H_2 as fuel (sometimes CH_3OH)
- A polymer membrane
- Works at a low temperature (≈ 60°C)
- Starts quickly



[51]

Fig. 5: PEMFC

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[51] https://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/fct_h2_fuelcell_factsheet.pdf

20.2 Technical and physical description of a fuel cell

Electrical energy is produced when hydrogen reacts at the anode and oxygen at the cathode. To release it, an activation energy must be supplied in order to overcome the energy hill. The reaction has the form shown in Figure 6. If the probability of a molecule having enough energy is low a slow reaction takes place. This is not the case for fuel cell reactions at very high temperatures. To speed up the reaction the most common solutions are:

- Increasing the electrode area
- The use of catalysts
- Raising the temperature

The latter two are applicable to any chemical reaction. The first one is the most important when working with fuel cells. For a reaction like the one in equation (4), fuel gas, OH^- ions and the necessary activation energy are needed. The hydrogen fuel and OH^- ions comes in contact on the surface of the electrode, and at the same time the produced electrons must be removed. The time that this take is reversed proportional to the area of the electrode, i.e., the larger the electrode area is the less time it takes. The area is such an important issue that the performance of a fuel cell is expressed in ampere/cm^2.

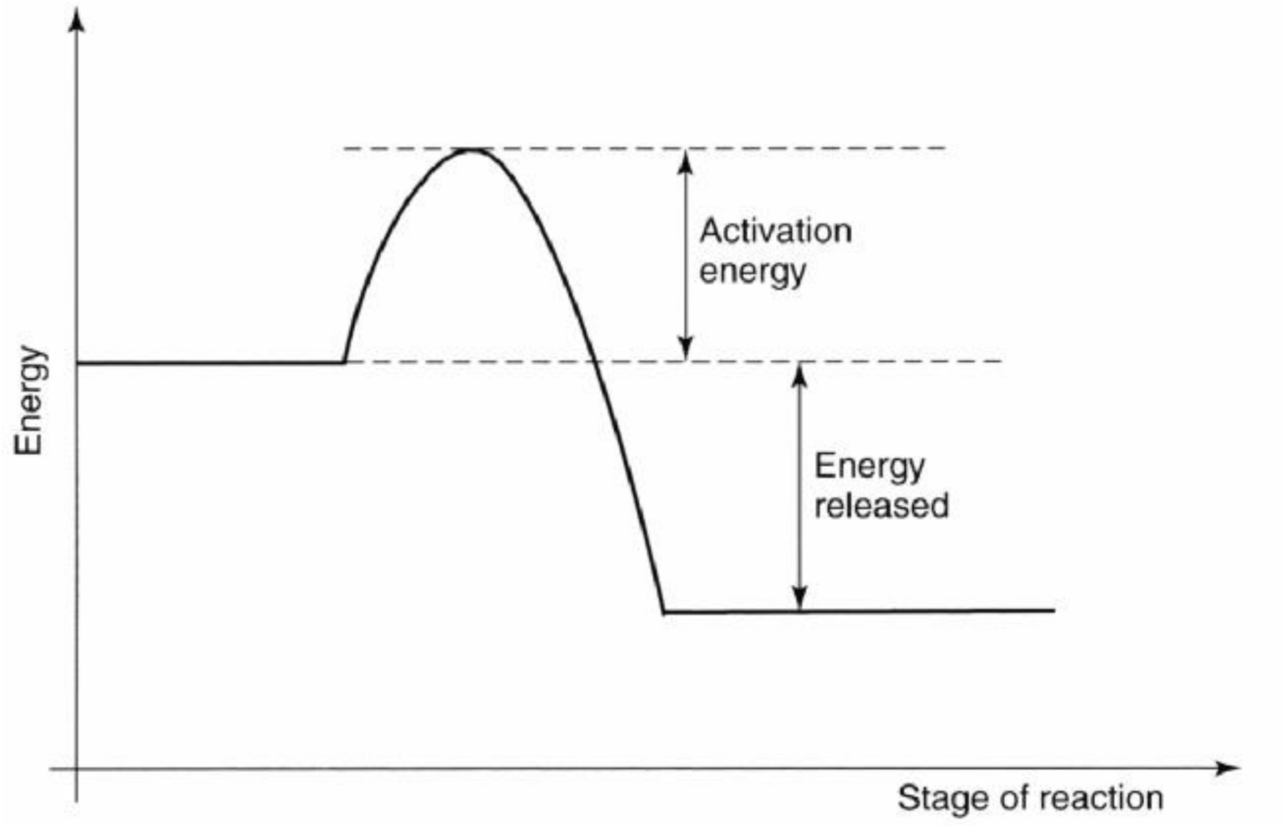


Fig. 6: Activation energy diagram for a simple exothermic chemical reaction.

20.3 Fuel cell stack

20.3.1 Simple series connection

A single fuel cell is made very thin for purposes stated before. This however limits the voltage across it. A typical value for the voltage is about 0.7 V when drawing a useful current. A higher voltage can be achieved by connecting several cells in series which is known as a stack. The easiest way of doing this is to connect the edge of the anode to the cathode of the next cell, Figure 7. With this configuration the electrons have to travel across the surface of the electrode to the edge. Even if the electrodes are good conductors there will be a voltage drop. This drop will be substantial in comparison to the low cell voltage and therefore this method is not used unless the current is very small.

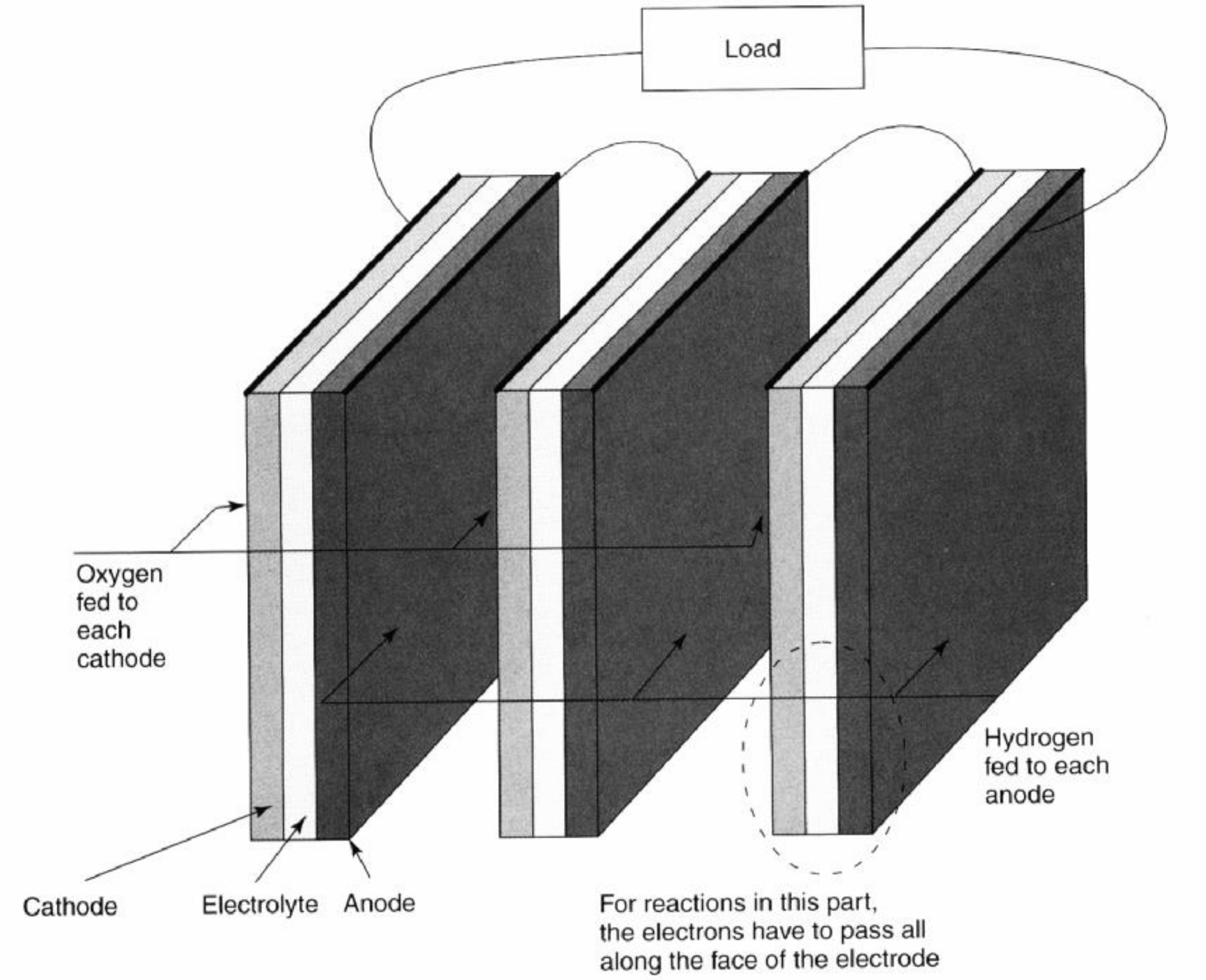


Fig. 7:Simple series connection from the anode of one cell to the cathode of the next one.

20.3.2 Bipolar series connection

A better solution for the construction of a stack is to make the connections with bipolar plates made from materials with good conductivity such as graphite or stainless steel. These plates make connections all over one cathode to the anode of the next cell, hence bipolar. The conditions that they must fulfill are that there has to be a good electric connection between the electrodes and that the different gases must be separated.

In the bipolar plates there are normally horizontal channels used to feed oxygen to the cathode and vertical channels to feed hydrogen to the anode, Figure 8. When assembling the stack with bipolar plates a solid block is formed where the current flows more or less straight through the cells instead of across the surface, resulting in better efficiency. The block also becomes more robust and strong due to that the electrodes are better supported. The design of the bipolar plate is somewhat complex where a balance between electrical contact and gas flow has to be considered. If the contact points are made as large as possible optimization of the electrical contact is achieved, but then the gas flow is decreased over the electrodes. Small contact points are also possible but then they should be frequent which makes the manufacturing difficult and expensive as well as a fragile plate. To obtain low resistivity and a small stack size the bipolar plate should be made thin. This results in narrow channels which makes it harder for the gas to flow around the cell.

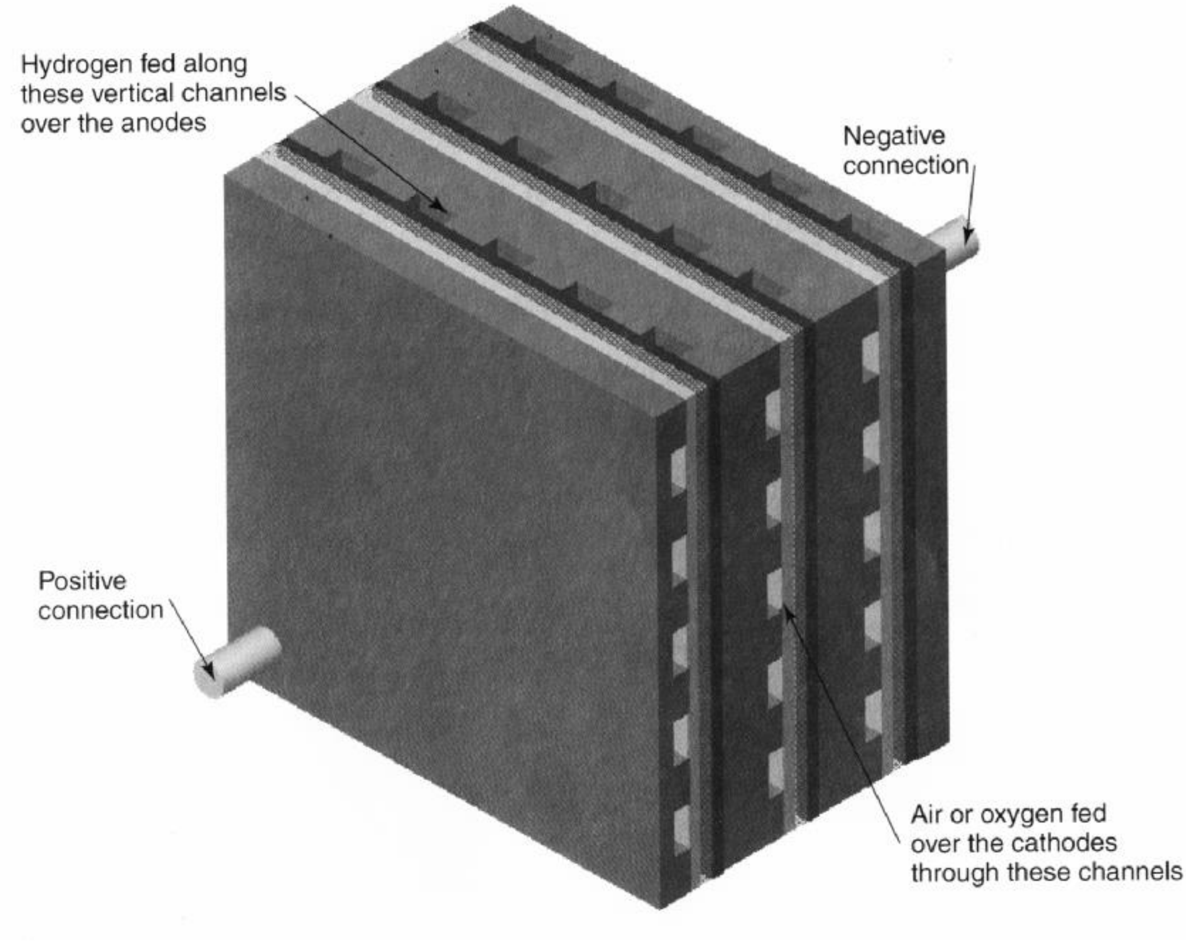


Fig. 8: A fuel cell stack, consisting of three cells connected with bipolar plates.

In reality, when designing a stack with bipolar plates further considerations have to be done. The difficulties include supply and leakage of the gases. As mentioned before the electrodes are made porous to allow the gas to pass through it. A result of this is that the gas can leak out of the edges of the electrodes. The solution to this problem is to seal the edges. This is done by making the electrodes smaller than the electrolyte and then fitting a sealing gasket around them, Figure 9.

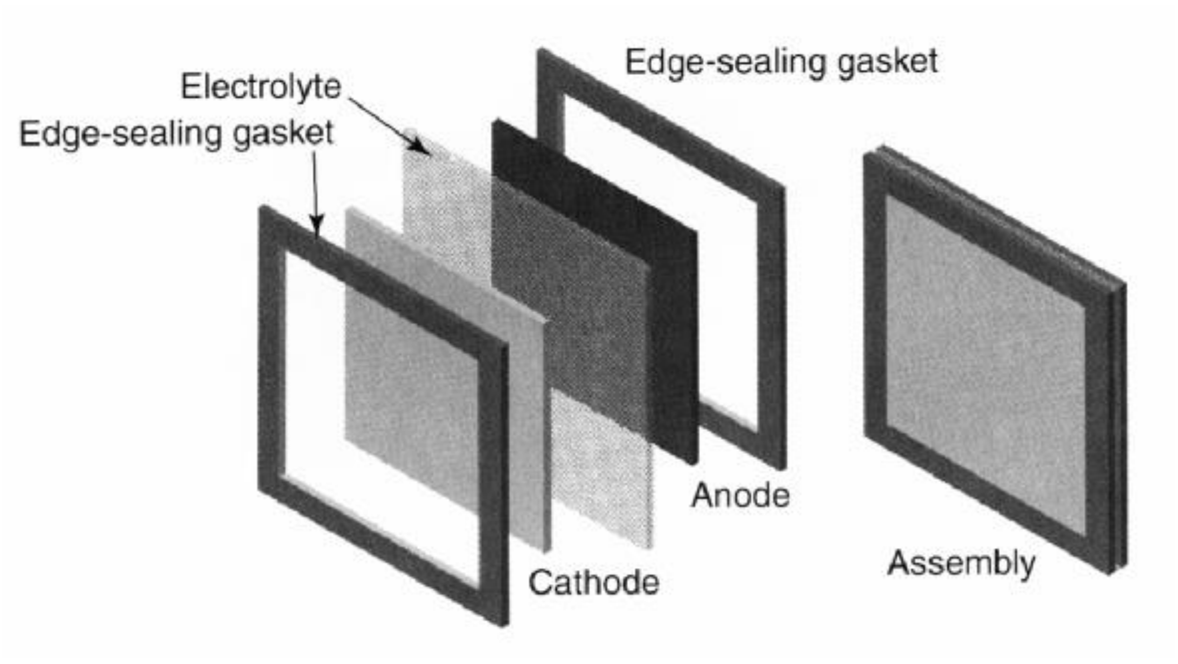


Fig. 9:Structure of a fuel cell with edge seals to prevent leakage of the gas at the edges of the electrodes.

When supplying fuel and oxygen to a fuel cell stack, where the edges of the electrodes are sealed, four manifolds, one at each side, are used. Because of the seals the hydrogen fed vertically only comes in contact with the anodes and the oxygen fed horizontally only comes in contact with the cathodes. The arrangement can be seen in Figure 10, where the manifolds are not assembled. This is called external manifolding and the main advantage is the simplicity of it. However, there are two important disadvantages. The first one is the problem regarding the cooling of the system. It is difficult to supply some kind of extra cooling and therefore the cells have to be cooled using the air passing through the cathodes. This leads to that the air has to be supplied at a higher rate than necessary. In some cases, this is enough to cool the cells but energy is wasted. The second disadvantage concerns the gasket around the edges of the electrode. At the points where there is a channel it is not pressed down evenly which can cause a leakage of the gases.

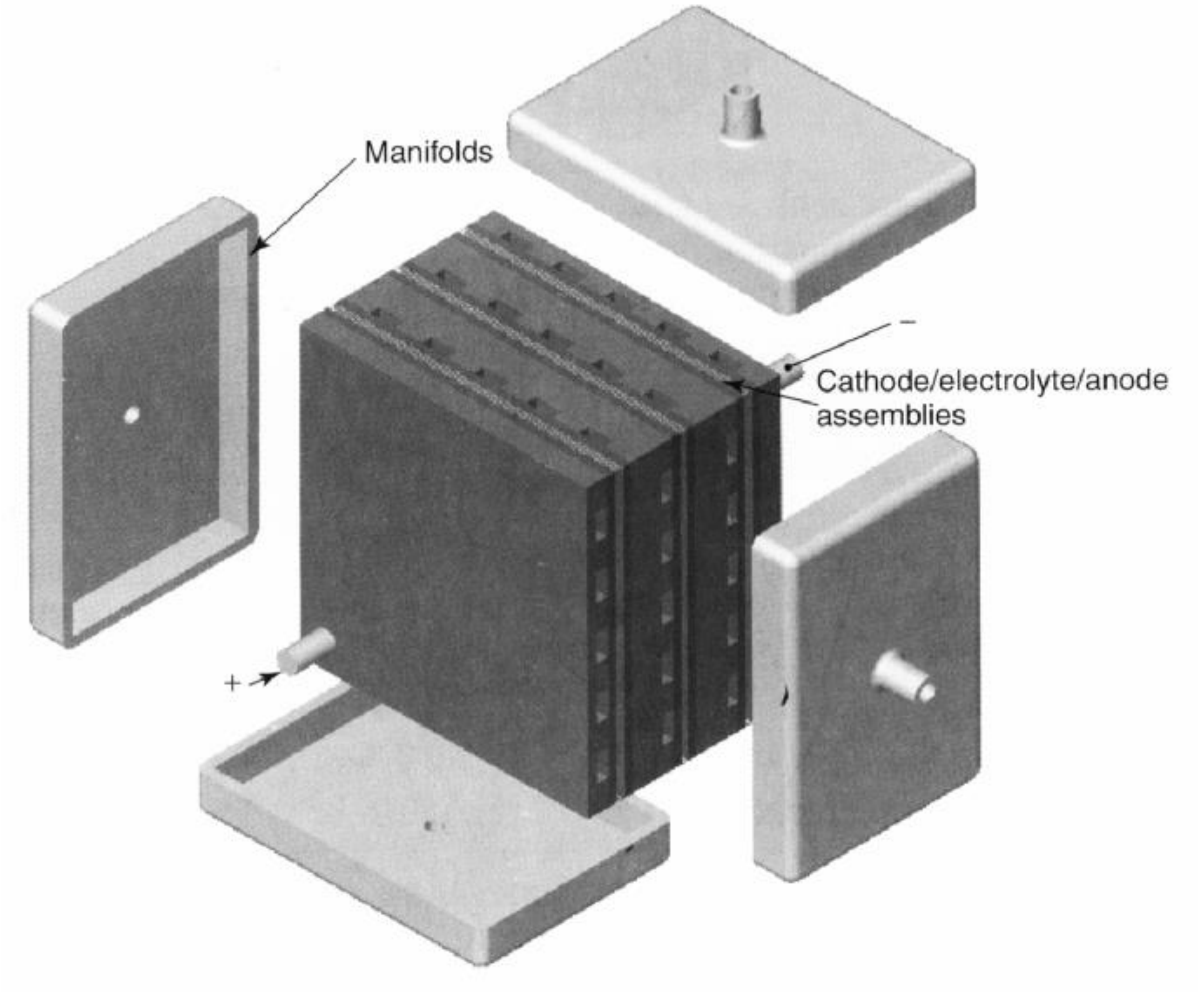


Fig. 10:Fuel cell stack with external manifolding

A better, yet more complex bipolar plate is made with internal manifolding where the channels are located inside the plate. The plates are also made larger than the electrodes with extra channels running through the stack, as seen in Figure 11. The fuel and the oxygen are fed into the channels via holes placed at each corner of the end plates. A fuel cell stack with internal manifolding has the appearance of a solid block and the gases are fed where the positive and negative connections are made. This arrangement can be cooled in different ways. The easiest way is to drive cooling air or water through the stack by channels at the edges.

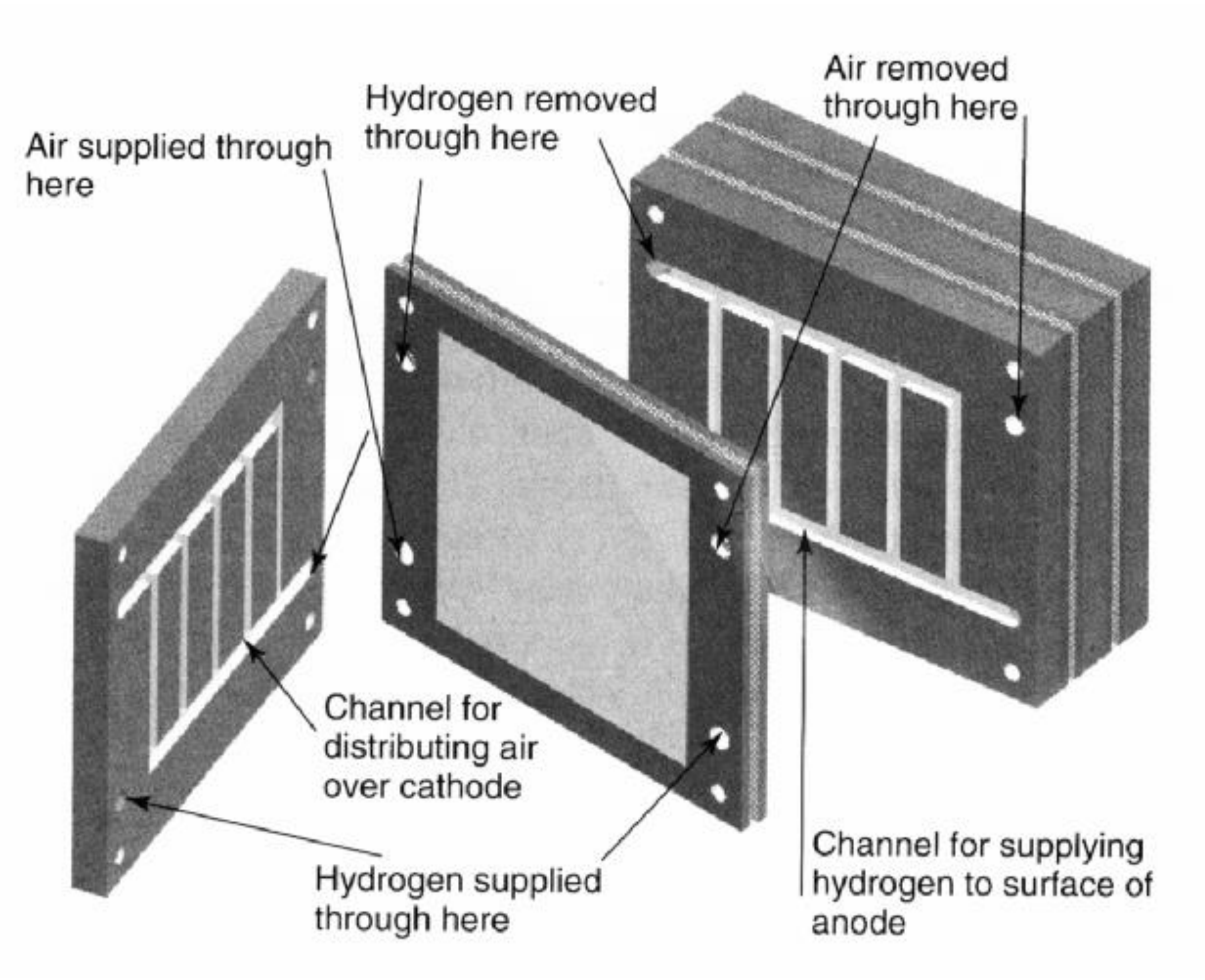


Fig. 11: Fuel cell stack with internal manifolding. A more complex bipolar plate is used to allow the reactant gases to be fed to the electrodes through internal channels.

20.4 Fuel cell system

In a fuel cell system the stack is the main component but it is only one part of the whole system. The other components are often called the balance of plant (BOP). Elements such as pumps or blowers are used to circulate the air and fuel in the stack. Compressors can be used, sometimes together with intercoolers, as for internal combustion engines. To drive the pumps, blowers and compressors, electric motors are needed.

The output of a fuel cell stack is a direct current (DC) which is almost never suitable for direct connection to any load. Therefore some kind of power conditioning is needed. What kind of device that is used depends on the need of the load. It can be a DC/DC converter or a DC/AC inverter.

Some kind of fuel storage will always be a part of the system. In the case when the fuel used is not hydrogen a fuel processing system is needed, e.g., to produce hydrogen from fossil fuels.

Different control valves, pressure regulators and in most cases a controller for coordination of the system are needed. Start-up and shutdown of the fuel cell system are complex problems for the controller.

In larger fuel cell systems, a cooling system is necessary. In the case of CHP systems, it is called a heat exchanger which takes care of the excess heat and uses it for another application. When using high temperature cells, the generated heat is sometimes used in fuel or air pre-heaters. In PEM fuel cells the reactant gases are often humidified.

20.5 Energy efficiency, Power and Lifetime

The energy efficiency from a fuel cell stack can be as high as 80%. For the total system the efficiency is lower. How high the efficiency is depending on the amount and what kind of components that are used. For a fuel cell car engine including the whole system, the efficiency from chemical input to kinetic energy is about 30 – 40%. For comparison it should be known that in a conventional internal combustion engine the same efficiency is typically around 18 – 22%.

The power drawn by the load is an important aspect for the lifetime of a fuel cell. A smoother power consumption, i.e., an even power outtake without that many peaks, is preferable. This gives a more durable fuel cell. Car engines can be used as an example to illustrate this. A normal internal combustion engine could be assumed to have a lifetime of approximately 5000 hours, in comparison with a fuel cell engine where the lifetime is around 2000 hours. This problem occurs due to the frequent speed variations during car travel as the power consumption rises during the accelerations. If the speed were more or less constant the lifetime could be increased with a factor of 10 to 20. An application where the fuel cells have better lifetime is in CHP systems of hundreds of kilo watts. In these systems the changes in output power are small which gives a longer lifetime.

20.6 Manufacturing and environment

Most people consider fuel cells to be an environmentally benign energy converter. That is true with some modifications. Depending on how the hydrogen fuel is produced the fuel is more or less carbon dioxide (CO_2) free. If it is produced with green electricity, i.e., environmentally benign produced energy from renewable and non-polluting energy sources, the fuel is said to be clean. However, when the production uses electricity from fossil fuels such as coal, oil and natural gas there will be emissions to the atmosphere.

An aspect that is seldom thought of is the manufacture of the cell. The fact that the electrodes and electrolyte are made thin and that the electrode surfaces have a microstructure makes the manufacturing energy demanding. When the cells are bound together into a stack, bipolar plates could be used. These are made from good conducting materials such as graphite or stainless steel. The mining of the raw materials for the plates is energy demanding and gives air pollution and soil contamination. Another environmental problem is that platinum often is used as a catalyst for the electrodes. Platinum is a very scarce metal and when mining, the percentage of pure platinum is very low. This leads to many different processes which are both energy demanding and polluting.

20.7 Advantages and Drawbacks

As all technical equipment fuel cells have both advantages and drawbacks. The different drawbacks are more or less important depending on the application and the economy of the project. A short summary of important advantages and drawbacks are listed below.

The advantages are:
- Low emissions
- More efficient compared to a conventional internal combustion engine
- Simplicity, few if any moving parts
- Reliable and long-lasting system
- Silent

The drawbacks are:
- Lifetime
- Cost
- Hydrogen has to be produced
- Not yet available infrastructure for hydrogen

20.8 Components of PEMFC

A typical PEM element consists of several components.

First, there is a current collector.

Fig. 12: Current collector

Next, gas diffusion layer for anode (the gas diffusion layer consists of carbon fibers)

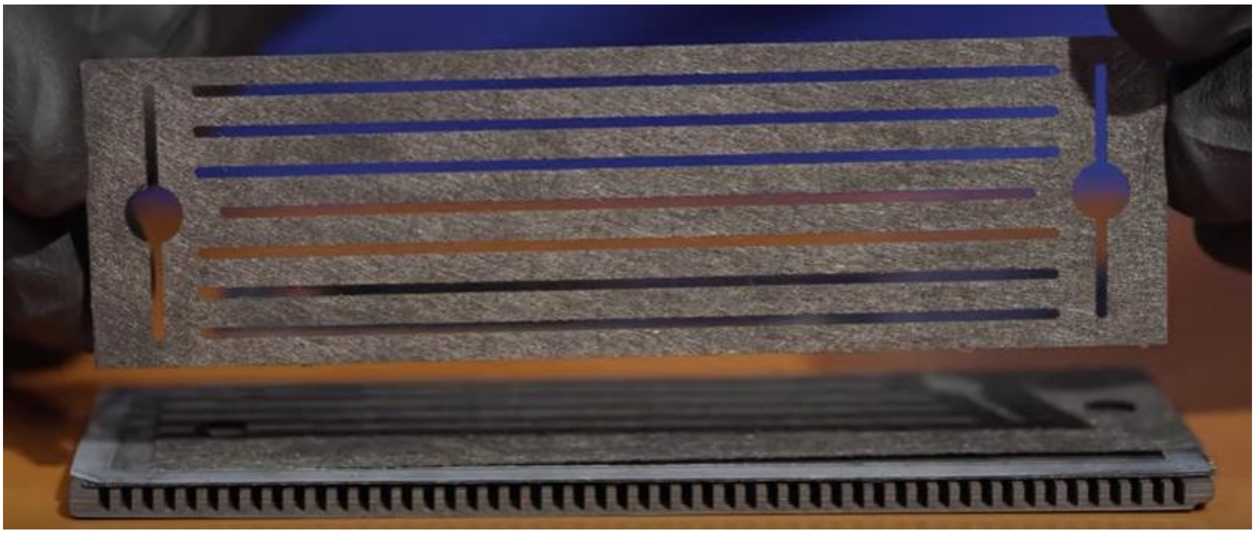


Fig. 13: Gas diffusion layer for anode

Then the membrane electrode assembly, which consists of anode and cathode catalysts deposited onto a nafion membrane (the electron microscopy shows that the cathode catalyst layer is much thicker than anode).

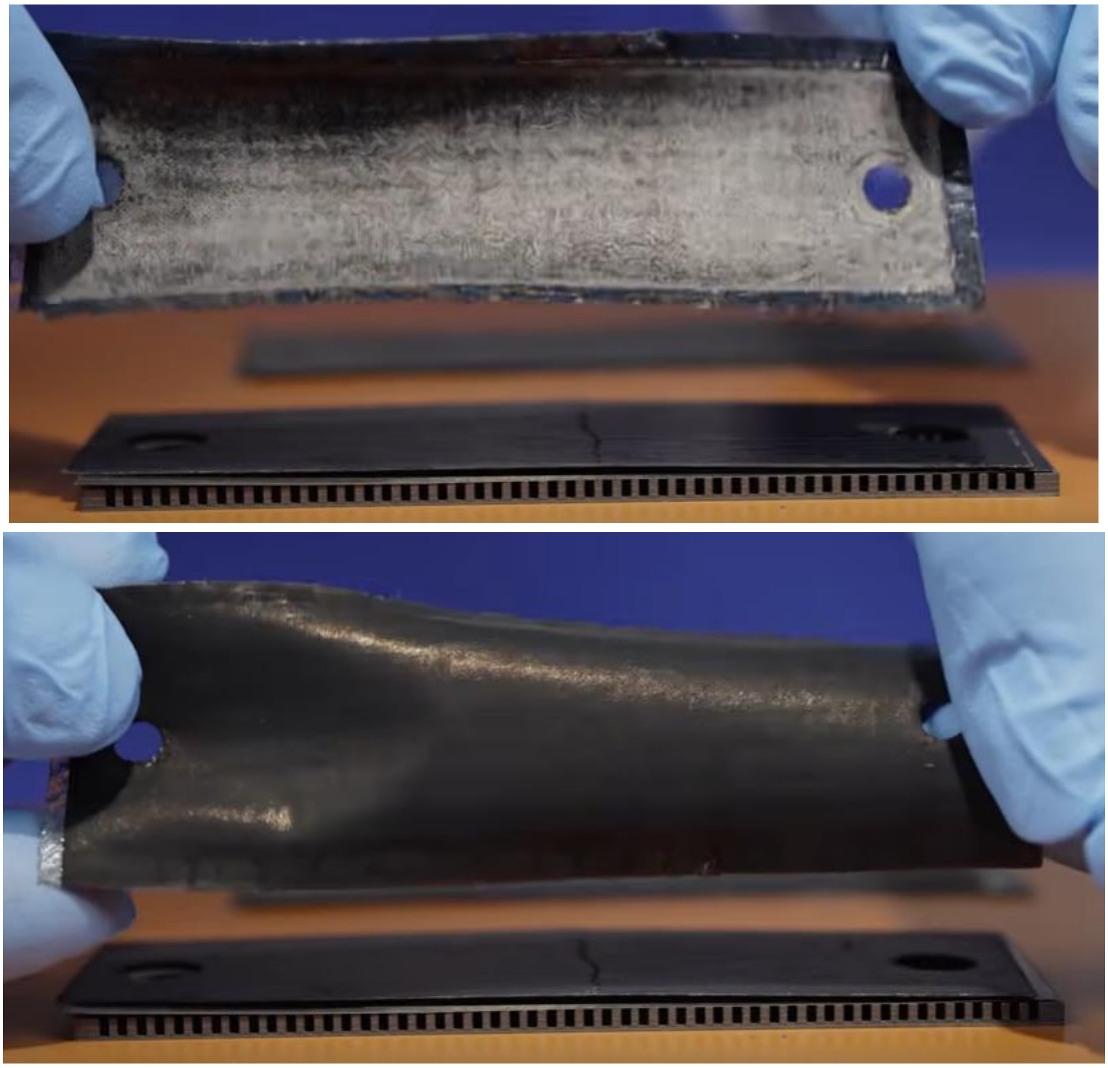


Fig. 14 : Membrane electrode assembly

Next , the cathode gas diffusion layer

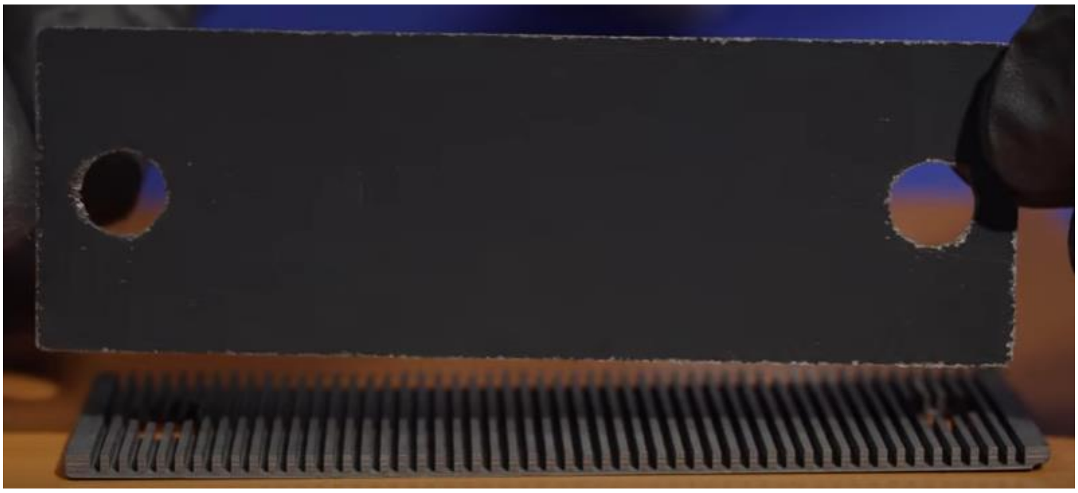


Fig. 15: Cathode gas diffusion layer

A perforated metal plate

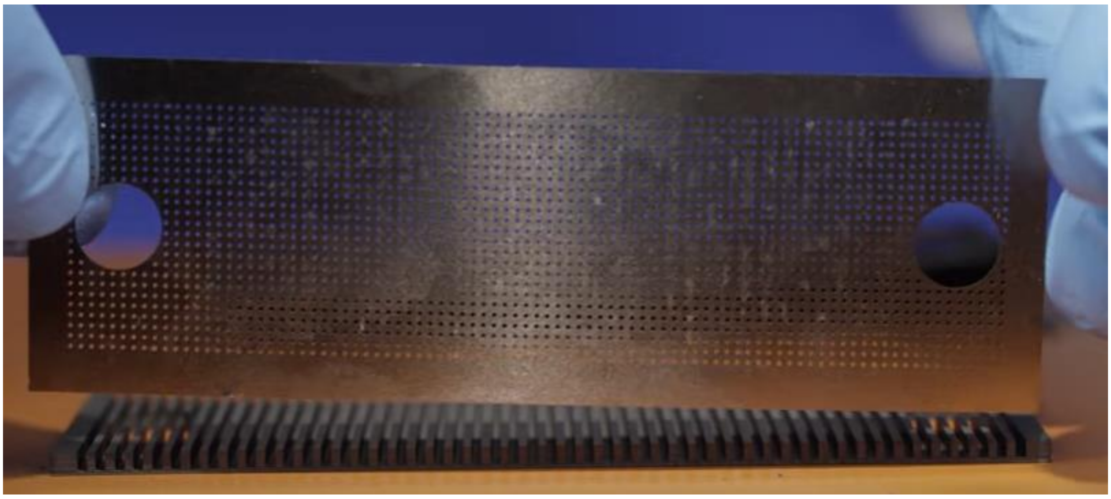


Fig. 16: Perforated metal plate

And finally the bipolar plate, which acts as a current collector and distributes air in the element.

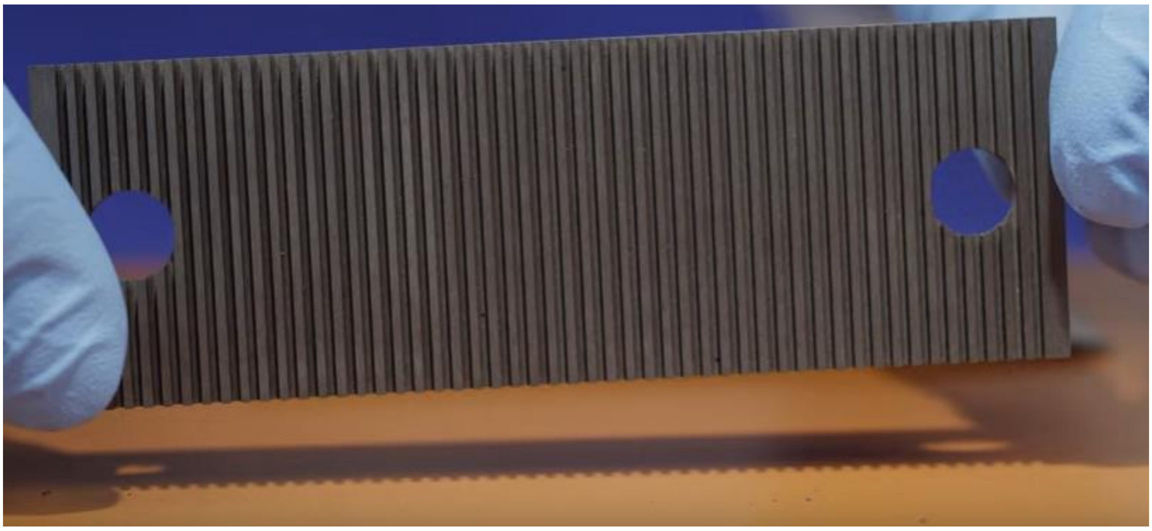


Fig. 17: Bipolar plate

To create a working fuel cell stack, several single cells are connected in series.

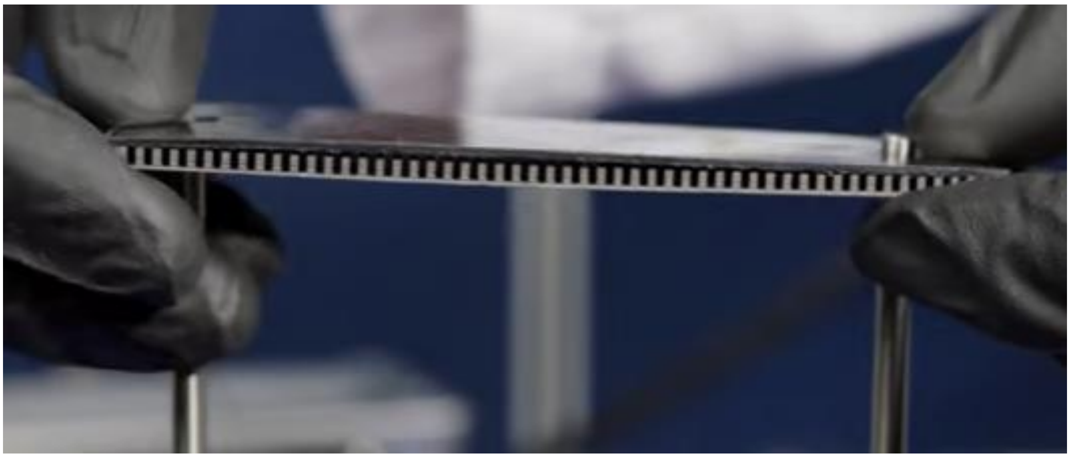
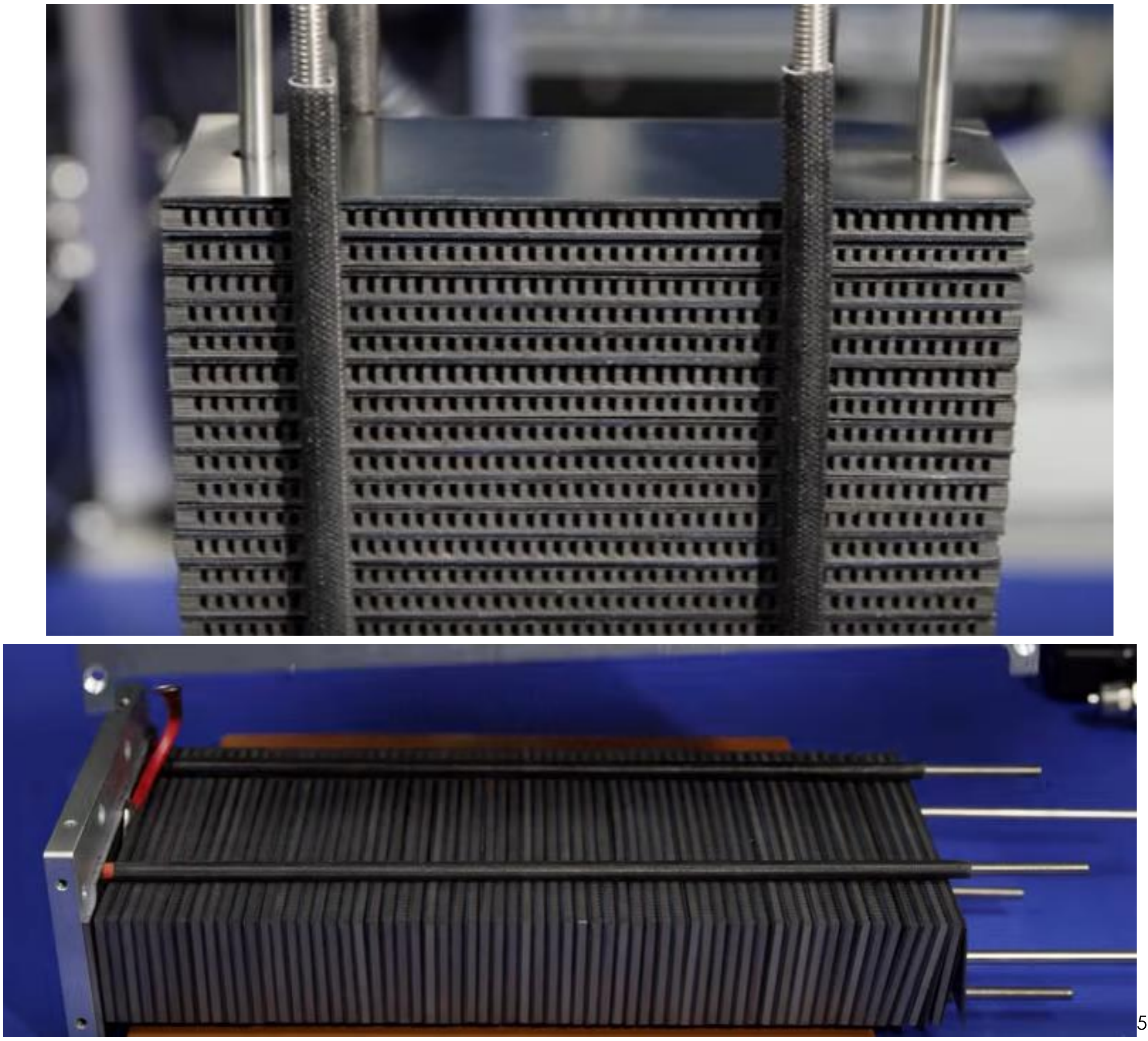


Fig. 18: Single cell



[52]

Fig. 19: Stack of PEMFC

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[52] https://www.youtube.com/watch?v=yrAAVOgBmcE

Fig. 20: Air inlet and cooling

20.9 How Fuel Cells Work [53]

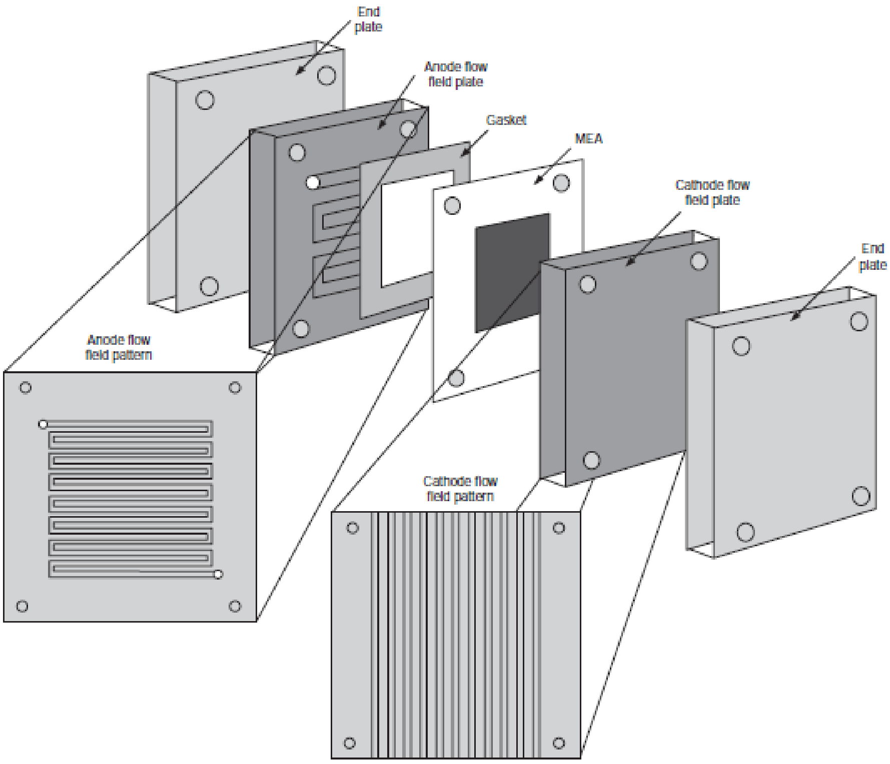

Fig. 21: An exploded view of a fuel cell stack [54]

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[53] https://www.energy.gov/eere/fuelcells/fuel-cells

[54] https://www.sciencedirect.com/book/9780123742599/pem-fuel-cell-modeling-and-simulation-using-matlab

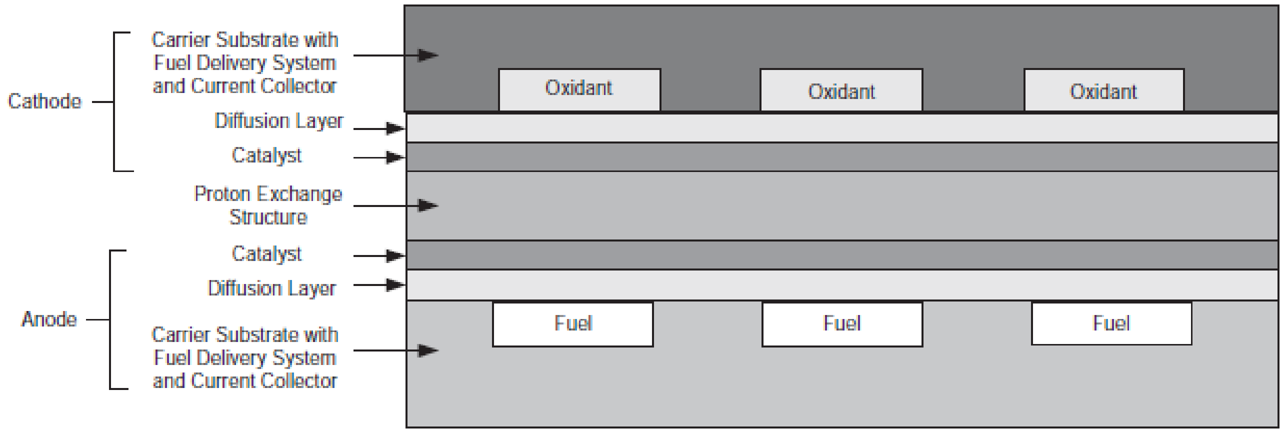

Fig. 22: Basic micro fuel cell based upon traditional fuel cell design [5]

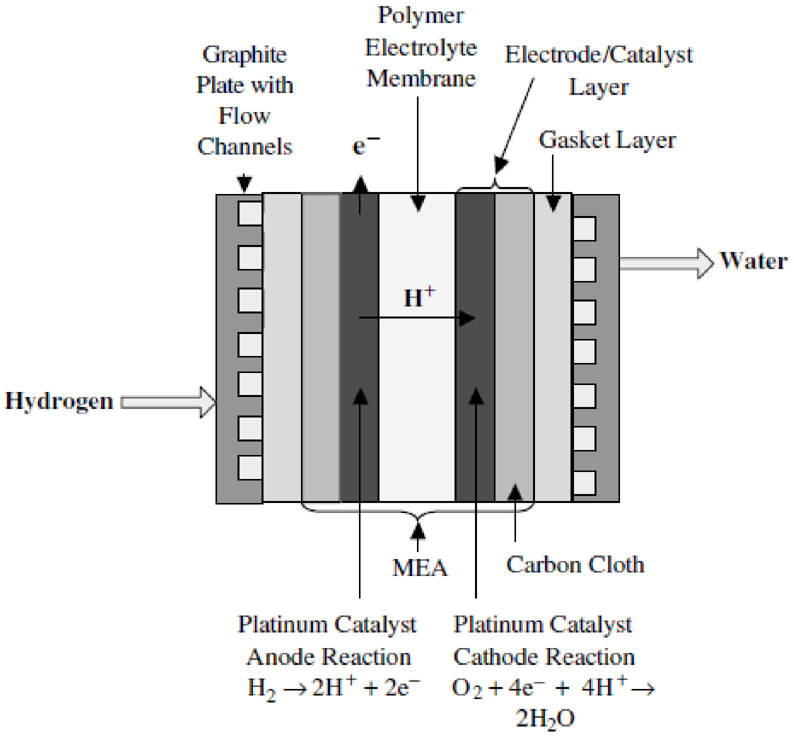

Fig. 23: Generalized schematic of a single fuel cell [55]

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[55] https://www.fuelcellstore.com/fuel-cell-education-products/educational-media/designing-and-building-fuel-cells-Speigel-hardcover

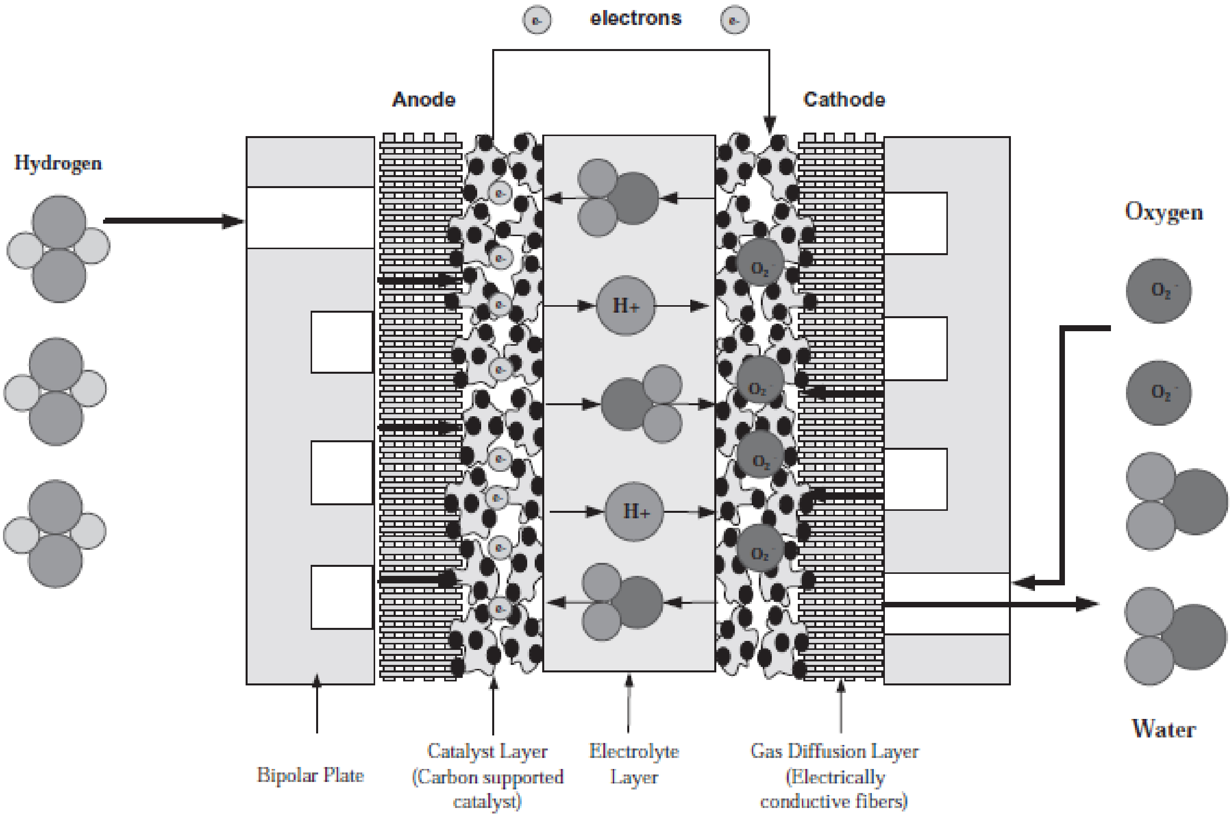

Fig. 24: Schematic of a PEM fuel cell stack [5]

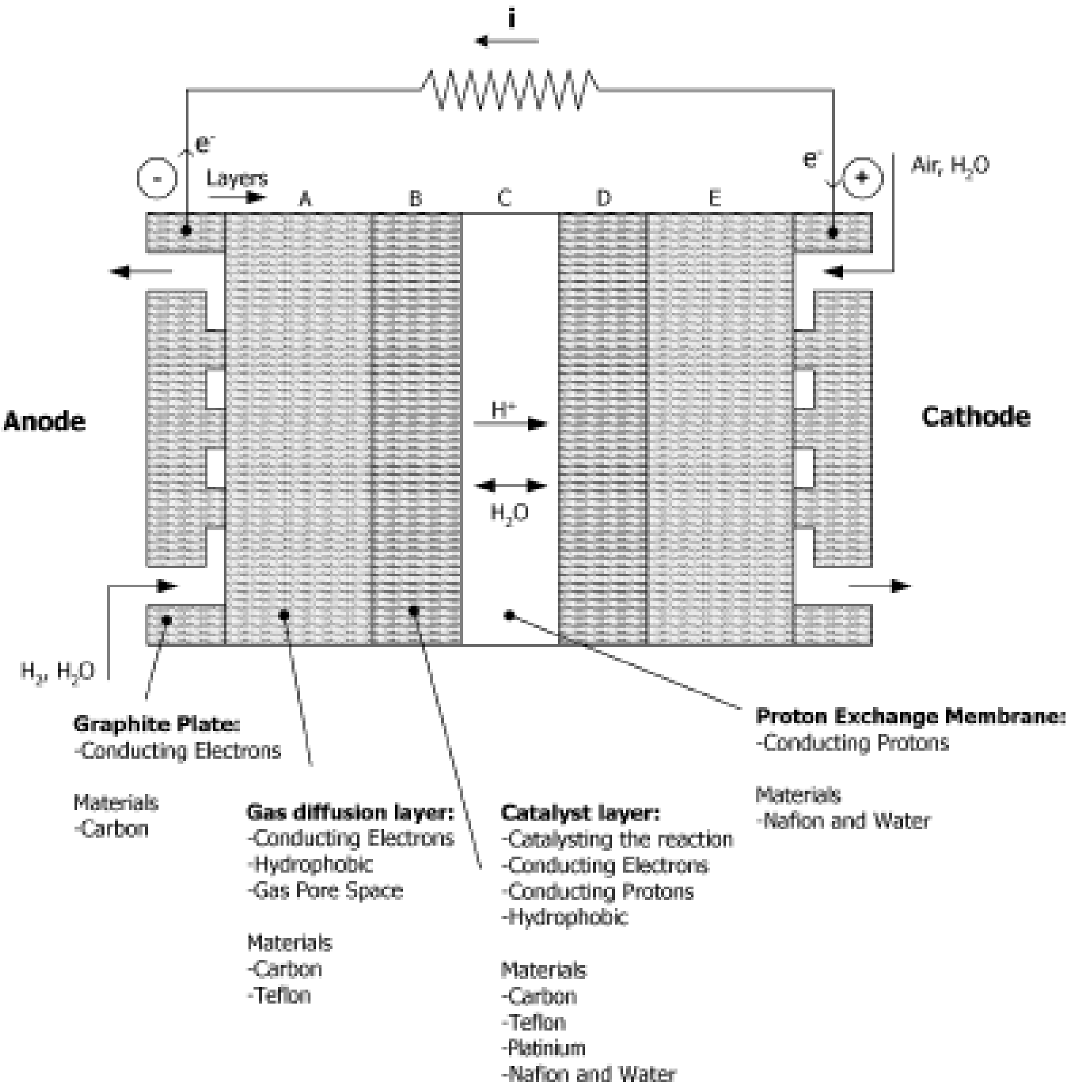

Fig. 25:A cross section of the PEM fuel cell. The unit cell is made of 7 layers which are made of different compositions of material providing the layers with different properties [56]

Fuel cells work like batteries, but they do not run down or need recharging. They produce electricity and heat as long as fuel is supplied. A fuel cell consists of two electrodes—a negative electrode (or anode) and a positive electrode (or cathode)—sandwiched around an electrolyte. A fuel, such as hydrogen, is fed to the anode, and air is fed to the cathode. In a hydrogen fuel cell, a catalyst at the anode separates hydrogen molecules into protons and electrons, which take different paths to the cathode. The electrons go through an external circuit, creating a flow of electricity. The protons migrate through the electrolyte to the cathode, where they unite with oxygen and the electrons to produce water and heat. Learn more about:

- Parts of a fuel cell
- Fuel cell systems

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[56] https://www.scribd.com/document/447288677/Design-and-Control-of-Fuel-Cell-System-for-Tran-z-lib-org-pdf

- Types of fuel cells.

20.9.1 Parts of a fuel cell

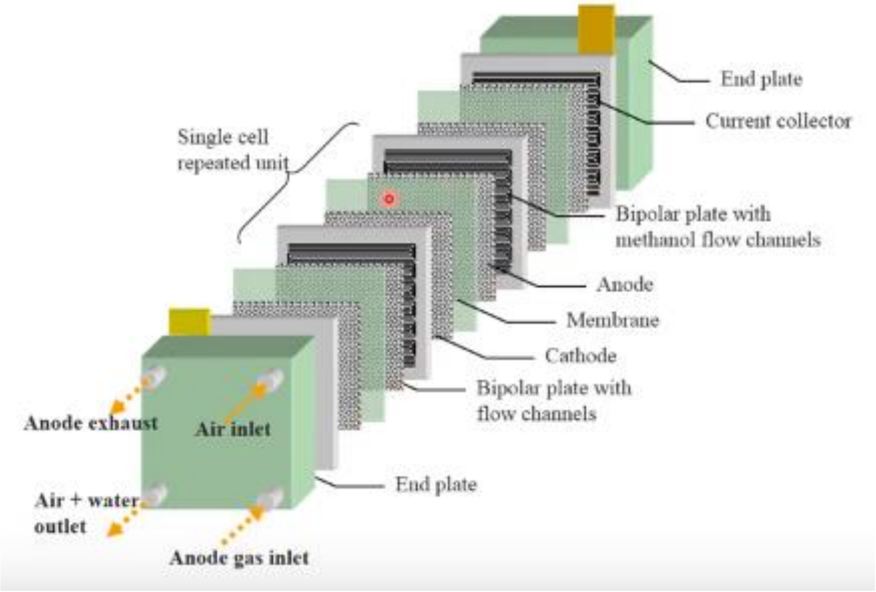

Fig. 26: PEMFC – flowing path of fuel and air

Polymer electrolyte membrane (PEM) fuel cells are the current focus of research for fuel cell vehicle applications. PEM fuel cells are made from several layers of different materials. The main parts of a PEM fuel cell are described below.

The heart of a PEM fuel cell is the ***membrane electrode assembly (MEA)***, which includes the ***membrane***, the ***catalyst layers***, and ***gas diffusion layers (GDLs)***.

Hardware components used to incorporate an MEA into a fuel cell include ***gaskets***, which provide a seal around the MEA to prevent leakage of gases, and ***bipolar plates***, which are used to assemble individual PEM fuel cells into a fuel cell stack and provide channels for the gaseous fuel and air.

20.9.1.1 Membrane Electrode Assembly

The membrane, catalyst layers (anode and cathode), and diffusion media together form the membrane electrode assembly (MEA) of a PEM fuel cell.

a) Polymer Electrolyte Membrane

The polymer electrolyte membrane, or PEM (also called a proton exchange membrane)—a specially treated material that looks something like ordinary kitchen plastic wrap—conducts only positively charged ions and blocks the electrons. The PEM is the key to the fuel cell technology; it must permit only the necessary ions to pass between the anode and cathode. Other substances passing through the

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electrolyte would disrupt the chemical reaction. For transportation applications, the membrane is very thin—in some cases under 20 microns.

b) Catalyst Layers

A layer of catalyst is added on both sides of the membrane—the anode layer on one side and the cathode layer on the other. Conventional catalyst layers include nanometer-sized particles of platinum dispersed on a high-surface-area carbon support. This supported platinum catalyst is mixed with an ion-conducting polymer (ionomer) and sandwiched between the membrane and the GDLs. On the anode side, the platinum catalyst enables hydrogen molecules to be split into protons and electrons. On the cathode side, the platinum catalyst enables oxygen reduction by reacting with the protons generated by the anode, producing water. The ionomer mixed into the catalyst layers allows the protons to travel through these layers.

c) Gas Diffusion Layers

The GDLs sit outside the catalyst layers and facilitate transport of reactants into the catalyst layer, as well as removal of product water. Each GDL is typically composed of a sheet of carbon paper in which the carbon fibers are partially coated with polytetrafluoroethylene (PTFE). Gases diffuse rapidly through the pores in the GDL. These pores are kept open by the hydrophobic PTFE, which prevents excessive water buildup. In many cases, the inner surface of the GDL is coated with a thin layer of high-surface-area carbon mixed with PTFE, called the microporous layer. The microporous layer can help adjust the balance between water retention (needed to maintain membrane conductivity) and water release (needed to keep the pores open so hydrogen and oxygen can diffuse into the electrodes).

20.9.1.2 Hardware

The MEA is the part of the fuel cell where power is produced, but hardware components are required to enable effective MEA operation.

a) Bipolar Plates

Each individual MEA produces less than 1 V under typical operating conditions, but most applications require higher voltages. Therefore, multiple MEAs are usually connected in series by stacking them on top of each other to provide a usable output voltage. Each cell in the stack is sandwiched between two bipolar plates to separate it from neighboring cells. These plates, which may be made of metal, carbon, or composites, provide electrical conduction between cells, as well as providing physical strength to the stack. The surfaces of the plates typically contain a “flow field,” which is a set of channels machined or stamped into the plate to allow gases to flow over the MEA. Additional channels inside each plate may be used to circulate a liquid coolant.

b) Gaskets

Each MEA in a fuel cell stack is sandwiched between two bipolar plates, but gaskets must be added around the edges of the MEA to make a gas-tight seal. These gaskets are usually made of a rubbery polymer.

20.9.2 Fuel cell systems

The design of fuel cell systems is complex and can vary significantly depending upon fuel cell type and application. However, several basic components are found in many fuel cell systems:

- Fuel cell stack
- Fuel processor
- Power conditioners
- Air compressors
- Humidifiers.

20.9.2.1 Fuel Cell Stack

The fuel cell stack is the heart of a fuel cell power system. It generates electricity in the form of direct current (DC) from electrochemical reactions that take place in the fuel cell. A single fuel cell produces less than 1 V, which is insufficient for most applications. Therefore, individual fuel cells are typically combined in series into a fuel cell stack. A typical fuel cell stack may consist of hundreds of fuel cells. The amount of power produced by a fuel cell depends upon several factors, such as fuel cell type, cell size, the temperature at which it operates, and the pressure of the gases supplied to the cell.

20.9.2.2 Fuel Processor

The fuel processor converts fuel into a form usable by the fuel cell. Depending on the fuel and type of fuel cell, the fuel processor can be a simple sorbent bed to remove impurities, or a combination of multiple reactors and sorbents.

20.9.2.3 Power Conditioners

Power conditioning includes controlling current (amperes), voltage, frequency, and other characteristics of the electrical current to meet the needs of the application. Fuel cells produce electricity in the form of direct current (DC). In a DC circuit, electrons flow in only one direction. The electricity in your home and workplace is in the form of alternating current (AC), which flows in both directions on alternating cycles. If the fuel cell is used to power equipment that uses AC, the direct current will have to be converted to alternating current.

Both AC and DC power must be conditioned. Current inverters and conditioners adapt the electrical current from the fuel cell to suit the electrical needs of the application, whether it is a simple electrical motor or a complex utility power grid. Conversion and conditioning reduce system efficiency only slightly, around 2%–6%.

20.9.2.4 Air Compressors

Fuel cell performance improves as the pressure of the reactant gases increases; therefore, many fuel cell systems include an air compressor, which raises the pressure of the inlet air to 2–4 times the ambient atmospheric pressure. For transportation applications, air compressors should have an efficiency of at least 75%. In some cases, an expander is also included to recover power from the high-pressure exhaust gases. Expander efficiency should be at least 80%.

20.9.2.5 Humidifiers

The polymer electrolyte membrane at the heart of a PEM fuel cell does not work well when dry, so many fuel cell systems include a humidifier for the inlet air. Humidifiers usually consist of a thin membrane, which may be made of the same material as the PEM. By flowing dry inlet air on one side of the humidifier and wet exhaust air on the other side, the water produced by the fuel cell may be recycled to keep the PEM well hydrated.

20.10 Cell structure

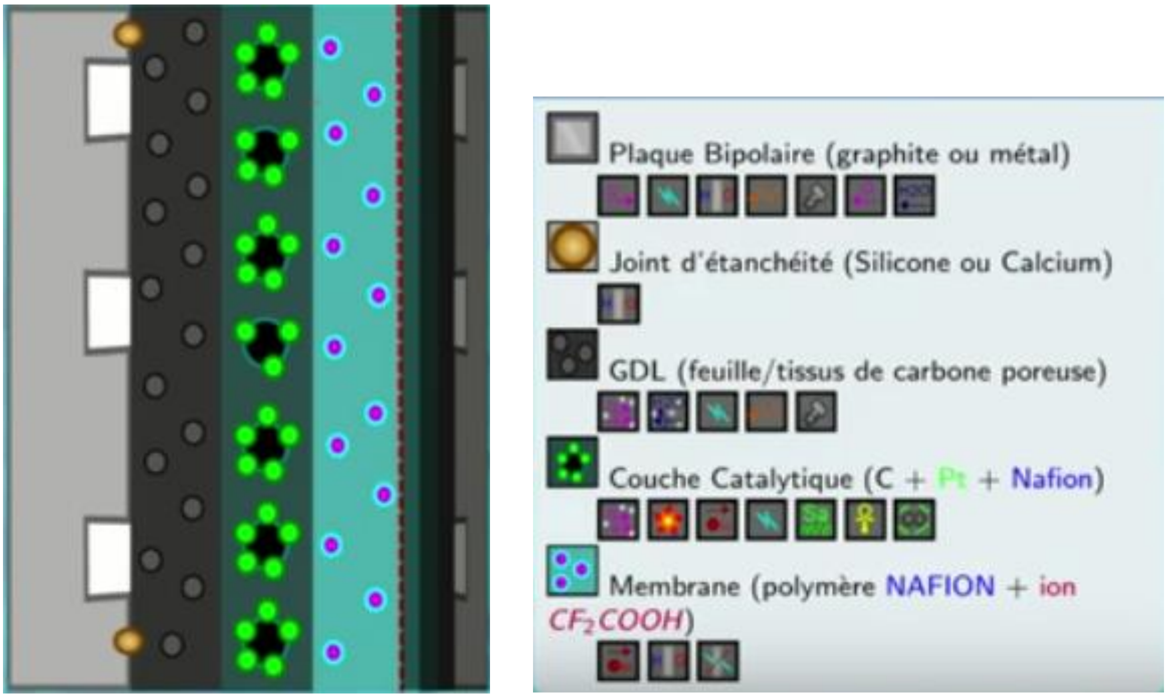


Fig. 27: Cell structure

We have here a half cell to represent is in a symmetrical structure although their function would be different so on each side, we will have what is called a bipolar plate, it is a plate which must lead, which must direct the gases in the channels. It must conduct electricity to collect electrons. It must make it possible to separate the hydrogen and the oxygen in order to avoid a possible explosion, it must allow the heat to be evacuated, it provides the mechanical support of the cell and it possibly makes it possible to evacuate gases, in particular from the gas. air which mainly exceeds nitrogen and water which is produced by the chemical reaction.

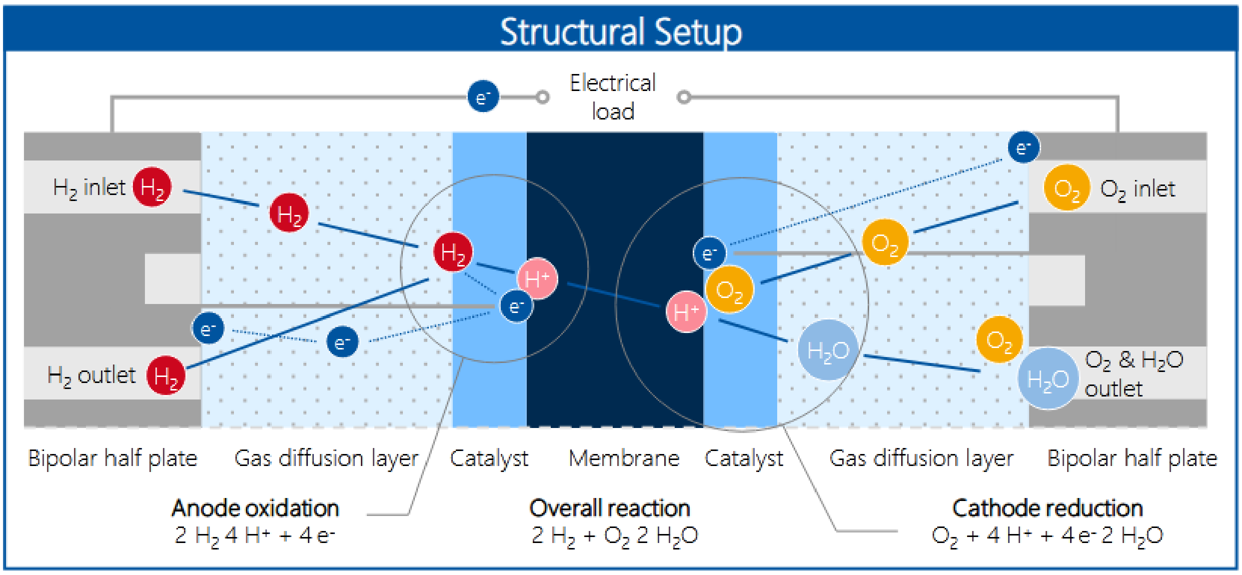
Then we have gaskets, gaskets are usually calcium or silicone, they are there only to avoid queues and hydrogen leakage is therefore a fuel cell explosion.

Then in the GDL of a gas diffuses the best therefore the diffusion layer which is generally a sheet or a carbon fabric for them which therefore catches the role of diffusing the gases on the whole of the catalytic layer to evacuate the water produced by the reaction. It must also conduct electricity must be made of carbon conduct heat to evacuate it and it provides a certain mechanical support which prevents the shape of the channels from destroying the membrane.

Then the catalytic layer which is formed of carbon on which their effects are the smaller platinum particles possibly mixing with a solution of Nafion. Nafion which is the solution which is used to produce the membrane so this catalytic layer and the sludge functions, it must allow the diffusion of gases that it can react, it must catalyze the reaction must allow proton to pass into the membrane. It must conduct electricity to the layers of the diffusions, it must have as large a surface area as possible to increase the power of our fuel cell at an equivalent volume, it must have the longest possible lifespan and we strive to make sure that it resists any form of imprisonment like carbon monoxide which can ruin fuel cells pretty fast.

Finally, we have the membrane which is made of a Nafion polymer containing the carboxylic ions with the same fluorine which has the property not to conduct electricity but to conduct protons which makes the reaction possible.

It must also ensure tightness so as to prevent hydrogen and oxygen from this mixture directly and causing an explosion.



[57]

Fig. 28: Structural setup

20.11 Analysis of quantities

20.11.1 Fluidic quantities

20.11.1.1 In the canals

Fluidic quantities

- The gases have a pressure of 1 to 8 bars
- Hydrogen flow rate: 0.1e-3 mol / sec to 1000 mol / sec
- Air flow: 1E-3 to 1000 mol / sec.

Settings

- Channel length: 1 - 8 m
- Channel diameter: 0.1 to 5 mm
- Parallel number: 1 – 8

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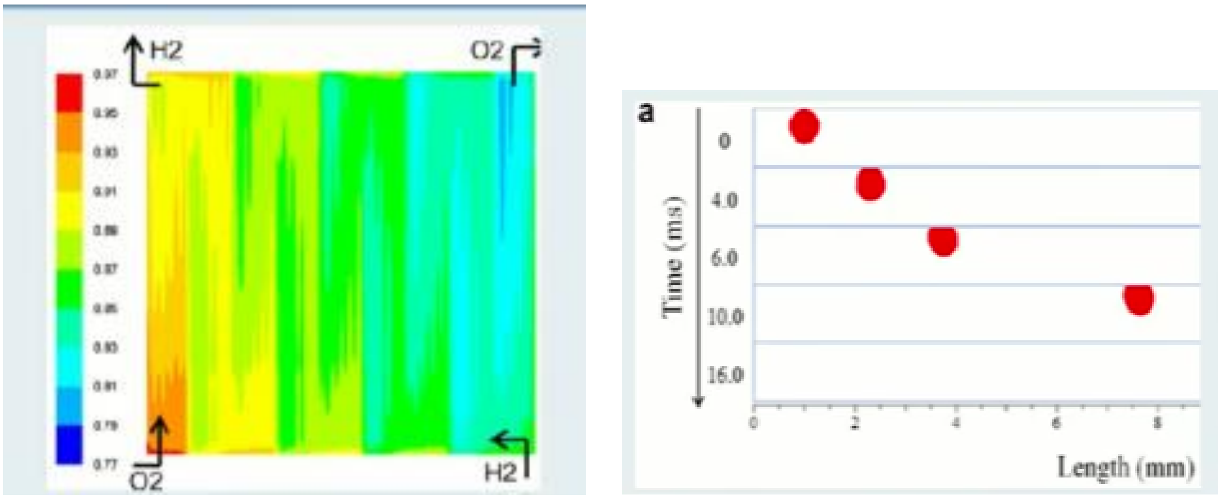
[57] https://bz.vdma.org/documents/266669/49673320/FuelCellProductionBrochures_FuelCellComponents_Edition1_online_en_PEM_v07_scn_1606398023504.pdf/35fca3ae-b8e5-37e6-a685-d2dcae8a3d15



Pressure distributions (O_2) **Dynamic**

Fig. 29: Fluidic quantities (Pressure distributions & dynamics) variations in the canals

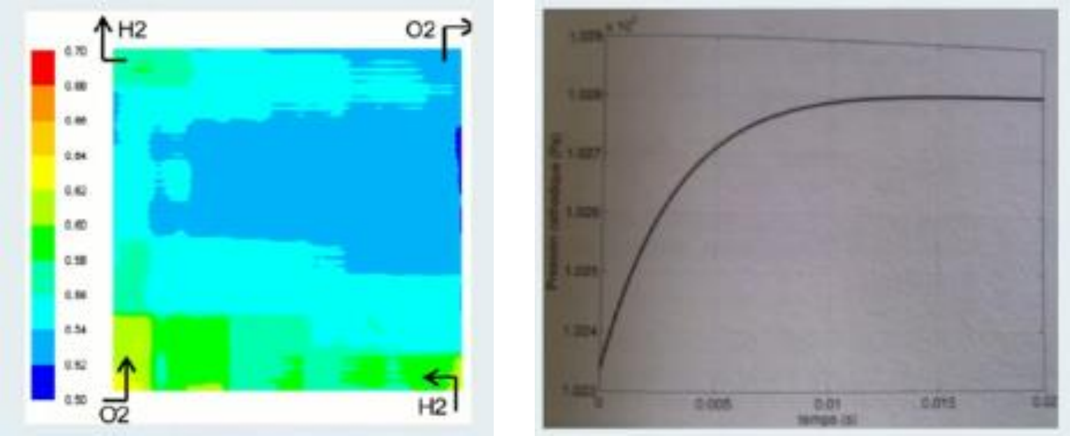
20.11.1.2 In the GDL

Sizes

- Pressure 1 - 2 bar
- Flow 0.1 - 1E-3 mol / sec

Setting

- Diffusion coefficient 2.5 - 9E-5
- Thickness of the scattering layer 0.2 - 0.6 mm



Distributions **Dynamic**

Fig. 30: Fluidic quantities (Distributions & dynamics) variations in the GDL

20.11.1.3 In the membrane

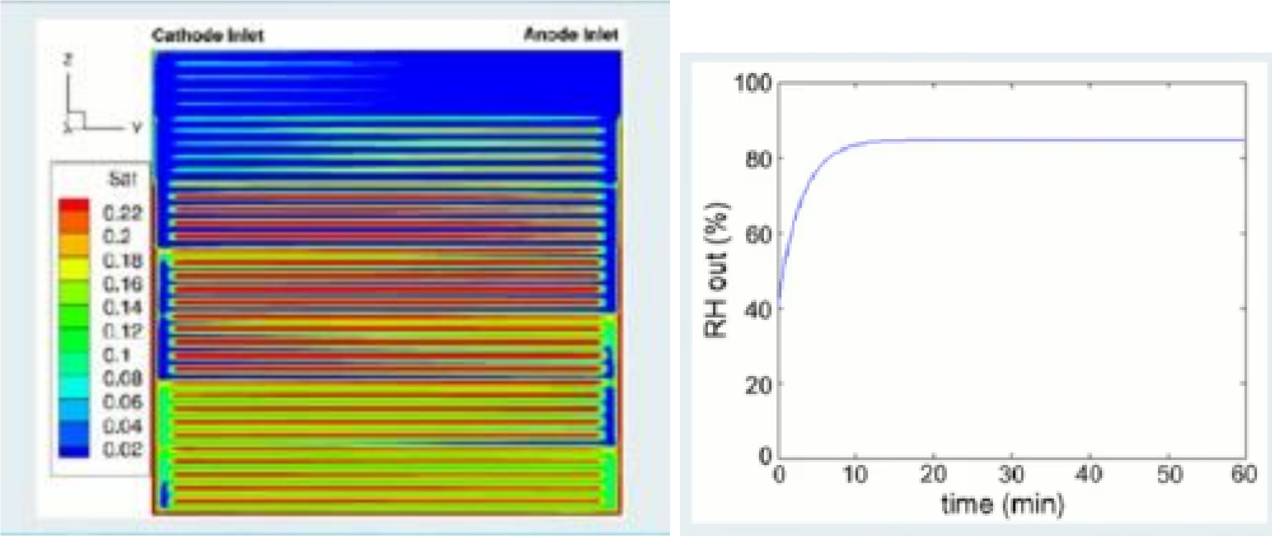
Sizes

- Water concentration: 0.001 to 0.2 mol / m^3

Setting

- Thickness 150 - 400 μm

But we make membranes thinner and thinner as we can improve their existence in order to reduce losses by Joule effect



Distributions (liquid saturation) **Dynamic**

Fig. 31:Fluidic quantities (Distributions & dynamics) variations in the membrane

20.11.2 Thermal quantities

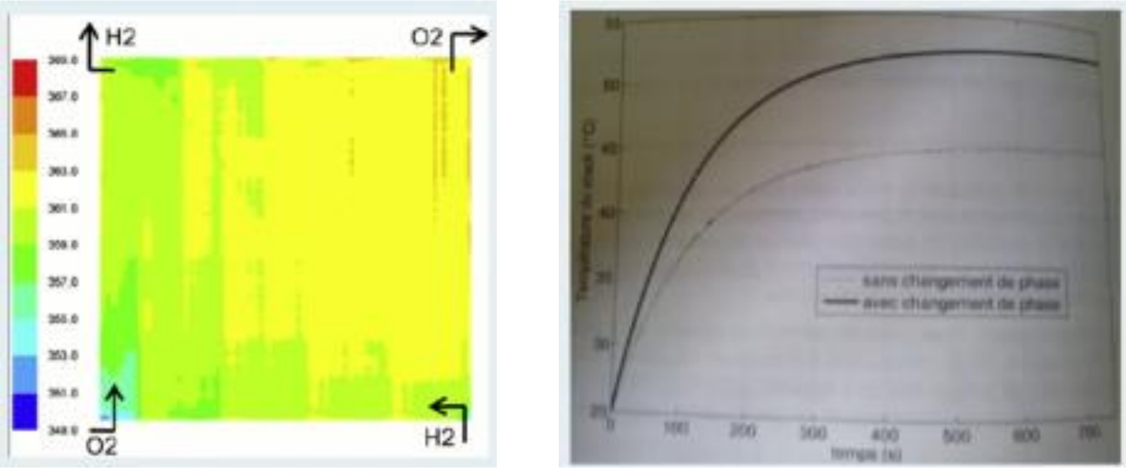
20.11.2.1 In the electrode

Size

- Temperature: from 290 to 333 K (from 20˚C to 60˚C)

Settings

- Thermal conduction 175 W/K
- Thermal capacity 24 J/K
- In a commercial pile such as the harness ball that it takes 1 sec to cancel 7 K with cooling system



Distributions ***Dynamic***

Fig. 32: Thermal quantities (Distributions & dynamics) variations in the electrode

20.11.2.2 In the GDL membrane / catalytic layer assembly

Size

- Temperature

Settings

- Thermal capacity 4 J/k
- Conduction 11 w/k
- 0.3 sec/k for temperature stabilization

20.11.3 Electric dynamic

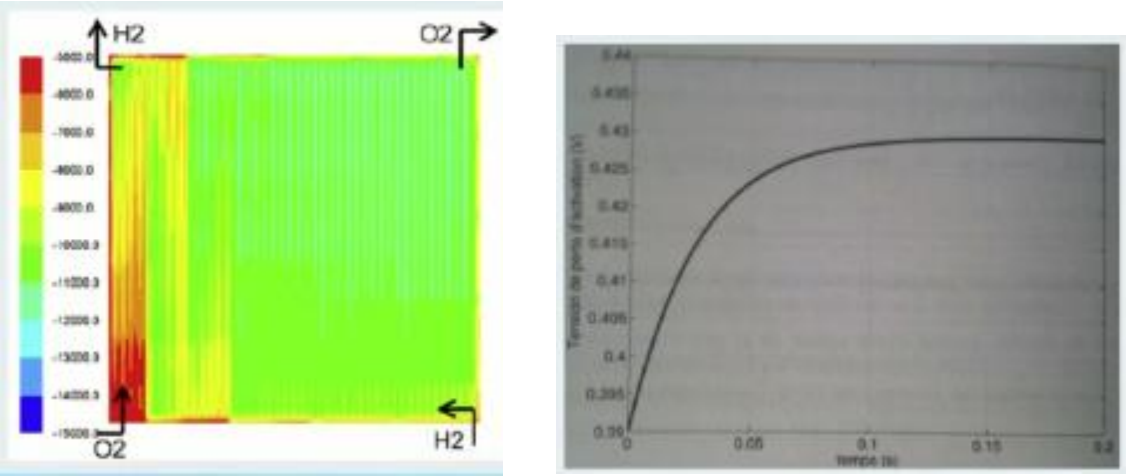
20.11.3.1 In the channels and the diffusion layer

Sizes

- Current: 0 - 50 A
- Voltage of a cell: 0.5 - 1.3 V

Setting

- Resistance of a cell: 15 µΩ



Distributions ***Dynamic***

Fig. 33: Electric dynamic (Distributions & dynamics) variations in the channel & the diffusion layer

20.11.3.2 In the catalytic layer

Sizes

- Voltage of one cell 0.5 - 1.3 v
- Current 0 - 50 A

Setting

- Double layer capacitance 2 - 3 F

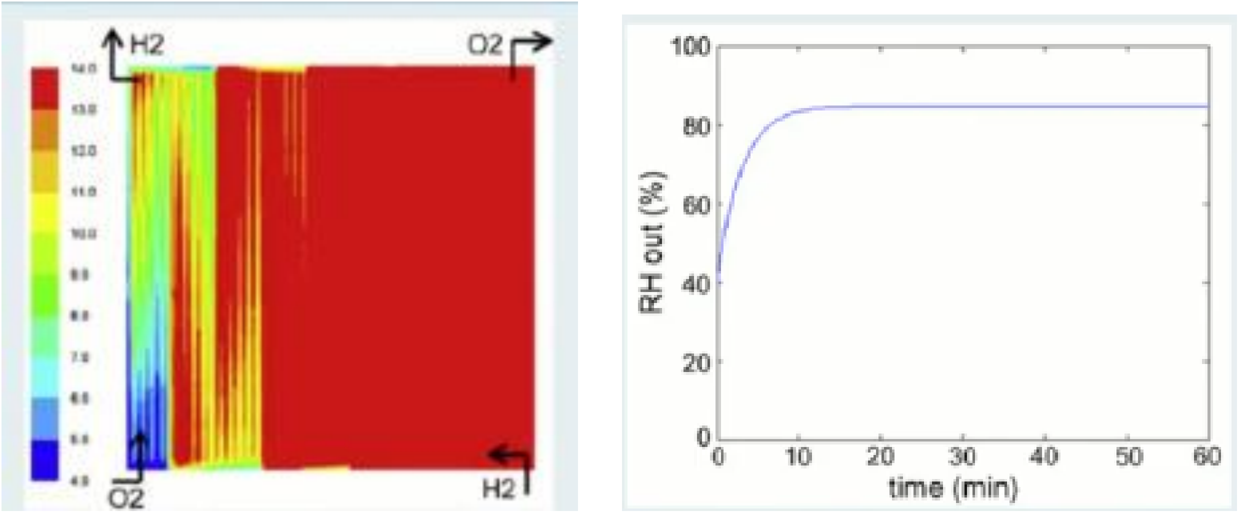
20.11.3.3 In the membrane

Sizes

- Voltage 0.5 - 1.3 v
- Current 0 - 50 A

Setting

- Resistance 0.25 – 3 Ω



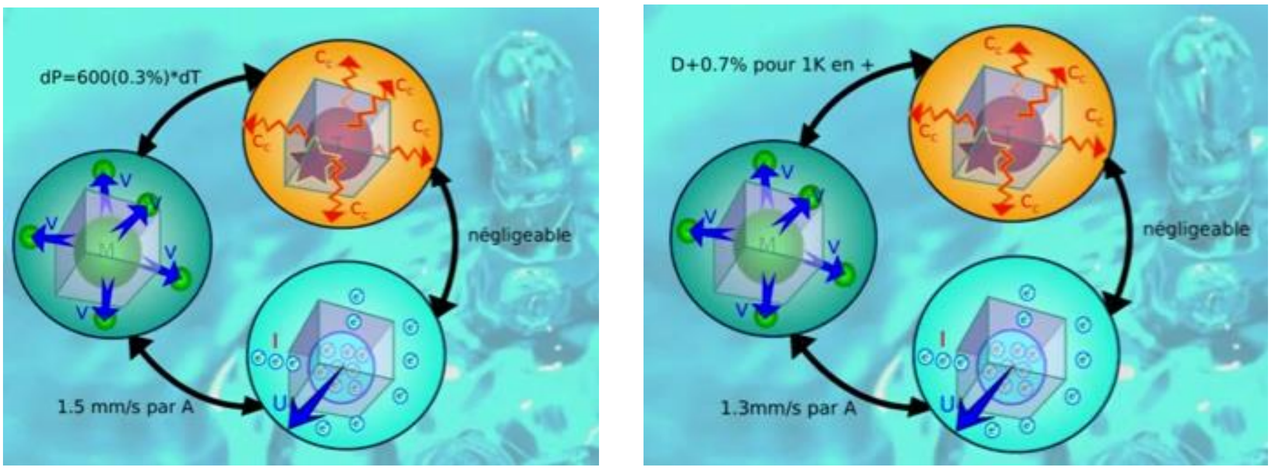
Distributions* (water content)** ***Dynamic

Fig. 34: Electric dynamic (Distributions & dynamics) variations in the membrane

20.12 Parametric influence

20.12.1 In the canals

A change in pressure has very little influence on heat and vice versa, and the device has relatively little input between heat and electric current and between electric current and movement. on the other hand, one can have an acceleration of 1.5 mm/sec per additional year pair in a conventional pile. Same in the diffusion layer.



Same in the diffusion layer ***In the diffusion layer***

Fig. 35: Parametric influence in the canal

20.12.1.1 In the catalytic layer

In the catalytic layer, 30% variation in attention for 100% variation in temperature so we still had an influence which can be significant between the temperature and the voltage which is linked to the losses. function the temperature we have not the same allowed the same result with the berne law is not to mention the effect of the temperature under the fuel cell the voltage little increased by 25% for an oxygen concentration 10% higher therefore also for strong currents. if we have an agreement between the oxygen concentration which decreases we have a significant loss of tension a temperature increase of 10 degrees in the membrane can multiply its electrical resistance by 3 and the influence of water it is also very important therefore we can divide by three the resistance for a concentration of other two times higher and when we have 75% we can still reduce the resistance by 30% so water is very important in the limbs there.

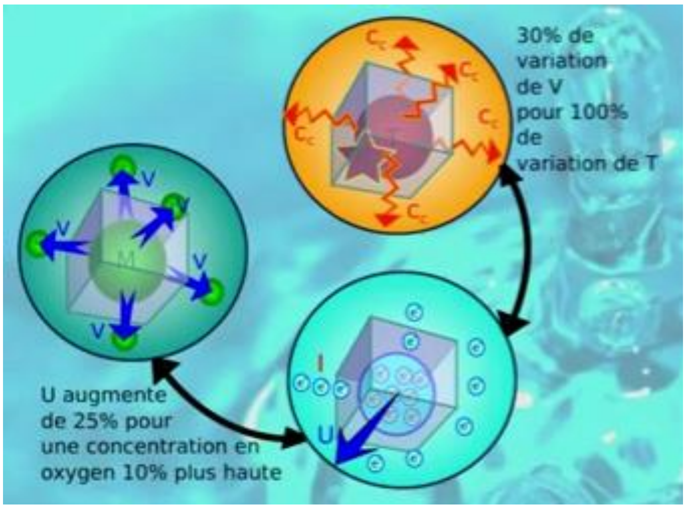


Fig. 36: Parametric influence in the catalytic layer

20.12.2 In the membrane

An increase in temperature of 10 degrees in the membrane can multiply its electrical resistance by three and the influence of water is also very important so we can divide by three the resistance for a concentration of other two times higher and when we at 75% we can further reduce the resistance by 30% so water is very important in the membrane there.

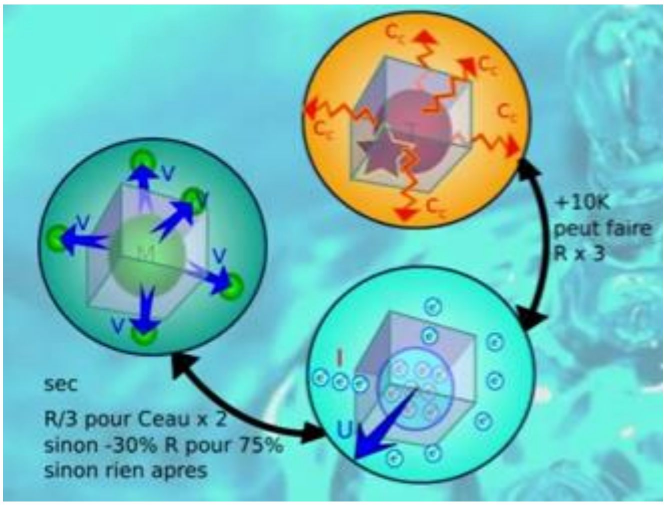
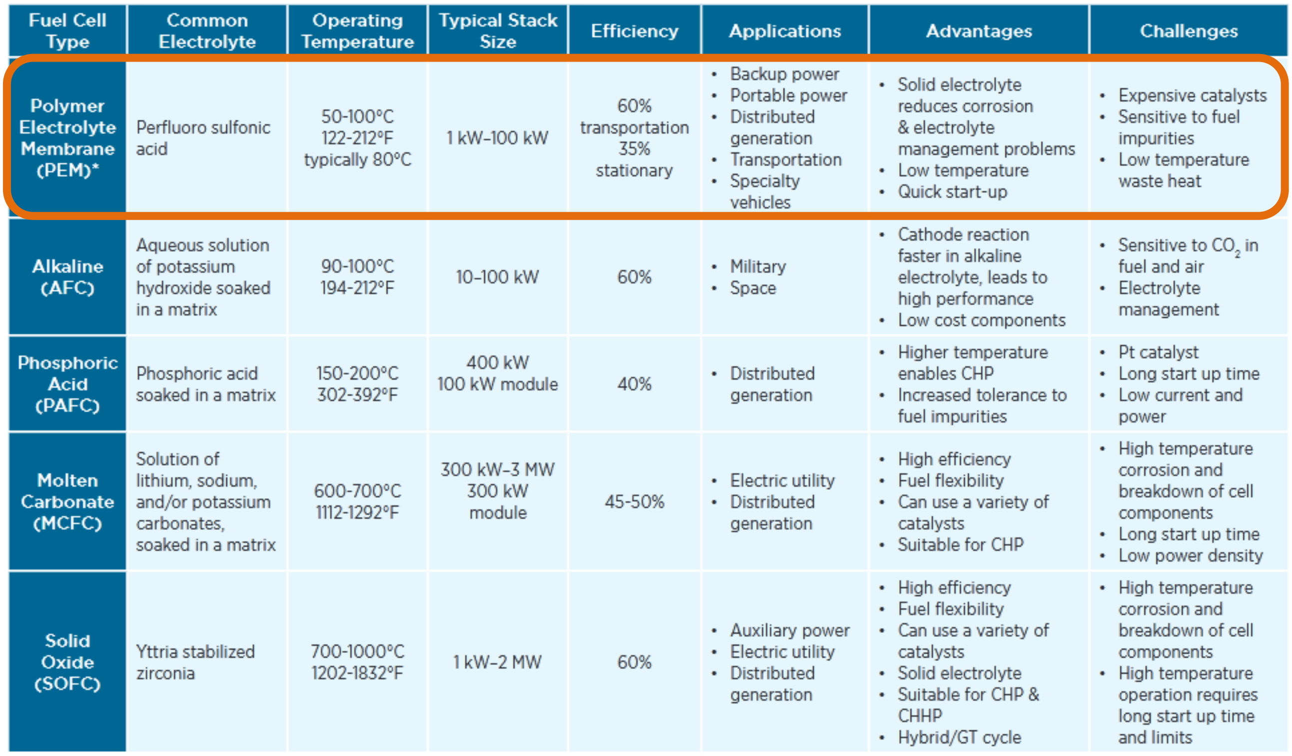


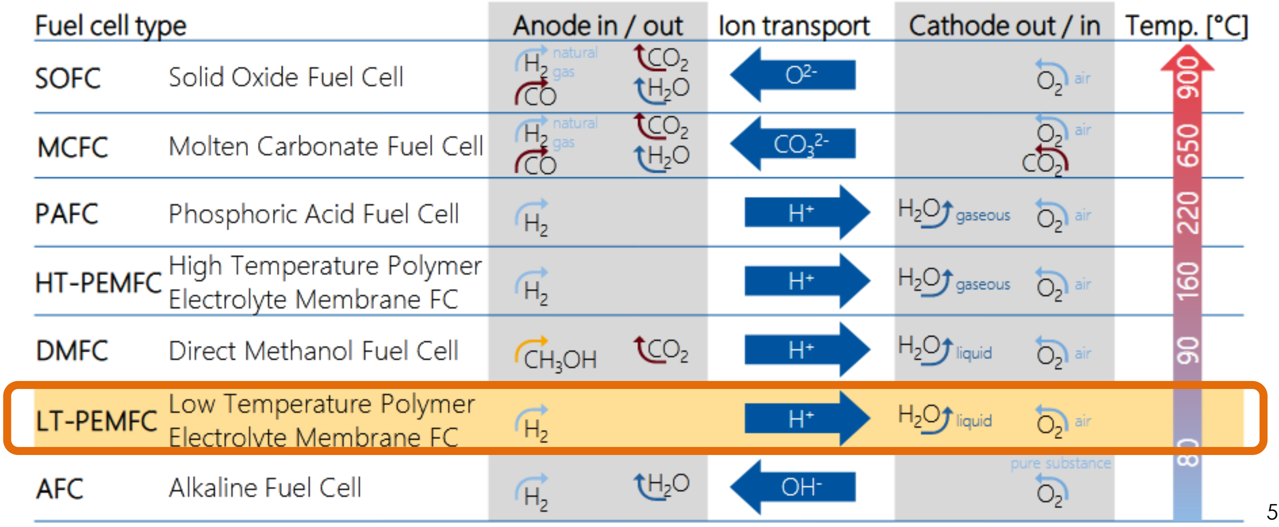
Fig. 37: Parametric influence in the membrane

20.13 Comparison of Fuel Cell technologies [58]



Fuel Cell Type	Common Electrolyte	Operating Temperature	Typical Stack Size	Efficiency	Applications	Advantages	Challenges
Polymer Electrolyte Membrane (PEM)*	Perfluoro sulfonic acid	50-100°C 122-212°F typically 80°C	1 kW–100 kW	60% transportation 35% stationary	• Backup power • Portable power • Distributed generation • Transportation • Specialty vehicles	• Solid electrolyte reduces corrosion & electrolyte management problems • Low temperature • Quick start-up	• Expensive catalysts • Sensitive to fuel impurities • Low temperature waste heat
Alkaline (AFC)	Aqueous solution of potassium hydroxide soaked in a matrix	90-100°C 194-212°F	10–100 kW	60%	• Military • Space	• Cathode reaction faster in alkaline electrolyte, leads to high performance • Low cost components	• Sensitive to CO_2 in fuel and air • Electrolyte management
Phosphoric Acid (PAFC)	Phosphoric acid soaked in a matrix	150-200°C 302-392°F	400 kW 100 kW module	40%	• Distributed generation	• Higher temperature enables CHP • Increased tolerance to fuel impurities	• Pt catalyst • Long start up time • Low current and power
Molten Carbonate (MCFC)	Solution of lithium, sodium, and/or potassium carbonates, soaked in a matrix	600-700°C 1112-1292°F	300 kW–3 MW 300 kW module	45-50%	• Electric utility • Distributed generation	• High efficiency • Fuel flexibility • Can use a variety of catalysts • Suitable for CHP	• High temperature corrosion and breakdown of cell components • Long start up time • Low power density
Solid Oxide (SOFC)	Yttria stabilized zirconia	700-1000°C 1202-1832°F	1 kW–2 MW	60%	• Auxiliary power • Electric utility • Distributed generation	• High efficiency • Fuel flexibility • Can use a variety of catalysts • Solid electrolyte • Suitable for CHP & CHHP • Hybrid/GT cycle	• High temperature corrosion and breakdown of cell components • High temperature operation requires long start up time and limits

Fig. 38: Comparison of Fuel Cell technologies



Fuel cell type		Anode in / out		Ion transport	Cathode out / in		Temp. [°C]
SOFC	Solid Oxide Fuel Cell	H_2 natural gas CO	CO_2 H_2O	O^{2-}		O_2 air	900
MCFC	Molten Carbonate Fuel Cell	H_2 natural gas CO	CO_2 H_2O	CO_3^{2-}		O_2 air CO_2	650
PAFC	Phosphoric Acid Fuel Cell	H_2		H^+	H_2O gaseous	O_2 air	220
HT-PEMFC	High Temperature Polymer Electrolyte Membrane FC	H_2		H^+	H_2O gaseous	O_2 air	160
DMFC	Direct Methanol Fuel Cell	CH_3OH	CO_2	H^+	H_2O liquid	O_2 air	90
LT-PEMFC	Low Temperature Polymer Electrolyte Membrane FC	H_2		H^+	H_2O liquid	O_2 air	80
AFC	Alkaline Fuel Cell	H_2	H_2O	OH^-		pure substance O_2	

[59]

Fig. 39: Comparison of Fuel Cell type

20.14 Production process of PEM fuel cell components

- Due to the small production volumes of fuel cells, there is currently no generally valid process chain for the series production of PEM fuel cell

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[58] https://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/fct_h2_fuelcell_factsheet.pdf

[59] https://bz.vdma.org/documents/266669/49673320/FuelCellProductionBrochures_FuelCellComponents_Edition1_online_en_PEM_v07_scn_1606398023504.pdf/35fca3ae-b8e5-37e6-a685-d2dcae8a3d15

components.

- Production of a PEM fuel cell system can be divided into three superordinate steps: component production, stack production and system production.
- This brochure presents the process steps that constitute the current state ofthe art in the production of PEM fuel cell components.
- Production of the fuel cell stack and system is explained in more detail in a separate brochure entitled "Production of Fuel Cell Systems".

Component Production:

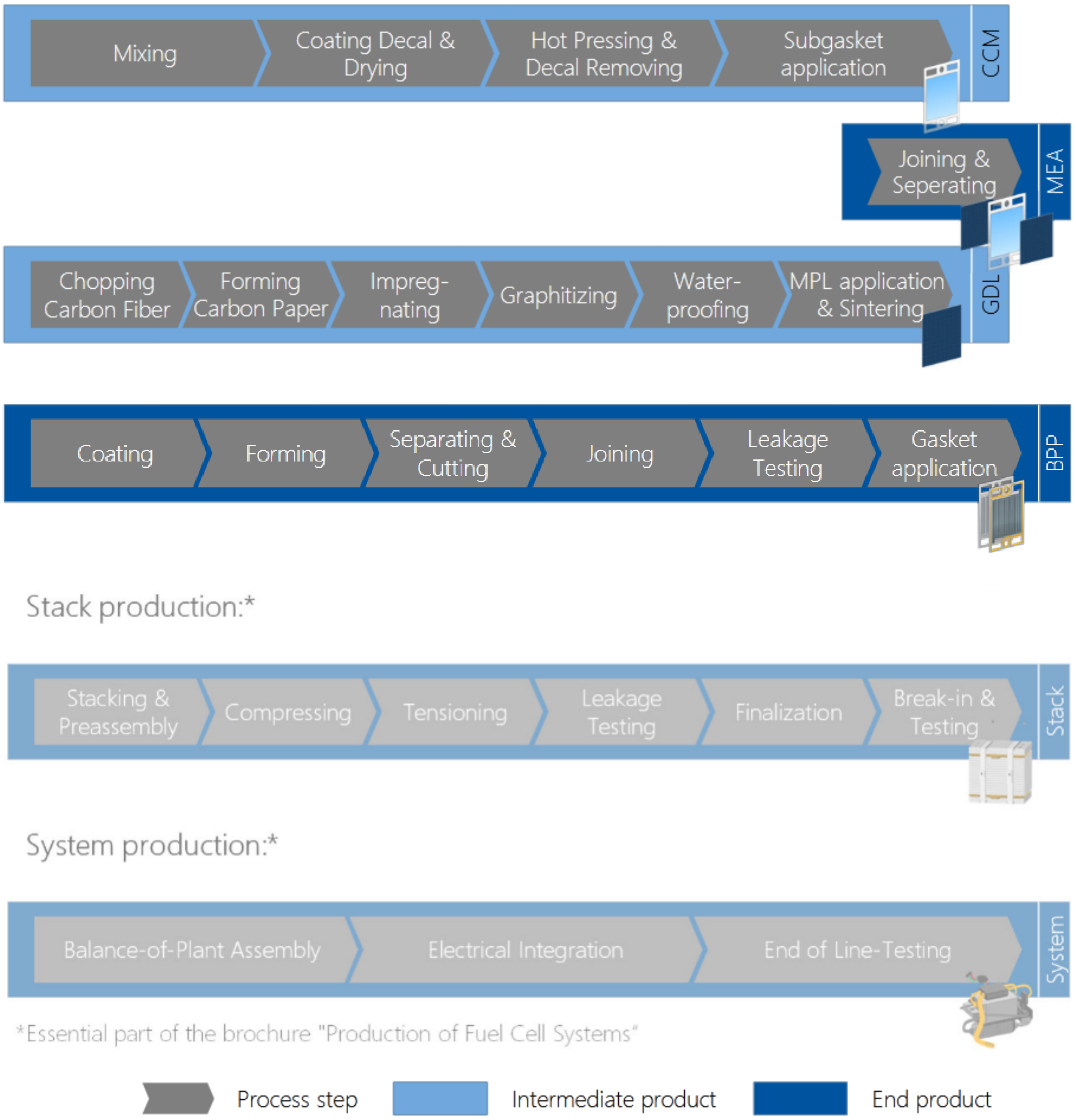


Fig. 40: Production process of PEM fuel cell components

20.15 Overview of PEM fuel cell components

Catalyst coated membrane

- The polymer membrane coated with platinum catalyst is called a catalyst coated membrane (CCM).
- There is one catalyst layer each on the anode and cathode side. The layers differ in their chemical composition and thickness.
- Hydrogen ion transport takes place via the CCM, the catalyst layers enable oxidation or reduction.

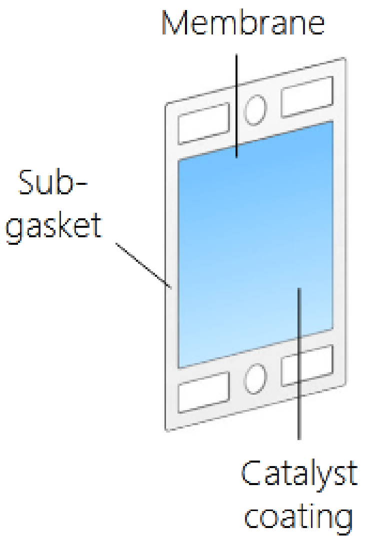


Fig. 41: Overview of catalyst coated membrane

Gas diffusion layer

- The gas diffusion layer (GDL) consists of carbon paper or nonwoven and has a significant influence on the efficiency of the fuel cell.
- The GDL enables a uniform distribution of the reaction media on the catalyst layers of the anode and cathode side.
- The microporous layer (MPL) improves the regulation of the water balance at the electrodes.

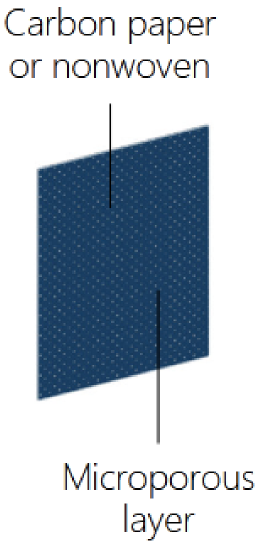
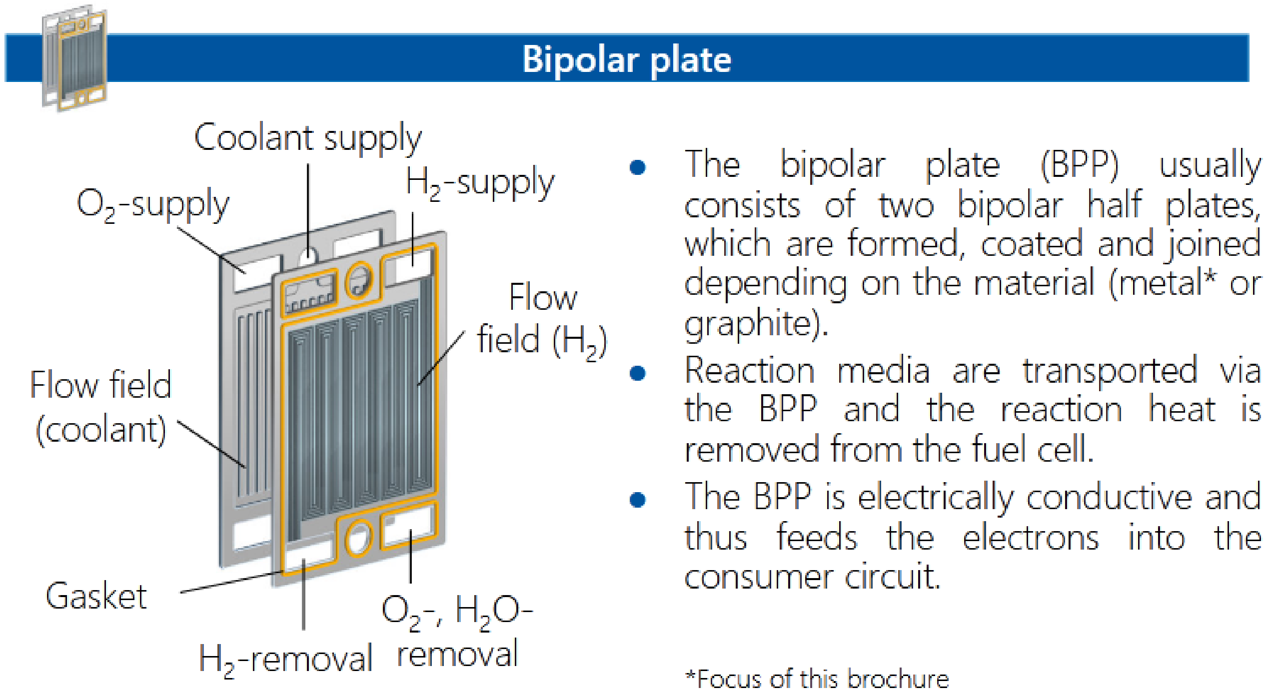


Fig. 42: Overview of Gas diffusion layer (GDL)



Bipolar plate

- The bipolar plate (BPP) usually consists of two bipolar half plates, which are formed, coated and joined depending on the material (metal* or graphite).
- Reaction media are transported via the BPP and the reaction heat is removed from the fuel cell.
- The BPP is electrically conductive and thus feeds the electrons into the consumer circuit.

*Focus of this brochure

Fig. 43: Overview of bipolar plate

20.16 Thermal Engineering Performance Evaluation of a Polymer Electrolyte Membrane Fuel Cell Stack at Partial Load [60]

20.16.1 Thermal Engineering Analysis

Stack heat generation is a theoretical heat quantity based on the conversion efficiency of the fuel cells. The theoretical maximum voltage for a single cell based on the Higher Heating Value of hydrogen is 1.482 V when the products are all in liquid state. The stack for this work has a design rating of 45% efficiency at full load, and the theoretical heat generation for the stack can be estimated using Equation (6).

$$Q_{th} = 1.482\ (1-\eta_{cell})I.n_{cell} \quad \textbf{(6)}$$

In equation (6), I represent the stack current in Ampere (A) and n_{cell} is the number of cells of the stack.

Equations 7 to 19 are applied accordingly for the analysis where the scope covers the relation of stack thermal conditions to output power, active-to-passive cooling contributions, and cooling system effectiveness.

The electrical power output in Watts,

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[60] file:///C:/Users/admin/AppData/Local/Temp/ThermalEngineeringPerfEvaluationofaPEMFCstackatpartialload.pdf

$$P_{el} = V \times I \qquad (7)$$

For a single cell, the cell efficiency

$$\eta_{cell} = \frac{V_{cell}}{V_{\max}} = \frac{V_{cell}}{1.482} \qquad (8)$$

Thus, the stack efficiency was evaluated using

$$\eta_{stack} = \frac{V_{stack,measured}}{V_{stack,rated}} = \frac{V_{stack,measured}}{48V} \qquad (9)$$

The cooling mechanism of the fuel cell stack is categorized as active cooling and passive cooling. Active cooling is achieved by circulating cooling water internally and using an air-cooled heat exchanger (radiator) to dissipate the heat to the surrounding. Active cooling theoretically contributes at least 90% [12] of the total cooling effect. Passive cooling plays only a minor role, but the effects are more significant as the stack temperature increases.

The calculation of active cooling rate is based on the energy property changes of the cooling water as it carries away the heat from the fuel cell stack.

Cooling water energy changes,

$$\dot{Q}_{cw} = \dot{m}_{cw} . C_{p,cw} . \left(T_{cw,e} - T_{cw,i}\right) \qquad (10)$$

Air energy changes,

$$\dot{Q}_{a} = \dot{m}_{a} . C_{p,a} . \left(T_{a,e} - T_{a,i}\right) \qquad (11)$$

The subscripts cw and a are for cooling water and air respectively, while subscripts e is for the exit state and i for the inlet state. The net heat in the stack related to the temperature difference over a certain time period,

$$\dot{Q}_{stack} = \frac{m_{stack} . C_{stack} . \Delta T_{stack}}{\Delta t} \qquad (12)$$

Passive cooling over the exposed stack surfaces consists of free (natural) convection by the ambient surroundings as well as heat transfer by radiation. The free convection cooling effect is based on

$$Q_{nc} = h . A_{surface} \left(T_{surface} - T_{ambient}\right) \qquad (13)$$

In this case, the surface areas involved are two vertical flat side surfaces, two vertical flat end surfaces, and one horizontal surface with heated surface facing upward. The Nusselt number correlations were calculated for each orientation and the respective free convection coefficient, h, and surface cooling is calculated.

Cooling by radiation heat transfer is expressed by

$$Q_{r} = \varepsilon . \sum A_{s} . \sigma . \left(T_{s}^{4} - T_{ambient}^{4}\right) \qquad (14)$$

σ is the Stefan-Boltzmann constant, equals to 5.67 x 10-8, and ε is the surface emissivity.

Thus, the passive cooling rate is the summation of free convection and radiative cooling over the stack surfaces,

$$Q_{passive} = \Sigma\, Q_{nc} + Q_r \qquad \textbf{(15)}$$

The total cooling effect is the summation of active and passive cooling rates.

$$\Sigma\, Q_{cooling} = Q_{active} + Q_{passive} \qquad \textbf{(16)}$$

From equations (7) and (11), the total stack thermal power can be calculated.

$$P_{th} = Q_{stack} + \Sigma\, Q_{cooling} \qquad \textbf{(17)}$$

For the radiator, the analysis on the radiator effectiveness is evaluated by,

$$\varepsilon = \frac{\dot{Q}_{actual}}{\dot{Q}_{\max}} \qquad \textbf{(18)}$$

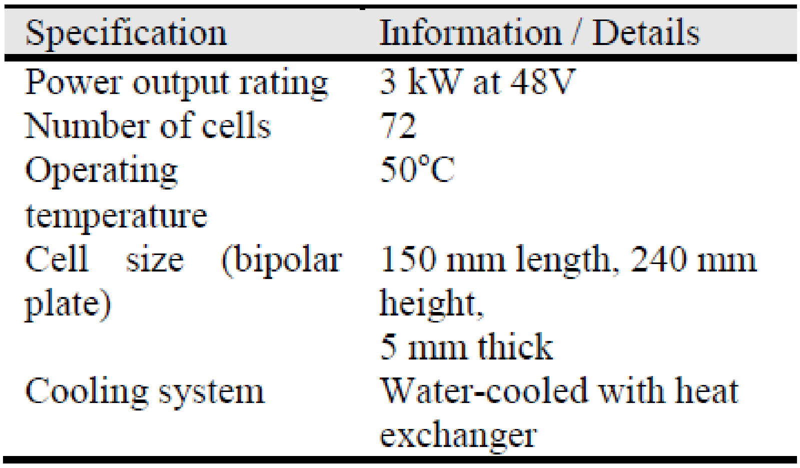
The maximum possible cooling rate in a heat exchanger is

$$\dot{Q}_{\max} = C_{\min}(T_{hot,in} - T_{cold,in}) \qquad \textbf{(19)}$$

where C_{min} is the smaller of $C_h = \dot{m}_h\, C_{p,h}$ and $C_c = \dot{m}_c\, C_{p,c}$.

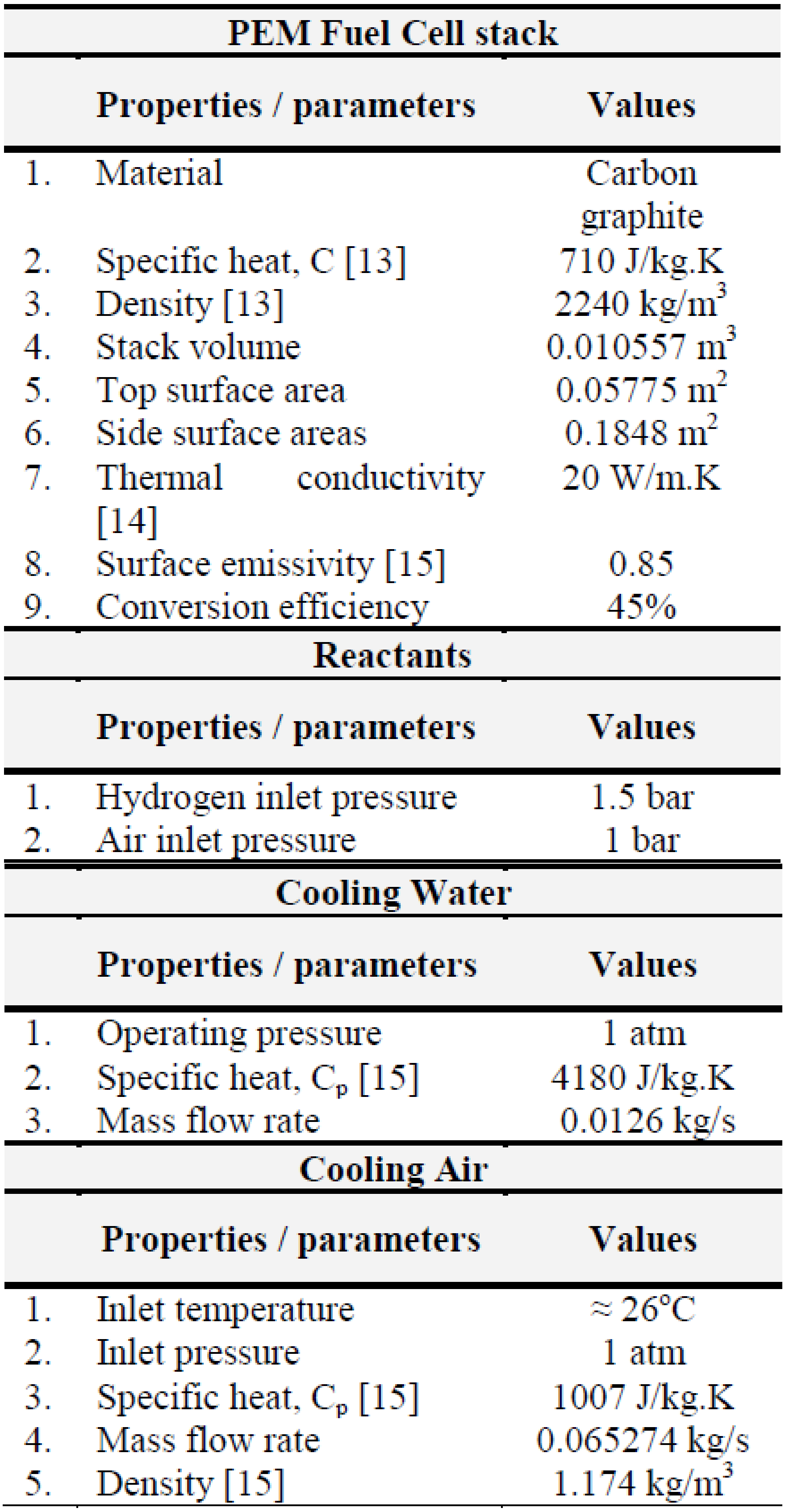
20.16.2 Experimental Method

The experiment was conducted using a PEM fuel cell system designed for Uninterrupted Power Supply (UPS). The system configuration and general specifications of the hardware are presented in Figure 44 & 45 respectively. The working fluids are hydrogen, reactant air, cooling water and cooling air. Figure 46 summarizes the operating conditions of the experimental. The measurements were taken at 3 minutes intervals using a thermal scanner and K-type thermocouples with data logger for local temperatures at 18 designated points of the stack, anemometer for air velocity and temperature, and a multi-meter for electrical power measurement at the resistant loader.



Specification	Information / Details
Power output rating	3 kW at 48V
Number of cells	72
Operating temperature	50°C
Cell size (bipolar plate)	150 mm length, 240 mm height, 5 mm thick
Cooling system	Water-cooled with heat exchanger

Fig. 44: PEM fuel cell system specifications



PEM Fuel Cell stack

	Properties / parameters	Values
1.	Material	Carbon graphite
2.	Specific heat, C [13]	710 J/kg.K
3.	Density [13]	2240 kg/m^3
4.	Stack volume	0.010557 m^3
5.	Top surface area	0.05775 m^2
6.	Side surface areas	0.1848 m^2
7.	Thermal conductivity [14]	20 W/m.K
8.	Surface emissivity [15]	0.85
9.	Conversion efficiency	45%

Reactants

	Properties / parameters	Values
1.	Hydrogen inlet pressure	1.5 bar
2.	Air inlet pressure	1 bar

Cooling Water

	Properties / parameters	Values
1.	Operating pressure	1 atm
2.	Specific heat, C_p [15]	4180 J/kg.K
3.	Mass flow rate	0.0126 kg/s

Cooling Air

	Properties / parameters	Values
1.	Inlet temperature	≈ 26°C
2.	Inlet pressure	1 atm
3.	Specific heat, C_p [15]	1007 J/kg.K
4.	Mass flow rate	0.065274 kg/s
5.	Density [15]	1.174 kg/m^3

Fig. 45: Operating conditions of fuel cell

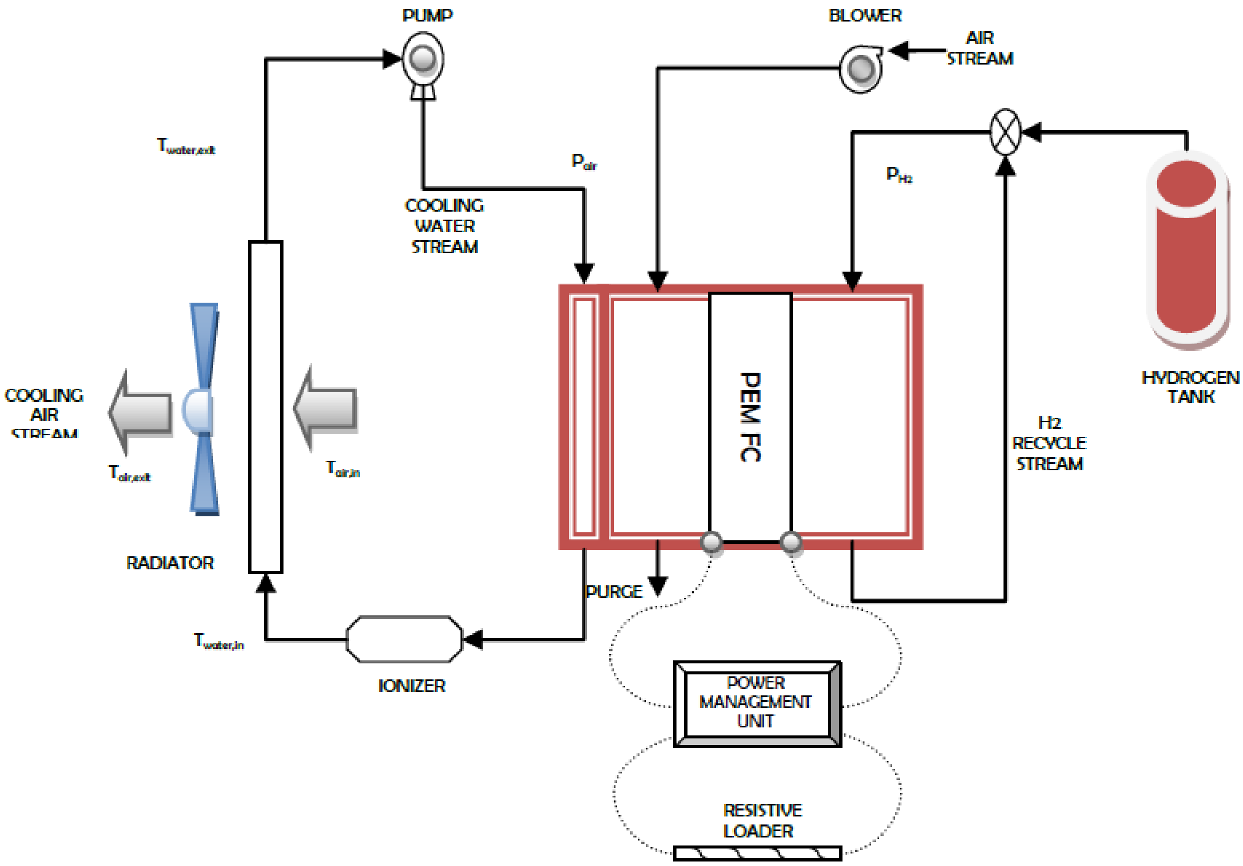


Fig. 46: The fuel cell system schematic

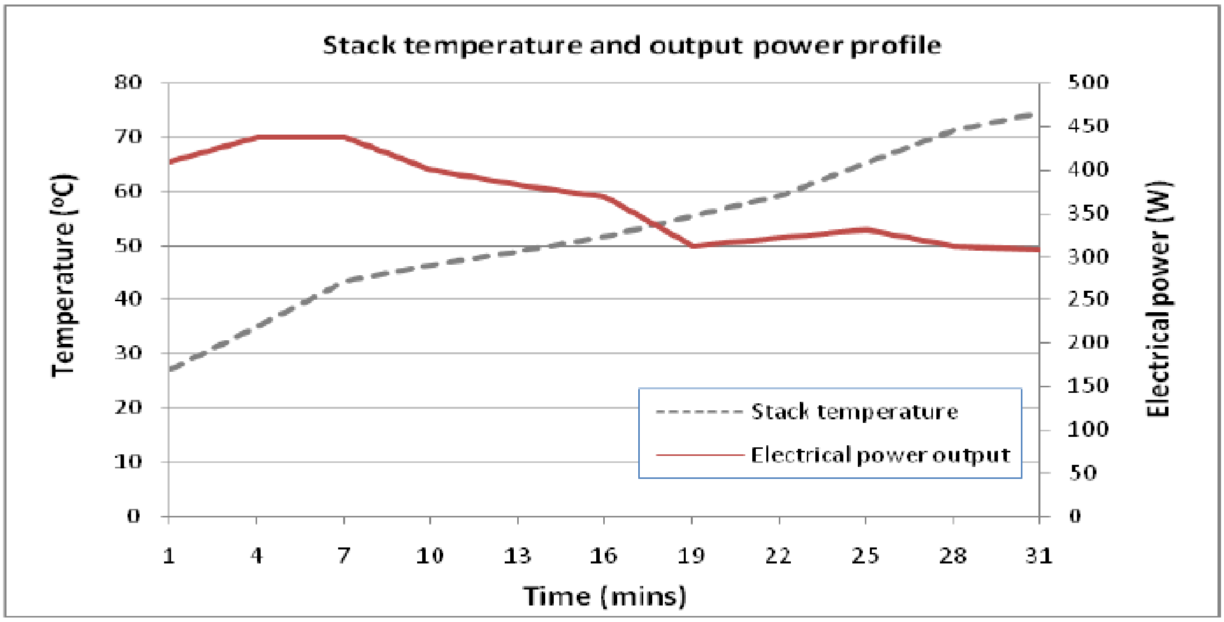


Fig. 47: Relation of stack temperature to electrical power

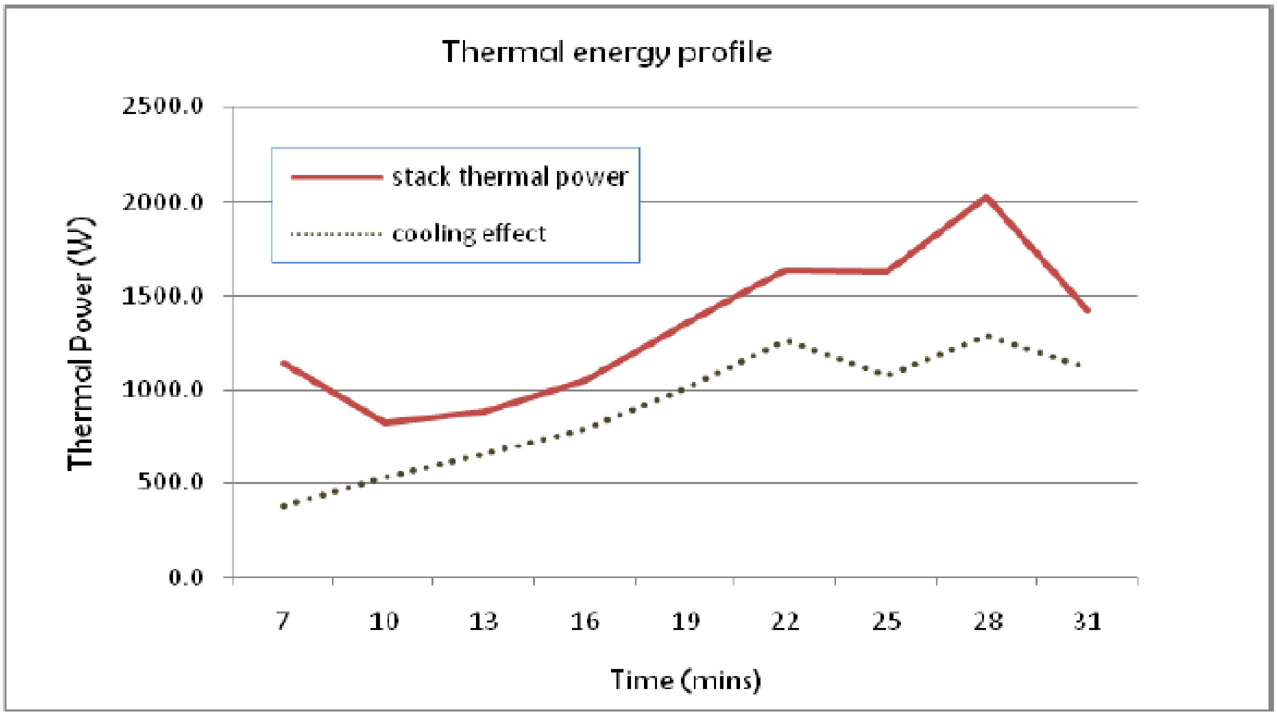


Fig. 48:The total stack thermal energy compared to combined cooling effects

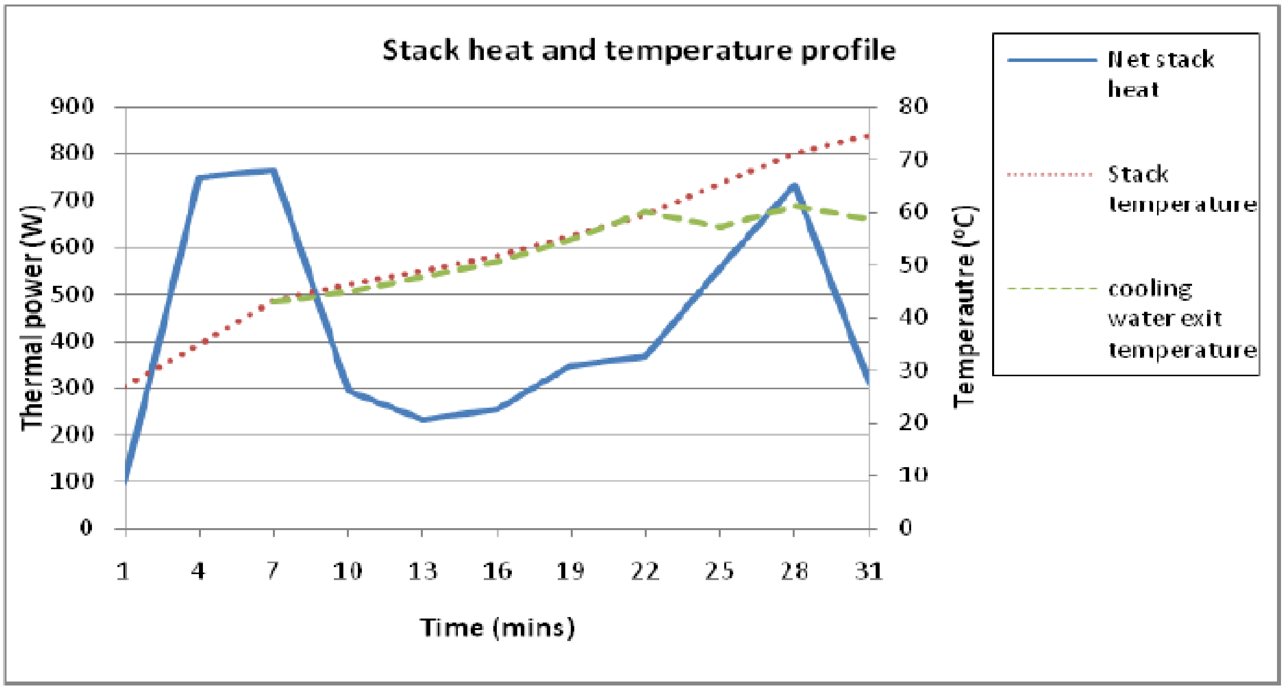


Fig. 49: Relation of stack heat and stack-to-cooling water temperature profile

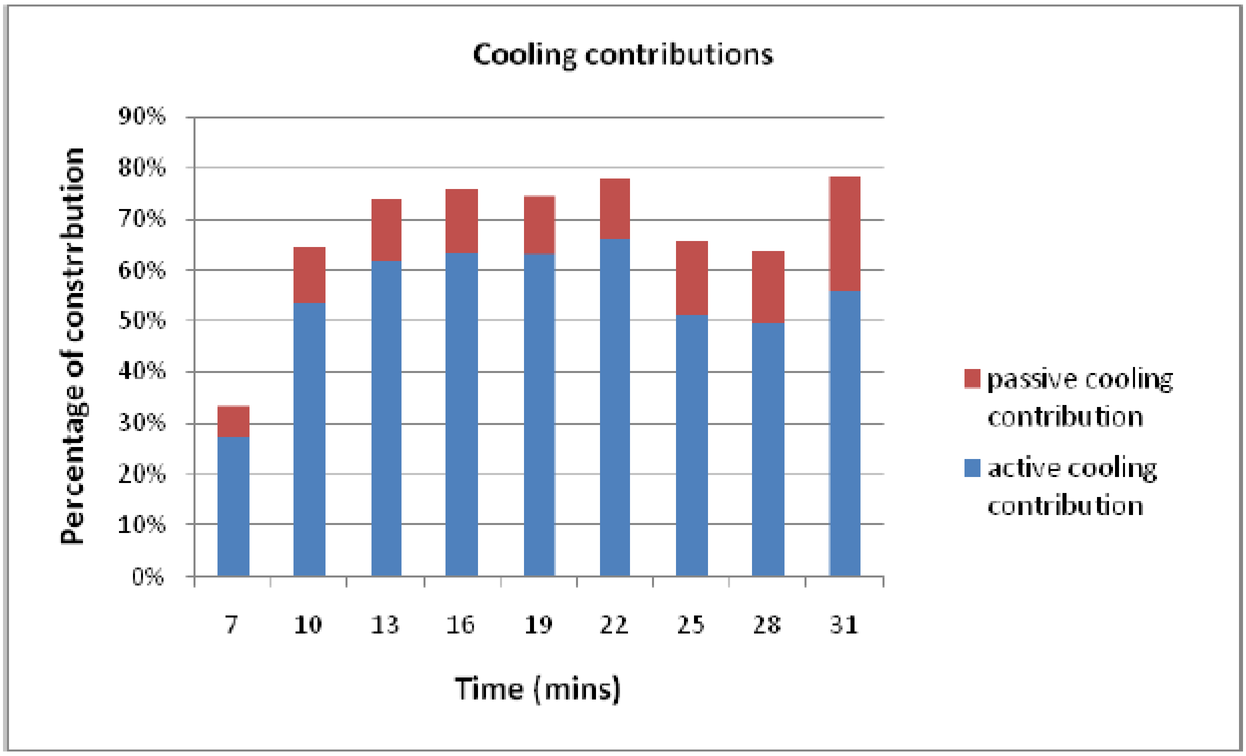


Fig. 50: Active and passive cooling contribution percentages

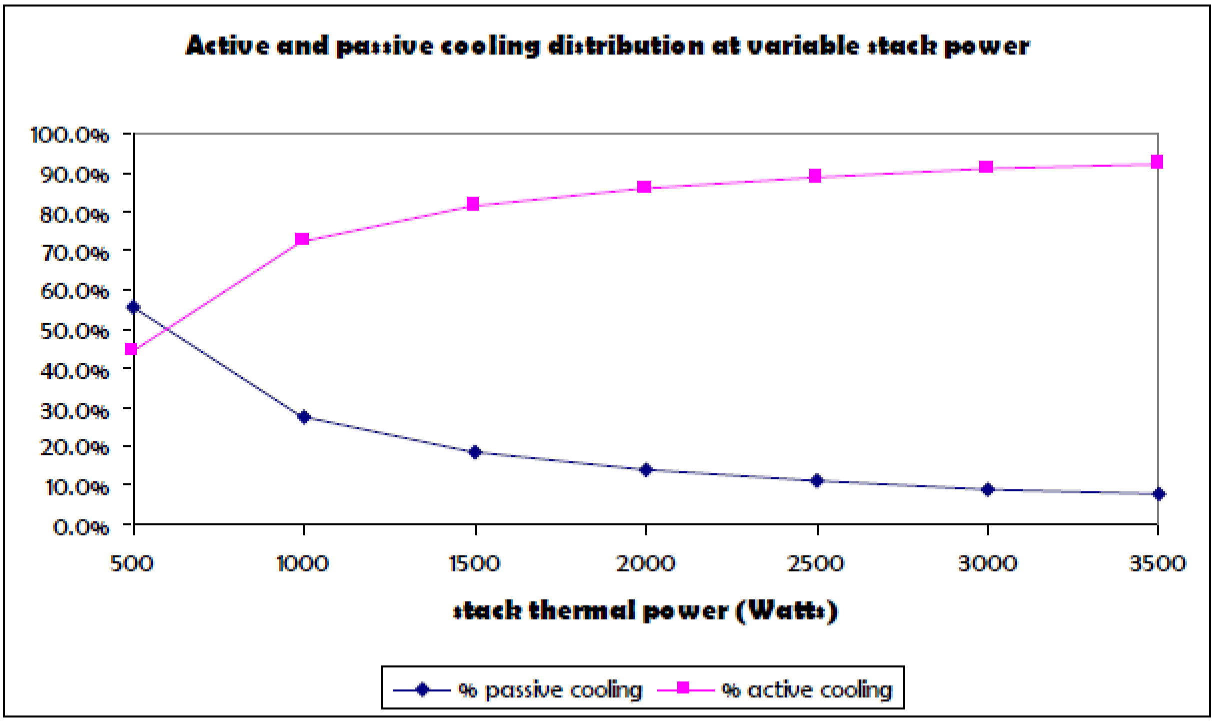


Fig. 51: Theoretical optimum cooling contributions of passive and active cooling

20.16.3 Cooling Performance

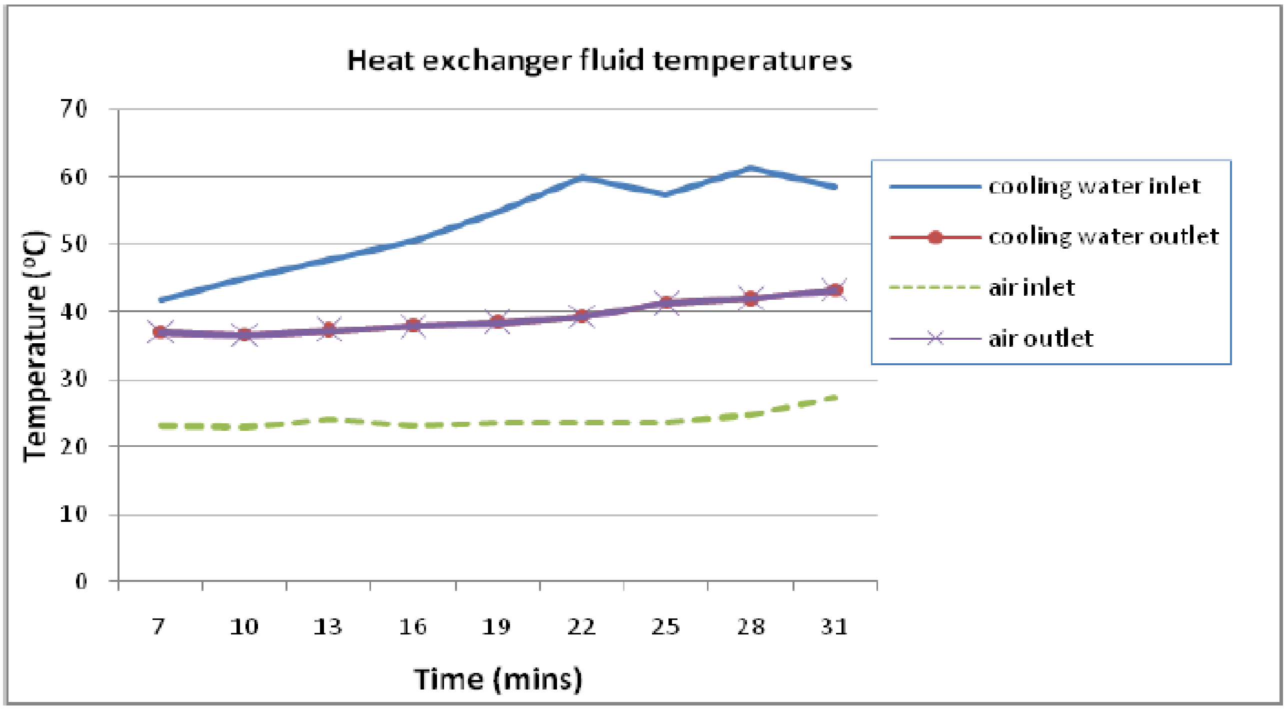


Fig. 52: Temperature profile at heat exchanger

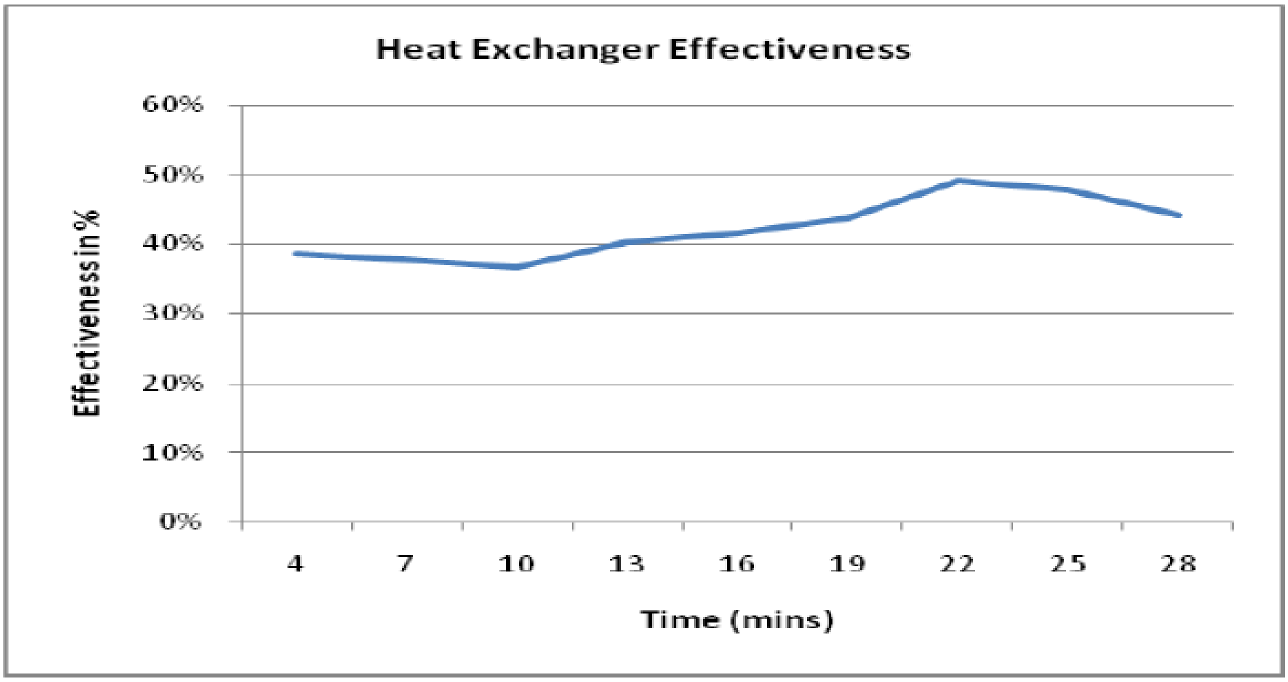


Fig. 53: Effectiveness of the heat exchanger at steady-state

20.16.4 Conclusions

Experimental analysis of a water-cooled PEM fuel cell system shows that the stack temperature can be largely influenced by the coolant. The stack temperature increased to unacceptable levels due to the influence from the cooling water temperature. To maintain the stack at the required operating temperature below 50°C, the generated heat needs to be adequately dissipated by an active cooling system operating higher than 90% cooling effectiveness, and the cooling water temperature at the inlet and outlets of the stack must also be controlled below 40°C at all times. With a registered effectiveness of less than 50%, unsuitable operating conditions of the heat exchanger was identified as the main cause for the thermal problem facing the stack, especially regarding the flow rates of both fluids.

20.17 Consideration for Fuel Cell Design

When you first consider your fuel cell stack design, you will need to calculate the following:

- Stack size
- Number of cells (**MEAs / CCMs**)
- Stack configuration (**flow field plates**, **GDL**, etc.)

This paragraph presents an overview of the initial considerations for fuel cell design in room-temperature fuel cells.

20.17.1 Fuel Cell Stack Size

The first step in engineering a **fuel cell stack** is to obtain the power requirements. The stack is then designed to meet those requirements, and the maximum power, voltage, and current are often known. The power output of a fuel cell stack is a product of stack voltage and current:

$$W_{FC} = V_{st} \cdot I \qquad \textbf{(20)}$$

The maximum power and voltage requirements are dependent upon the application. The engineer must understand these specifications to build an appropriately-sized fuel cell stack. It is helpful to know the current and power density when designing a fuel cell stack. These are often unavailable initially but can be calculated from the desired power output, stack voltage, efficiency, and volume and weight limitations. The current is a product of the current density and the cell active area:

$$I = i * A_{cell} \qquad \textbf{(21)}$$

The cell potential and the current density are related by the polarization curve:

$$V_{cell} = f(i) \qquad \textbf{(22)}$$

An example of a polarization curve is shown in Figure below. The polarization curve can be used to help initially design the fuel cell stack.

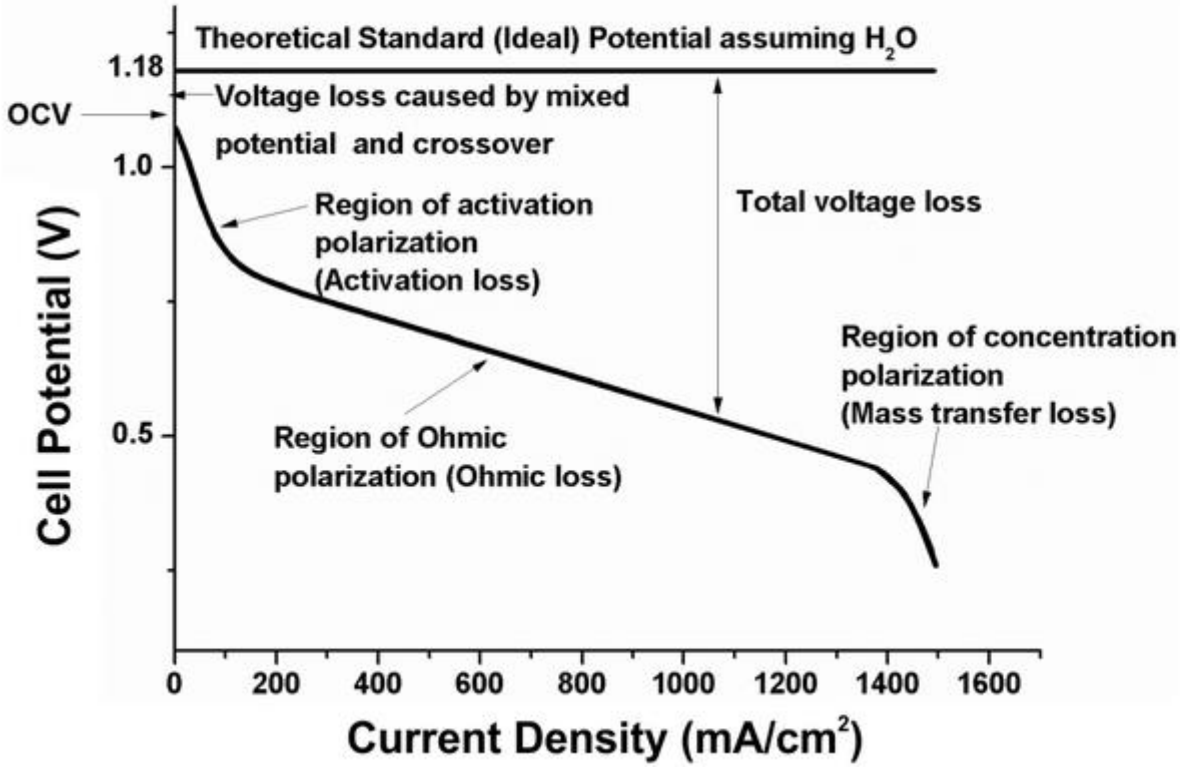


Fig. 54: Typical polarization curve for a PEM fuel cell stack.

Most fuel cell developers use a nominal voltage of 0.6 to 0.7 V at nominal power. Fuel cell systems can be designed at nominal voltages of 0.8 V per cell or higher if the correct design, materials, operating conditions, balance-of-plant, and electronics are selected.

The actual fuel cell performance is determined by the pressure, temperature, and humidity based on the application requirements, and can often be improved (depending upon **fuel cell type**) by increasing the temperature, pressure, and humidity, and optimizing other important fuel cell variables. The ability to increase these variables is application-dependent because system issues, weight, and cost play important factors when optimizing certain parameters.

20.17.2 Number of Cells

The number of cells in the stack is often determined by the maximum voltage requirement and the desired operating voltage. The total stack potential is the sum of the stack voltages or the product of the average cell potential and number of cells in the stack:

$$V_{st} = \sum_{i=1}^{N_{cell}} V_i = \overline{V}_{cell} * N_{cell} \qquad \textbf{(23)}$$

The cell area must be designed to obtain the required current for the stack. When this is multiplied by the total stack voltage, the maximum power requirement for the stack must be obtained. Most fuel cell stacks have the cells connected in series, but stacks can be designed in parallel to increase the total output current. When considering the stack design, it is preferable to not have cells with a small or very large active area because the cells can result in resistive losses. With fuel cells that have large active areas, it can be difficult to achieve uniform temperature, humidity and water management conditions.

The cell voltage and current density is the operating point at nominal power output and can be selected at any point on the polarization curve. The average voltage and corresponding current density selected can have a large impact on stack size and efficiency. A higher cell voltage means better cell efficiency, and this can result from the MEA materials, flow channel design, and optimization of system temperature, heat, humidity, pressure, and reactant flow rates. The fuel cell stack efficiency can be approximated with the following equation:

$$\eta_{stack} = \frac{V_{cell}}{1.482} \qquad (24)$$

20.17.3 Stack Configuration

In the traditional bipolar stack design, the fuel cell stack has many cells stacked together so that the cathode of one cell is connected to the anode of the next cell. The main components of the fuel cell stack are the **membrane electrode assemblies (MEAs)**, **gaskets**, bipolar plates with electrical connections and end plates. The stack is connected by bolts, rods, or other methods to clamp the cells together.

When contemplating the appropriate fuel cell design, the following should be considered:

- Fuel and oxidant should be uniformly distributed through each cell, and across their surface area.
- The temperature must be uniform throughout the stack.
- If designing a fuel cell with a polymer electrolyte, the membrane must not dry out or become flooded with water.
- The resistive losses should be kept to a minimum.
- The stack must be properly sealed to ensure no gas leakage.
- The stack must be sturdy and able to withstand the necessary environments.

The most common fuel cell configuration is shown in Figure 2. Each cell (MEA) is separated by a plate with flow fields on both sides to distribute the fuel and oxidant. The fuel cell stack end plates have only a single-sided flow field. Most fuel cell stacks, regardless of fuel cell type, size and fuels used are of this configuration.

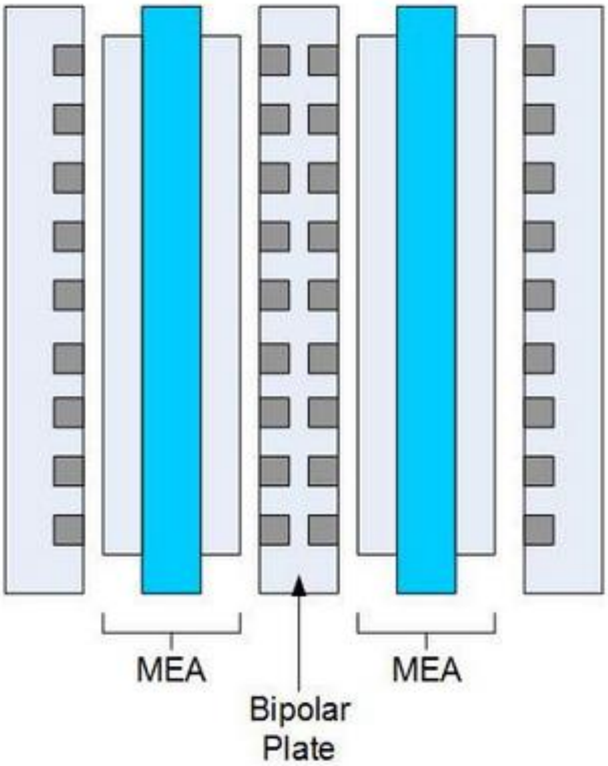
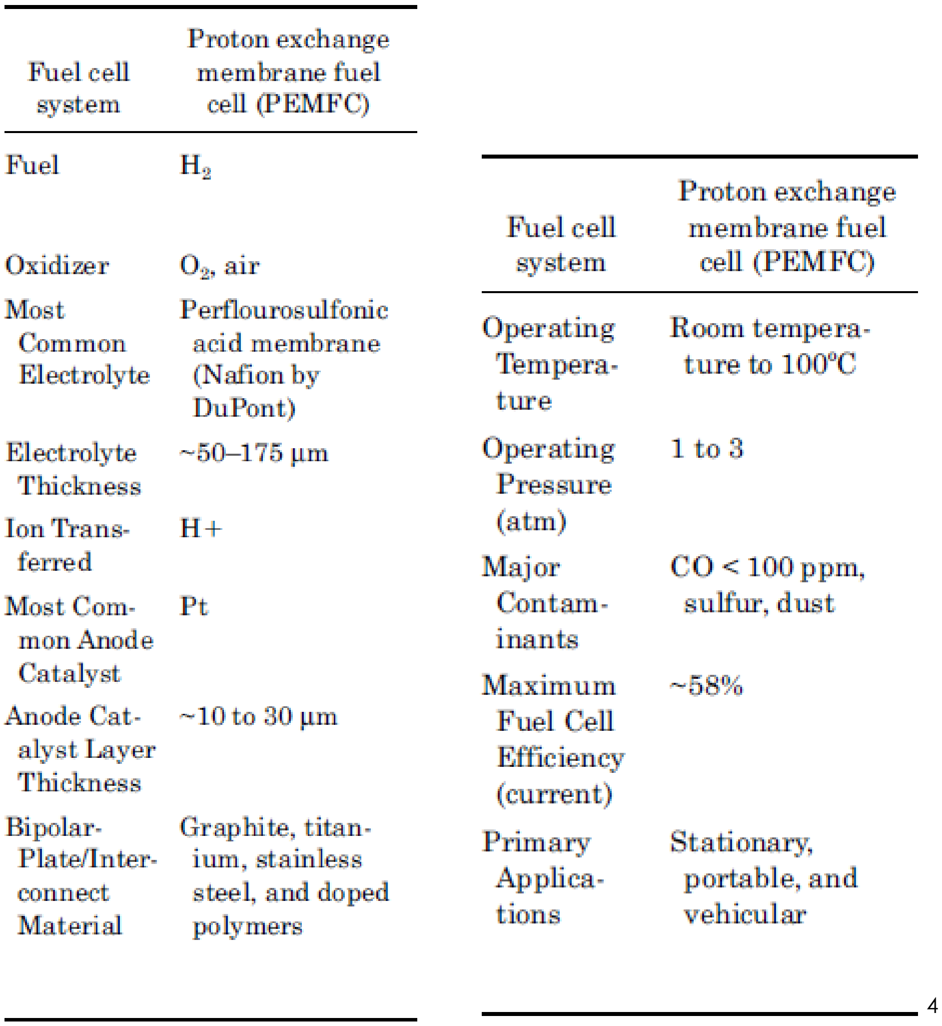


Fig. 55: Typical fuel cell stack configuration (a two-cell stack)

20.18 Polymer Electrolyte Membrane Fuel Cells (PEMFCs)

The polymer electrolyte (also called proton exchange membrane or PEM) fuel cell delivers high-power density while providing low weight, cost, and volume. A PEM fuel cell consists of a negatively charged electrode (anode), a positively charged electrode (cathode), and an electrolyte membrane, as shown in Figure 56. Hydrogen is oxidized on the anode and oxygen is reduced on the cathode. Protons are transported from the anode to the cathode through the electrolyte membrane and the electrons are carried over an external circuit load. On the cathode, oxygen reacts with protons and electrons forming water and producing heat.

In the PEM fuel cell, transport from the fuel flow channels to the electrode takes place through an electrically conductive carbon paper, which covers the electrolyte on both sides. These backing layers typically have a porosity of 0.3 to 0.8 and serve the purpose of transporting the reactants and products to and from the bipolar plates to the reaction site [1]. An electrochemical oxidation reaction at the anode produces electrons that flow through the bipolar plate/cell interconnect to the external circuit, while the ions pass through the electrolyte to the opposing



Fuel cell system	Proton exchange membrane fuel cell (PEMFC)
Fuel	H_2
Oxidizer	O_2, air
Most Common Electrolyte	Perflourosulfonic acid membrane (Nafion by DuPont)
Electrolyte Thickness	~50–175 μm
Ion Transferred	H+
Most Common Anode Catalyst	Pt
Anode Catalyst Layer Thickness	~10 to 30 μm
Bipolar-Plate/Interconnect Material	Graphite, titanium, stainless steel, and doped polymers
Operating Temperature	Room temperature to 100°C
Operating Pressure (atm)	1 to 3
Major Contaminants	CO < 100 ppm, sulfur, dust
Maximum Fuel Cell Efficiency (current)	~58%
Primary Applications	Stationary, portable, and vehicular

[4]

Fig. 56: Physical characters of proton exchange membrane fuel cell (PEMFC)

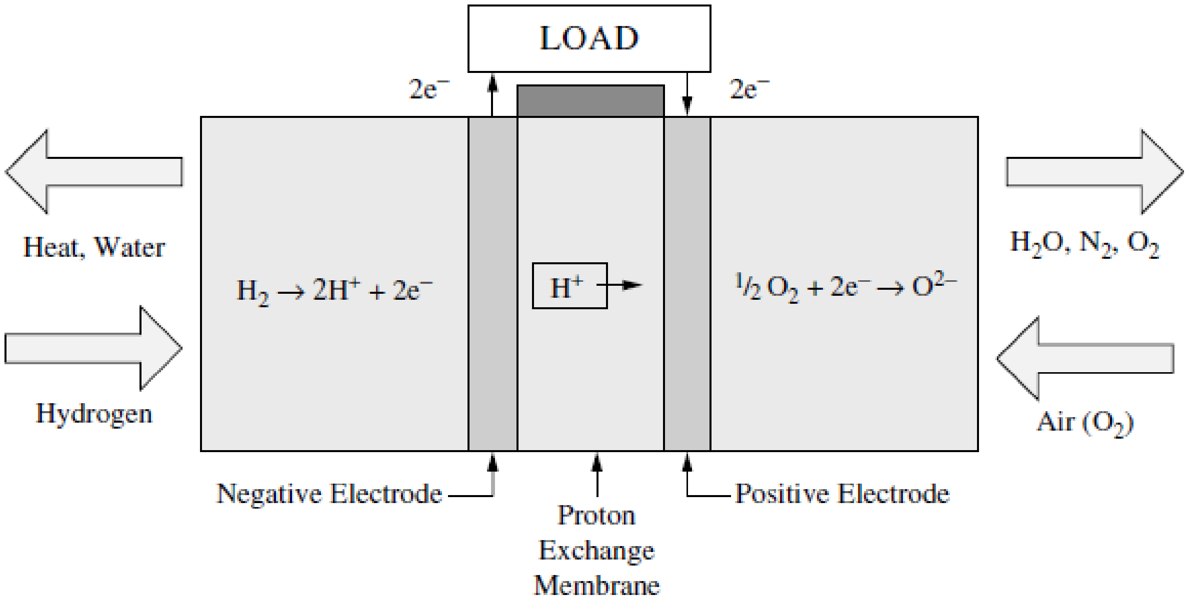


Fig. 57: The polymer electrolyte fuel cell (PEMFC) [4]

electrode. The electrons return from the external circuit, while the ions pass through the electrolyte to the opposing electrode. The electrons return from the external circuit to participate in the electrochemical reduction reaction at the cathode. The reactions at the electrode are

Anode: $H_2\ (g) \rightarrow 2H^+\ (aq) + 2e^-$
Cathode: $\frac{1}{2}O_2\ (g) + 2H^+\ (aq) + 2e^- \rightarrow H_2O\ (l)$
Overall: $H_2\ (g) + \frac{1}{2}O_2\ (g) \rightarrow H_2O\ (l)$

The standard electrolyte material currently used in PEM fuel cells is a fully fluorinated Teflon-based material produced by DuPont for space applications in the 1960s. The DuPont electrolytes have the generic brand name Nafion, and the types used most frequently are 1135, 115, and 117. The Nafion membranes are fully fluorinated polymers that have very high chemical and thermal stability. The electrodes are thin films that are bonded to the membrane. Electrodes with low platinum loading perform as well or better than high-platinumloaded electrodes. To improve the utilization of platinum, a soluble form of the polymer is incorporated into the porosity of the carbon support structure. This increases the interface between the electrocatalyst and the solid polymer electrolyte [2].

20.18.1 Basic stationary fuel cell calculations.

In order to evaluate and compare stationary fuel cell systems, the following efficiencies can be calculated for all of the components and aspects of the fuel cell system. The total efficiency of the fuel cell system is defined as:

Total efficiency = (electric power output + thermal output) / fuel consumption ***(25)***

Or
$$\eta_{total} = \frac{P_{net} + Q_{net}}{HHV_{fuel} * n_{fuel}} \quad \textbf{(26)}$$

where P_{net}, and Q_{net} is the usable power and heat amounts respectively, and n_{fuel} is the amount of fuel input into the fuel cell system. The total efficiency of the fuel cell system can also be calculated by multiplying the efficiencies of the individual components, and the ratio of parasitic power and fuel cell gross power output (ξ_p). An example of this equation is as follows:

$$\eta_{total} = \sum \eta - \xi_p \quad \textbf{(27)}$$

The electrical efficiency of the stationary fuel system is:

$$\eta_{electrical} = \frac{P_{net}}{HHV_{fuel} * n_{fuel}} \quad \textbf{(28)}$$

Where
$$P_{net} = P_{AC} - P_{aux\_equipment} \quad \textbf{(29)}$$

And $$P_{aux\_equipment} = P_{compressor} + P_{pump} + P_{control} \quad \textbf{(30)}$$

where PAC is the usable AC power generated, $P_{aux\_equipment}$ is the power required by auxiliary equipment, $P_{compressor}$ is the power required by compressor, P_{pump} is the power required by the pump, and $P_{control}$ is the power required by the control system.

The thermal efficiency of the stationary fuel cell system is:

$$\eta_{thermal} = \frac{Q_{net}}{HHV_{fuel} * n_{fuel}} \quad \textbf{(31)}$$

If the stationary fuel cell system uses a fuel processor, the efficiency of the fuel processor is:

$$\eta_{fuel\_processor} = \frac{HHV_{H_2} * n_{H_2}}{HHV_{fuel} * n_{fuel}} \quad \textbf{(32)}$$

The DC/AC efficiency of the stationary fuel cell system is:

$$\eta_{DC/AC} = \frac{P_{AC}}{P_{stack}} \quad \textbf{(33)}$$

For any auxiliary equipment used, the efficiency is:

$$\eta_{aux\_equipment} = \frac{P_{stack} - P_{aux\_equipment}}{P_{stack}} \quad \textbf{(34)}$$

The efficiency of the fuel cell stack is:

$$\eta_{stack} = \frac{P_{net}}{HHV_{H_2} * n_{H_2}} \quad \textbf{(35)}$$

20.18.2 Fuel Cell Reversible and Net Output Voltage

The maximum electrical energy output, and the potential difference between the cathode and anode is achieved when the fuel cell is operated under the thermodynamically reversible condition. This maximum possible cell potential is the reversible cell potential. The net output voltage of a fuel cell at a certain current density is the reversible cell potential minus the irreversible potential which is discussed in this section, and can be written as [3]:

$$V(i) = V_{rev} - V_{irrev} \quad \textbf{(36)}$$

where $V_{rev} = E_r$ is the maximum (reversible) voltage of the fuel cell, and V_{irrev} is the irreversible voltage loss (overpotential) occurring at the cell.

The maximum electrical work (W_{elec}) a system can perform at a constant temperature and pressure process is given by the negative change in Gibbs free energy change (ΔG) for the process. This equation in molar quantities is:

$$W_{elec} = -\Delta G \quad \textbf{(37)}$$

The Gibbs free energy represents the net energy cost for a system created at a constant temperature with a negligible volume, minus the energy from the environment due to heat transfer. This equation is valid at any constant temperature and pressure for most fuel cell systems. From the second law of thermodynamics, the maximum useful work (change in free energy) can be obtained when a “perfect” fuel cell operating irreversibly is dependent upon temperature. Thus, W_{elec}, the electrical power output is:

$$W_{elec} = \Delta G = \Delta H - T\Delta S \quad \textbf{(38)}$$

where G is the Gibbs free energy, H is the heat content (enthalpy of formation), T is the absolute temperature, and S is entropy. Both reaction enthalpy and entropy are also dependent upon the temperature. The absolute enthalpy can be determined by the system temperature and pressure and is usually defined as combining both chemical and thermal bond energy. The change in the enthalpy of formation for the chemical process can be expressed from the heat and mass balance:

$$\Delta H = \sum_i m_i h_i - \sum_j m_j h_j \quad \textbf{(39)}$$

where $\sum_i m_i h_i$ the summation of the mass times the enthalpy of each substance leaving the system, and $\sum_j m_j h_j$ is the summation of the mass times the enthalpy of each substance entering the system. Asimple diagram of the heat and mass balance is shown in Figure below.

The potential of a system to perform electrical work by a charge, Q (coulombs) through an electrical potential difference, E in volts is [4]:

$$W_{elec} = EQ \quad \textbf{(40)}$$

If the charge is assumed to be carried out by electrons:

$$Q = nF \quad \textbf{(41)}$$

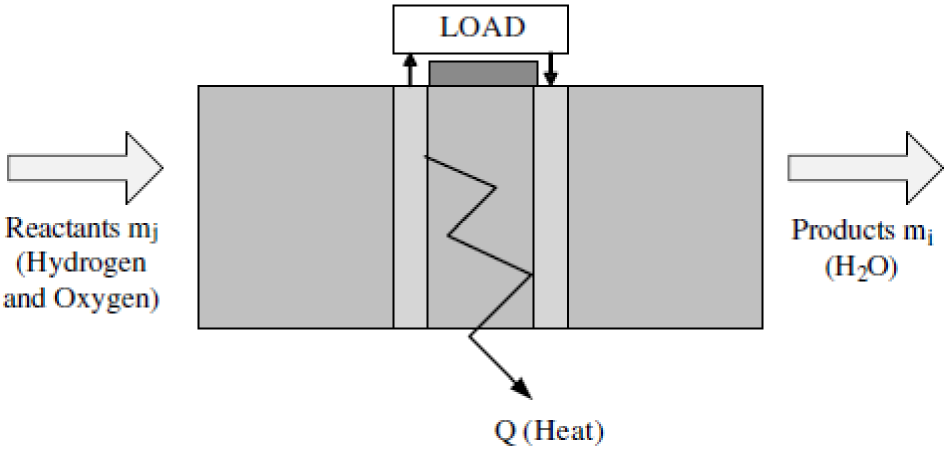


Fig. 58: Fuel cell heat and mass balance

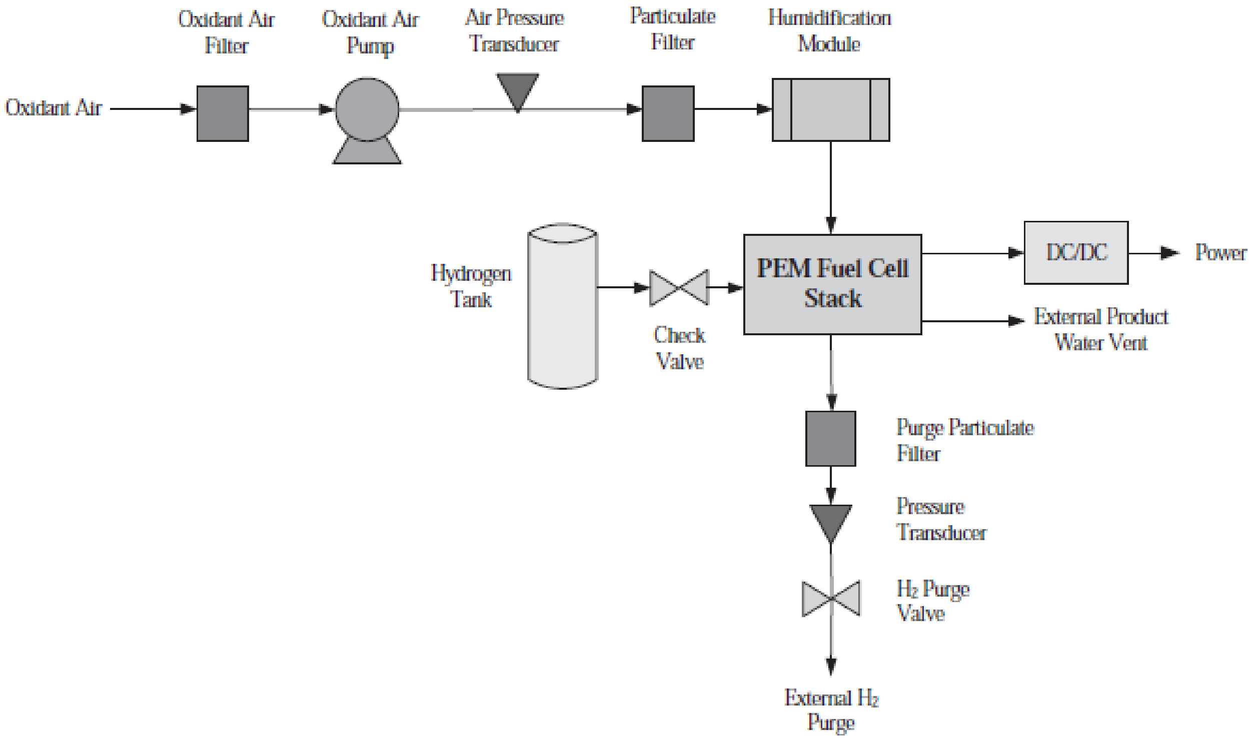


Fig. 59: Simple PEM fuel cell system [5]

20.19 Model creation of PEM fuel cell [61]

S.NO.	PARAMETER	VALUE
1	Channel length	50 mm
2	Outlet channel height	2 mm
3	Inlet channel height	2 mm
4	Thickness of catalyst layer	0.08 mm
5	Thickness of GDL	0.3 mm
6	Thickness of membrane	0.127 mm
7	Active area	25 cm^2

Fig. 60: Dimensions of PEM fuel cell model

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[61] https://www.researchgate.net/publication/341095046_IMPACT_OF_PRESSURE_ON_THE_PERFORMANCE_OF_PROTON_EXCHANGE_MEMBRANE_FUEL_CELL

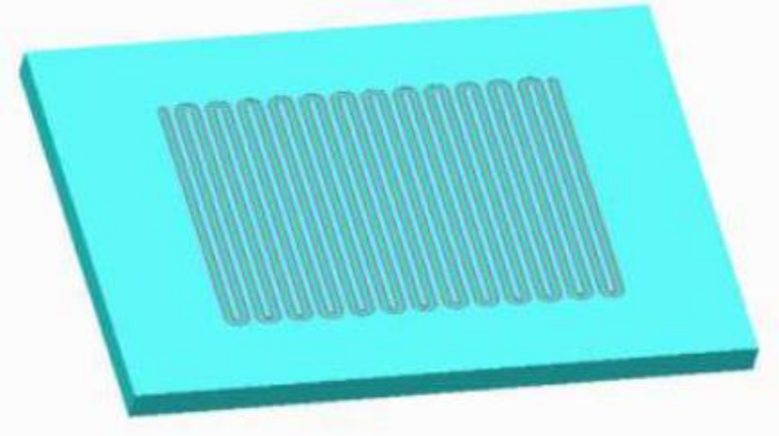

Fig. 61: Model of serpentine channel flow field of PEM fuel cell

S.No.	Pressure (bar)	Voltage (V)	Current density (A/cm^2)	Power density (W/cm^2)
1	1	0.55	1.206385	0.66351175
2	1.5	0.55	1.206648	0.6636564
3	2	0.55	1.207008	0.6638544

Fig. 62: The analysis was done with three different pressure (1 bar, 1.5 bar, 2 bar) and voltage (0.25 V-0.85 V) at constant temperature of 323 K (50oc) using Ansys and checked

20.19.1 Material and assembly (exp) [62]

Table below summarises the material properties of the fuel cell components used in this study and Fig below shows the assembly steps of the PEM fuel cell. The optimised OPCF flow plate housing was machined and wiped thoroughly using isopropyl alcohol to ensure that the housing is clean and no dust or grease present. The flow plate housing is placed horizontally in a flat position. OPCF was polished using silicon carbide grinding paper on a polishing wheel. The OPCMF is placed inside the housing and bolts are placed through the housing as shown in Fig below, photo 2. A gasket is then placed into position as shown in Fig below, photo 3. The MEA is positioned onto the housing as shown in Fig below, photo 4. A second gasket is then placed onto the MEA as shown in Fig below, photo 5. A second OPCF flow plate is placed into a second housing as shown in Fig below, photo 6. The second housing is then placed onto the bolts of the first housing. The MEA and gasket positions are checked and both housings are closed. Nuts are placed on the bolts and they are tightened. The push-in fittings for hydrogen pipes are placed in their positions. The final assemble fuel cell is shown in Fig below, photo 7.

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[62] https://www.researchgate.net/publication/265412592_Design_and_Development_of_Proton_Exchange_Membrane_Fuel_Cell_using_Open_Pore_Cellular_Foam_as_Flow_Plate_Material/download

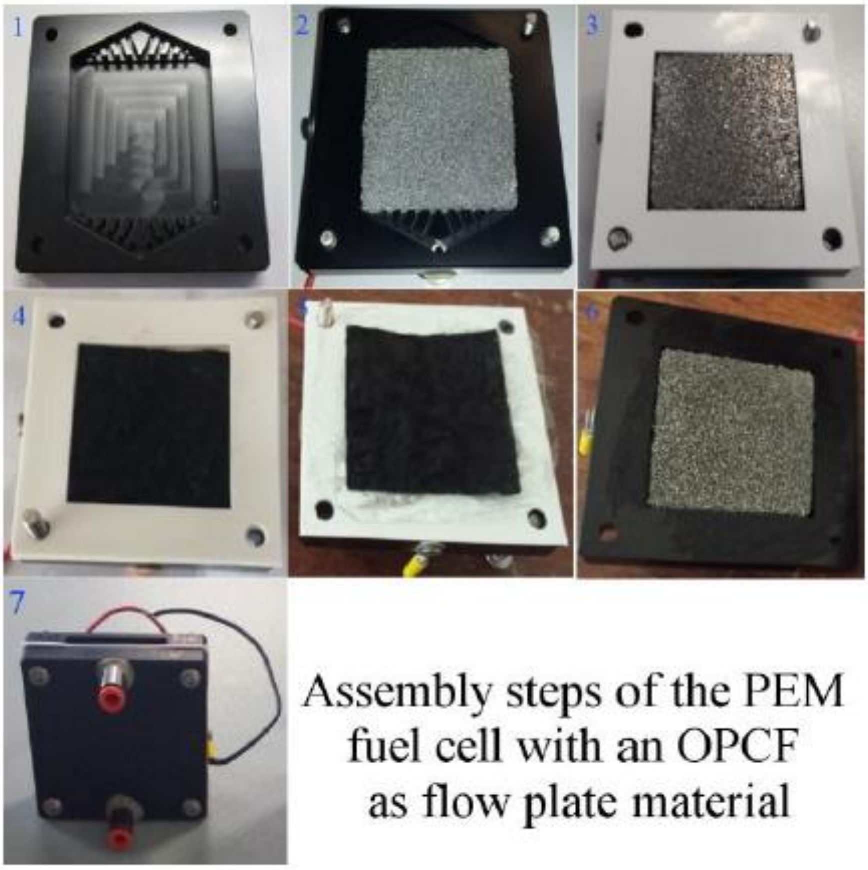

Fig. 63: Assembly steps of the PEM fuel cell

Fuel cell component	*material*	*Properties*
OPCF housing	Acetal	Supplier: Impact Ireland
MEA	Nafion 212	active area: 5×5 (cm*cm), Catalyst loading: 0.4mg/cm2 Pt/C, GDL: Sigracet SGL 24BC, 0.55g.cm-3 Bulk density. Supplier: EES ltd UK
Flow plate	OPCMF	24 Pores/cm , thickness: 6.35 (mm)
Gaskets	Silicon	Thickness: 0.8 (mm)

Fig. 64: Material properties of the fuel cell component

20.19.2 Experimental set-up and procedure [14]

The experimental setup is similar to Carton & Olab [6]. The reactant gas, hydrogen, is stored in a compressed cylinder. A specialized hydrogen pressure controls the hydrogen gas flow pressure. The gas then passes through volumetric flow meters. The flow controllers are calibrated for the hydrogen gas and air. The flow controllers are controlled by the data acquisition (DAQ) software (Lab View). Both air and hydrogen gases were humidified as stated by the manufacturer of the MEA. The open circuit voltage and the fuel cell operating voltage are detected by the DAQ hardware and analyzed through the software. The open circuit voltage reading is also double checked at the anode and cathode using a multi-meter (Fluke 8808A digital multi-meter). The fuel cell current is measured using a multi-meter (Fluke 8808A digital multi-meter) in series with the external load.
Every effort was made to keep parameters constant during the experiments to ensure that the values of resistance, pressure and flow were not changed from one experiment to the next. These parameters were checked throughout the experiment to identify any unwanted errors. The only effect on the performance was that of the flow plate design.

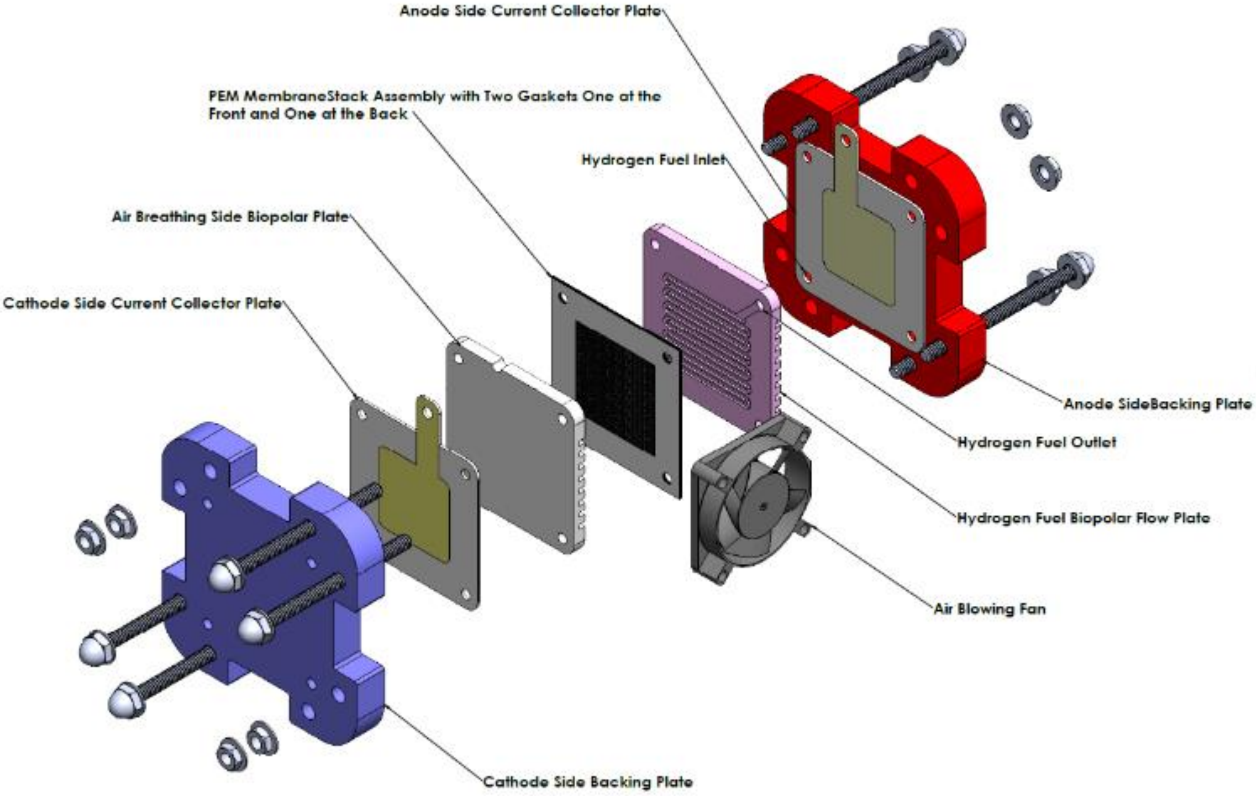

Fig. 65: *The Polymer Electrolyte Membrane Fuel Cell (PEMFC)*[63]

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[63] https://wlv.openrepository.com/bitstream/handle/2436/621478/AAM-A%20Baroutaji-%20Developments%20of%20electric%20cars%20and%20fuel%20cell%20hydrogen%20electric%20cars-Wire.pdf?sequence=8

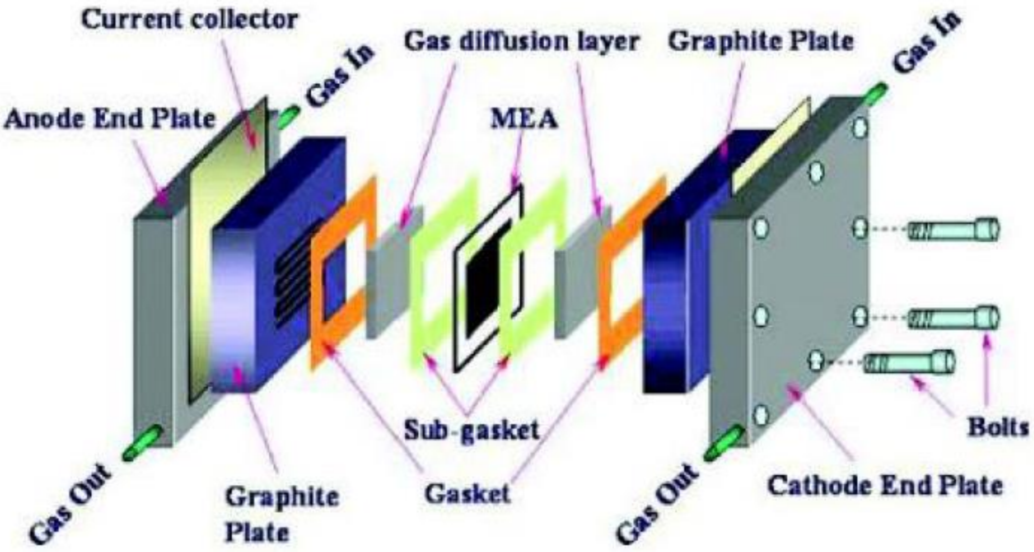

Fig. 66: Schematic of Polymer Electrolyte Membrane Fuel Cell showing different components [64]

Fig. 67: Condensation of water produced by a PEMFC on the air channel wall. The gold wire around the cell ensures the collection of electric current

20.20 Study of PEM Fuel Cell End Plate Design by Structural Analysis Based on Contact Pressure [65]

20.20.1 Introduction

Polymer electrolyte membrane fuel cell (PEMFC) is one of the promising technologies for electrical power generation. Presently, PEMFCs utilize solid polymer membrane as an electrolyte and porous carbon cloth/paper as electrode. The electrode and electrolyte together are referred to as the membrane electrode assembly (MEA) which is equipped with bipolar plate (BPP) on both the sides for reactant flow and current collection. A number of such units (single cells) are connected in series

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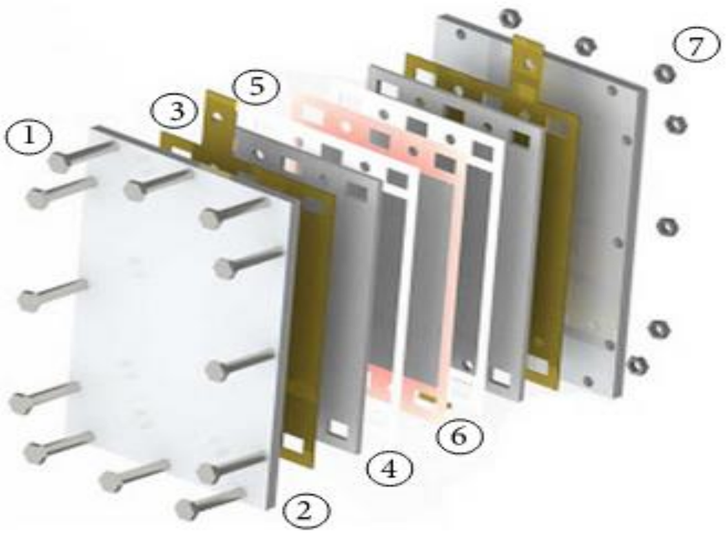
[64] https://www.researchgate.net/publication/282896560_Proton_Exchange_Membrane_Fuel_Cell_Technology_India's_Perspective/download

[65] https://www.hindawi.com/journals/jen/2019/3821082/

and are flanked by endplate at both ends to form a fuel cell stack. Graphite is usually the material of choice for bipolar plates due to its high corrosion resistance but still lighter material is preferred for the endplate [7, 8]. PEMFC has received considerable attention, especially in the automotive sector as the low operating temperature (< 100°C) allows quick start-up and portability [9, 10].

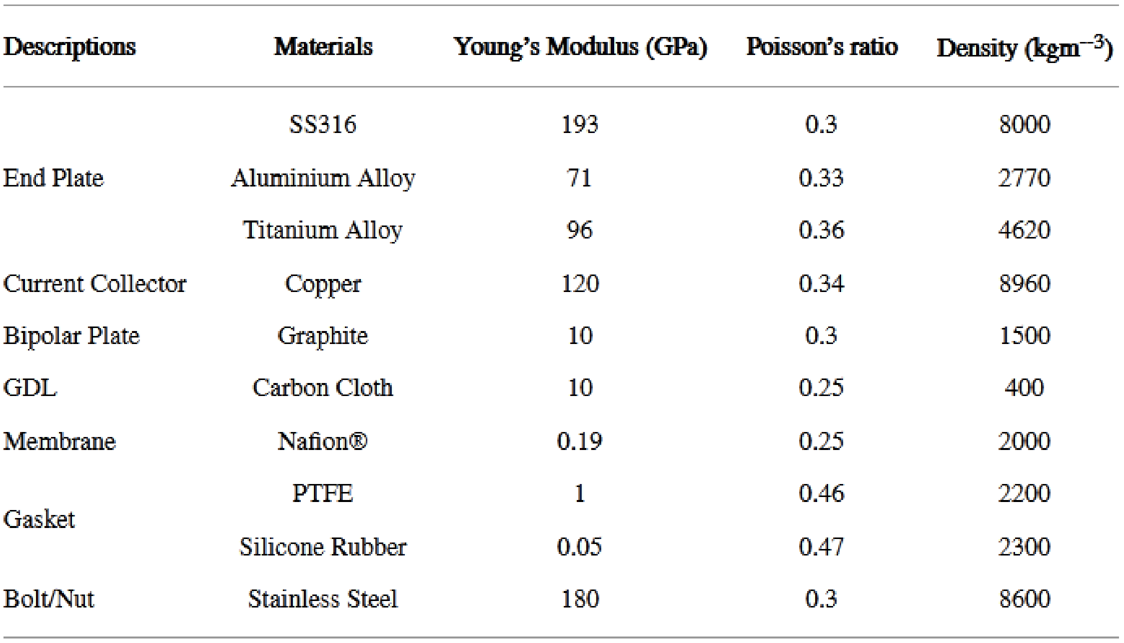
20.20.2 Description of Geometry

The geometry considered in the simulation includes the end plates, two bipolar plates, two gaskets, two GDLs, and a membrane. GDLs are joined to the membrane as nonseparable entities. As in common assembly procedure, the membrane is placed in the middle, with GDL on each side, followed by the gasket. This assembly is sandwiched between the bipolar plates and is enclosed by the end plates as shown in Figure above. In the geometry analysis ten bolts are considered with two configurations, one is with all bolts outside the graphite plates and the other one is with all bolts inside the graphite plates.



1: Bolt
2: End Plate
3: Current Collector
5: Gasket
6: Membrane
7: Nut

Fig. 68: Schematic geometry of PEMFC



Descriptions	Materials	Young's Modulus (GPa)	Poisson's ratio	Density (kgm^{-3})
End Plate	SS316	193	0.3	8000
	Aluminium Alloy	71	0.33	2770
	Titanium Alloy	96	0.36	4620
Current Collector	Copper	120	0.34	8960
Bipolar Plate	Graphite	10	0.3	1500
GDL	Carbon Cloth	10	0.25	400
Membrane	Nafion®	0.19	0.25	2000
Gasket	PTFE	1	0.46	2200
	Silicone Rubber	0.05	0.47	2300
Bolt/Nut	Stainless Steel	180	0.3	8600

Fig. 69: Material properties of PEMFC components

Geometries have been created in SOLIDWORKS and are imported in ANSYS® Academic Research, Release 14.0 workbench. Materials assigned are as shown in the Table 1. The flow channels of the bipolar plate are not included. Gasket material is selected as PTFE. GDL material is selected as carbon paper as it gives good performance due to high porosity (>70%) [6]. The clamping bolts considered are supposed to have standard M10 specifications. While evaluating the geometries, only the change in its external shape is considered, the total physical volume of the plate being kept constant. Reference end plate for the study is as depicted in Figure below.

Case 1 (evaluation of geometry). The size of end plate in our study is 300x200 mm2. Graphite plate, gasket, membrane, and current collector are each of dimension 267 × 172 mm2. Active area for all geometries is constant and it is equal to 199x154 mm2. All design features on end plates have same height of extrusion or cut 2 mm.

Case 2 (effect of number of bolts and position and its effect on contact pressure distribution). After obtaining the results of Case 1, the selected geometry is subjected to analysis in order to determine the effect bolt number and their arrangement.

For each of these schemes, the spacing between the adjacent bolts for each side of the end plate is given by

$$d = \frac{L}{n+1}$$

where "d" is the distance between adjacent bolts, "L" is the edge length, and n is the number of bolts.

Case 3 (analysis of pressure distribution considering that the bolt passes through the bipolar plate). After completing the analysis in Cases 1 and 2, the geometry and number and bolts are selected. The bolt position is then shifted such that it lies inside the bipolar plate and the change in pressure distribution is determined.

Case 4 (evaluation of the effect of gasket thickness). In most of the previous studies, the BPP is assumed to be in perfect contact with GDL while performing the FEA. However, in most practical scenarios, there is some difference between the gasket and GDL thickness. This mismatch produces an initial no-contact region between BPP and GDL, when compressive forces are gradually applied.

The final geometry obtained after three successive case studies is subjected to further analysis for evaluating the effect of change in the gasket thickness. Gasket thickness is changed in three equal steps from 0.1 to 0.2 mm, keeping the thickness of GDL constant (0.4mm).

Case 5 (evaluation of different end plate materials). The influence of the end plate material on the pressure distribution, stresses, and deformation is investigated using different materials. It is implemented using the configuration chosen after analysing the result of the previous cases.

20.20.3 Boundary condition

The current study shall act as a guideline for future fuel cell design activities, since it provides a comprehensive solution for ensuring homogeneous pressure distribution, leakage proof operation, and improving performance.

Several end plate geometries were considered in this study, along with number of bolts used in tightening and their position with respect to the cell. Extruded hexagonal geometry for end plate shows better distribution of contact pressure. Number of bolts is found to have a significant impact on average contact pressure and distribution. In the study, it is found that 10 bolts are suitable for obtaining uniformity for the structure under study. Bolt placement also has a considerable impact on the average contact pressure and contact pressure distribution, i.e., by placing all bolts through the graphite plate has contributed to more uniform contact pressure distribution.

Another important aspect of cell assembly is to choose a gasket thickness complementary to thickness of the GDL for a given compressive pressure. The evaluations of gasket thickness from this study shall provide insights into the permissible gasket thickness. It is found that the difference between GDL and gasket is tolerable between 0.15 mm to 0.2mm. Thus, by optimizing geometry, number of bolts, their position, and gasket thickness, average contact pressure of ~ 0.8 MPa is obtained at a bolt loading of 8–10 Nm. Change in material is found to be of lesser importance. However, lighter materials like aluminium alloys can be effectively utilized, producing weight savings of ~65% while retaining better contact pressure distribution.

20.21 Components in a single cell

The figure above shows the expansion diagram of a single cell. Inside the single cell, we can see the first of course the MEA which had a no catalyst layer Castle Caturday, and separator which is a counter ionic conductive but electronically is insulate. And next to the MEA is the TDA of gaskets if you layer will be mentioned them. Since the it had to be carried transport the gas in and out so it's a porous medium and even the outside the oscar of the is also porous so the gas will leak out from the outside here so we need the gasket to prevent gas leakage, and the gas key is made of flexible Teflon, so it's a chemical inner but also still the guest so that will not let the gas leak of an outside and also acting as a insulation.

Then we call the graphite plate. The graphite plate actually might be the graphite powder or carbon powder mixed with phenolic resin and compressed into a plate and the under surface of the play had a curve into the flow channel so the reactant the guest will be when a flow through the channel will be able to evenly distribute through the GDL to the electrode surface and also the current or electron generation.

And know we flow out through the GDL and to the graphite plate. Because the disk graphite plate is in touch with korg component for the sphere cell is maybe corrosive so it's had to be used carbon material to make sure it's when a corrode and but also the current and outside will be the current collector, the current carried out by the current collector an outer cell. The reason we had to need a current collector is the electronic conductivity of the current collector is a more than a thousand times higher than the graphite plate. This current quality usually made of copper maybe but usually is highly electronic conductive but because we use a graphite plate to insolate to prevent any corrosive gas or the environment so they will be not corroded but this will very highly conductive so the current can be disputed evenly through th egraphite plate to the GDL and then we had end plate. The purpule for the end plate is try to contact or transmit the screw pressure even into the center because the channel graphite plate.

The channel plate and then GDL and the electro here need a pressure to compress together to reduce possible interfacial resistance electronically distance between a graphite plate or GDL to the catalyst layer. You need a pressure to press down to reduce the individual pressure but you cannot punch a hole and make a school to tight it up so you had to add a screw tigher on the periphery of the graphite plate to this one had to enough pressure to press on the GDL. So this end plate have a stick and then will become complete the screw pressure to the center even a

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dispute so that said understand the pressure can be evenly compressed. There's a basic a key component for a single cell that for the MEA the GDL cascade graphite plate current collector and end plate.

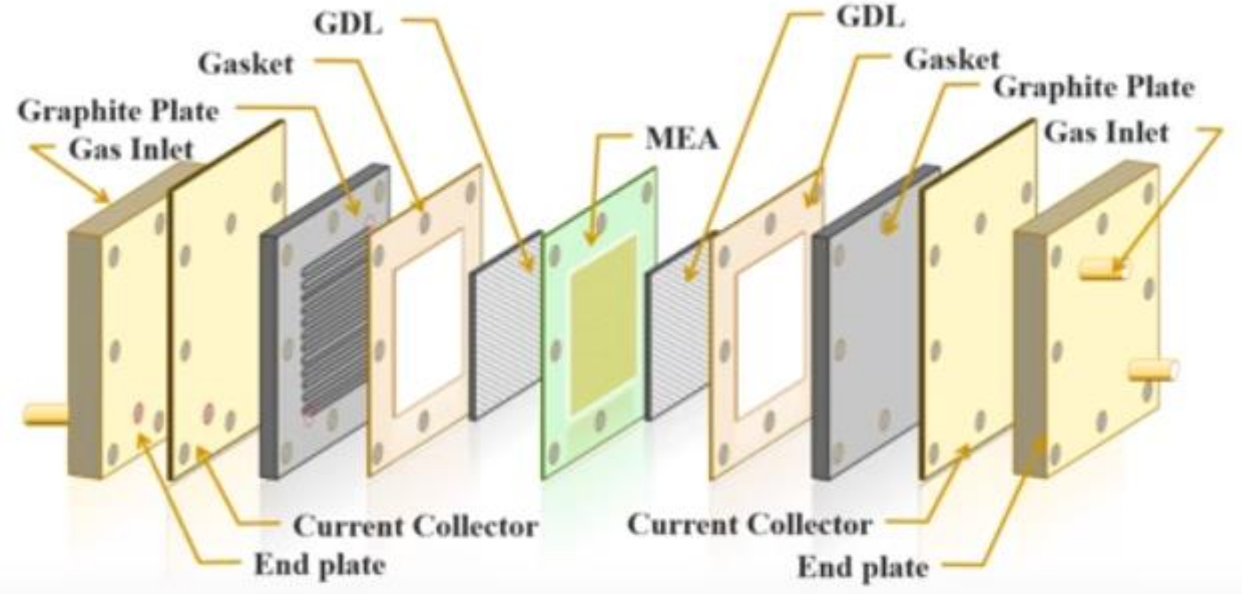
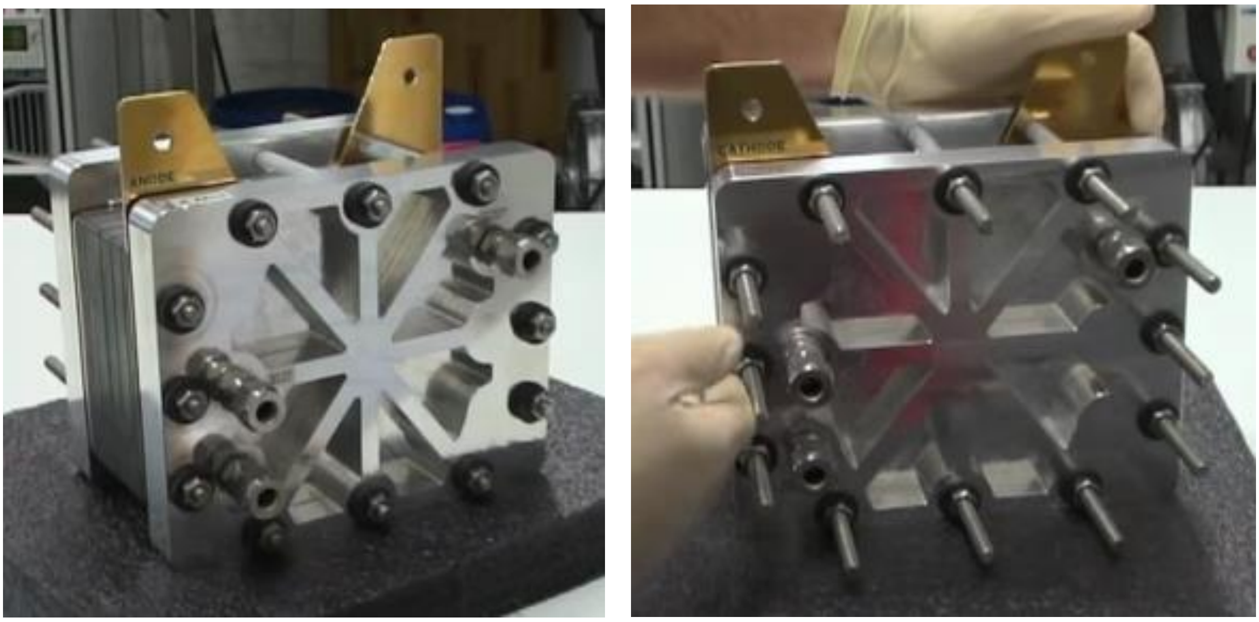


Fig. 70: Components in a single cell

20.22 Fuel cell stack

20.22.1 Add cell to the stack



Form the anode's side ***From the cathode's side***

Fig. 71: Stack of the PEMFC from the anode & cathode side

We have 5 cells in our hydrogen fuel cell. To add 2 cells to the fuel cell, you must first remove the bolts and nuts

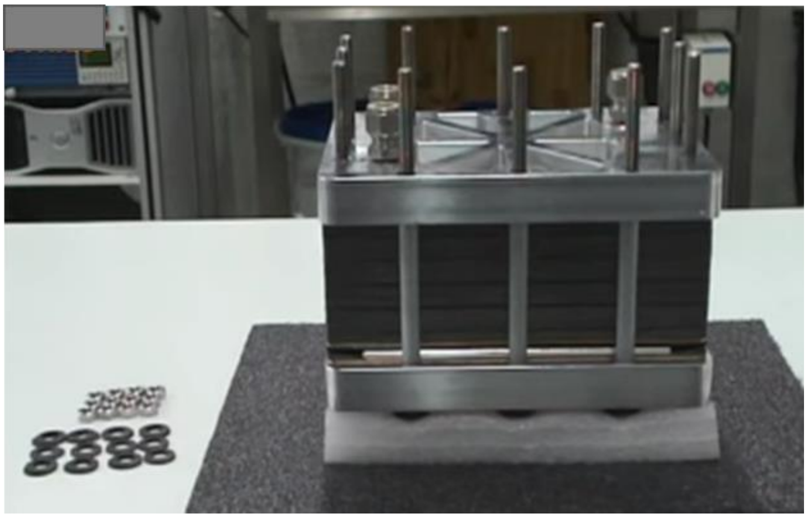


Fig. 72: Remove the bolts and nuts from stack

Then we remove the end plate

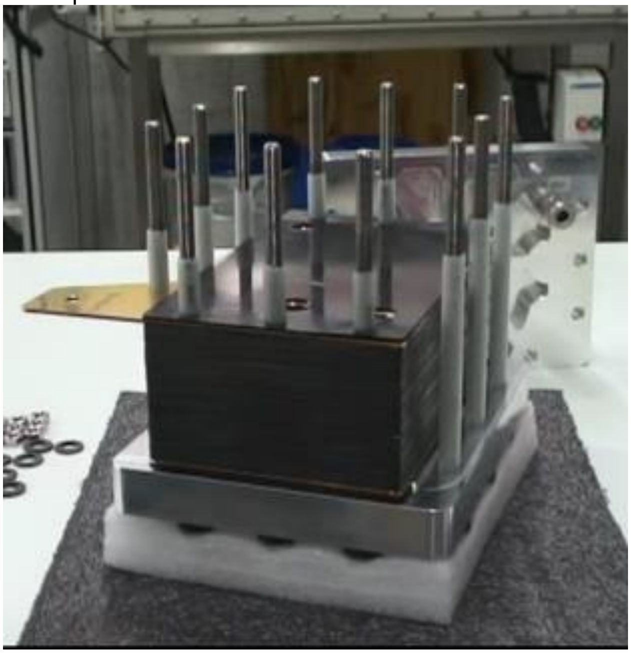


Fig. 73: Remove the end plate from the stack

Then we remove the current plate collector, with the gasket

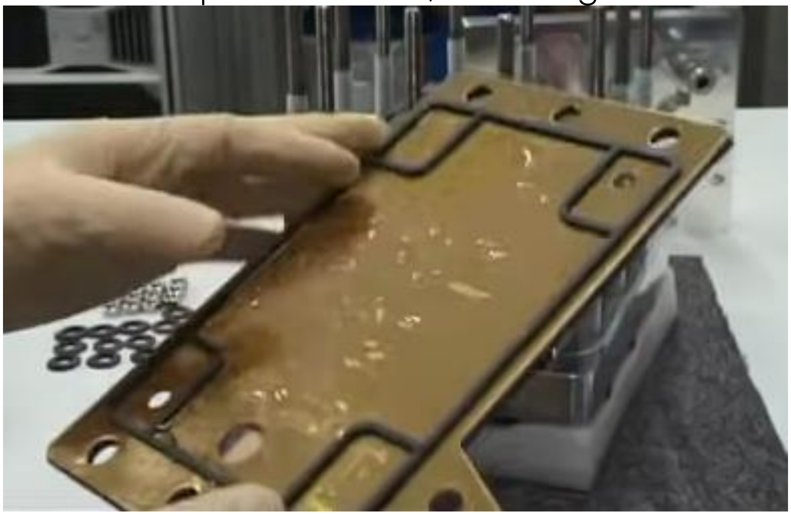


Fig. 74: Remove the current plate collector, with the gasket from the stack

This is what we have. It's the first cell next to the current collector. We can see there is a channel. And this channel is the liquid cooling add in the end plate

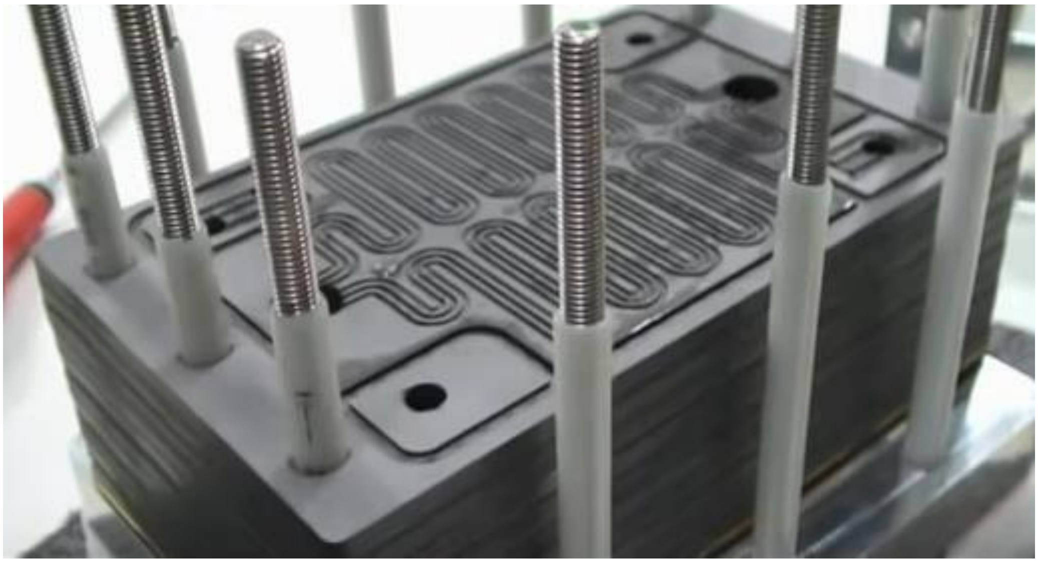


Fig. 75: First cell next to the current collector

For more details, we will review the details of a single cell. These is the cell itself, so that the components required for single cell. Two graphite plate and one membrane electrode assembly (MEA).

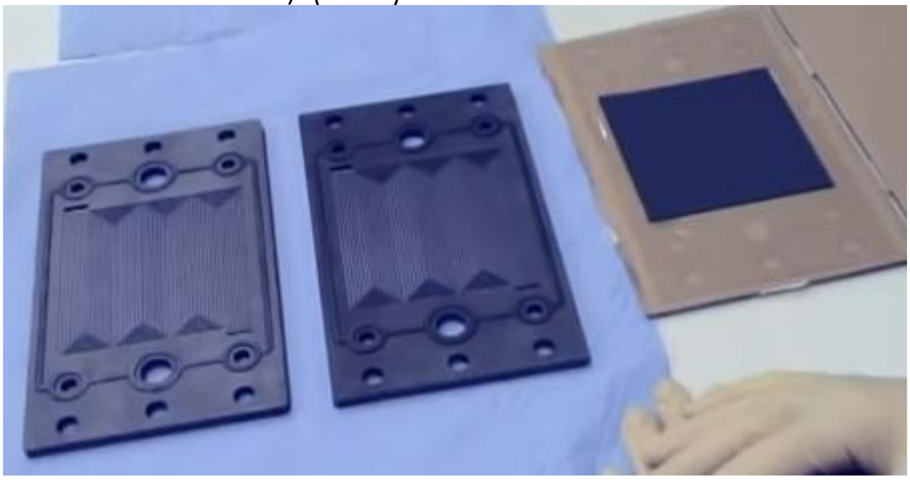


Fig. 76: Overview of a single cell (Two graphite plate and one MEA)

We can see the gasket layers and the subgasket use two support the electrolytic membrane

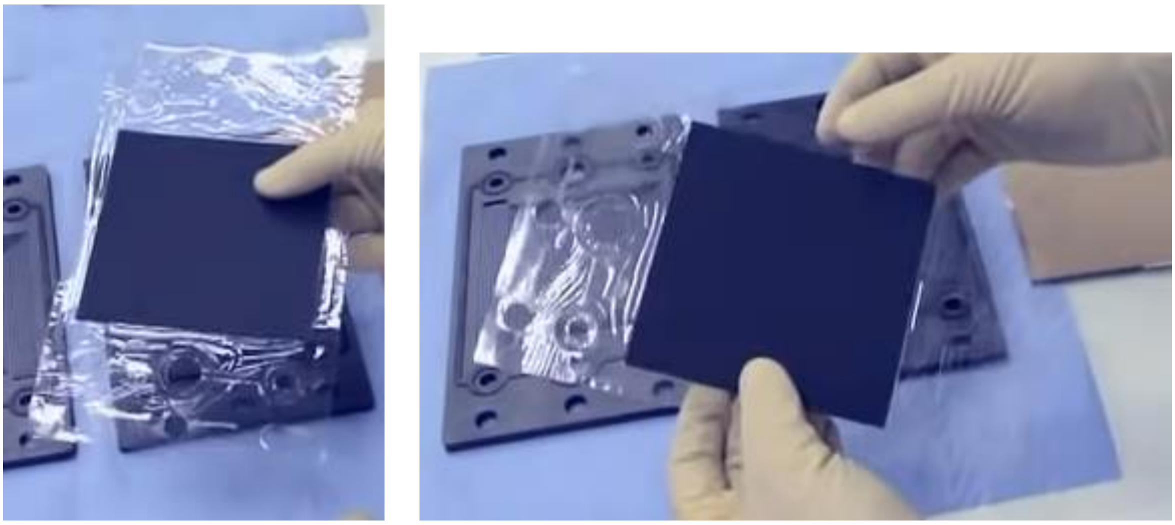


Fig. 77: The MEA layer

Each plate equiped with the single gasket and the gas distribution channel with multiple support flow field, and field gasket and in the middle holes to field the liquid cool.

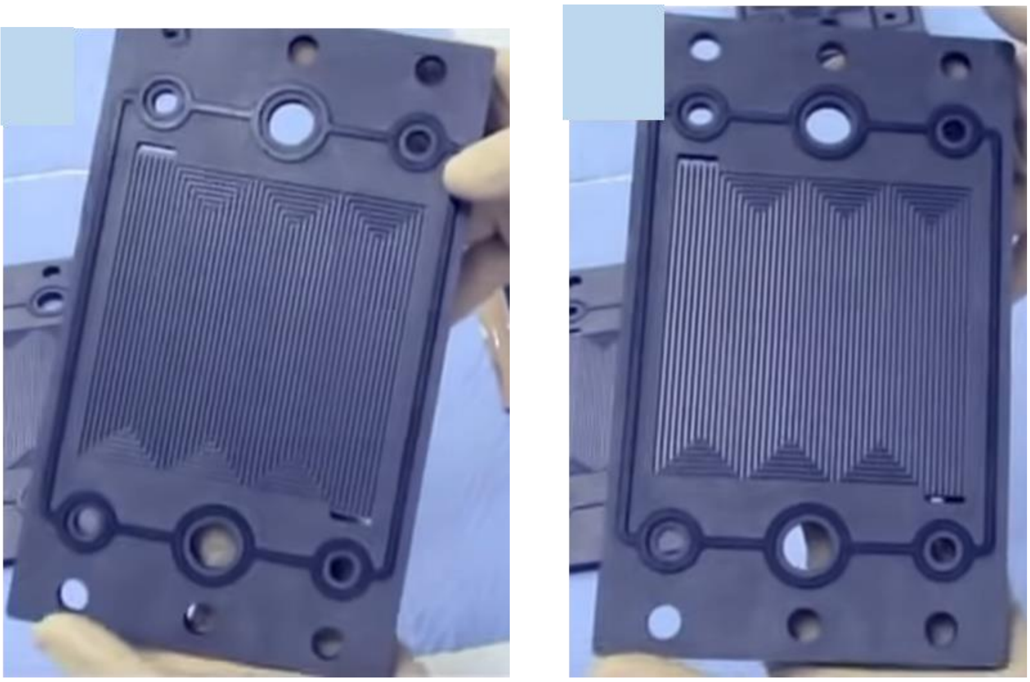


Fig. 78: Gas distribution channel with multiple support flow field, and field gasket at the front side

We turn the plate, we can see the hole is connected through the plate.

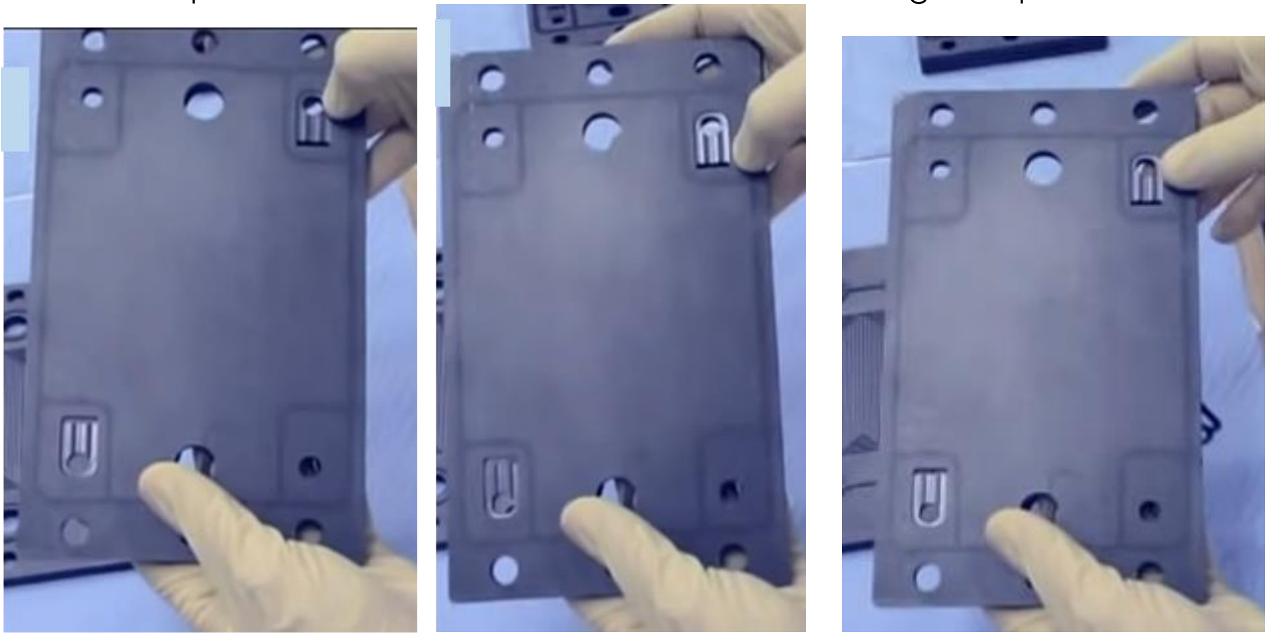


Fig. 79: Gas distribution channel with multiple support flow field, and field gasket at the back side

Basicly, how it is made very simple. One plate, from the channel side, one MEA placed on the plate with gasket and the another plate ,with gasket, puted on the MEA like this. And we have like one cell.

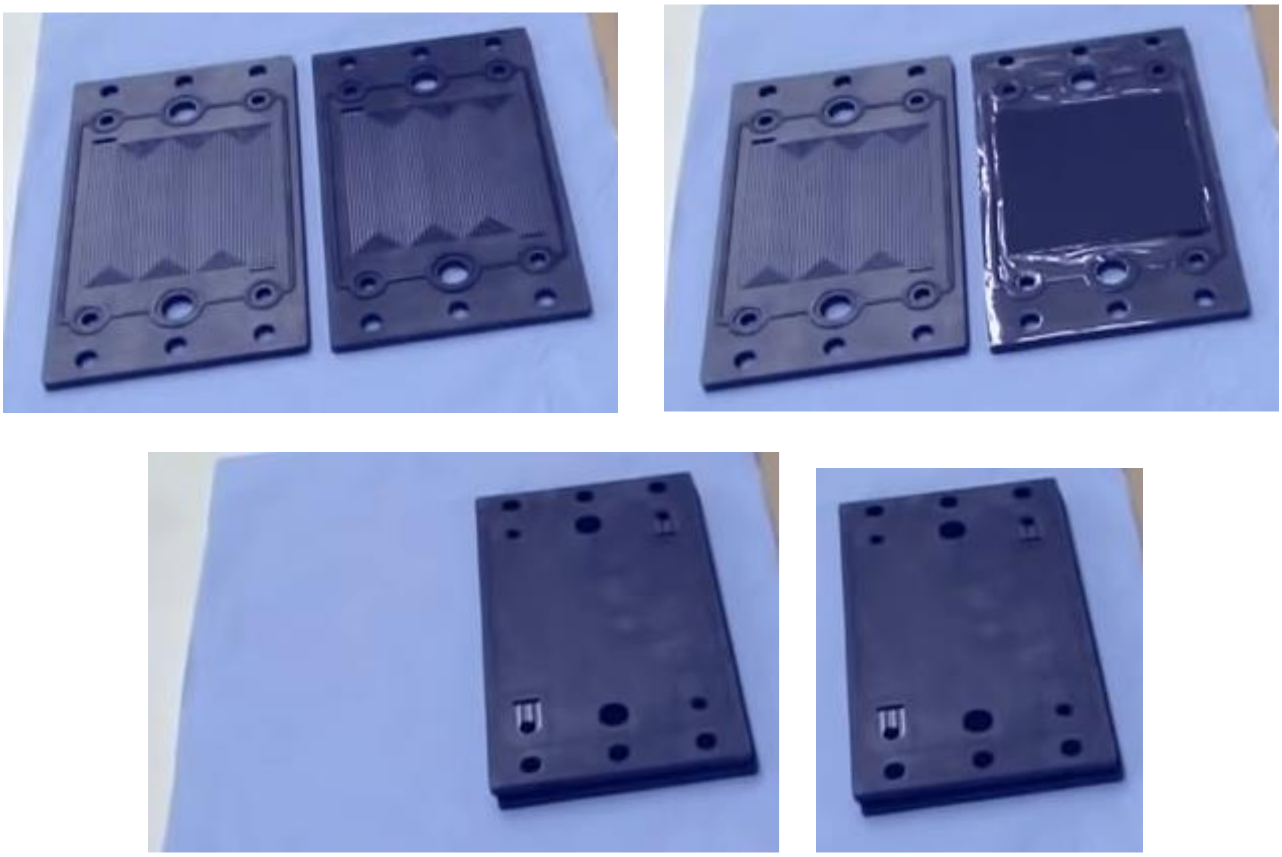
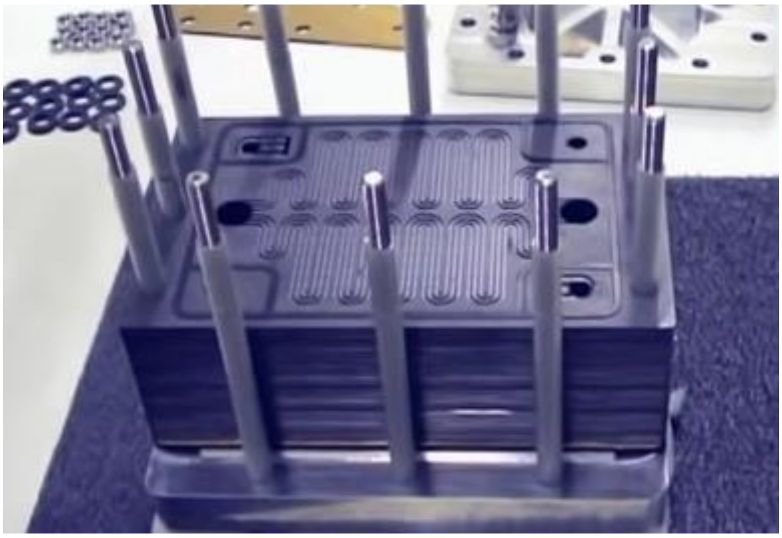


Fig. 80: Steps to build a cell

And now, we want to add this cell to the rest of the stack



I will first take this plate. We will start with this plate because it is flush. If we have like this gasket is here and cooling channel is here so we will place plate flush.

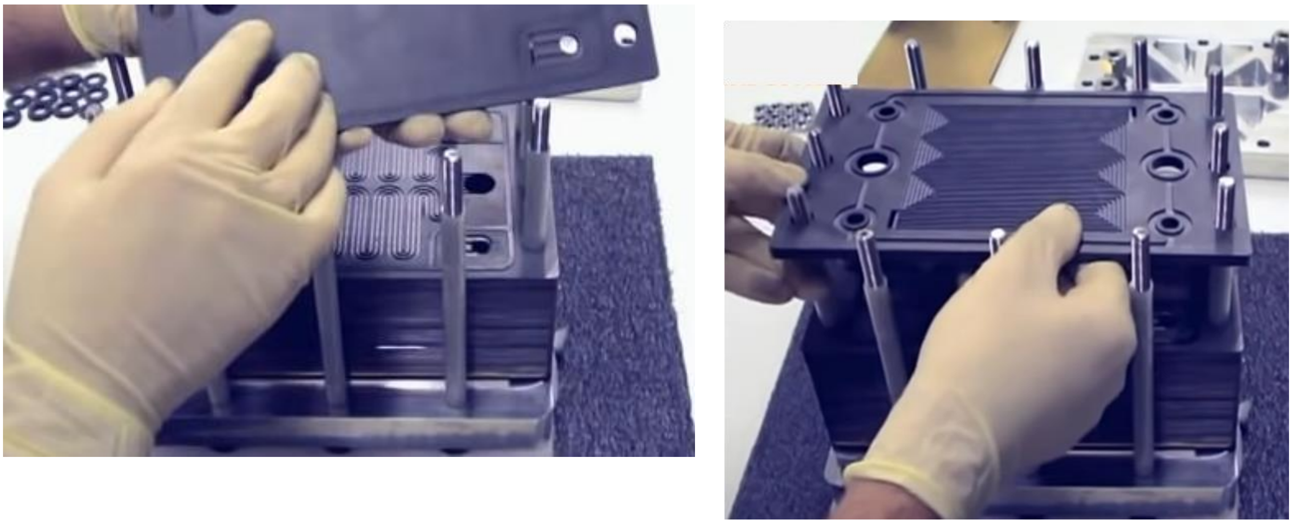


Fig. 81: Add the plate in the appropriate direction to the stack

Add the gasket

Fig. 82: Add the gasket

Now we added the MEA

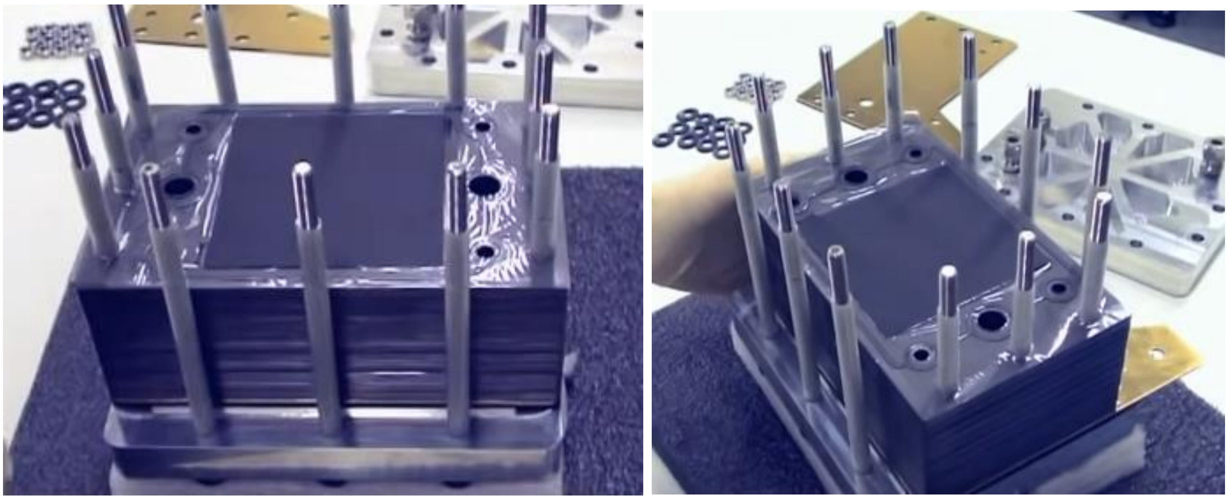


Fig. 83: Add the MEA

And add the gasket

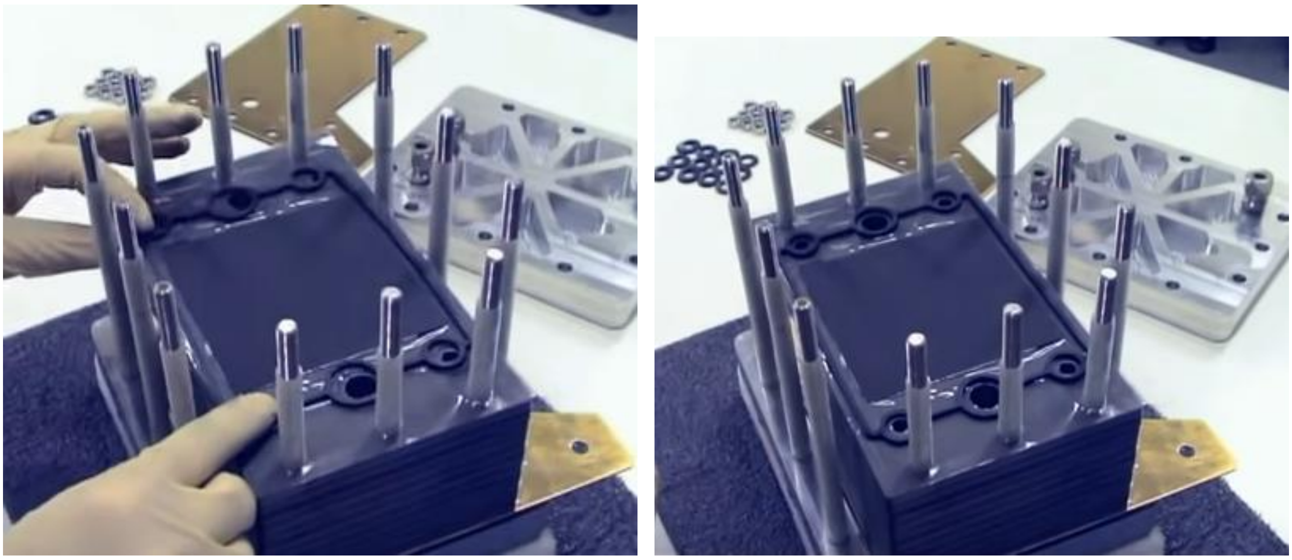


Fig. 84: Add the second gasket

And emplacing the plate through the tie rod.

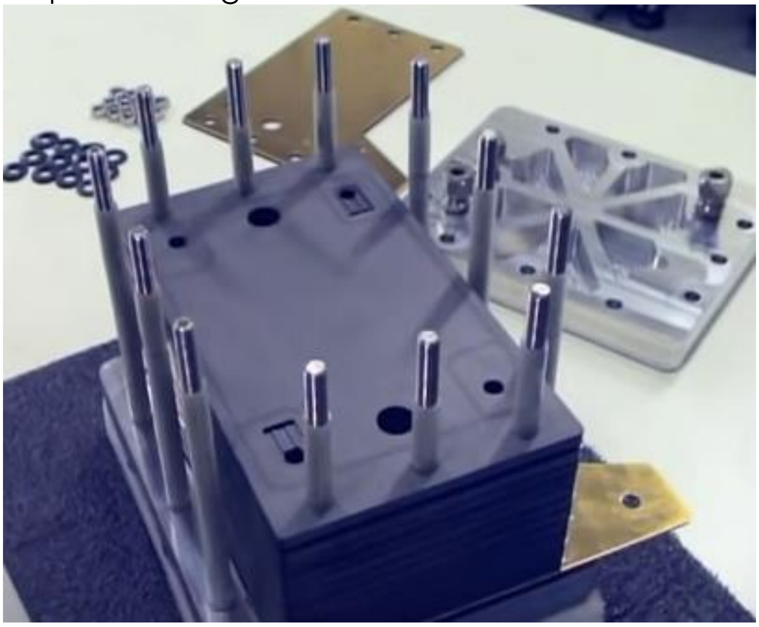


Fig. 85: Emplacing the plate through the tie rod

I will now move to add the second cell. I want to add to the stack the cell. we seen before is ready with MEA inside. And this cell is equiped with cooling channel on both side. For a simple reason, the last cell is flush so one cooling channel between the two half plate here and because it will be the last cell in the stack, there is also the cooling channel had is trun the side of the cell

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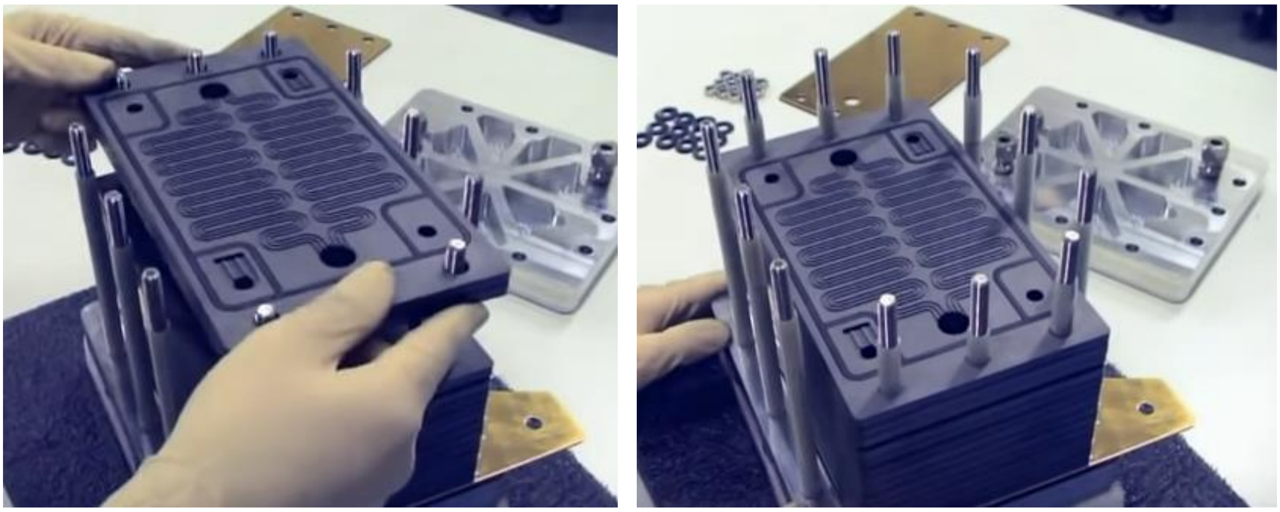

Fig. 86: Add the second cell

Now what i need is again the current collector. We placed back.

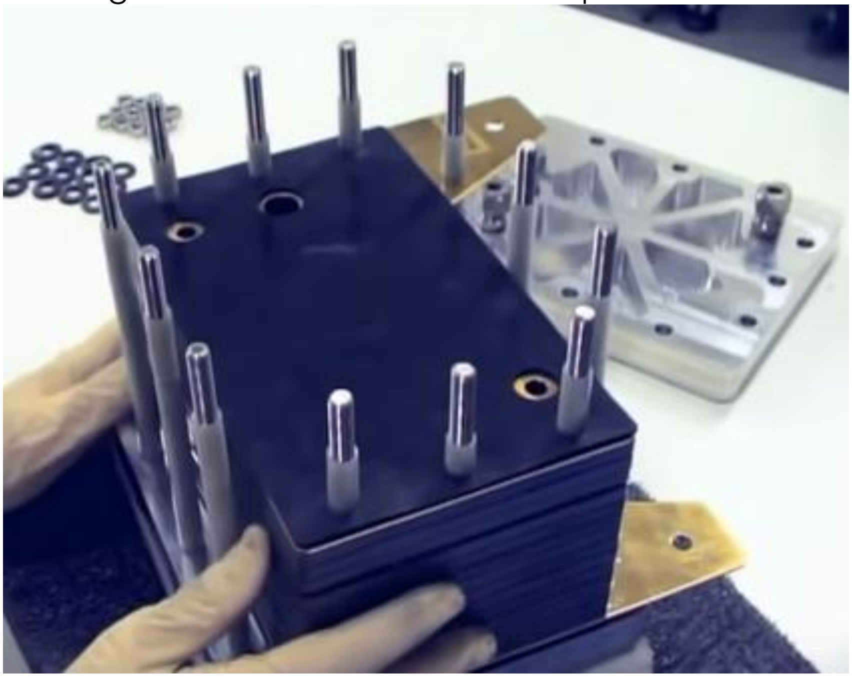

Fig. 87: Placed back the current collector

And go nicely to placed the end plate

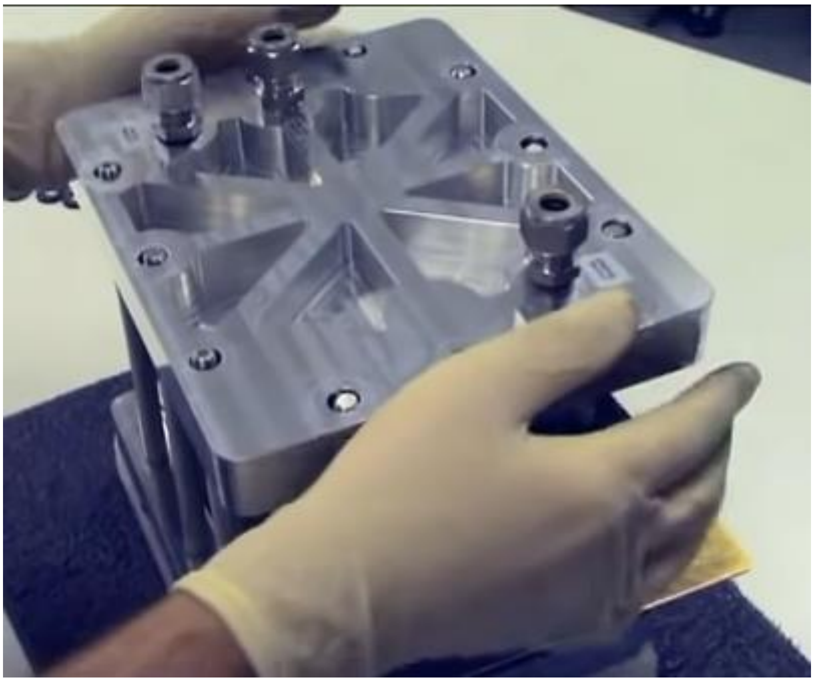

Fig. 88: Placed back the end plate

20.22.2 Working prototype

How to make a working prototype of such a do-it-yourself hydrogen fuel cell.

To do that, first, we need to make a platinum electrode we'll use for oxidizing hydrogen and generating electricity . Metallic platinum is a great catalyst, which means it increases the rate of chemical reactions for instance. Since pure platinum is too expensive, to make electrdes from a thin platinum film on the surface of another metal will suffice for my experiment.

I am using such a nickel sponge sheet as a base for my platinum electrode, because Platinum coats this metal quite smoothly and without coming off. It besides because of this spanish sporus structure the surface area is maximized and the obtained catalyst will be extermely effective. Before going platinum plating, we need to remove grease and prepare the surface of the nickel sheet which is why first a large strips of the nickel sponge into an ultrasonic cleaner filled with soap solution. After cleaning nickel for 10 minutes i'm lowering these strips of nickel into a 50 alcohol solution in order to remove vestiges of soap and dirt. When running ultrasonic cleaning cavitation bubbles been released make sure that other dirt is removed from the pores of the nickel sponge. When the strips dried i got two clean electrodes.

Next for coating the nickel electrode with platinum, i'm using a quite expensive chemical called chloroplatinic acid costing 19 euros because this substance easily absorbs moisture from the air and melts. It is stored in sealed ampoules we'll need an extremely weak solution of this substance, Just seven millimole per liter. First of all, i'm dissolving one gram of cloroplatinic acid in 15 mL of water,

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fortunately this chemical dissolves very well in water. and after that, i am pouring 9 grs of this solution into another beaker increasing the volume of the solution to 200 mL.

Now, i am lowering a pretty expensive and durable titanium electrode covered in irridium and russinium oxides into the obtained light yellowish solution such electrodes are used in gold and rhodium plating in order for the reaction to run more smoothly and for the solution not to get tainted in such an aggressive medium by the disintegrating anode.

To do platinum plating, i'm allowing a purified nickel sponge into the solution and starting to run electricity through it using my laboratory adapter during this process. Platinum is slowly covering the surface of nickel creating a very thin gray layer because of its slightly grainy structure it took me 20 minutes to cover one electrode with patinum. After that, i'm lowering it into distilled water in order to rinse off vestiges of the electrolyte. In some time, i got such two platinum electrodes for hydrogen batteries of quite good quality the dark areas are completely covered in pure platinum.

The next stage is making a case a hydrogen fuel cell, which i am going to make from two syringe cases. To increase their efficiency i have attached two valves to them which in the future will help me to run oxygen and hydrogen through my setup more smoothly. Now, i'm solderimg one platinum plated electrode to each syringe case using epoxy raisin on top of which i'm going to run chemical reactions.

This seemingly unremarkable film called nafion is the most important components of my hydrogen battery. They are sold as sandwiches in between two protective plastic layers. If we take a look at its chemical structure, from a chemical point of view it resembles teflon which is used to cover frying pans. The difference through is that several sulfur groups are added to the teflon skeleton enabling such a film to pass protons through it, which are hydrogen ions.

after separating nafion film from the protective plastic layer, It needs to be sandwiched in between the syringe cases, which i am also going to glue together the epoxy raisin hardens in 30 minutes. and after that, we can test my do-it-yourself hydrogen fuel cell for the first test.

I'm going to use a balloon filled with hydrogen. Then using a special burner, i began to supply halogen into the lower part of my setup, because these guys is lighter than air and it will be rising up towards the platinum catalyst. The upper syringe case will be filled with just air 20% of which is oxygen and i think it will be enough for my experiment as i start supplying hydrogen.

We can notice that the multimeter shows how the voltage is beginning to increase and it means that my setup works in some time the voltage reached 0.7 volt and remains more or less stable at this level. When i supply air through the upper part of the cell. The voltage slightly changes but not for long. So, what is happening here and how does this hydrogen fuel cell work.

To explain in simple terms, electricity in my cell is generated in the very middle at the interface of the two platinum electrons upon closing of the circuit when hydrogen is streamed into the lower part of the setup towards the surface of the lower platinum electrode. It gives off its electron which runs through the wire. The ion of hydrogen being created, or in other words proton which passes through that very naphthene film and ends up on the upper electrode there it is oxidized by the oxygen in the ear and receives the electron from the other electrode creating water.

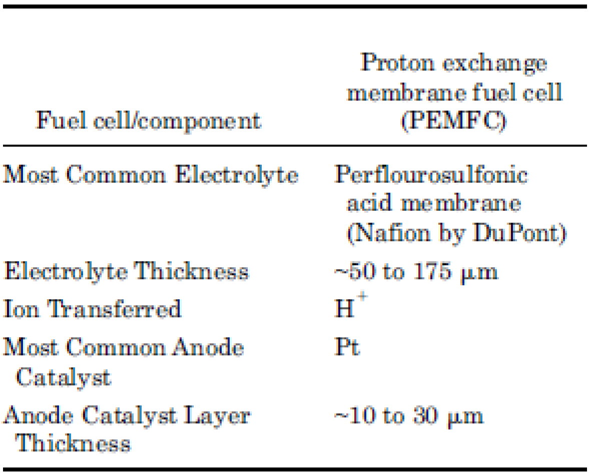
As a result the lower electrode is negative or is an anode and the upper electrode is positive or in other words is cathode. in some time, there even condensed some water on the upper part of my setup which is a main by-product of this battery. My cell generates 0.7 V out of 1.3 theoretically possible. However the intensity of current isn’t very high being just 15 mA that is why unfortunately i won’t be able to connect anything to my hydrogen battery. The only way to increase the energy conversion efficiency of my battery is to make a more concentrated source of hydrogen.

For instanc to use sodium borohydride solution instead this compound can frequently be encountered at organic synthesis laboratoires, it is often used for reducing organic compounds because sodium borohydride easily gives off its hydrogen. It does is so easily than when dissolved in water. We can even see how bubbles are gradually being released from the sodium borohydride solution because this chemical isn’t stable in water and quickly breaks down.

If i turn my setup upside down and pour some sodium borohydrides into the upper part of the cell. I’ll immediately see how the multi-meter detects an increase in the voltage because in this case i am pouring concentrated hydrogen. Alright on the electrode thus, i can achieve high efficiency of my do-it-yourself hydrogen fuel cell having reached the maximum possible voltage. Unfortunately through not even sodium borohydride can increase the intensity of the electric current because my battery is too primitive because i cannot make a more efficient and beautiful fuel cell to continue my experiments.

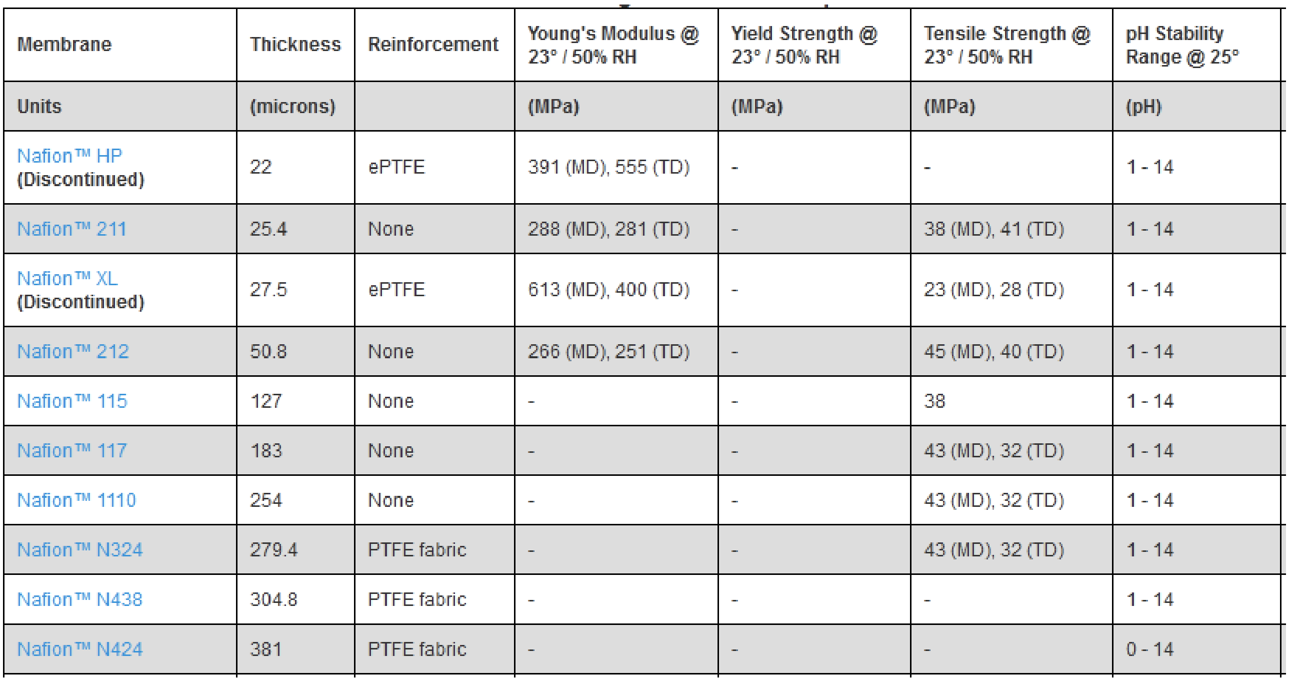
20.23 Fuel Cell Materials

20.23.1 Electrolyte Layer



Fuel cell/component	Proton exchange membrane fuel cell (PEMFC)
Most Common Electrolyte	Perflourosulfonic acid membrane (Nafion by DuPont)
Electrolyte Thickness	~50 to 175 μm
Ion Transferred	H^+
Most Common Anode Catalyst	Pt
Anode Catalyst Layer Thickness	~10 to 30 μm

Fig. 89: Common Materials Used for Each Fuel Cell Type



Membrane	Thickness	Reinforcement	Young's Modulus @ 23° / 50% RH	Yield Strength @ 23° / 50% RH	Tensile Strength @ 23° / 50% RH	pH Stability Range @ 25°
Units	(microns)		(MPa)	(MPa)	(MPa)	(pH)
Nafion™ HP (Discontinued)	22	ePTFE	391 (MD), 555 (TD)	-	-	1 - 14
Nafion™ 211	25.4	None	288 (MD), 281 (TD)	-	38 (MD), 41 (TD)	1 - 14
Nafion™ XL (Discontinued)	27.5	ePTFE	613 (MD), 400 (TD)	-	23 (MD), 28 (TD)	1 - 14
Nafion™ 212	50.8	None	266 (MD), 251 (TD)	-	45 (MD), 40 (TD)	1 - 14
Nafion™ 115	127	None	-	-	38	1 - 14
Nafion™ 117	183	None	-	-	43 (MD), 32 (TD)	1 - 14
Nafion™ 1110	254	None	-	-	43 (MD), 32 (TD)	1 - 14
Nafion™ N324	279.4	PTFE fabric	-	-	43 (MD), 32 (TD)	1 - 14
Nafion™ N438	304.8	PTFE fabric	-	-	-	1 - 14
Nafion™ N424	381	PTFE fabric	-	-	-	0 - 14

Fig. 90: Cation Exchange Membrane Comparison Chart [66]

20.23.2 Fuel Cell Electrode Layers - PEMFC catalysts

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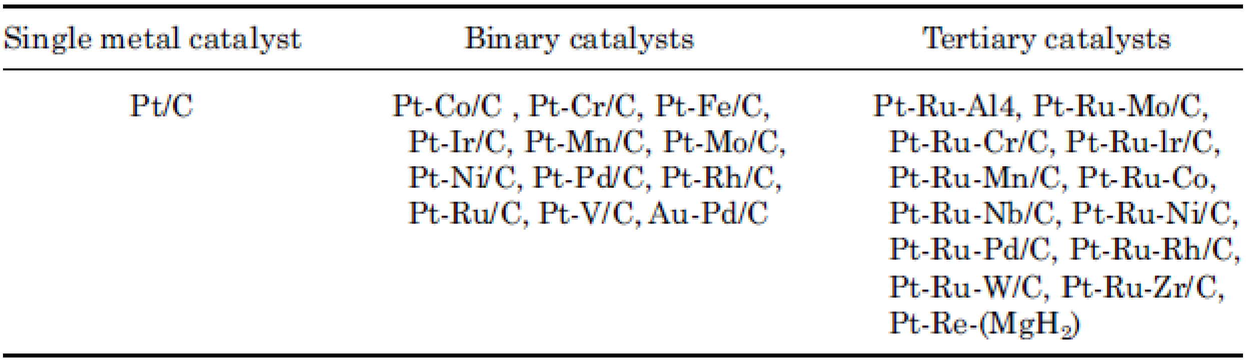
[66] https://www.fuelcellstore.com/blog-section/fuel-cell-materials-blog-articles/membrane-comparison-chart-2021



Single metal catalyst	Binary catalysts	Tertiary catalysts
Pt/C	Pt-Co/C , Pt-Cr/C, Pt-Fe/C, Pt-Ir/C, Pt-Mn/C, Pt-Mo/C, Pt-Ni/C, Pt-Pd/C, Pt-Rh/C, Pt-Ru/C, Pt-V/C, Au-Pd/C	Pt-Ru-Al4, Pt-Ru-Mo/C, Pt-Ru-Cr/C, Pt-Ru-Ir/C, Pt-Ru-Mn/C, Pt-Ru-Co, Pt-Ru-Nb/C, Pt-Ru-Ni/C, Pt-Ru-Pd/C, Pt-Ru-Rh/C, Pt-Ru-W/C, Pt-Ru-Zr/C, Pt-Re-(MgH_2)

Fig. 91: Anode catalyst materials

20.23.3 PEMFC gas diffusion layers

The gas diffusion layer is between the catalyst layer and the bipolar plates. In a PEMFC, the fuel cell layers (MEA) are sandwiched between flow field plates. On each side of the catalyst layer, there are gas diffusion backings. They provide electrical contact between the electrodes and the bipolar plates, and distribute reactants to the electrodes. They also allow reaction product water to exit the electrode surface and permit the passage of water between the electrodes and the flow channels.

Gas diffusion backings are made of a porous, electrically conductive material (usually carbon cloth or carbon paper). An illustration of carbon cloth and Toray paper is shown in Figure below. The substrate can be treated with a fluoropolymer and carbon black to improve water management and electrical properties. These material types promote effective diffusion of the reactant gases to the membrane/electrode assembly. The structure allows the gas to spread out as it diffuses to maximize the contact surface area of the catalyzed membrane. The thicknesses of various gas diffusion materials vary between 0.0017 to 0.04 cm, density varies between 0.21 to 0.73 g/cm2, and the porosity varies between 70 and 80 percent.

The GDL also helps with managing water in PEMFCs because it only allows an appropriate amount of water vapor to contact the membrane electrode assembly to keep the membrane humidified. In addition, it promotes the exit of liquid water from the cathode to help eliminate flooding. This layer is typically wet-proofed to ensure the pores in the carbon cloth or paper do not become clogged with water. The most common wet-proofing agent is PTFE.

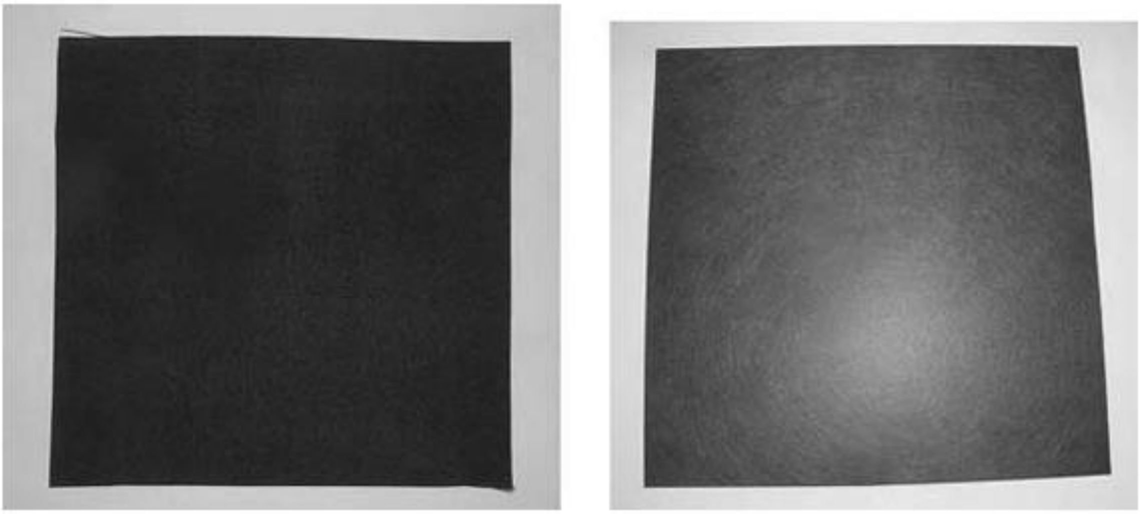
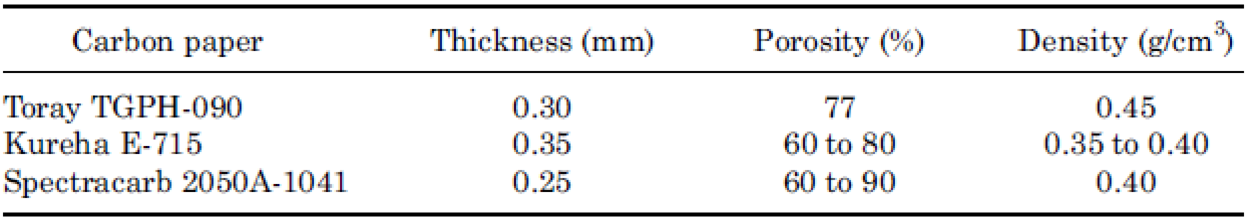


Fig. 92: Carbon cloth and toray paper (picture courtesy of Fuel Cell Scientific)

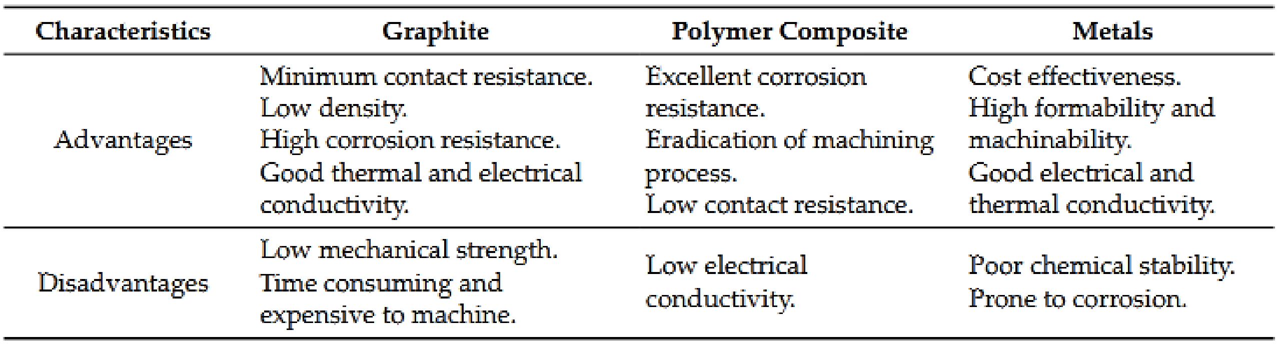


Carbon paper	Thickness (mm)	Porosity (%)	Density (g/cm^3)
Toray TGPH-090	0.30	77	0.45
Kureha E-715	0.35	60 to 80	0.35 to 0.40
Spectracarb 2050A-1041	0.25	60 to 90	0.40

Fig. 93: Properties of Commercially Available Carbon Papers Used as Substrates In PEMFC Electrodes

20.24 Constructing the Fuel Cell Bipolar Plates, Gaskets, End Plates, and Current Collectors

20.24.1 Bipolar plate design



Characteristics	Graphite	Polymer Composite	Metals
Advantages	Minimum contact resistance. Low density. High corrosion resistance. Good thermal and electrical conductivity.	Excellent corrosion resistance. Eradication of machining process. Low contact resistance.	Cost effectiveness. High formability and machinability. Good electrical and thermal conductivity.
Disadvantages	Low mechanical strength. Time consuming and expensive to machine.	Low electrical conductivity.	Poor chemical stability. Prone to corrosion.

Fig. 94: Properties of various types of bipolar plates for PEM fuel cells [67]

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[67] https://www.mdpi.com/1996-1073/11/11/3203/htm

Material	Process options	Plate size(s)
Aluminum	Machining Cold closed die forging Stamping Die-casting Investment casting Powder metal forging	Machining and cold closed die forging can be used for almost any size. Investment casting and powder metal forging can only be used for larger-faced, thinner plates.
Stainless steel	Machining Cold closed die forging Stamping Investment casting Powder metal forging	Machining and cold closed die forging can be used for almost any size. Investment casting and powder metal forging can only be used for larger-faced, thinner plates.
Titanium	Machining Cold closed die forging Stamping Investment casting Powder metal forging	Machining, stamping, and cold closed die forging can be used for almost any size. Investment casting and powder metal forging can only be used for certain-sized larger-faced, thinner plates.
Nickel	Machining Cold closed die forging Stamping Investment casting Powder metal forging Electroforming	Machining and cold closed die forging can be used for almost any size. Investment casting and powder metal forging can only be used for larger-faced, thinner plates. Electroforming should only be used for smaller-faced, thicker plates.
Carbon composite	Compression molding Injection molding Transfer molding Reaction injection molding	These processes should only be used for smaller-faced, thicker plates.

Fig. 95: Process Options for Bipolar Plates

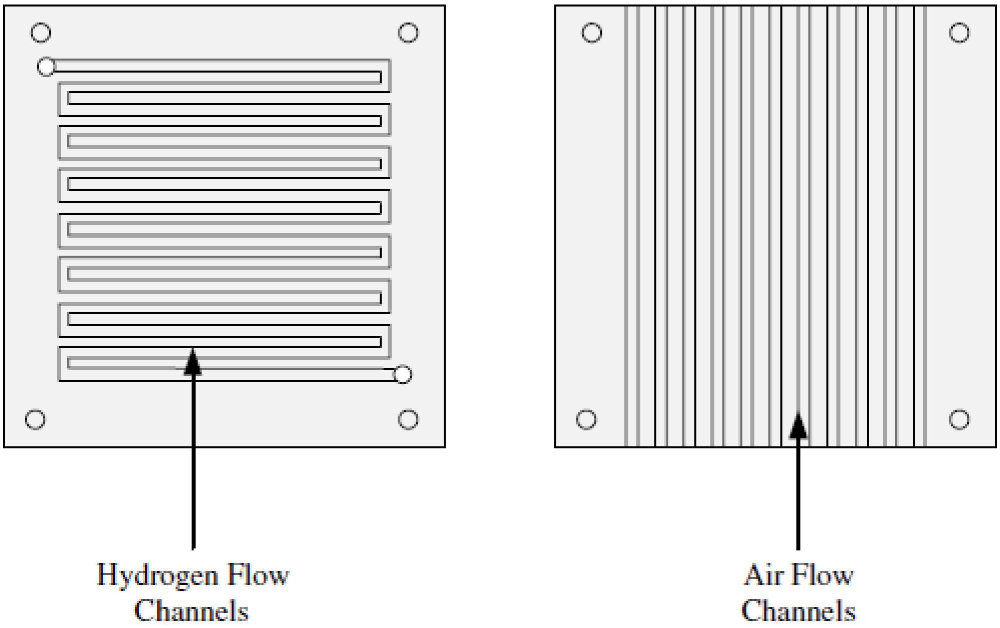


Fig. 96: Bipolar plate design for hydrogen and air flow channels for a PEMFC

20.24.2 Gasket selection

For the small air-breathing stack 0.010 or 0.020-inch silicone gaskets can be used (depending upon the fuel cell [MEA] thickness). Another popular option is using a 0.010-inch thick fiberglass reinforced silicone rubber anode gasket, and a 0.010-inch thick furan cathode gasket. The gasket is placed around the flow fields next to the electrode/diffusion layers to create a seal to prevent gas leakage.

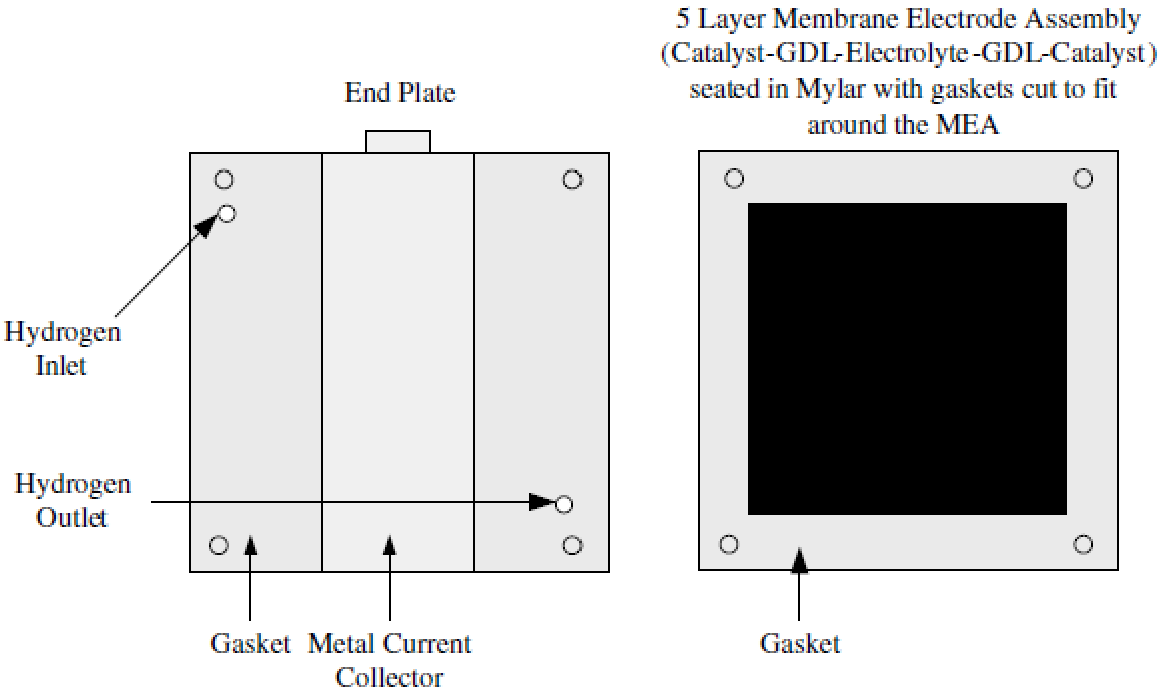


Fig. 97: Gaskets, end plate, and MEA for PEMFC

20.24.3 End plates

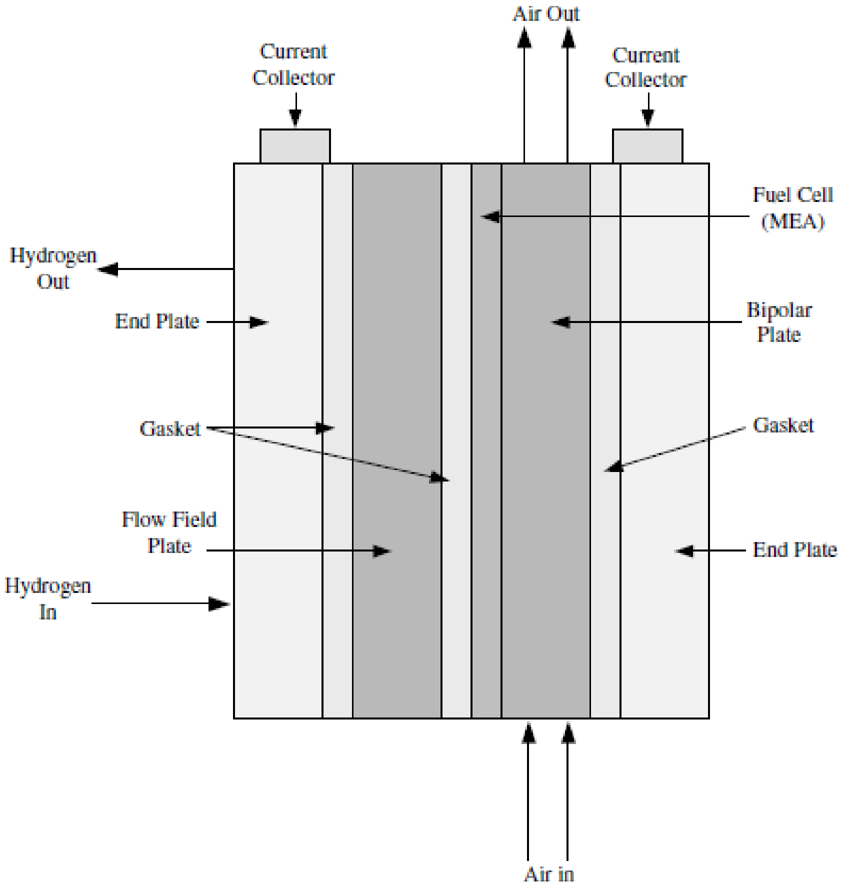


Fig. 98: End and flow field plates, gaskets, current collectors, and MEA for a single-cell PEMFC stack

20.25 Conclusion of Fuel Cell components

Components	Materials	Thickness
Electrolyte	Nafion 212	50 to 175 µm
	Nafion 117	~180 µm
Catalyst	Pt/C (platinum and carbon powder)	10 to 30 µm
GDL (Gas Diffusion Layer)	Carbon fiber paper	0.0017 to 0.04 cm
Bipolar plate	Graphite Titanium Stainless (Austenic TM349 , Ferritic AISI 446) Doped polymers	
Gaskets	Silicone EPDM PTFE	
Current collector	Graphite Titanium Copper Stainless	
End plate	Graphite Titanium Stainless Aluminum Nickel and polymers PVC Metal foams Polyethylene	

Fig. 99: Resumed the materials needed for our fuel cell

20.26 Bipolar plate design

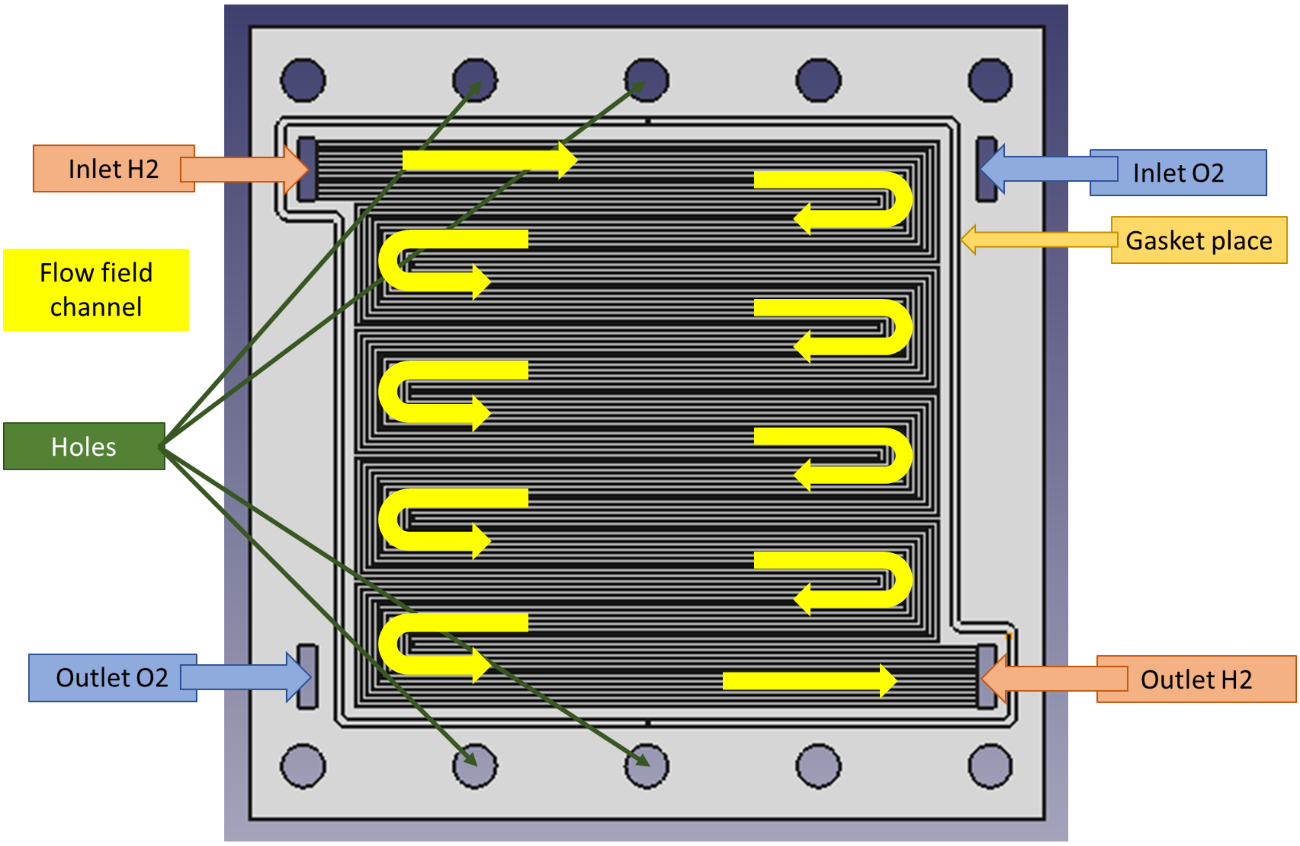
bipolar plate _
square design.FCStc

The description of the design :

Active area dimensions: 22 x 26 cm
Total Area Dimensions: 23.1 x 29 cm
Overall Dimensions (L x W x D): 30 x 30 x 0.4 cm

Graphite Plate Side A & B:

- Depth of Flow Fields: 0.75 mm
- Length Per Flow Field: 223.6 cm
- Number of Flow Field Lines: 6
- Total Length of Flow Fields: ~13.4 m



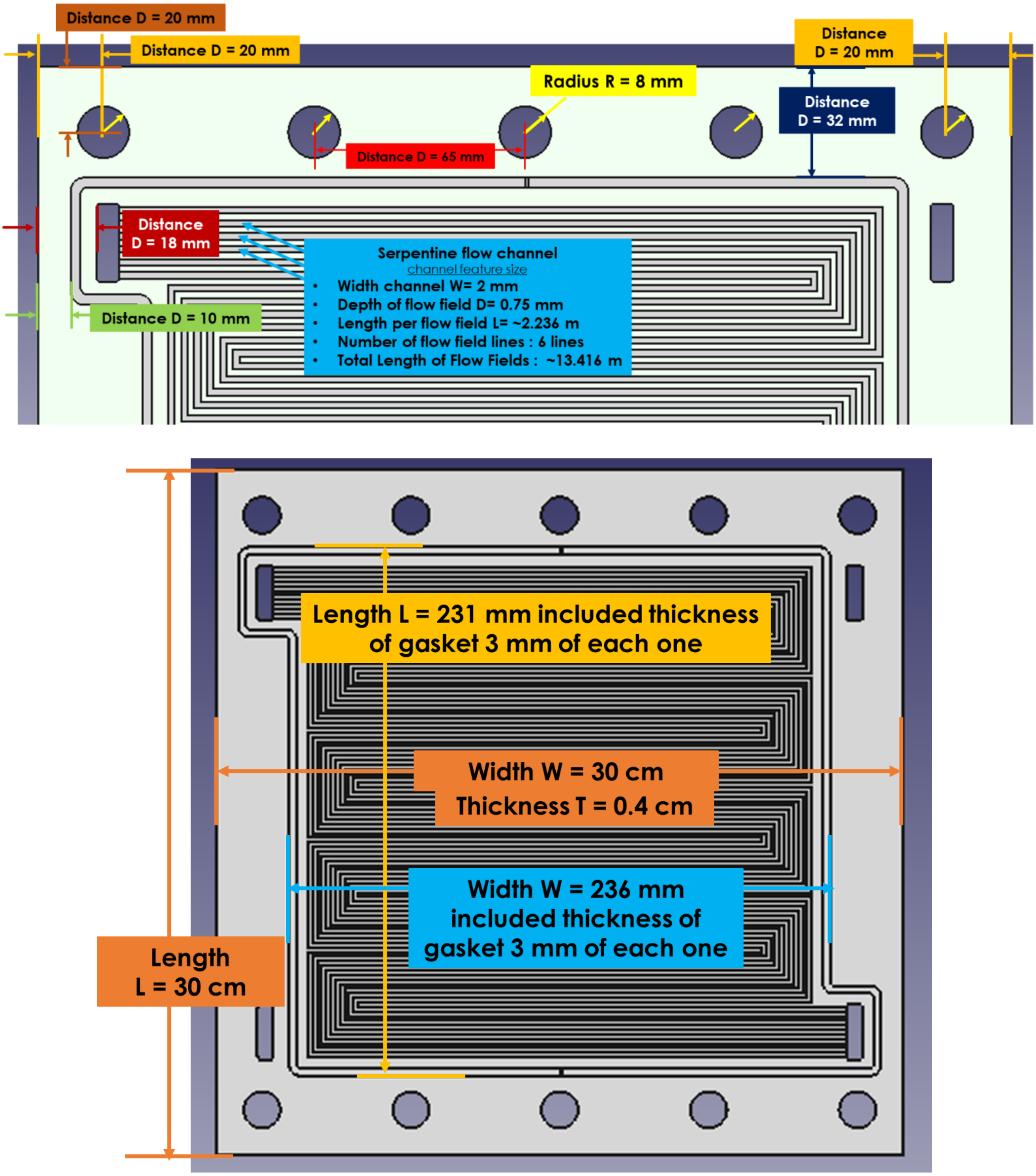
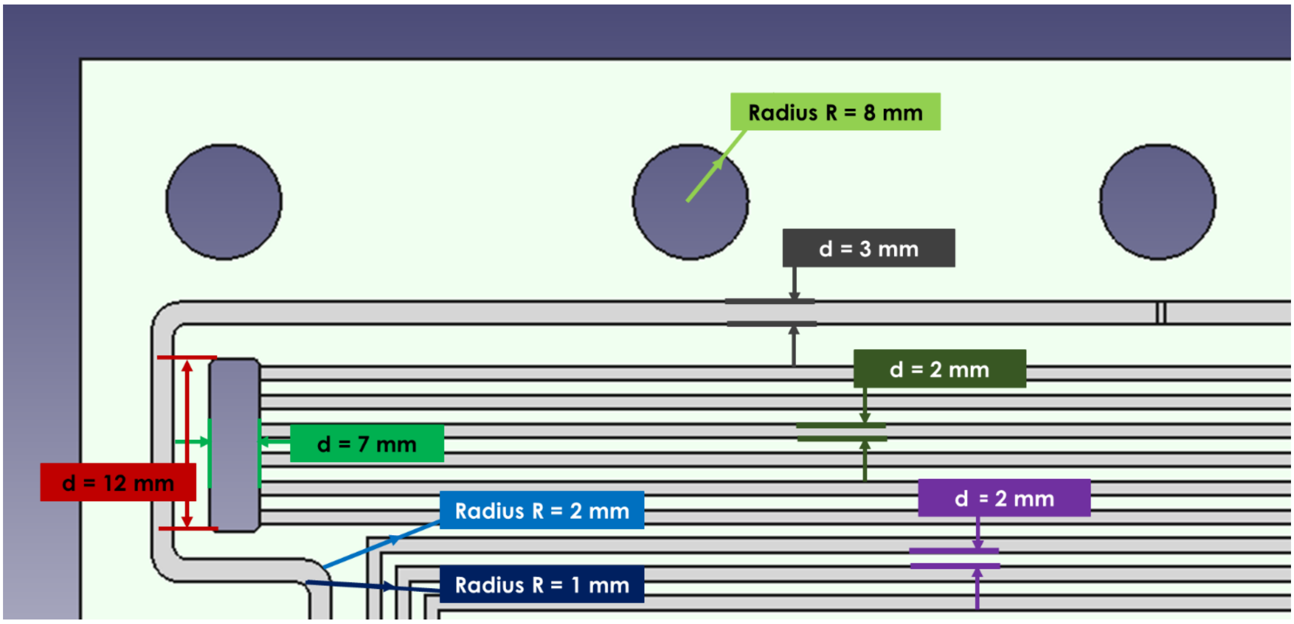
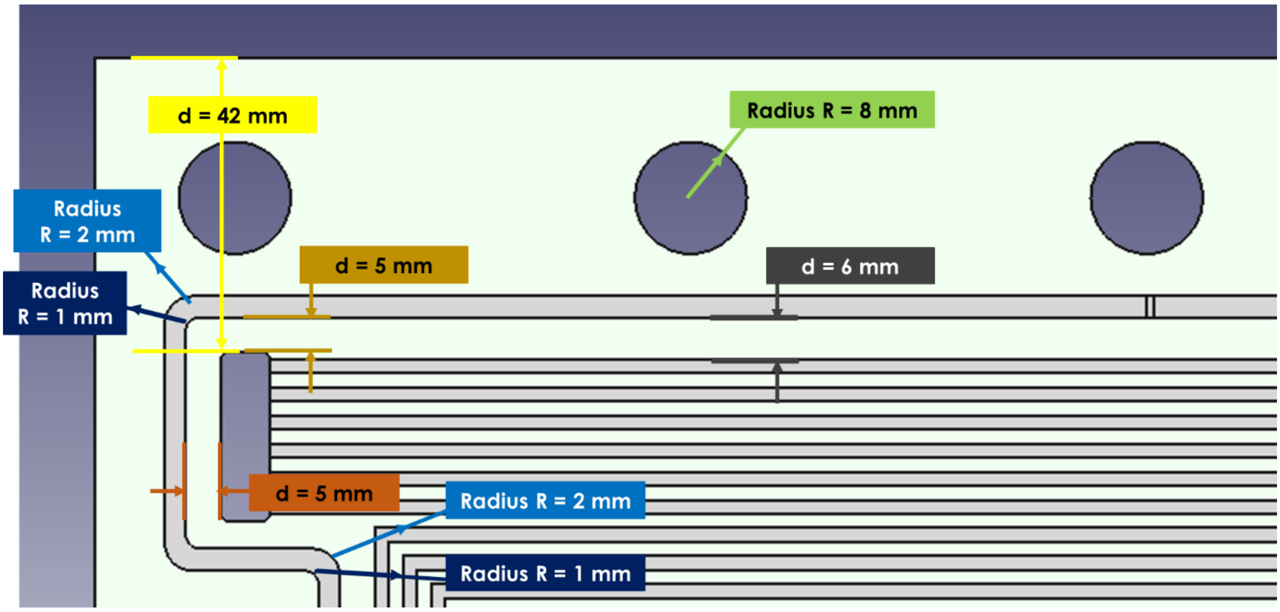
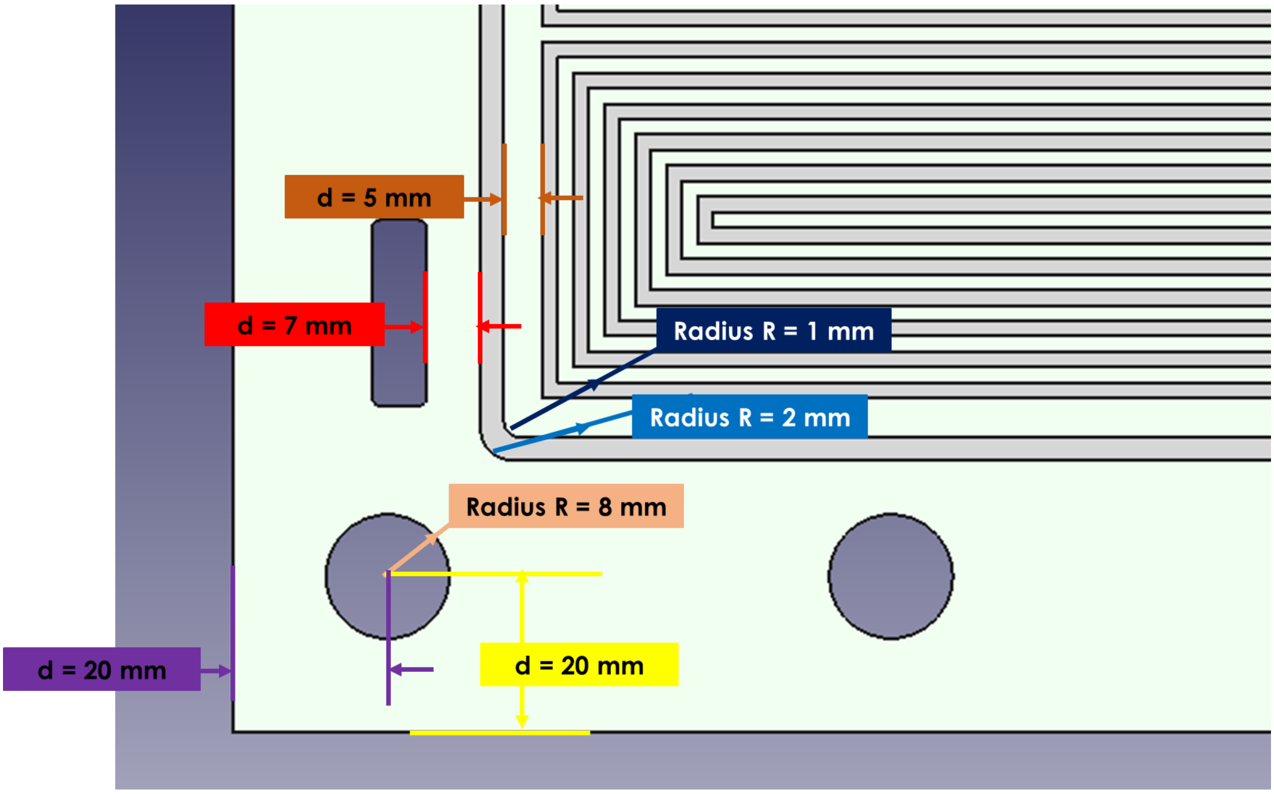


Fig. 100: Sizing of our fuel cell design

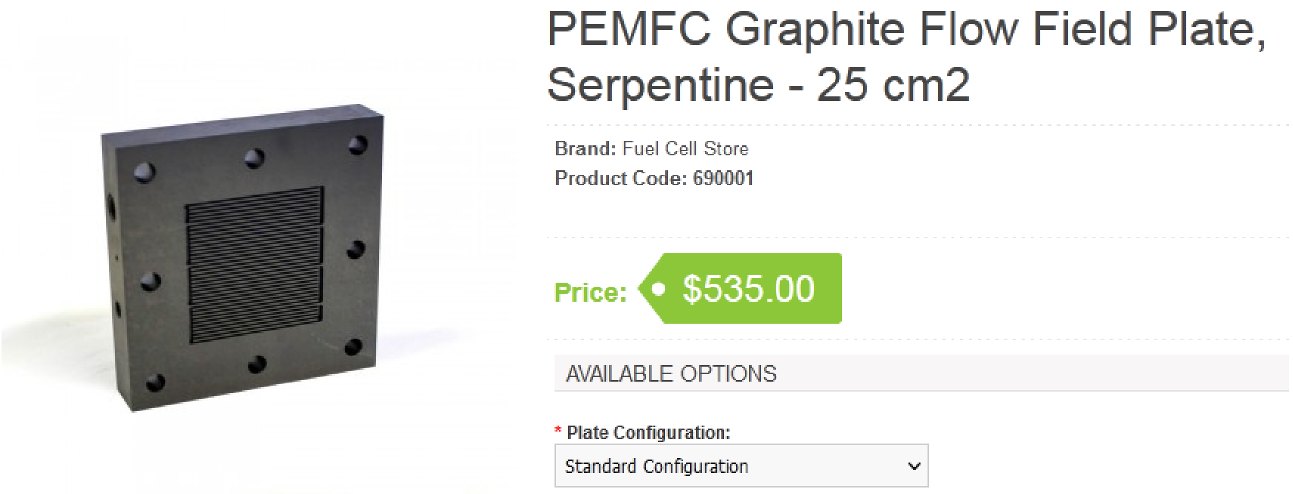

Radius R = 8 mm
d = 3 mm
d = 2 mm
d = 7 mm
d = 12 mm
d = 2 mm
Radius R = 2 mm
Radius R = 1 mm


d = 42 mm
Radius R = 8 mm
Radius R = 2 mm
Radius R = 1 mm
d = 5 mm
d = 6 mm
d = 5 mm
Radius R = 2 mm
Radius R = 1 mm



20.27 Components costs of one cell

20.27.1 PEMFC


PEMFC Graphite Flow Field Plate, Serpentine - 25 cm2

Brand: Fuel Cell Store
Product Code: 690001

Price: $535.00

* **Plate Configuration:** Standard Configuration

Active Area Dimensions: 5 x 5 cm (1.97" x 1.97")

Active Area: 25 cm^2 (or 3.87 in^2)

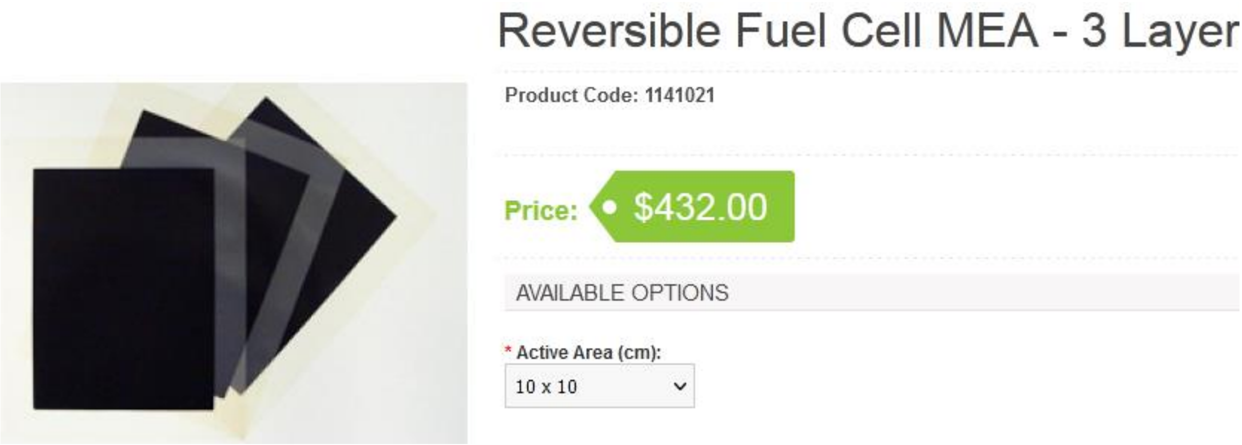
Flow Pattern or Channel Design: Serpentine (5-channels)

Total Physical Dimensions for Graphite Plates: 9.6 x 9.6 cm (3.77" x 3.77")

Thickness of the Graphite Plates: 1.9 cm (0.75")

20.27.2 MEA

Item #1:



Reversible Fuel Cell MEA - 3 Layer

Product Code: 1141021

Price: $432.00

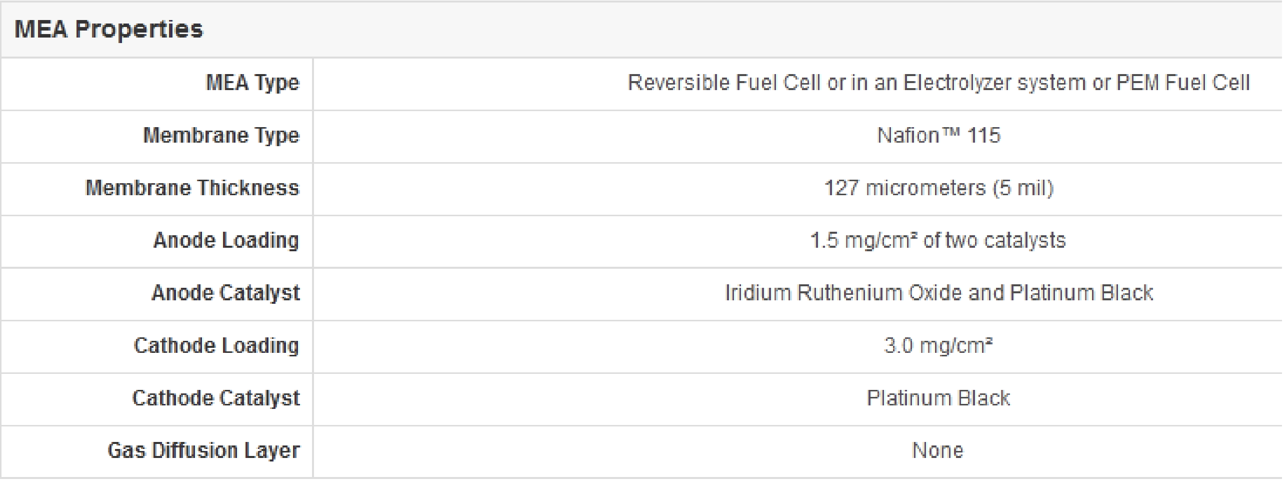
AVAILABLE OPTIONS

* Active Area (cm): 10 x 10

[68]

These Reversible Membrane Electrode Assemblies (MEA) can be used as in an Electrolyzer for Hydrogen production or in Polymer Electrolyte Fuel Cell (PEMFC) for electricity production. Perfect for educational products or demonstrations of the advantages of hydrogen as an energy storage medium. We can assist with additional customization as well as the unique design aspects of Reversible Fuel Cell / Electrolyzer systems. These Reversible MEAs come in a 3-Layer configuration, also known as a Catalyst Coated Membrane (CCM).

Active Area	Membrane Area	Costs
2.2cm x 2.2cm	10.0cm x 10.0cm	192 $
5.0cm x 5.0cm	10.0cm x 10.0cm	239 $
7.1cm x 7.1cm	13.0cm x 13.0cm	317 $
10.0cm x 10.0cm	13.0cm x 13.0cm	432 $



MEA Properties

MEA Type	Reversible Fuel Cell or in an Electrolyzer system or PEM Fuel Cell
Membrane Type	Nafion™ 115
Membrane Thickness	127 micrometers (5 mil)
Anode Loading	1.5 mg/cm² of two catalysts
Anode Catalyst	Iridium Ruthenium Oxide and Platinum Black
Cathode Loading	3.0 mg/cm²
Cathode Catalyst	Platinum Black
Gas Diffusion Layer	None

Item #2:

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[68] https://www.fuelcellstore.com/fuel-cell-components/membrane-electrode-assembly/reversible-fuel-cell-ccm

Hydrogen Air CCM - 3 Layer

Product Code: 2014013

Price: $232.00

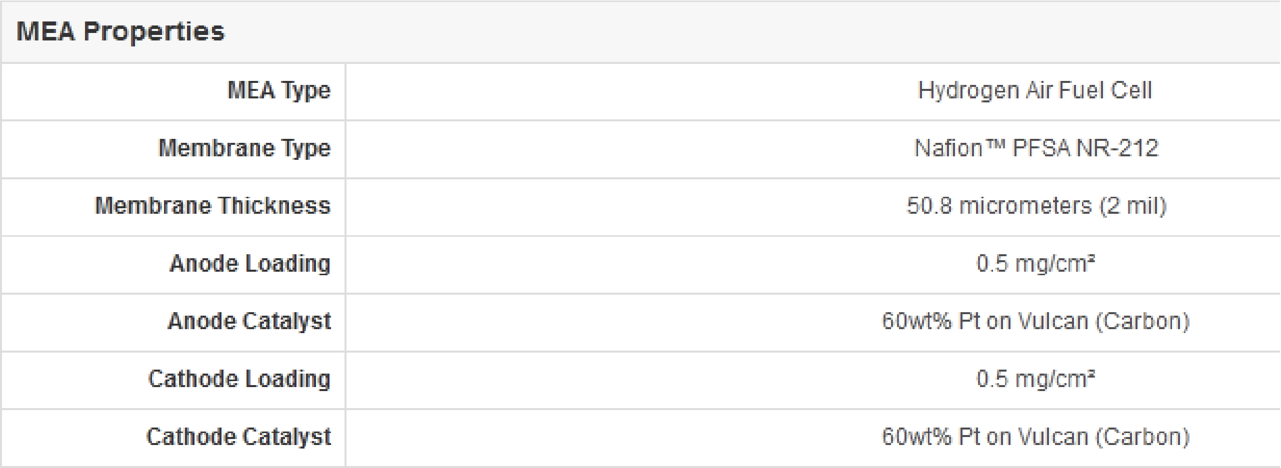
AVAILABLE OPTIONS

* Active Area (cm): 10 x 10

[69]

3-Layer, Catalyst Coated Membrane Electrode Assembly (MEA) for use in Hydrogen/Air Fuel Cells. One of the most economical and cost effective MEAs on the market, the standard configuration features a mid-range Platinum loading (0.5 mg/cm^2) on a 0.002″ membrane (Nafion® 212). Custom sizes and configurations are also available with no minimum order quantities and typical lead times of 1 to 5 business days, even for custom configurations. These Hydrogen Air MEAs are 3-Layer.

Active Area	Membrane Area	Costs
2.2cm x 2.2cm	10.0cm x 10.0cm	173 $
5.0cm x 5.0cm	10.0cm x 10.0cm	183 $
7.1cm x 7.1cm	13.0cm x 13.0cm	208 $
10.0cm x 10.0cm	13.0cm x 13.0cm	232 $



MEA Properties	
MEA Type	Hydrogen Air Fuel Cell
Membrane Type	Nafion™ PFSA NR-212
Membrane Thickness	50.8 micrometers (2 mil)
Anode Loading	0.5 mg/cm²
Anode Catalyst	60wt% Pt on Vulcan (Carbon)
Cathode Loading	0.5 mg/cm²
Cathode Catalyst	60wt% Pt on Vulcan (Carbon)

Item #3:

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[69] https://www.fuelcellstore.com/fuel-cell-components/membrane-electrode-assembly/ha-ccm


MEA for PEM Research Test Cell - 250cm²

Product Code: 550029

Price: $381.00

Qty: 1

[70]

This 5-Layer Membrane Electrode Assembly (MEA) is the standard MEA for use in the **PEM Research Test Cell - 250cm²**. Please contact us for custom configurations.

Specifications:

- Custom Die Cut to fit
- Membrane Type: **Nafion™ 212**
- Active Area: 256.5 x 97.5 mm
- Membrane Area: 310 x 115 mm
- Anode Loading & Catalyst: 0.3 mg/cm² Platinum on Carbon 40%
- Cathode Loading & Catalyst: 0.3 mg/cm² Platinum on Carbon 40%
- Gas Diffusion Layer: **Sigracet 28BC**
- Gas Diffusion Layer Type : Carbon Paper

Item #4:


Hydrogen Oxygen MEA - 5 Layer

Product Code: 591214

Price: $453.00

AVAILABLE OPTIONS

* Active Area (cm): 10 x 10

[71]

High performance Polymer Electrolyte Fuel Cell (PEMFC) Membrane Electrode Assembly (MEA) where performance and efficiency is critical. They can be used in Hydrogen/Air or Hydrogen/Oxygen fuel cells. The most economical high performance MEA on the market, the standard configuration features a high Platinum loading (4 mg/cm²) and a 0.005" membrane (Nafion™ 115) with a 365 um thick carbon cloth GDL (others

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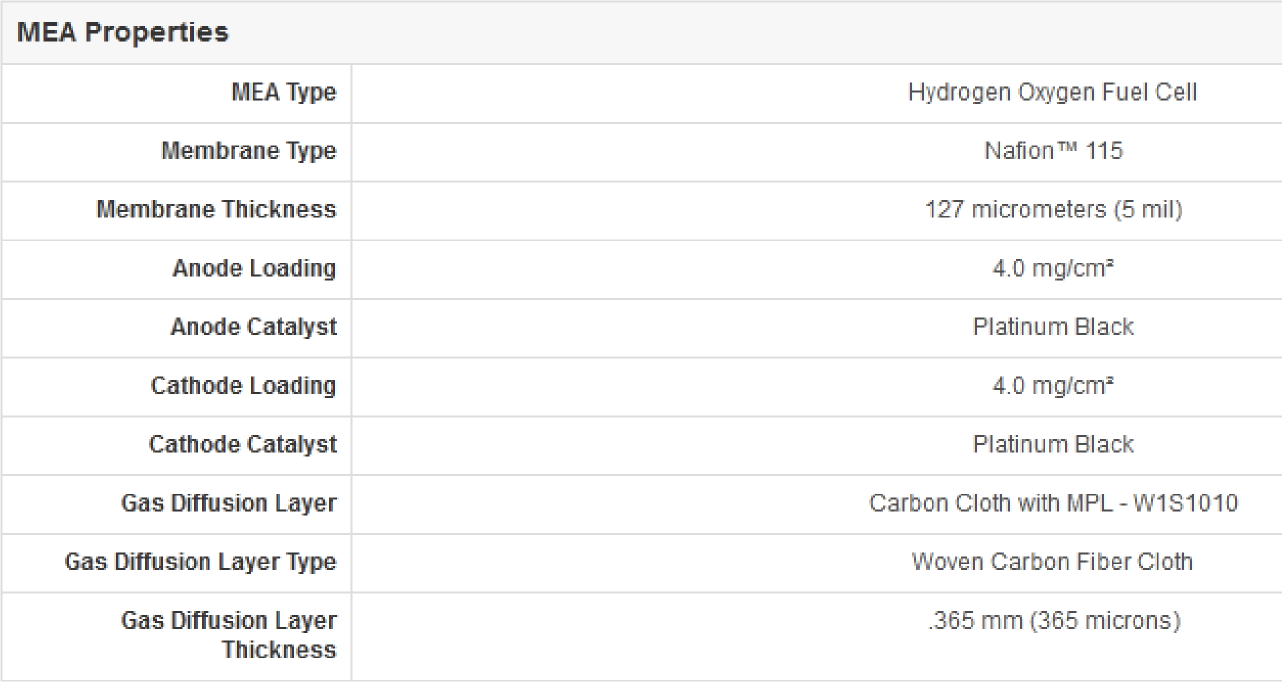
[70] https://www.fuelcellstore.com/fuel-cell-components/membrane-electrode-assembly/mea-pem-research-test-cell-250cm

[71] https://www.fuelcellstore.com/fuel-cell-components/membrane-electrode-assembly/hydrogen-oxygen-mea

available). Custom sizes and configurations are also available with no minimum order quantities and typical lead times of 1 to 5 days, even for custom configurations. These Hydrogen Oxygen MEAs are 5-Layer.

Active Area	Membrane Area	Costs
2.2cm x 2.2cm	10.0cm x 10.0cm	165 $
5.0cm x 5.0cm	10.0cm x 10.0cm	222 $
7.1cm x 7.1cm	13.0cm x 13.0cm	312 $
10.0cm x 10.0cm	13.0cm x 13.0cm	453 $



MEA Properties

MEA Type	Hydrogen Oxygen Fuel Cell
Membrane Type	Nafion™ 115
Membrane Thickness	127 micrometers (5 mil)
Anode Loading	4.0 mg/cm²
Anode Catalyst	Platinum Black
Cathode Loading	4.0 mg/cm²
Cathode Catalyst	Platinum Black
Gas Diffusion Layer	Carbon Cloth with MPL - W1S1010
Gas Diffusion Layer Type	Woven Carbon Fiber Cloth
Gas Diffusion Layer Thickness	.365 mm (365 microns)

20.27.2.1 21.2.1. Nafion for Electrolyte

Item #1:

Nafion™ HP

Brand: Chemours

Product Code: 1600000-2

Price: $184.00

AVAILABLE OPTIONS

* Size (cm): 30 x 30

[72]

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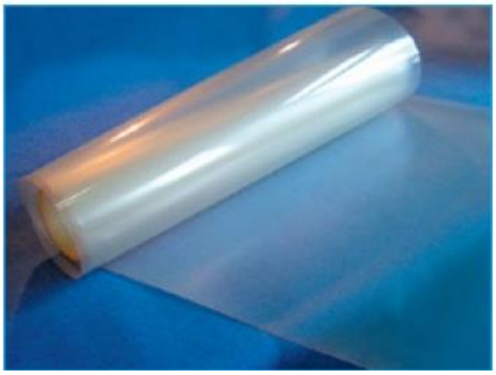
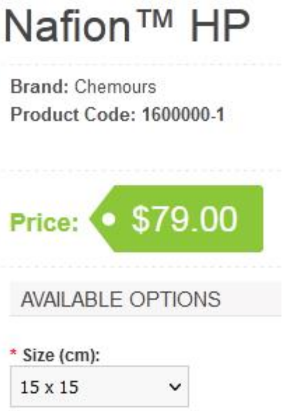
[72] https://www.fuelcellstore.com/fuel-cell-components/nafion-hp?sort=p.sort_order&order=ASC





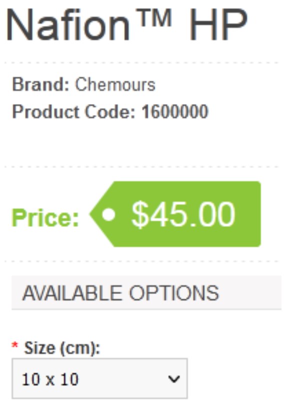
Nafion™ HP

Brand: Chemours
Product Code: 1600000-1

Price: $79.00

AVAILABLE OPTIONS

* **Size (cm):** 15 x 15



Nafion™ HP

Brand: Chemours
Product Code: 1600000

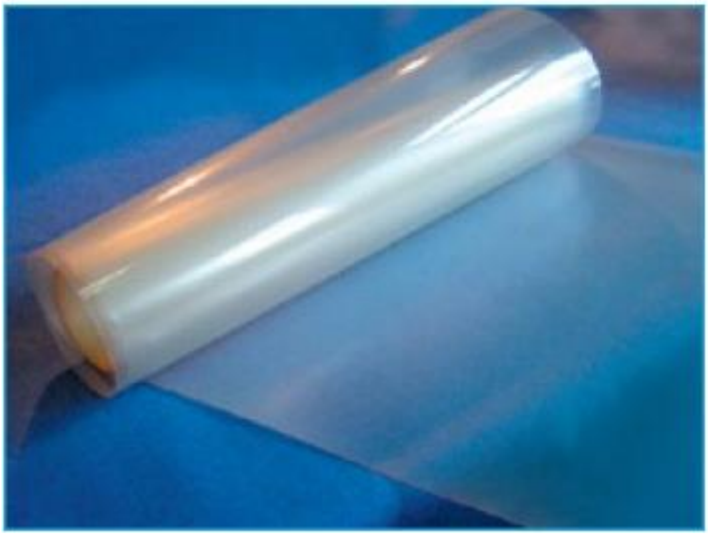
Price: $45.00

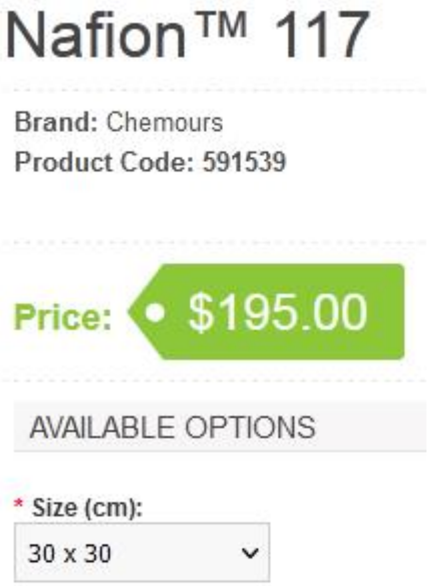
AVAILABLE OPTIONS

* **Size (cm):** 10 x 10

Nafion™ HP membranes are ultra-thin cation exchange membranes that are manufactured by the Chemours Company. These membranes are reinforced and designed for lower relative humidity environments and high operating temperature. The reinforcement improves the membrane's handling and physical properties. When the reinforcement is combined with the chemically stabilized polymer, the Nafion™ HP membrane exhibits both substantially lower fluoride ion release and longer operating durability under challenging fuel cell conditions. Nafion™ HP is 20.3 micrometers (0.8 mil) thick. The membrane is positioned between a backing film and a coversheet.

Item #2:





Nafion™ 117

Brand: Chemours
Product Code: 591539

Price: $195.00

AVAILABLE OPTIONS

* **Size (cm):** 30 x 30

[73]

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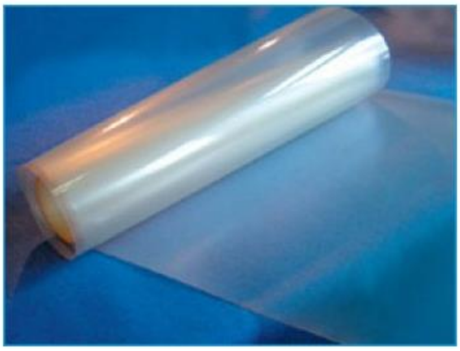
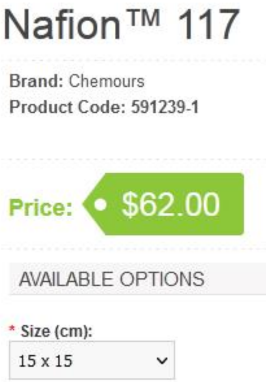
[73] https://www.fuelcellstore.com/nafion-117





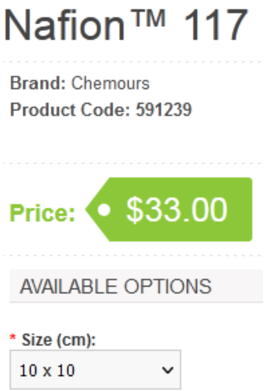
Nafion™ 117

Brand: Chemours
Product Code: 591239-1

Price: $62.00

AVAILABLE OPTIONS

* **Size (cm):** 15 x 15



Nafion™ 117

Brand: Chemours
Product Code: 591239

Price: $33.00

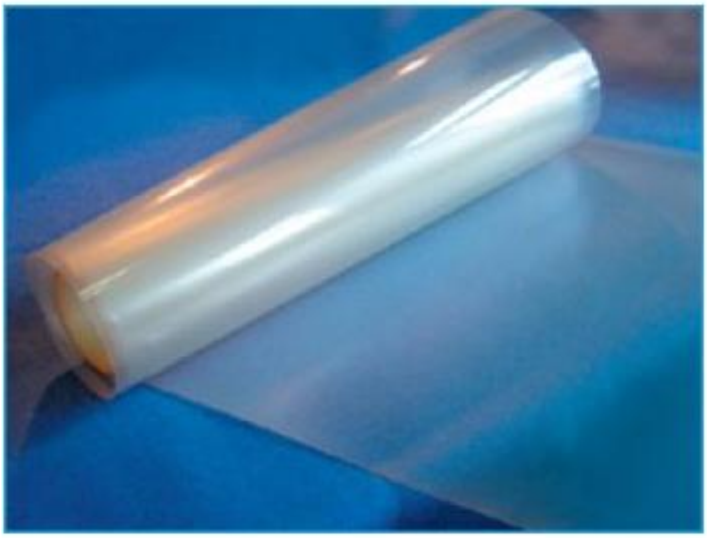
AVAILABLE OPTIONS

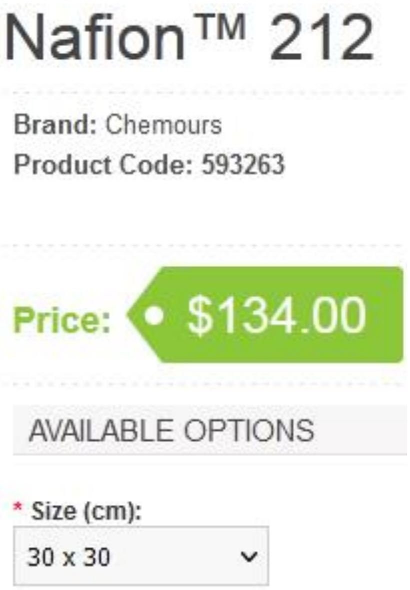
* **Size (cm):** 10 x 10

Nafion™ Membrane is used to separate the anode and cathode compartment of Proton Exchange Membrane fuel cells and water electrolyzers. The thickness of this particular cation exchange membrane, Nafion™ 117 makes it suitable for Direct Methanol Fuel Cells (DMFC). Nafion™ 117 is 183 micrometers (7.2 mil) thick.

Chemours (formerly DuPont) Nafion™ 117 membranes are non-reinforced films based on chemically stabilized perfluorosulfonic acid/PTFE copolymer in the acid (H+) form. The physical properties remain the same for the chemically stabilized membranes, which exhibit substantially lower fluoride ion release compared to the non-stabilized polymer – a sign of improved chemical durability. Nafion™ PFSA membranes are widely used for Proton Exchange Membrane (PEM) fuel cells and water electrolyzers. The membrane performs as a separator and solid electrolyte in a variety of electrochemical cells that require the membrane to selectively transport cations across the cell junction. The polymer is chemically resistant and durable.

Item #3:





Nafion™ 212

Brand: Chemours
Product Code: 593263

Price: $134.00

AVAILABLE OPTIONS

* **Size (cm):** 30 x 30

[74]

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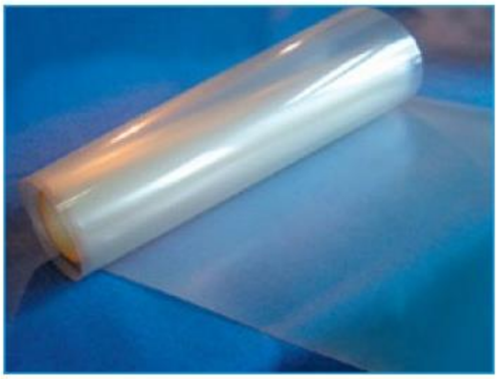
[74] https://www.fuelcellstore.com/nafion-212



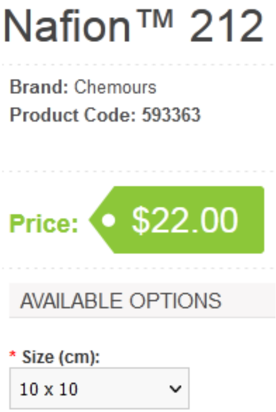
Nafion™ 212

Brand: Chemours
Product Code: 593363-1

Price: $39.00

AVAILABLE OPTIONS

* **Size (cm):**
15 x 15



Nafion™ 212

Brand: Chemours
Product Code: 593363

Price: $22.00

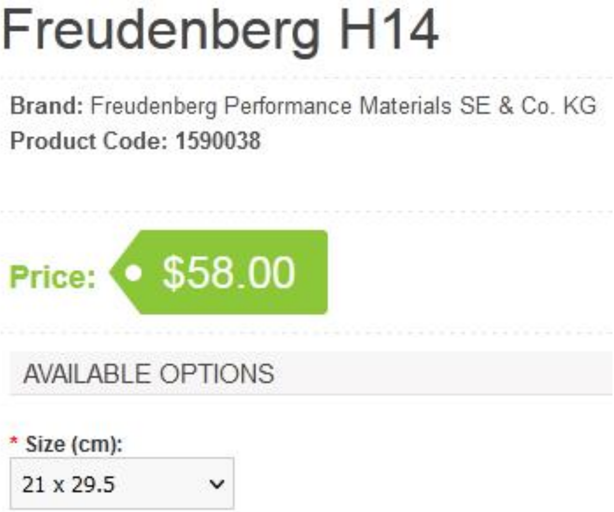
AVAILABLE OPTIONS

* **Size (cm):**
10 x 10

Nafion™ Membrane is used to separate the anode and cathode compartment of Proton Exchange Membrane fuel cells and water electrolyzers. The thickness of this particular cation exchange membrane, Nafion™ 212 makes it suitable for many Hydrogen Air/Oxygen Fuel Cell applications. Nafion™ 212 is 50.8 micrometers (2 mil) thick. The membrane is positioned between a backing film and a coversheet.

Chemours (formerly DuPont) Nafion™ PFSA NR-212 membranes are based on chemically stabilized perfluorosulfonic acid/PTFE copolymer in the acid (H+) form, and exhibit substantially lower fluoride ion release compared to the non-stabilized polymer – a sign of improved chemical durability. Nafion™ PFSA membranes are widely used for Proton Exchange Membrane (PEM) fuel cells and water electrolyzers. The membrane performs as a separator and solid electrolyte in a variety of electrochemical cells that require the membrane to selectively transport cations across the cell junction. The polymer is chemically resistant and durable.

20.27.2.2 21.2.2. Carbon paper for GDL



Freudenberg H14

Brand: Freudenberg Performance Materials SE & Co. KG
Product Code: 1590038

Price: $58.00

AVAILABLE OPTIONS

* **Size (cm):**
21 x 29.5

[75]

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[75] https://www.fuelcellstore.com/fuel-cell-components/freudenberg-h1410?sort=p.model&order=ASC

Freudenberg H14

Brand: Freudenberg Performance Materials SE & Co. KG
Product Code: 1590039

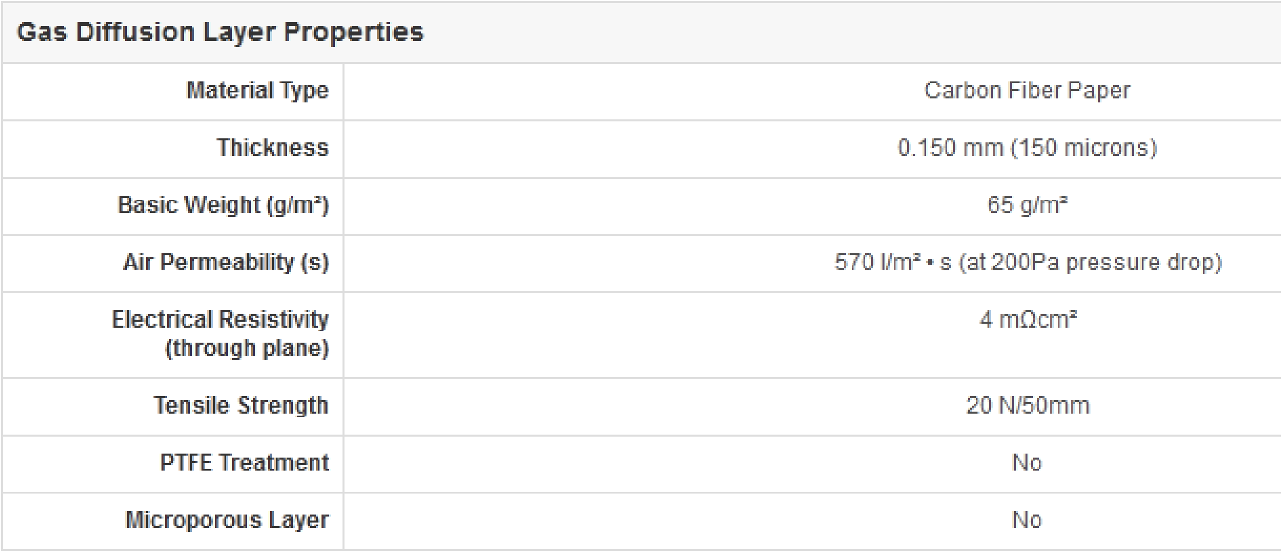
Price: $92.00

AVAILABLE OPTIONS

* **Size (cm):**
42 x 29.5

Freudenberg H14 is a flexible and easy to use **base carbon paper** Gas Diffusion Layer (GDL) **without** a Microporous Layer (MPL) and **without** a hydrophobic treatment. It is 150 um (microns) thick.

Freudenberg H14 is formerly known as H1410.



Gas Diffusion Layer Properties	
Material Type	Carbon Fiber Paper
Thickness	0.150 mm (150 microns)
Basic Weight (g/m²)	65 g/m²
Air Permeability (s)	570 l/m² • s (at 200Pa pressure drop)
Electrical Resistivity (through plane)	4 mΩcm²
Tensile Strength	20 N/50mm
PTFE Treatment	No
Microporous Layer	No

20.27.2.3 21.2.3. GDL+Catalyst

0.2 mg/cm^2 20% Platinum on Vulcan - Carbon Cloth Electrode (W1S1010)

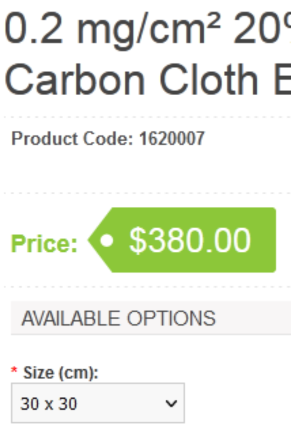
Product Code: 1620007-1

Price: $634.00

AVAILABLE OPTIONS

* Size (cm): 40 x 40

[76]



0.2 mg/cm^2 20

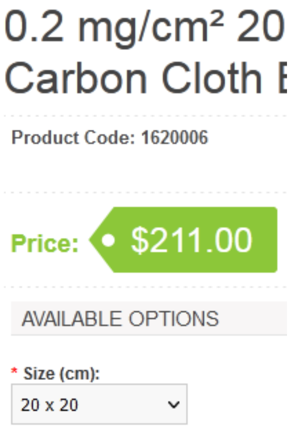
Carbon Cloth E

Product Code: 1620007

Price: $380.00

AVAILABLE OPTIONS

* Size (cm): 30 x 30



0.2 mg/cm^2 20

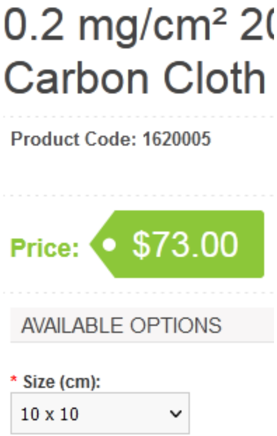
Carbon Cloth

Product Code: 1620006

Price: $211.00

AVAILABLE OPTIONS

* Size (cm): 20 x 20



0.2 mg/cm^2 2

Carbon Cloth

Product Code: 1620005

Price: $73.00

AVAILABLE OPTIONS

* Size (cm): 10 x 10

A low-cost electrode utilizing a woven carbon cloth substrate and a 20% Platinum on Vulcan Carbon support catalyst. This low loading is designed for cost sensitive applications and is suitable for electrochemical systems needing low amounts of Platinum to support the reaction. This electrode is perfect for Hydrogen/Air Fuel Cell applications where the extra cost of the higher loading GDE may not be justified. The Gas Diffusion Layer (GDL) used is a standard carbon cloth with MPL which is 365 microns thick. Other GDL materials are also available by custom request, as are custom sizes and loadings.

Includes a Nafion Post Coat for improved water management and adhesion to the membrane.

0.2 mg/cm^2 20% Platinum on Vulcan - Carbon Cloth Electrode (W1S1009) has been discontinued and was permanently replaced by 0.2 mg/cm^2 20% Platinum on Vulcan - Carbon Cloth Electrode (W1S1010).

20.27.3 Bipolar plate

Item #1:

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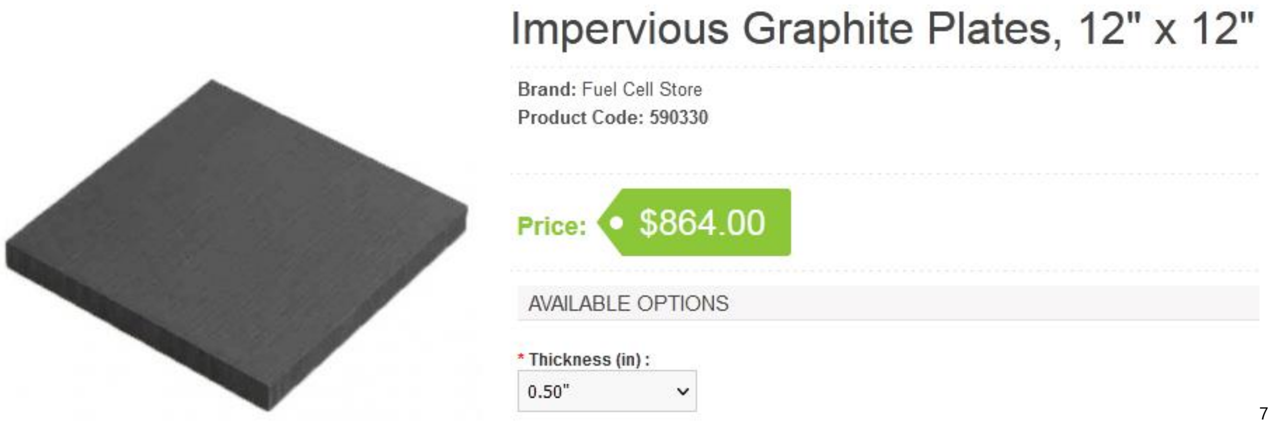
[76] https://www.fuelcellstore.com/fuel-cell-components/carbon-cloth-02-ptc-gas-diffusion-electrode-w1s1010?sort=p.sort_order&order=ASC



Impervious Graphite Plates, 12" x 12"

Brand: Fuel Cell Store
Product Code: 590330

Price: $864.00

AVAILABLE OPTIONS

* Thickness (in) :
0.50"

[77]

Impervious Graphite Plates, 12" x 12"

Brand: Fuel Cell Store
Product Code: 590329

Price: $452.00

AVAILABLE OPTIONS

* Thickness (in) :
0.25"

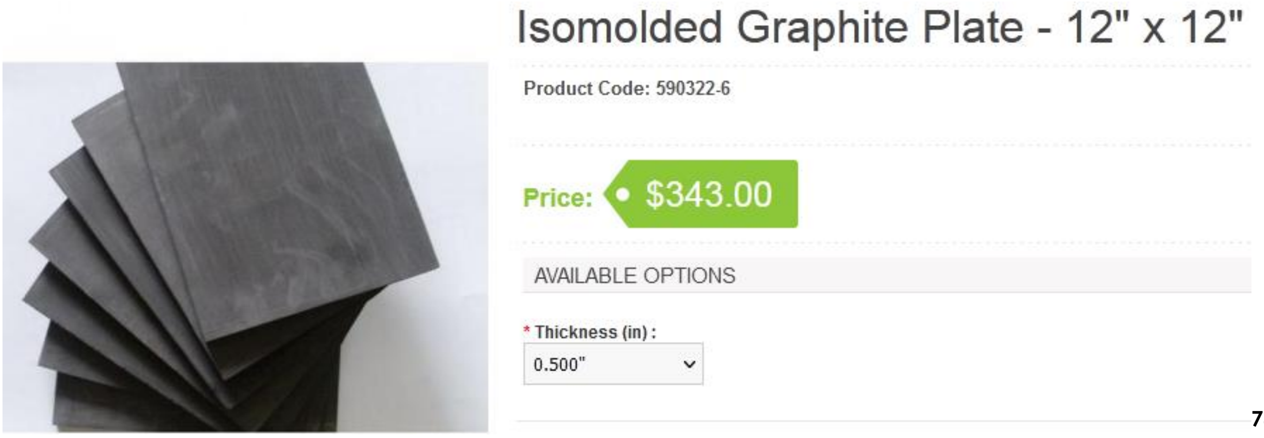
Fuel Cell Grade Graphite Plates can be machined on both sides to be used as bi-polar plates. These plates exhibit high electrical and thermal conductivity, incredible resistance to chemicals, and are densified and resin-filled for low permeability.

Length x Width: 12.0"x 12.0"

Thickness Tolerance: +0.125" / -0"

Length and Width Tolerance: +0.75" / -0"

Item #2:



Isomolded Graphite Plate - 12" x 12"

Product Code: 590322-6

Price: $343.00

AVAILABLE OPTIONS

* Thickness (in) :
0.500"

[78]

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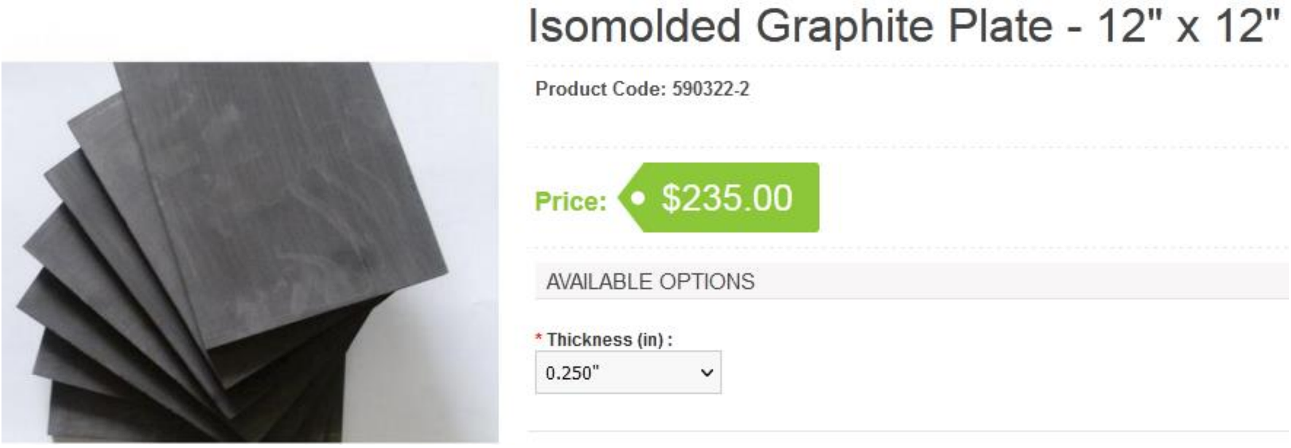
[77] https://www.fuelcellstore.com/impervious-bipolar-graphite-plates

[78] https://www.fuelcellstore.com/isomolded-plate-144



Isomolded Graphite Plate - 12" x 12"

Product Code: 590322-2

Price: $235.00

AVAILABLE OPTIONS

* Thickness (in) :

0.250"

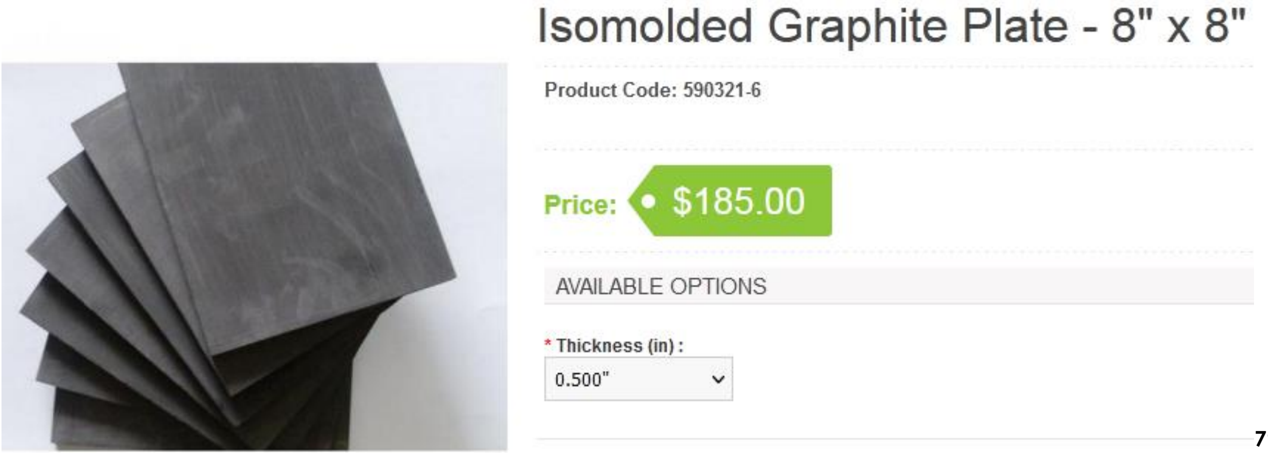
These Isomolded Graphite Plates can be machined on both sides. Isomolded plates are made out of very fine grain, high strength and density graphite. These plates are Isostatically pressed.

Size - 12.0" x 12.0"

Thickness Tolerance +/- 0.001"

Length and Width Tolerance +/- 0.005"

<u>Item #3:</u>



Isomolded Graphite Plate - 8" x 8"

Product Code: 590321-6

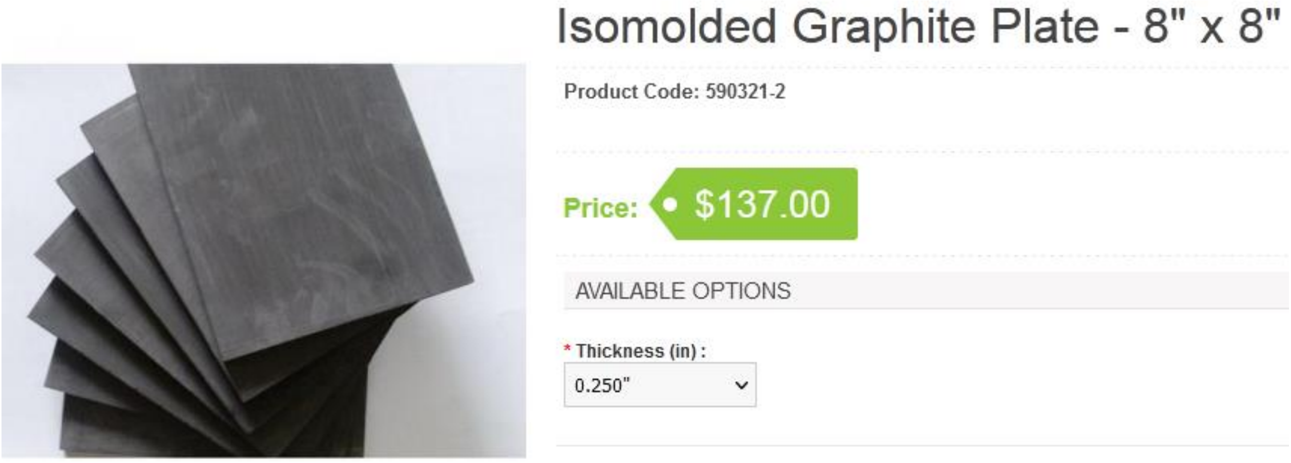
Price: $185.00

AVAILABLE OPTIONS

* Thickness (in) :

0.500"

[79]



Isomolded Graphite Plate - 8" x 8"

Product Code: 590321-2

Price: $137.00

AVAILABLE OPTIONS

* Thickness (in) :

0.250"

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[79] https://www.fuelcellstore.com/isomolded-plate-064

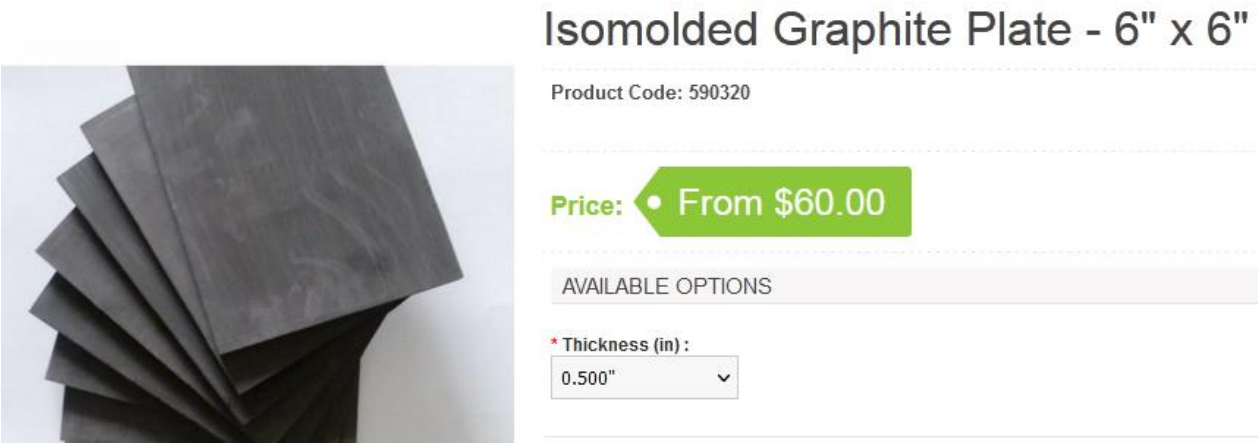
These Isomolded Graphite Plates can be machined on both sides. Isomolded plates are made out of very fine grain, high strength and density graphite. These plates are Isostatically pressed.

Size - 8.0" x 8.0"

Thickness Tolerance +/- 0.001"

Length and Width Tolerance +/- 0.005"

Item #4:



Isomolded Graphite Plate - 6" x 6"

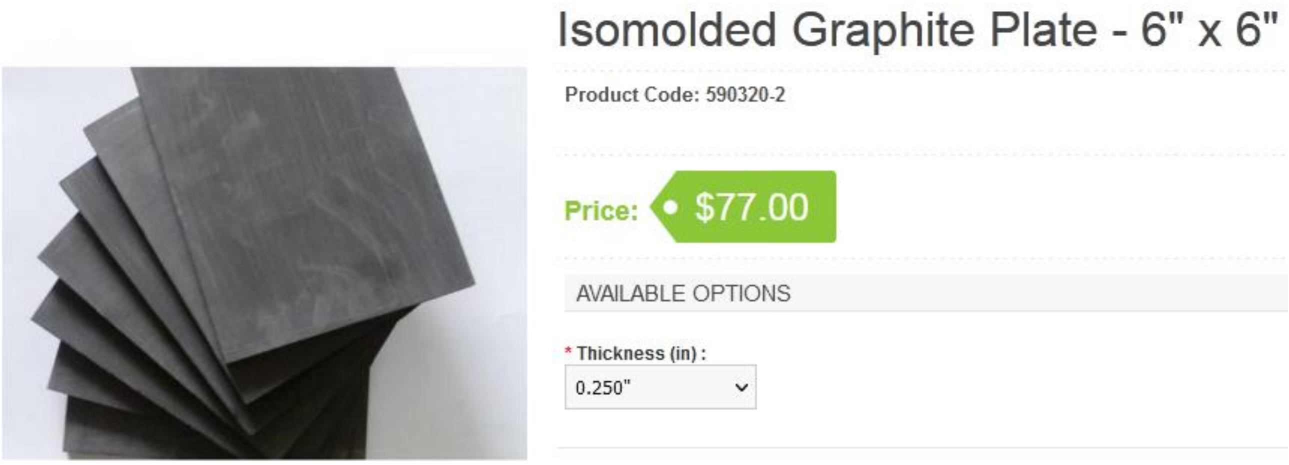
Product Code: 590320

Price: From $60.00

AVAILABLE OPTIONS

* Thickness (in) : 0.500"

[80]



Isomolded Graphite Plate - 6" x 6"

Product Code: 590320-2

Price: $77.00

AVAILABLE OPTIONS

* Thickness (in) : 0.250"

These Isomolded Graphite Plates can be machined on both sides. Isomolded plates are made out of very fine grain, high strength and density graphite. These plates are Isostatically pressed.

Size - 6.0" x 6.0"

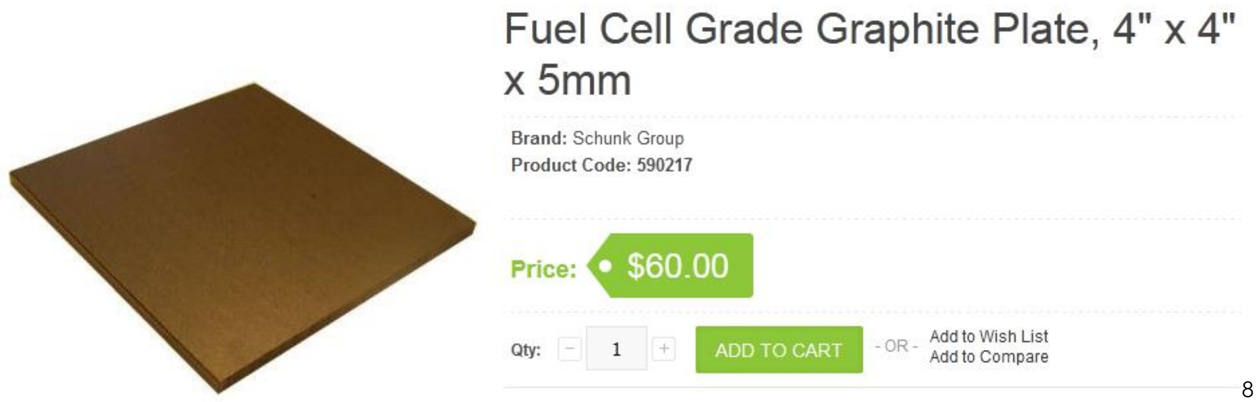
Thickness Tolerance +/- 0.001"

Length and Width Tolerance +/- 0.005"

Item #5:

---

[80] https://www.fuelcellstore.com/isomolded-plate-036



Fuel Cell Grade Graphite Plate, 4" x 4" x 5mm

Brand: Schunk Group
Product Code: 590217

Price: $60.00

Qty: 1

[81]

Fuel Cell Grade Graphite Plates can be machined on both sides to be used as bi-polar plates. The materials used in production allow for very high fuel cell performance. Continuous compound production permits homogeneity and high material quality. These bipolar plates allow fuel cells to operate at high temperatures and have excellent electrical and thermal conductivity.

Length x Width - 4"x 4"

Thickness - 5mm (0.197")

Flex-Stak Closed Bipolar Graphite Plate - 10 cm²

Product Code: 590335

Price: $59.00

Qty: 1

[82]

These closed bipolar graphite plates can be used as replacements plates for the [Flex-Stak Electrochemical Cell](), or you can use them as the basis to build your own closed fuel cell.

Active Area Dimensions: 3.2 x 3.2 cm

Total Area Dimensions: 5.3 x 5.3 cm

Overall Dimensions (L x W x D): 6.3 x 6.3 x 0.4 cm

Graphite Plate Specifications:

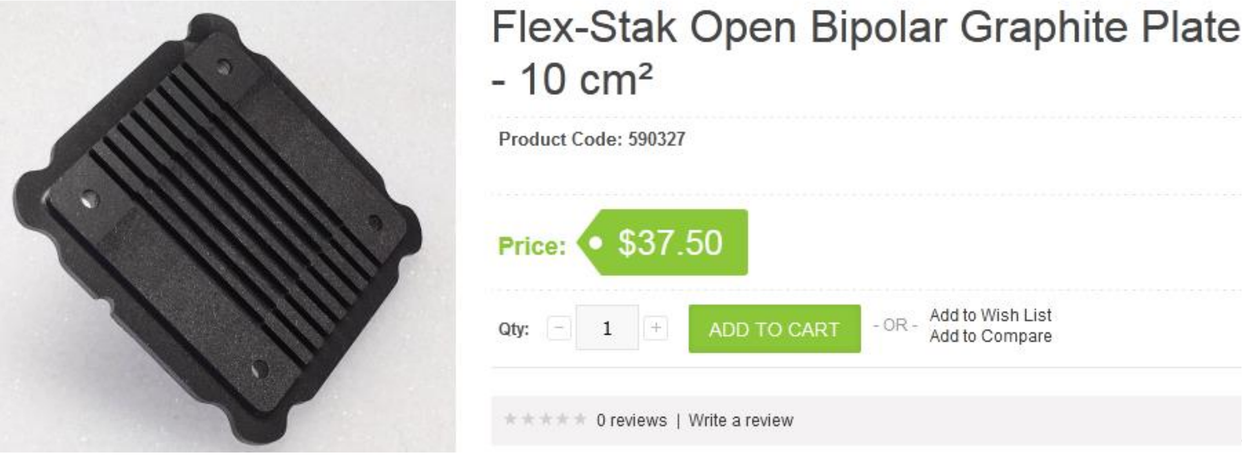
---

[81] https://www.fuelcellstore.com/bipolar-plate-5mm

[82] https://www.fuelcellstore.com/flex-stak-anode-bipolar-plate?search=Bipolar%20Graphite%20Plate

- Depth of Flow Fields: 0.75 mm
- Length Per Flow Field: 30 mm
- Number of Flow Field Lines: 8
- Total Length of Flow Fields: 240 mm

Item #6:



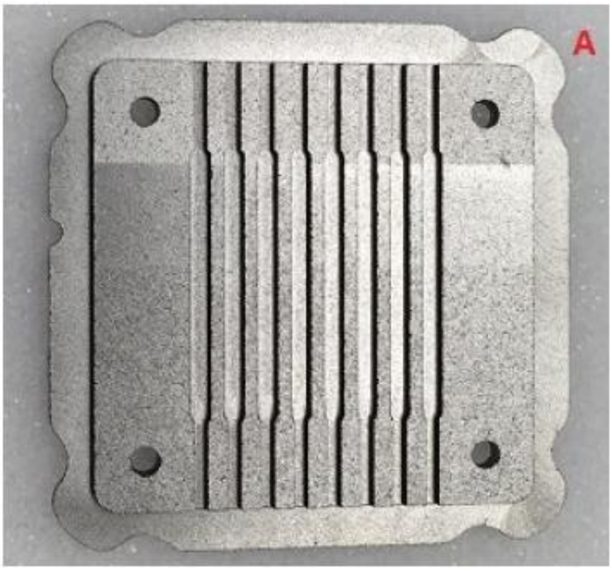
Flex-Stak Open Bipolar Graphite Plate - 10 cm²

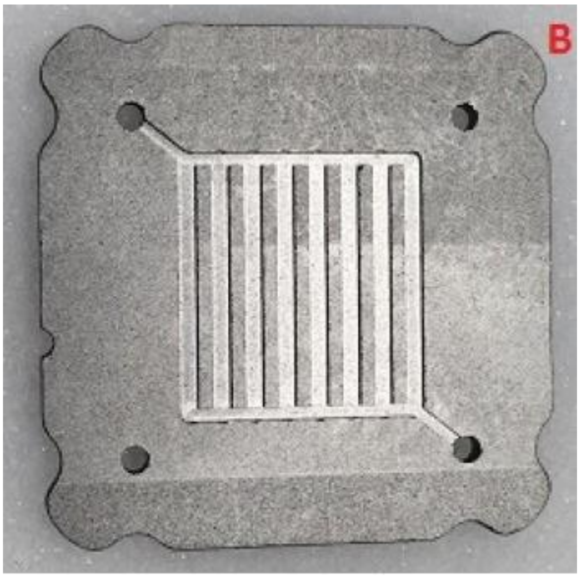
Product Code: 590327

Price: $37.50

Qty: 1

[83]





10 cm^2 Open Bipolar Graphite plate suitable for small Hydrogen / Air Fuel Cells and Methanol Fuel Cells. These bipolar plates can be used as replacement components for the Parker TekStak or the Flex-Stak series fuel cells, or you can use them as the basis to build your own open fuel cell.

They incorporate a parallel path design for even hydrogen or methanol distribution and a straight channel design on the reverse side for Air supply and cooling of the fuel cell. These cells can be used in conjuction with the older

Perfect for replacement parts or to experiment with your own designs.

Active Area Dimensions: 3.2 x 3.2 cm

Total Area Dimensions: 5.3 x 5.3 cm

Overall Dimensions (L x W x D): 6.3 x 6.3 x 0.4 cm

---

[83] https://www.fuelcellstore.com/fuel-cell-components/plates/flex-stack-bipolar-graphite-plate

Graphite Plate Side A:

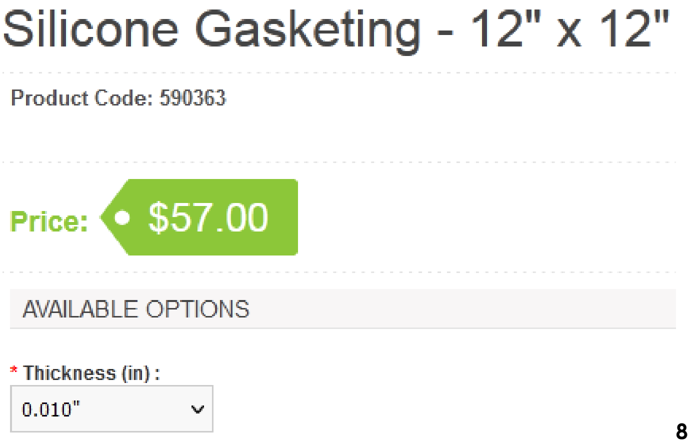
- Depth of Flow Fields: 2 mm
- Length Per Flow Field: 54 mm
- Number of Flow Field Lines: 8
- Total Length of Flow Fields: 432 mm

Graphite Plate Side B:

- Depth of Flow Fields: 0.75 mm
- Length Per Flow Field: 30 mm
- Number of Flow Field Lines: 8
- Total Length of Flow Fields: 240 mm

20.27.4 Gaskets

Item #1:



Silicone Gasketing - 12" x 12"

Product Code: 590363

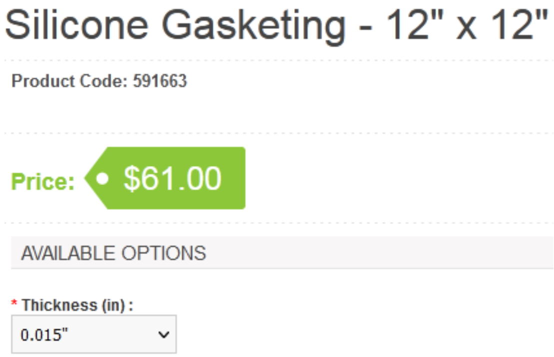
Price: $57.00

AVAILABLE OPTIONS

* Thickness (in) :

0.010"

[84]



Silicone Gasketing - 12" x 12"

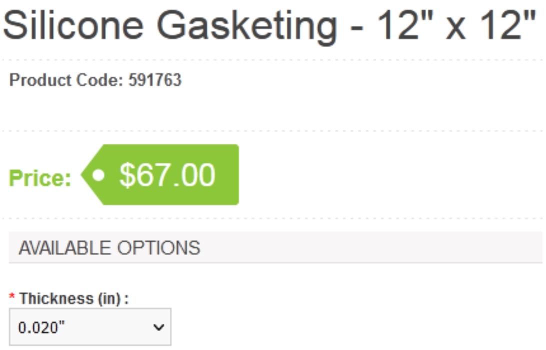
Product Code: 591663

Price: $61.00

AVAILABLE OPTIONS

* Thickness (in) :

0.015"



Silicone Gasketing - 12" x 12"

Product Code: 591763

Price: $67.00

AVAILABLE OPTIONS

* Thickness (in) :

0.020"

Thin gauge 12 x 12 inch Silicone Rubber Gasketing for use in fuel cell fixtures. Like other silicone, this rubber stays flexible over a wide temperature range, but its softness gives it better conformability than other rubber. A peel-off protective masking keeps this rubber free from dust and debris. Width and length tolerances are ±1/4". Durometer tolerance is ±5.

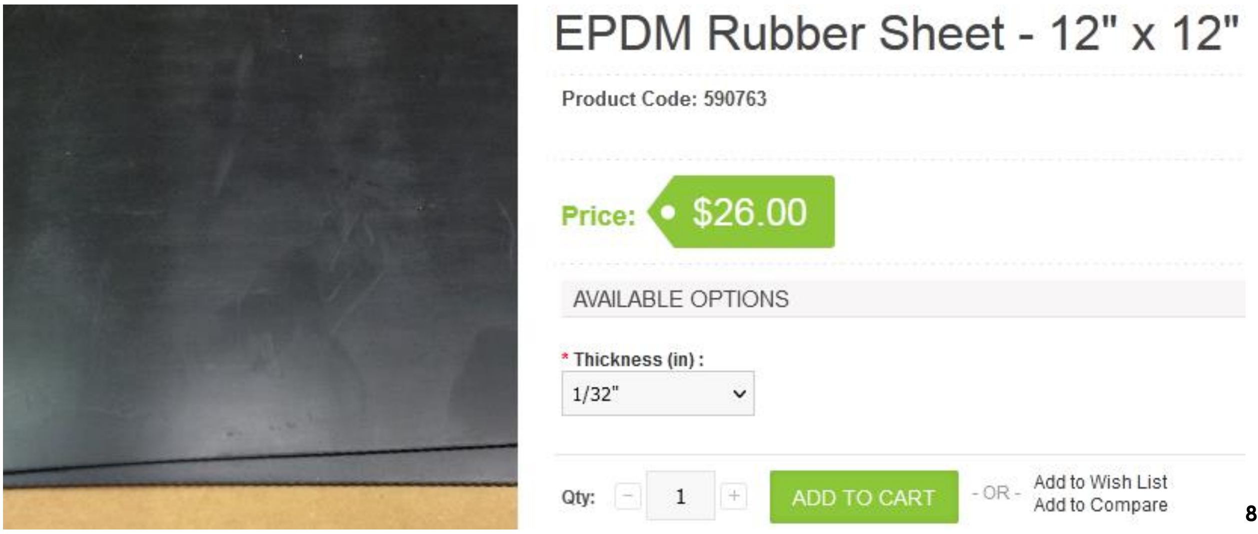
Teflon and fiberglass reinforced Teflon are used in high temperature applications such as High Temperature Polymer Electrolyte Membrane Fuel Cells (HT-PEMFC) and Phosphoric Acid Fuel Cells (PAFC).

HT6135 Silicon gasketing is a solid silicone elastomer. Silicone elastomers exhibit a natural shrinkage when the carrier or liner is removed. Thickness measurements do not include carrier or liner.

---

[84] https://www.fuelcellstore.com/fuel-cell-components/gaskets/silicone-gasket-35a?sort=p.model&order=ASC

Item #2:



EPDM Rubber Sheet - 12" x 12"

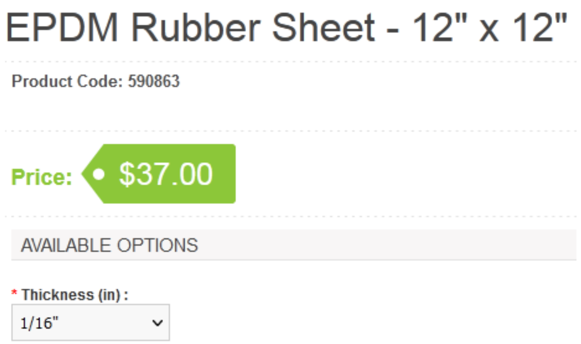
Product Code: 590763

Price: $26.00

AVAILABLE OPTIONS

* Thickness (in) : 1/32"

[85]



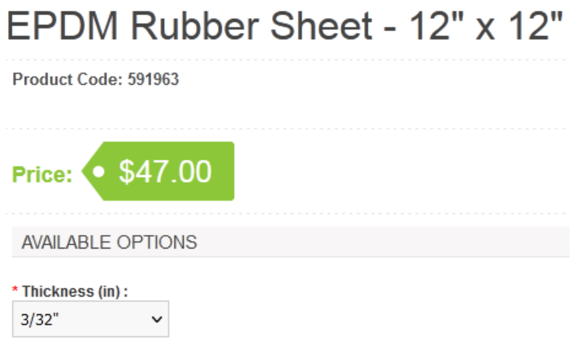
EPDM Rubber Sheet - 12" x 12"

Product Code: 590863

Price: $37.00

AVAILABLE OPTIONS

* Thickness (in) : 1/16"



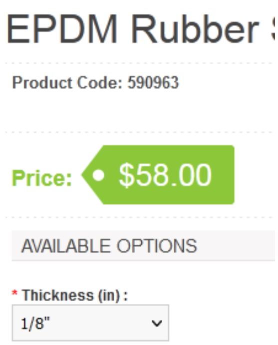
EPDM Rubber Sheet - 12" x 12"

Product Code: 591963

Price: $47.00

AVAILABLE OPTIONS

* Thickness (in) : 3/32"



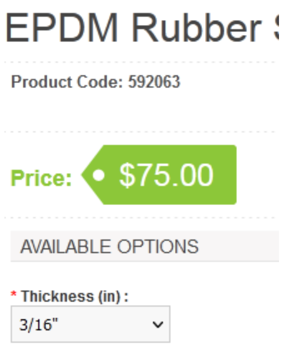
EPDM Rubber

Product Code: 590963

Price: $58.00

AVAILABLE OPTIONS

* Thickness (in) : 1/8"



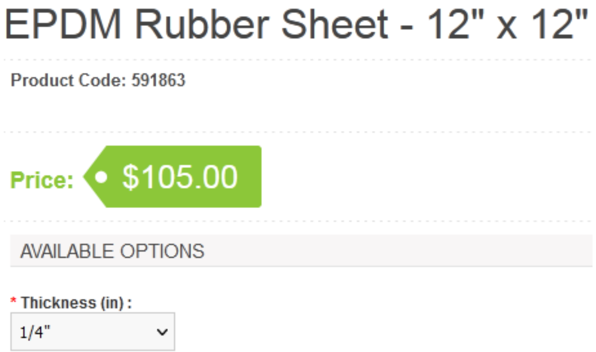
EPDM Rubber

Product Code: 592063

Price: $75.00

AVAILABLE OPTIONS

* Thickness (in) : 3/16"



EPDM Rubber Sheet - 12" x 12"

Product Code: 591863

Price: $105.00

AVAILABLE OPTIONS

* Thickness (in) : 1/4"

Cut your own gaskets out of this 12 inch x 12 inch sheet of high-performance EPDM (Ethylene Propylene Diene Monomer) Rubber. Provides excellent seals for both Hydrogen and Direct Methanol fuel cells.

With greater strength than standard Weather-Resistant EPDM Rubber, these sheets provide better shock-absorbing qualities and longer life. They are resistant to sunlight, ozone, and water.

EPDM Rubber is peroxide cured for increased temperature resistance.

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[85] https://www.fuelcellstore.com/epdm-rubber-50A

20.27.5 Current plate

20.27.6 End plate


Garolite Sheet - 12" x 12"

Product Code: 72043001-3

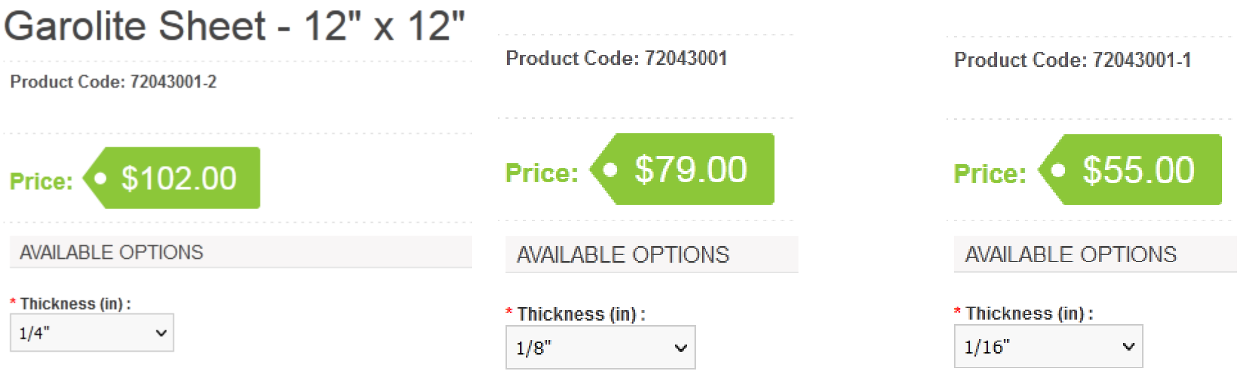
Price: $145.00

AVAILABLE OPTIONS

* Thickness (in) :

3/8"

[86]


Garolite Sheet - 12" x 12"

Product Code: 72043001-2

Price: $102.00

AVAILABLE OPTIONS

* Thickness (in) :

1/4"

Product Code: 72043001

Price: $79.00

AVAILABLE OPTIONS

* Thickness (in) :

1/8"

Product Code: 72043001-1

Price: $55.00

AVAILABLE OPTIONS

* Thickness (in) :

1/16"

This Garolite sheet can be used to make fuel cell end plates. This Garolite grade is the flame-retardant version of G-10 Garolite, offering excellent strength, low water absorption, and good electrical insulating qualities in dry and humid conditions. The material is fiberglass-cloth with a flame-retardant epoxy resin. It meets MIL-I-24768/27 and UL 94V0 for flame retardance.

These sheets are unmachined and generally come in a black, blue, or tan color.

Thickness Tolerance

At 1/16" ±0.008"

At 1/8" ±0.012"

At 1/4" ±0.022"

At 3/8" ±0.038"

Width and Length Tolerances ±1/4"

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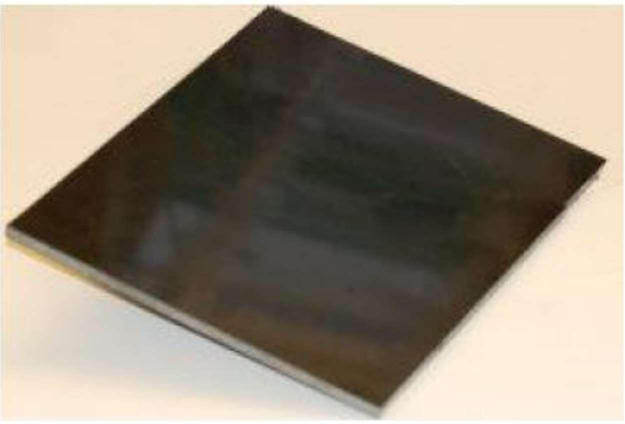
[86] https://www.fuelcellstore.com/fuel-cell-components/plates/end-plates/garolite-sheet-144



Garolite Sheet - 6" x 6"

Product Code: 72043000-3

Price: $58.00

AVAILABLE OPTIONS

* Thickness (in) : 3/8"

[87]

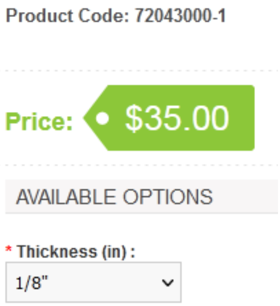
Garolite Sheet - 6" x 6"

Product Code: 72043000-2

Price: $44.00

AVAILABLE OPTIONS

* Thickness (in) : 1/4"

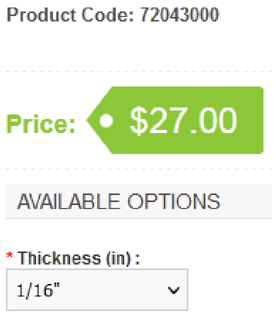


Product Code: 72043000-1

Price: $35.00

AVAILABLE OPTIONS

* Thickness (in) : 1/8"



Product Code: 72043000

Price: $27.00

AVAILABLE OPTIONS

* Thickness (in) : 1/16"

This Garolite sheet can be used to make fuel cell end plates. This Garolite grade is the flame-retardant version of G-10 Garolite, offering excellent strength, low water absorption, and good electrical insulating qualities in dry and humid conditions. The material is fiberglass-cloth with a flame-retardant epoxy resin. It meets MIL-I-24768/27 and UL 94V0 for flame retardance.

These sheets are unmachined and generally come in a black, blue, or tan color.

Thickness Tolerance

At 1/16" ±0.008"

At 1/8" ±0.012"

At 1/4" ±0.022"

At 3/8" ±0.038"

Width and Length Tolerances ±1/4"

20.28 Description of our prototype fuel cell system

20.28.1 Existing electrical system

The electrical system in the prototype consists of the low voltage (12 V) DC system.

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[87] https://www.fuelcellstore.com/fuel-cell-components/plates/end-plates/garolite-sheet-036

20.28.2 Fuel cell stack

The parameter that will be crucial for the size of the stack is the maximum power that should be delivered. As an example, a maximum power level of 1 kW is chosen.

20.28.2.1 Size

The first step to obtain the size of the fuel cell stack is to calculate the number of cells needed to deliver a specific voltage level. The cell voltage is chosen to 0.7 V based on the voltage-current density graph seen in Figure 101. At 0.7 V the power is about its maximum value. In this example the needed voltage will be assumed to be 12 V. The number of cells will be 18 (17.143) when the fuel cells produce this voltage.

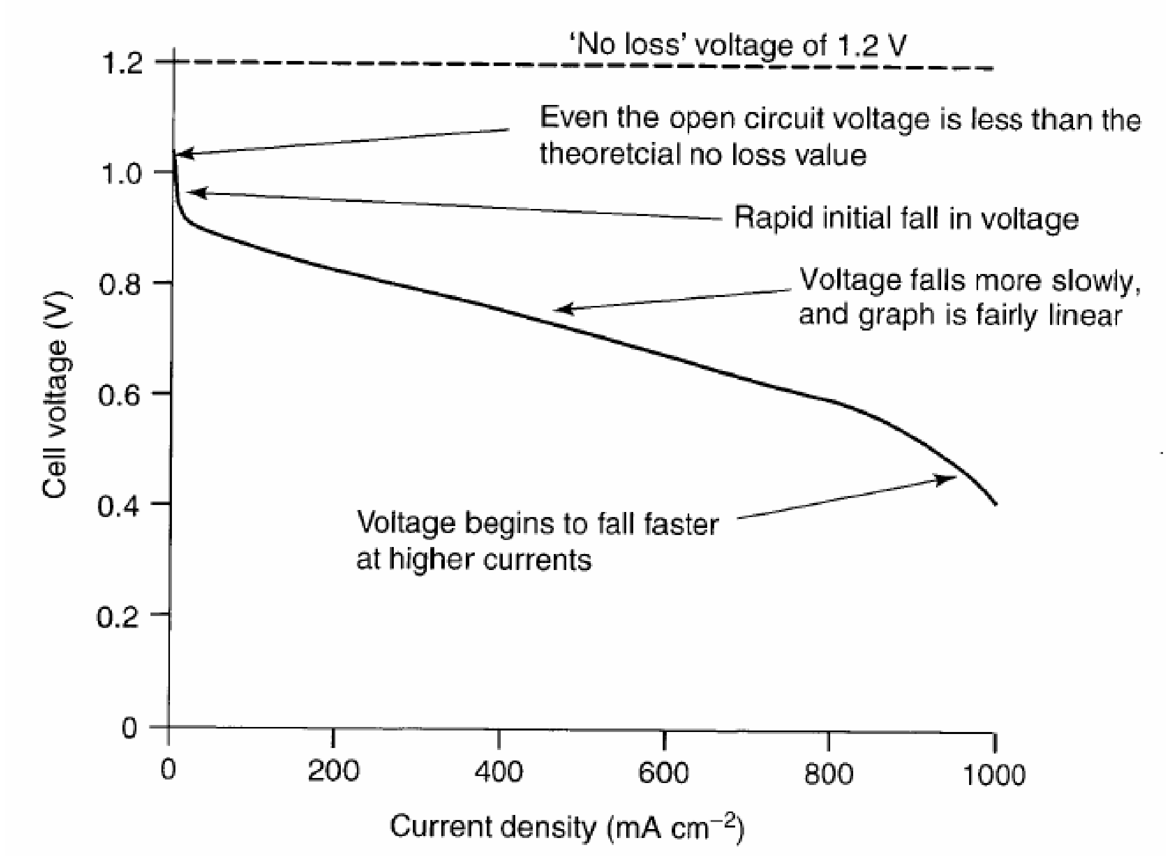


Fig. 101: Voltage-current density diagram for a low temperature, air pressure fuel cell

The total current from the stack when supplying the maximum power can now be calculated.

$$P = U \times I \quad \longrightarrow \quad I = \frac{P}{U} = \frac{1000}{12*18} = 4.63\ A \qquad \textbf{(42)}$$

Where, P = Power [W]
U = Voltage [V]
I = Current [A]

For a specific power rate, the current can be increased or decreased, depending on the need of the load, if the voltage is altered by changing the number of cells. If the needed voltage is different from the stack voltage, a voltage regulator could be used to achieve the right level.

From Figure 101 it can be found that the current density for 0.7 V is around 550 mA/cm^2. The area of each cell can now be calculated using the current calculated in equation (42).

$$A = \frac{I}{J} = \frac{4.63}{0.55} = 8.42 \text{ cm}^2 \qquad \textbf{(43)}$$

Where,
A = Fuel cell area [cm^2]
J = Current density [A/cm^2]

The total size of the stack depends on this area, the number of cells and the thickness of each cell. This thickness depends on material and design.

20.28.2.2 Fuel cell types

There are two main groups of cells that are available, low temperature and high temperature fuel cells. What determines which type to use is the field of application. In low temperature cells the hydrogen has to be more pure than in the other case. In the case of high temperature cells, hydrogen can be produced internally in the stack by reforming other fuels, such as Liquefied Petroleum Gas (LPG), methanol, etc.

In this prototype, we are looking to fuel cell generates electrical power from hydrogen gas and humid air. There is no need for high temperature so the suitable type for our prototype is PEMFC low temperature.

20.28.3 Converters

20.28.3.1 DC/DC converter

In the calculations on the fuel cell stack the number of cells is chosen with respect to that the voltage over the stack should have the same voltage as the grid voltage. If for some reason the number of cells is chosen differently a DC/DC converter can be used to achieve the right output voltage level.

The voltage over the stack is normally not constant and when the current increases there will be a voltage drop. In fuel cells this voltage drop is greater than in normal electrical power generators. In this case there is also need for a DC/DC converter to solve this problem.

20.28.3.2 DC/AC inverter

As mentioned before on fuel cells the output from a stack is a DC current. When using a DC/AC inverter there is no use for a DC/DC converter because it is also capable of regulating the output voltage level.

20.28.4 Hydrogen storage

To be able to use hydrogen as a fuel, there are different ways of achieving this and the most common ways are by buying H2 tubes, by using an electrolyzer or by using a reformer. In this project, hydrogen gas was obtained from the electrolyzer.

An interesting observation to keep in mind is that hydrogen will take a lot of room at low pressures. To illustrate how the density varies with the pressure, an example is that 1 m^3 contains 0.1 kg H_2 at

---

a pressure of 1 bar and 15 kg H_2 at a pressure of 200 bar. Another interesting fact is that one kilogram of hydrogen has the same energy content as one gallon (about 4 liters) of gasoline.

- ***Using an Electrolyzer***

The theory of this is based on the electrolysis of water. By letting a current pass through the water, hydrogen and oxygen are separated. With this method the hydrogen is produced with an electrolyzer and is stored in tubes. The greatest advantage of this method is that the produced hydrogen is very pure.

20.28.5 Energy and fuel estimation

The objective of this paragraph is to calculate the quantity of fuel needed for the fuel cells to deliver power during an estimated time. The first step is to find out the energy consumed for the level below 1 kW, i.e. the power which the fuel cells will provide. The energy was supposed to be about 10 kWh/day (24 hours).

The energy content LHV (Low Heating Value) in one kilogram of hydrogen at room temperature and at atmospheric pressure is around 120 MJ which equals 33.3 kWh (H_2 E).

$$E_{\text{one day}} = 10 \times 1 = 10 \text{ kWh} \qquad \textbf{(44)}$$

$$m = \frac{E\ (one\ day)}{E\ (H2)} = \frac{10}{33.3} = 0.3 \text{ Kg} \qquad \textbf{(45)}$$

Where,

$E_{\text{one day}}$ = Energy during one day delivered by the fuel cell system [kWh]
E_{H2} = Energy content of one Kg of H_2 [kWh]
m = Mass of the hydrogen [Kg]

As said before electrolyzer delivers hydrogen gas at a pressure of 1 bar. At this pressure the volume needed for 0.1 kg of H_2 is 1 m^3. the mass needed for one day has a volume of thirteen of a cubic meter (13000 dm^3) with this pressure. This volume can be decreased if a higher pressure is used.

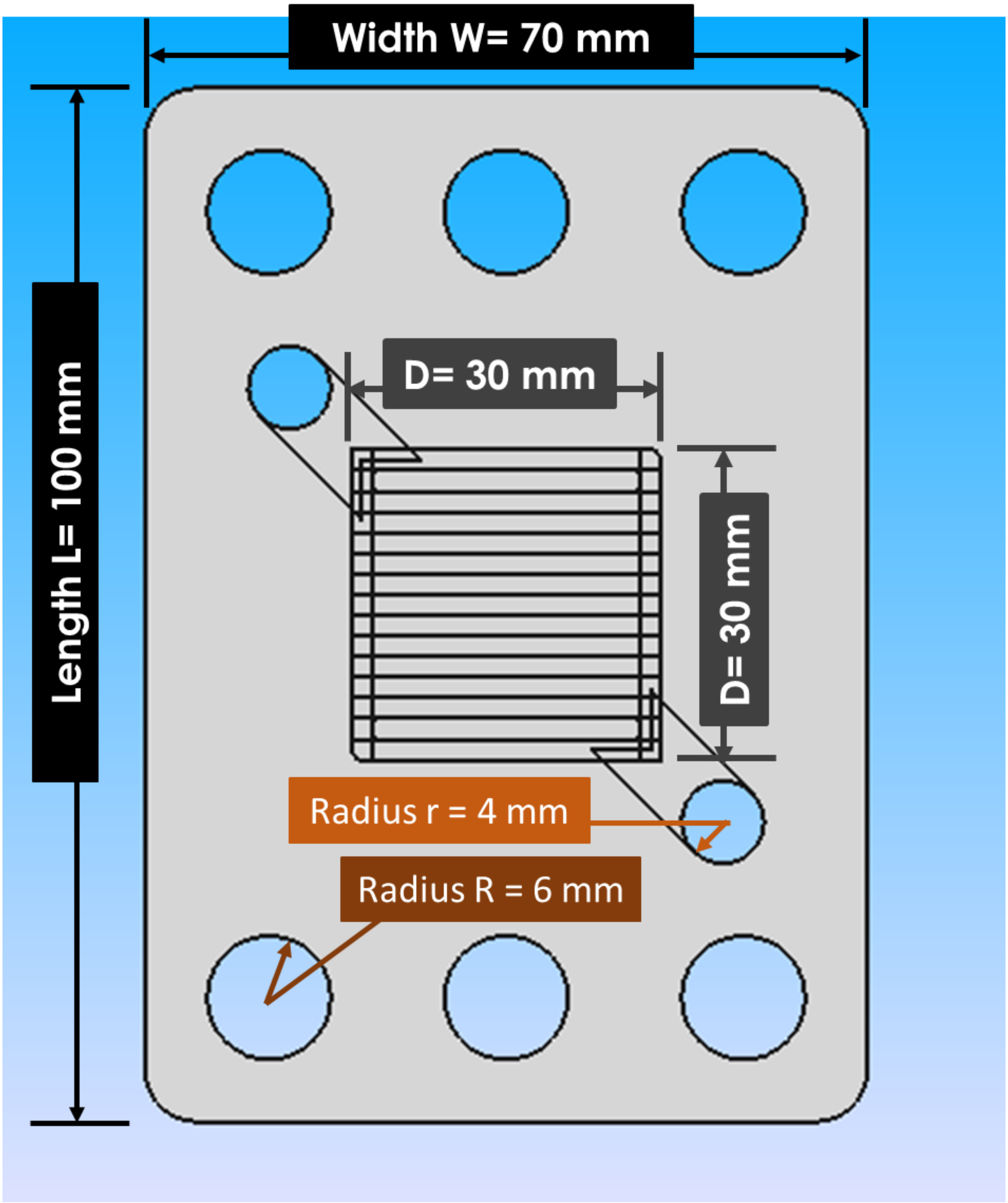
if hydrogen gas is available at a pressure of 200 bar. At this pressure the volume needed for 15 kg of H_2 is 1 m^3. It is easy to see that the mass needed for one day has a volume of 0.087 m3 (87 dm^3) with this pressure.

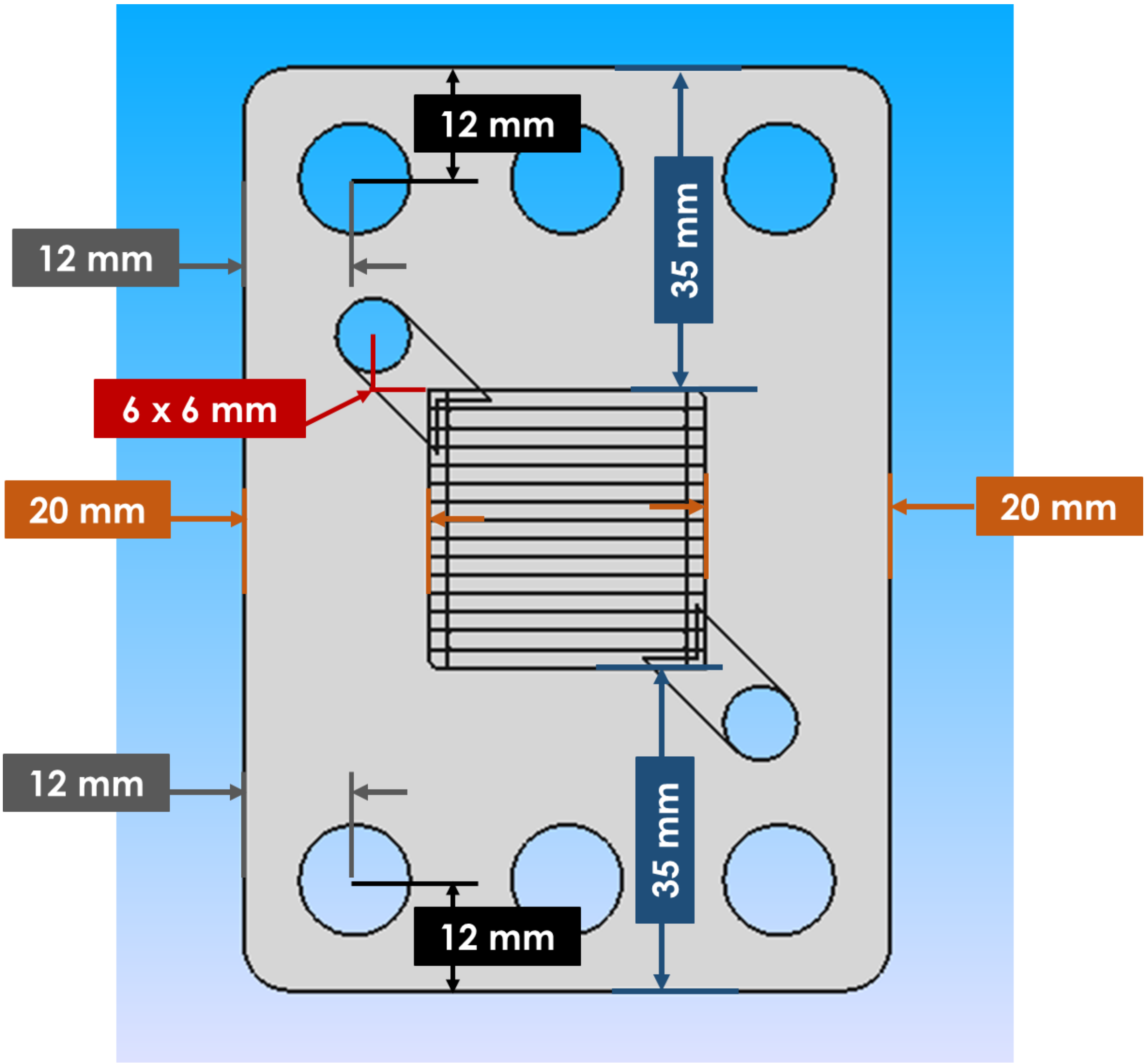
20.28.6 FreeCAD design

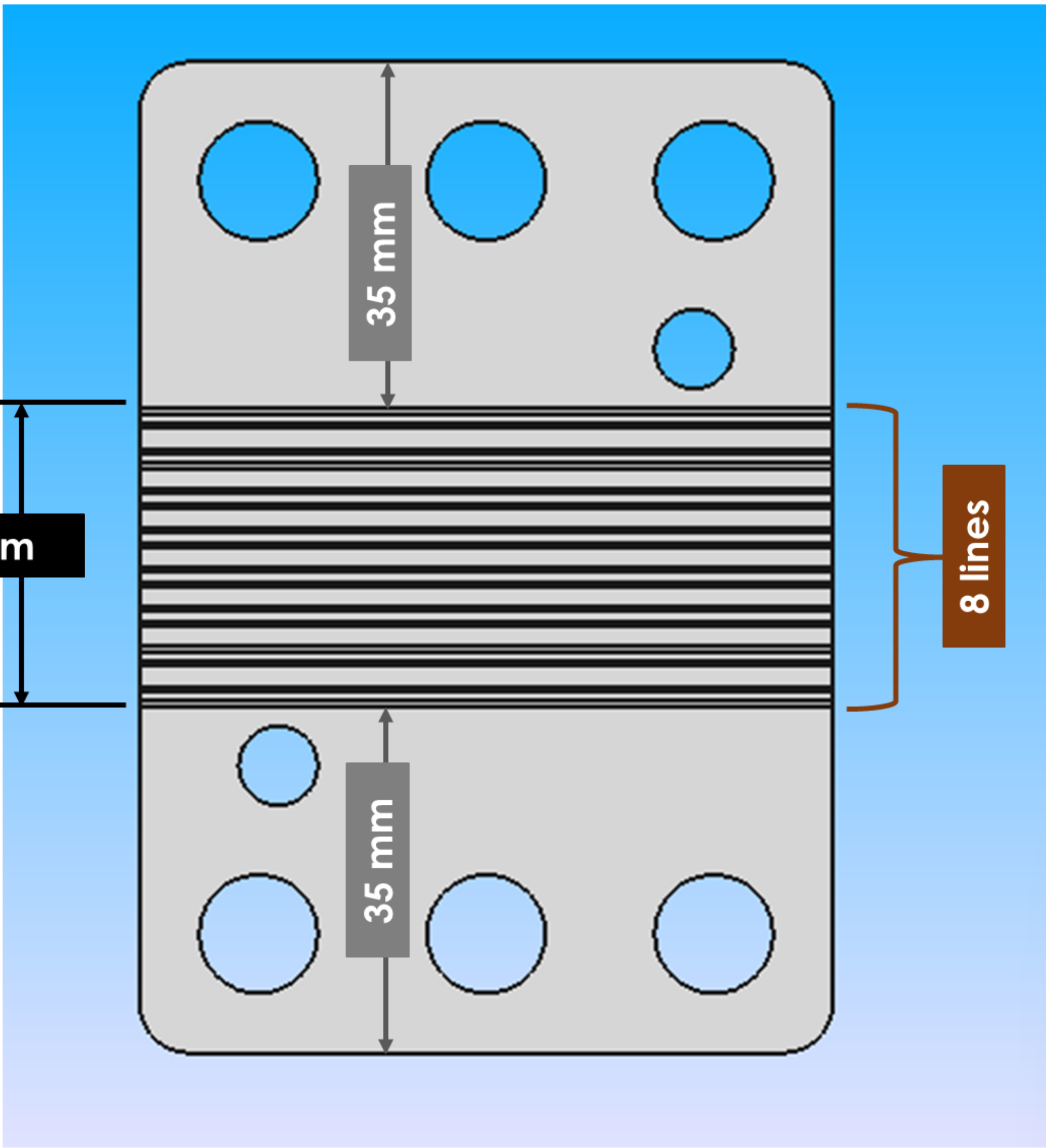
20.28.6.1 Bipolar plate design

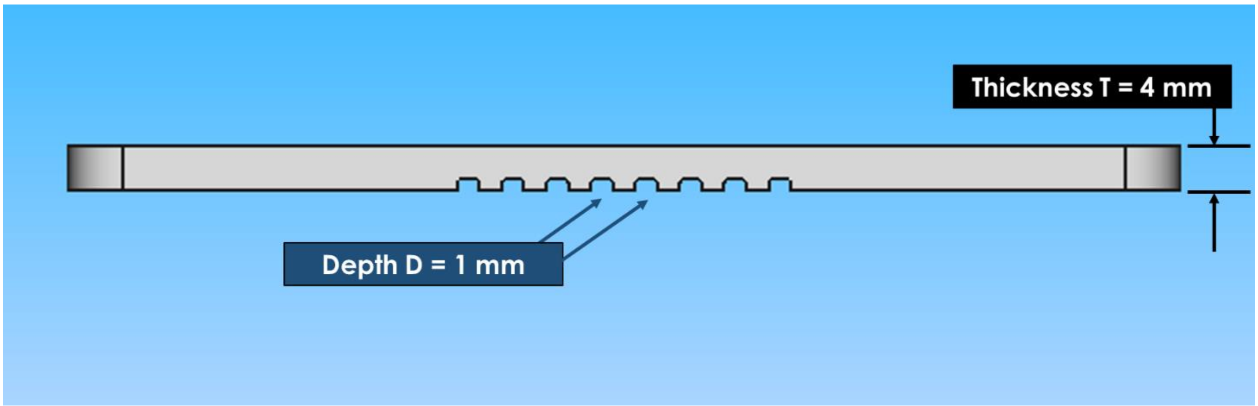
prototype
BBP.FCStd

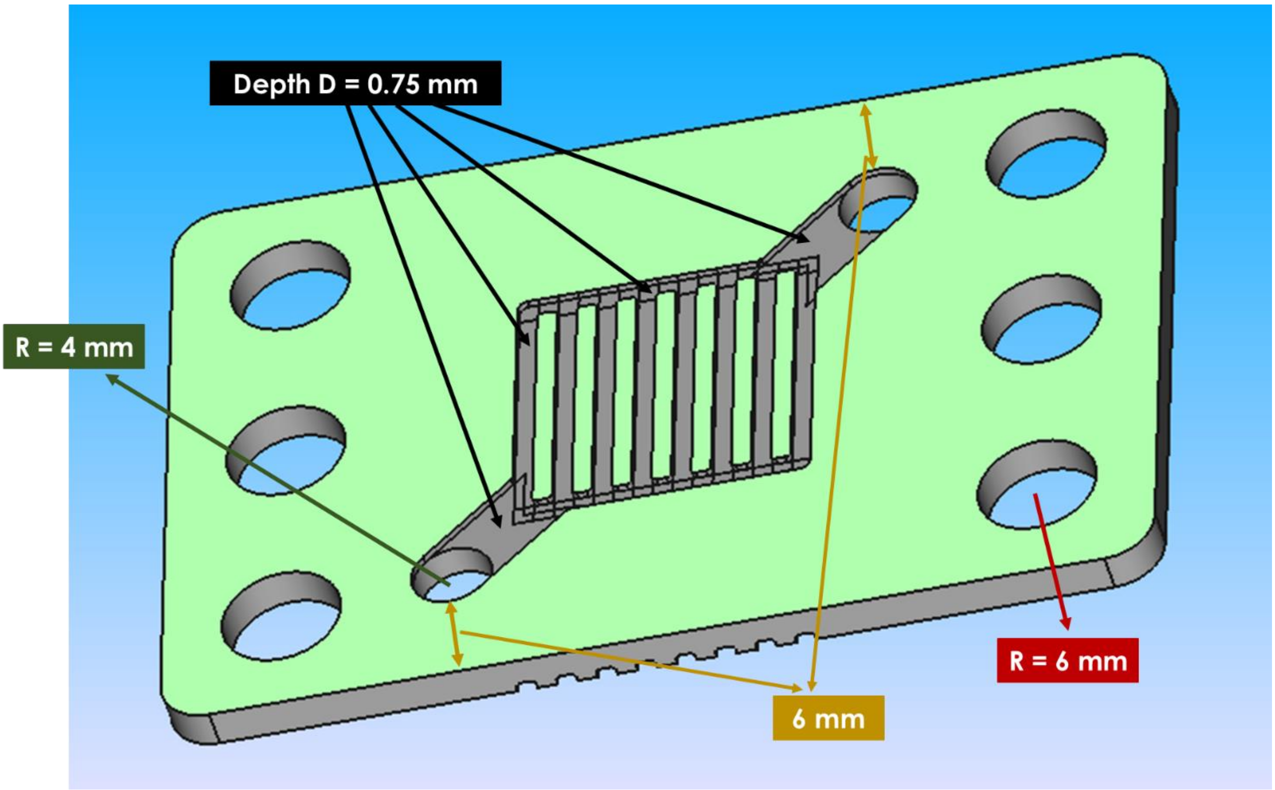
- **Design details**


Width W= 70 mm
Length L= 100 mm
D= 30 mm
D= 30 mm
Radius r = 4 mm
Radius R = 6 mm


12 mm
12 mm
35 mm
6 x 6 mm
20 mm
20 mm
12 mm
35 mm
12 mm


35 mm
30 mm
8 lines
35 mm

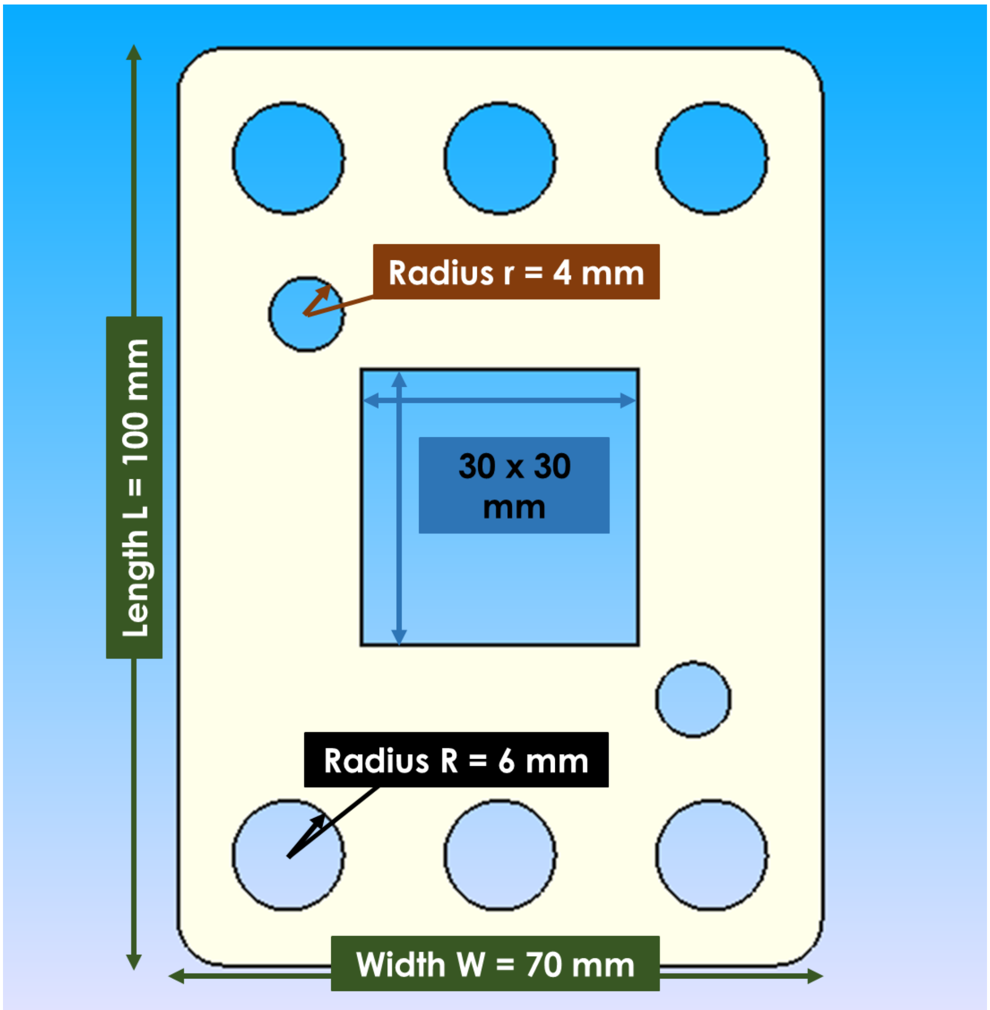

Thickness T = 4 mm
Depth D = 1 mm

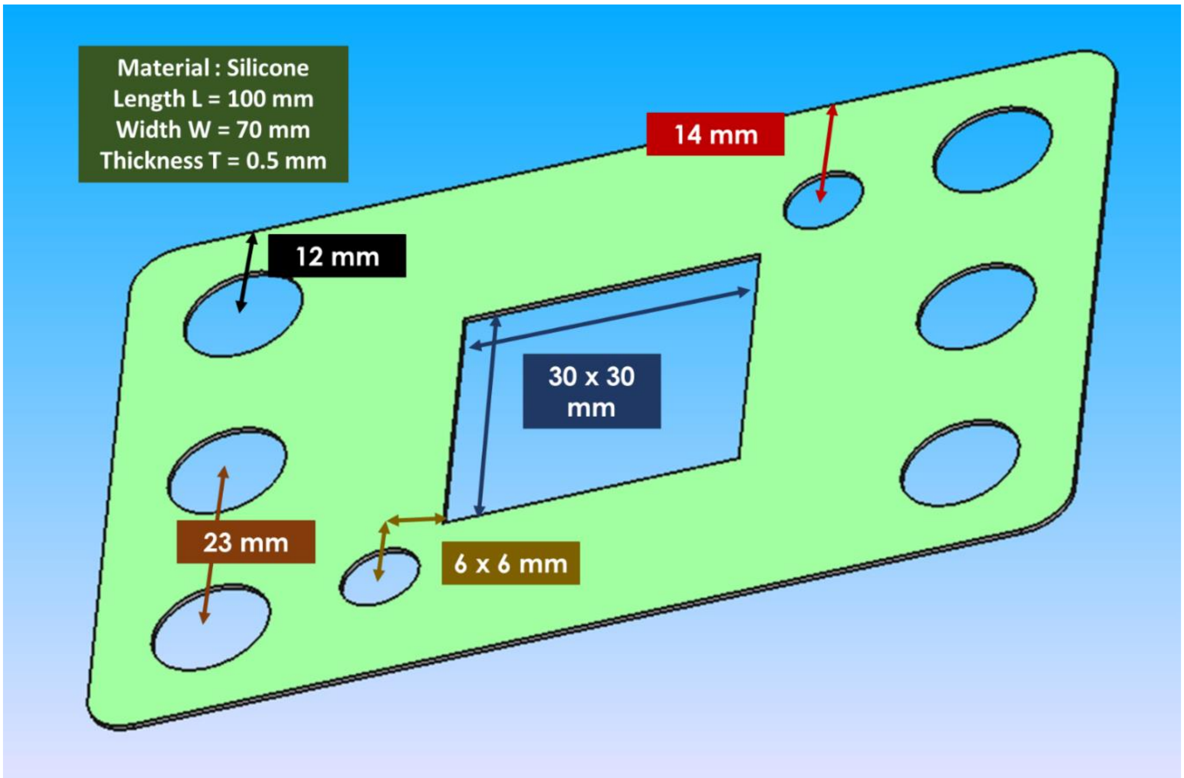


20.28.6.2 Gasket design

prototype
GASKET.FCStd

- **Design details**

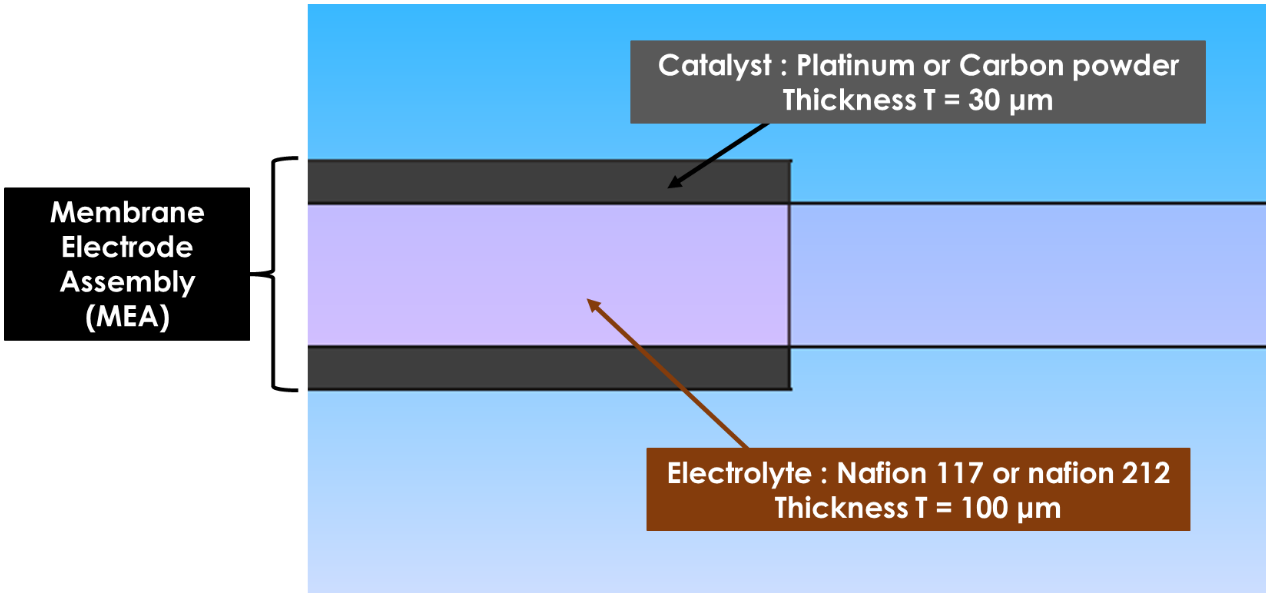

Length L = 100 mm
Radius r = 4 mm
30 x 30 mm
Radius R = 6 mm
Width W = 70 mm

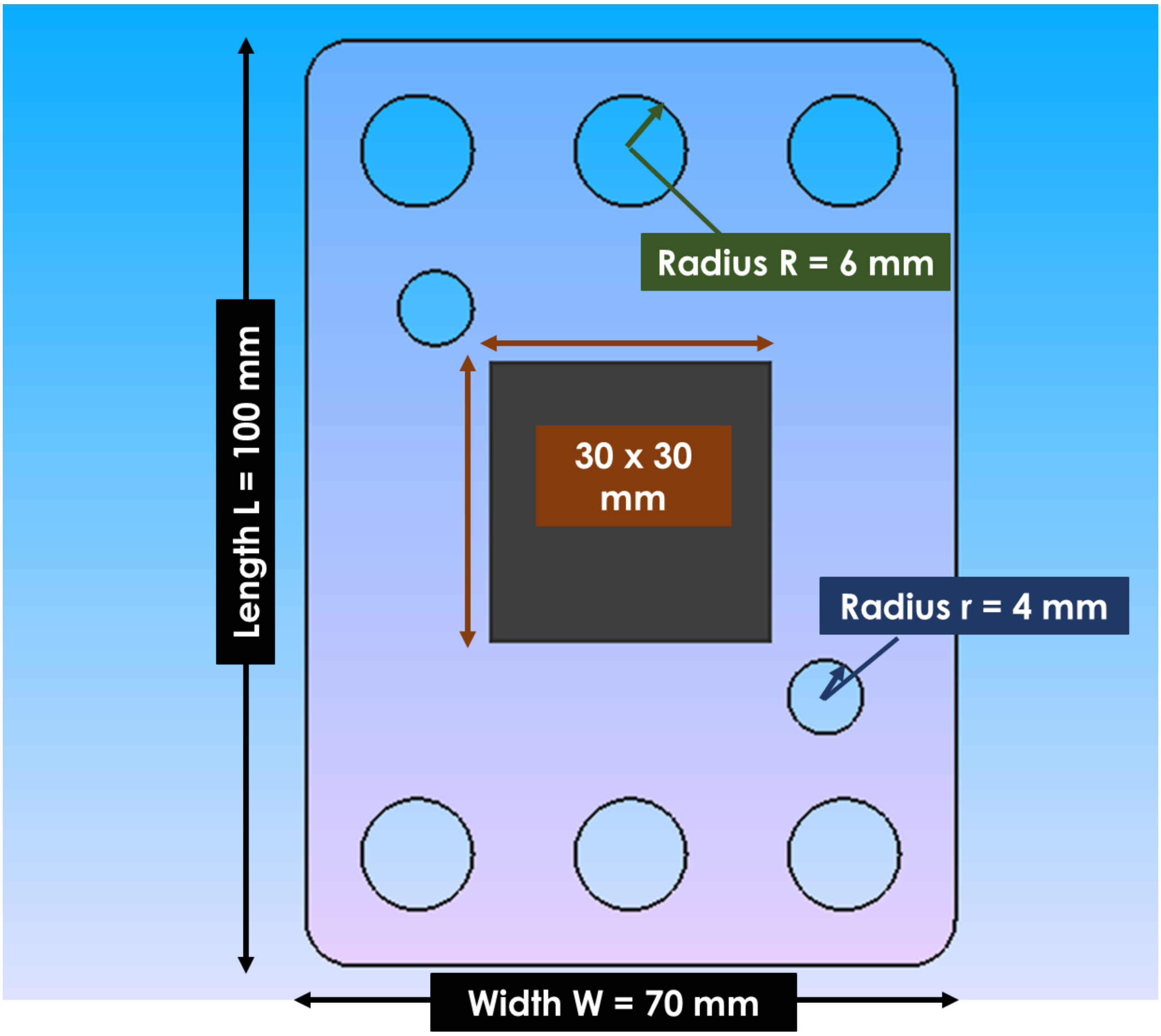

Material : Silicone
Length L = 100 mm
Width W = 70 mm
Thickness T = 0.5 mm
14 mm
12 mm
30 x 30 mm
23 mm
6 x 6 mm

20.28.6.3 MEA design

prototype
MEA.FCStd

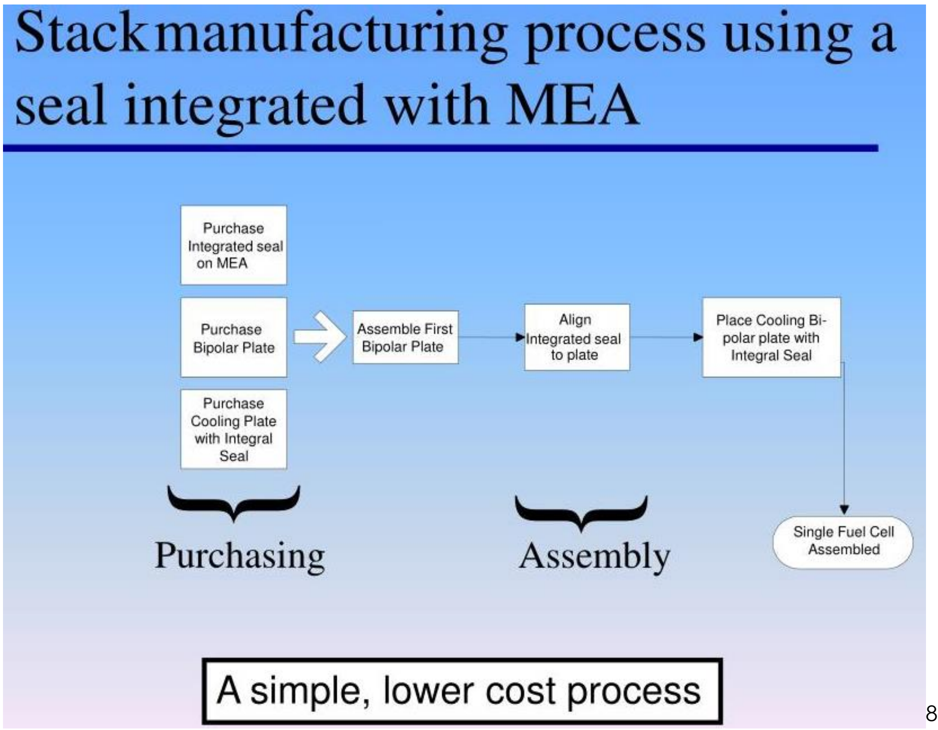
- **Design details**





20.28.7 Specification of requirements

Description	Specifications
Power rating	1 kW
Output voltage	12 V
Fuel	H2
Fuel storage (per day)	13000 dm3 at 1 bar 87 dm3 at 200 bar



Stackmanufacturing process using a seal integrated with MEA

Purchase Integrated seal on MEA

Purchase Bipolar Plate

Purchase Cooling Plate with Integral Seal

Assemble First Bipolar Plate

Align Integrated seal to plate

Place Cooling Bi-polar plate with Integral Seal

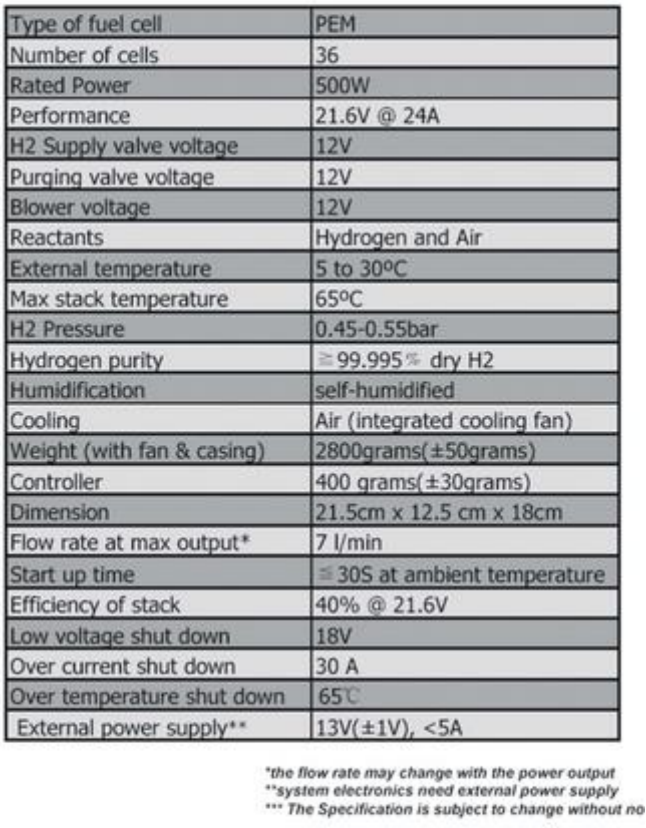
Single Fuel Cell Assembled

Purchasing

Assembly

A simple, lower cost process

[88]



Type of fuel cell	PEM
Number of cells	36
Rated Power	500W
Performance	21.6V @ 24A
H2 Supply valve voltage	12V
Purging valve voltage	12V
Blower voltage	12V
Reactants	Hydrogen and Air
External temperature	5 to 30°C
Max stack temperature	65°C
H2 Pressure	0.45-0.55bar
Hydrogen purity	≧99.995% dry H2
Humidification	self-humidified
Cooling	Air (integrated cooling fan)
Weight (with fan & casing)	2800grams(±50grams)
Controller	400 grams(±30grams)
Dimension	21.5cm x 12.5 cm x 18cm
Flow rate at max output*	7 l/min
Start up time	≦30S at ambient temperature
Efficiency of stack	40% @ 21.6V
Low voltage shut down	18V
Over current shut down	30 A
Over temperature shut down	65℃
External power supply**	13V(±1V), <5A

*the flow rate may change with the power output
**system electronics need external power supply
*** The Specification is subject to change without no [89]

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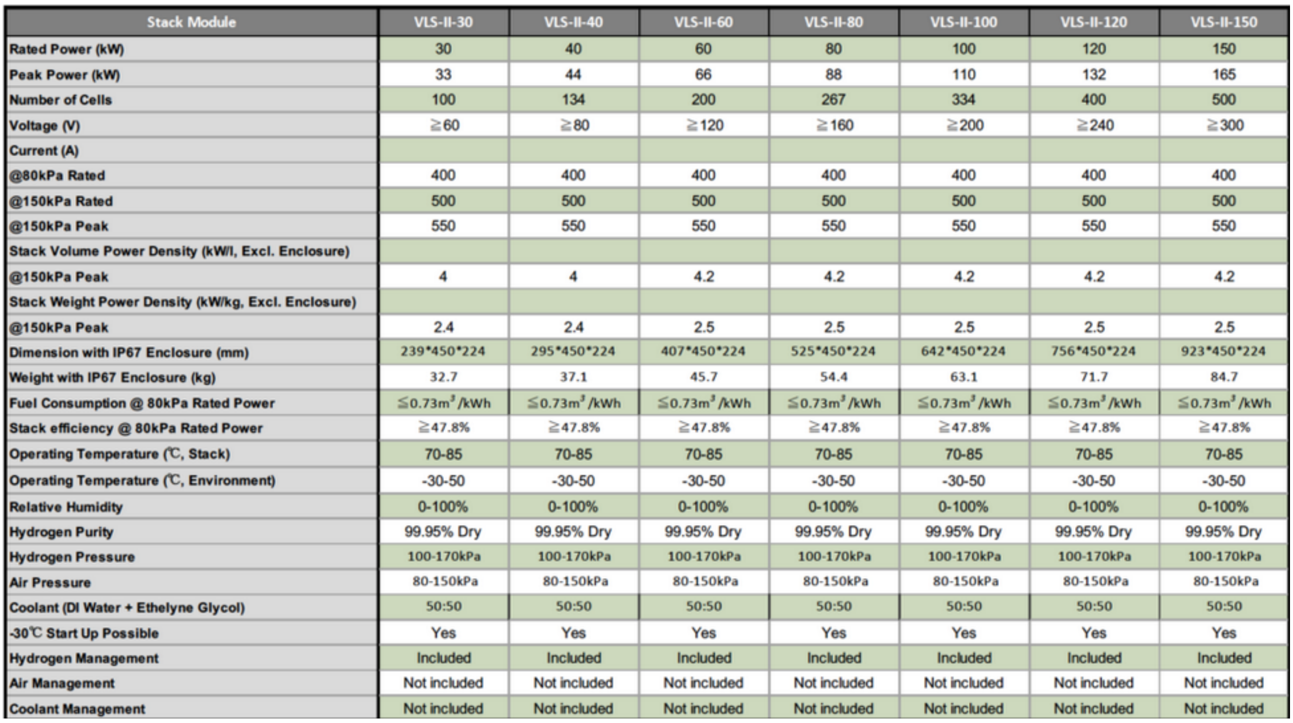
[88] https://www.slideserve.com/Mercy/pem-fuel-cell-stack-sealing-powerpoint-ppt-presentation

[89] https://www.google.com/imgres?imgurl=http%3A%2F%2Fwww.hhomart.com%2Fimg%2Fcms%2FPEMFC%2520500w%2520Specs.jpg&imgrefurl=https%3A%2F%2Fwww.hhomart.com%2Fen%2Ffuellcell%2F6-500w-pem-fuel-cell-stack.html&tbnid=0ZzJW5PkHVmXeM&vet=12ahUKEwi9ga6k7JnzAhUPTBoKHSmHBHwQMygZegUIARDSAQ..i&docid=EmtxcOEaOV26XM&w=2066&h=2725&q=dimension%20of%20fuel%20cell&client=firefox-b-d&ved=2ahUKEwi9ga6k7JnzAhUPTBoKHSmHBHwQMygZegUIARDSAQ



Stack Module	VLS-II-30	VLS-II-40	VLS-II-60	VLS-II-80	VLS-II-100	VLS-II-120	VLS-II-150
Rated Power (kW)	30	40	60	80	100	120	150
Peak Power (kW)	33	44	66	88	110	132	165
Number of Cells	100	134	200	267	334	400	500
Voltage (V)	≧60	≧80	≧120	≧160	≧200	≧240	≧300
Current (A)							
@80kPa Rated	400	400	400	400	400	400	400
@150kPa Rated	500	500	500	500	500	500	500
@150kPa Peak	550	550	550	550	550	550	550
Stack Volume Power Density (kW/l, Excl. Enclosure)							
@150kPa Peak	4	4	4.2	4.2	4.2	4.2	4.2
Stack Weight Power Density (kW/kg, Excl. Enclosure)							
@150kPa Peak	2.4	2.4	2.5	2.5	2.5	2.5	2.5
Dimension with IP67 Enclosure (mm)	239*450*224	295*450*224	407*450*224	525*450*224	642*450*224	756*450*224	923*450*224
Weight with IP67 Enclosure (kg)	32.7	37.1	45.7	54.4	63.1	71.7	84.7
Fuel Consumption @ 80kPa Rated Power	≦0.73m^3/kWh	≦0.73m^3/kWh	≦0.73m^3/kWh	≦0.73m^3/kWh	≦0.73m^3/kWh	≦0.73m^3/kWh	≦0.73m^3/kWh
Stack efficiency @ 80kPa Rated Power	≧47.8%	≧47.8%	≧47.8%	≧47.8%	≧47.8%	≧47.8%	≧47.8%
Operating Temperature (℃, Stack)	70-85	70-85	70-85	70-85	70-85	70-85	70-85
Operating Temperature (℃, Environment)	-30-50	-30-50	-30-50	-30-50	-30-50	-30-50	-30-50
Relative Humidity	0-100%	0-100%	0-100%	0-100%	0-100%	0-100%	0-100%
Hydrogen Purity	99.95% Dry	99.95% Dry	99.95% Dry	99.95% Dry	99.95% Dry	99.95% Dry	99.95% Dry
Hydrogen Pressure	100-170kPa	100-170kPa	100-170kPa	100-170kPa	100-170kPa	100-170kPa	100-170kPa
Air Pressure	80-150kPa	80-150kPa	80-150kPa	80-150kPa	80-150kPa	80-150kPa	80-150kPa
Coolant (DI Water + Ethelyne Glycol)	50:50	50:50	50:50	50:50	50:50	50:50	50:50
-30℃ Start Up Possible	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Hydrogen Management	Included	Included	Included	Included	Included	Included	Included
Air Management	Not included	Not included	Not included	Not included	Not included	Not included	Not included
Coolant Management	Not included	Not included	Not included	Not included	Not included	Not included	Not included

[90]

20.29 References

[1] Mikkola, Mikko. “Experimental Studies on Polymer Electrolyte Membrane Fuel Cell Stacks.” Helinski University of Technology, Department of Engineering Physics and Mathematics, Masters Thesis, 2001.

[2] Lin, Bruce. “Conceptual Design and Modeling of a Fuel Cell Scooter for Urban Asia.” Princeton University, Masters Thesis, 1999.

[3] Hussain, M.M., J.J. Baschuk, X. Li, and I. Dincer. “Thermodynamic Analysis of a PEM Fuel Cell Power System.” *International Journal of Thermal Sciences*. 2005. Vol. 44, pp. 903–911.

[4] O’Hayre, Ryan, Suk-Won Cha, Whitney Colella, and Fritz B. Prinz. *Fuel Cell Fundamentals*. 2006. New York: John Wiley & Sons.

[5] Ibid.

[6] J.G. Carton and A.G. Olab, “Design of experiment study of the parameters that affect performance of three flow plate configurations of a proton exchange membrane fuel cell”, Energy, 35 (7), pp 2796-2806, 2010.

[7] B. C. Steele and A. Heinzel, “Materials for fuel-cell technologies,” *Nature*, vol. 414, no. 6861, pp. 345–352, 2001.

[8] J. Zhang, J. Wu, H. Zhang, and J. Zhang, *Pem Fuel Cell Testing and Diagnosis*, Elsevier, Oxford, UK, 2013.

[9] R. O'Hayre, S-.W. Cha, W. Colella, and B. F. Prinz, *Fuel Cell Fundamentals*, John Wiley & Sons, Oxford, UK, 2nd edition, 2009.

[10] M. Ji and Z. Wei, “A review of water management in polymer electrolyte membrane fuel cells,” *Energies*, vol. 2, no. 4, pp. 1057–1106, 2009.

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[90] https://fuelcellsworks.com/news/throwback-thursday-spotlight-horizon-automotive-pem-fuel-cells-to-set-300kw-benchmark/

21 Project H 23-25: Fuel Cell project (ICPT - FC)

21.1 Position of Project

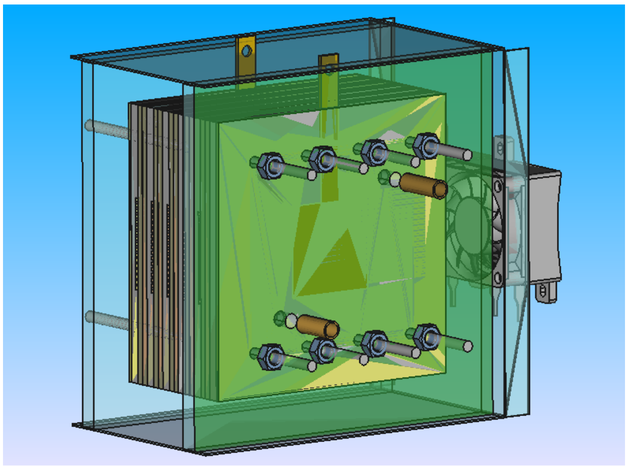
Work on this project will begin this year, as a simulation of the fuel cell project was conducted, and a small pilot project for the project was designed and implemented, with the project to be expanded and used as a source of stored energy instead of the traditional battery in the coming years.

21.2 Mechanical design

In this paragraph, we will present the mechanical design of Fuel Cell

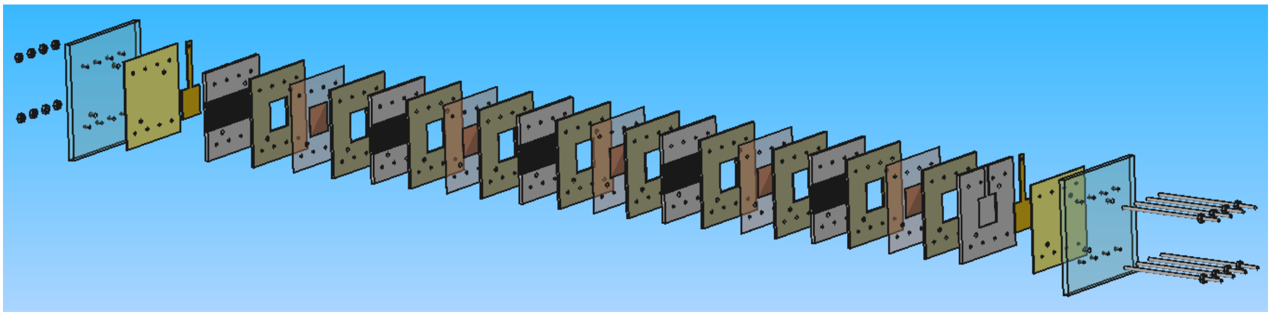
21.2.1 Overview of stack

22042024_Fuel cell - full design.FCStd



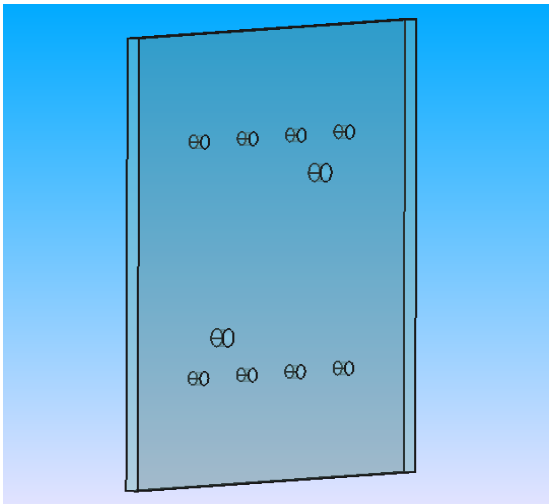
21.2.2 Fuel Cell exploded design

29052024_Fuel cell - Exploded.FCStd



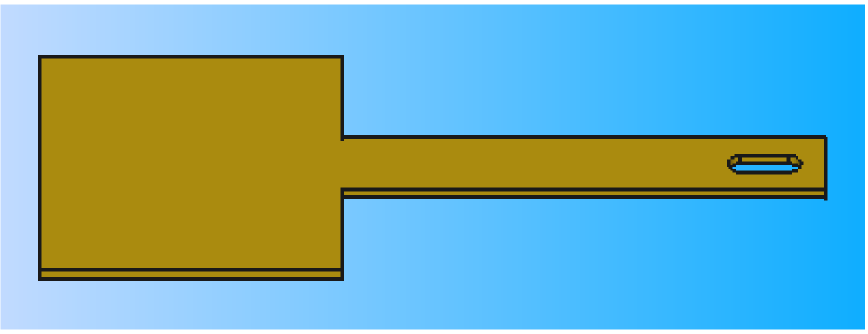
21.2.2.1 End plate of FC stack

22042024_End plate redesign.FCStd



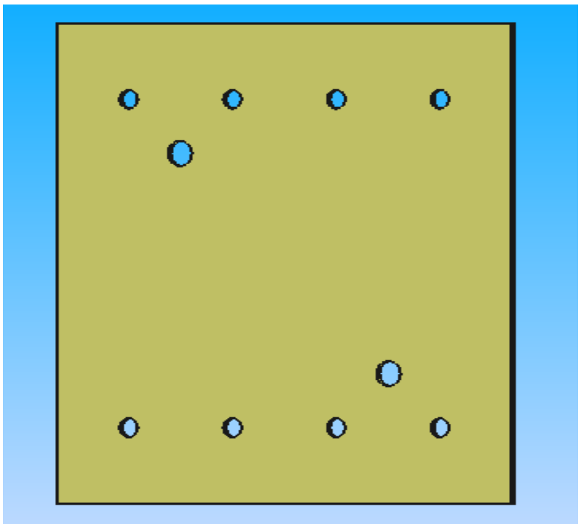
21.2.2.2 Current plate of FC stack

29052024_Current plate.FCStd



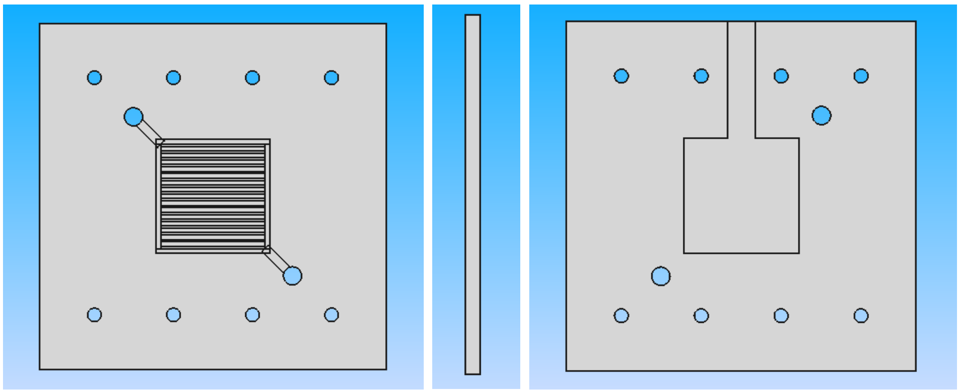
21.2.2.3 Gasket behind the current plate of FC stack

22042024_Gasket behind Current plat



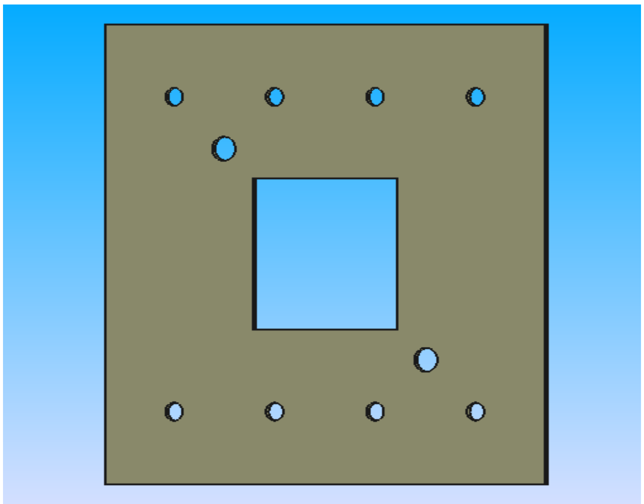
21.2.2.4 H_2 graphite plate of FC stack

18042024_Graphite plate of H2.FCStd



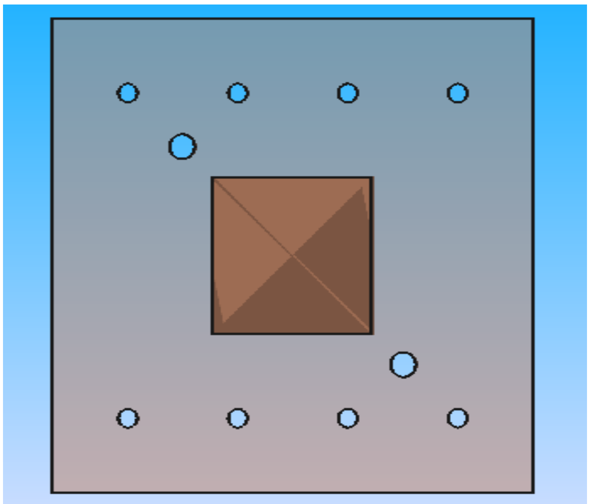
21.2.2.5 Gasket of FC stack

19042024_Gasket redesign.FCStd



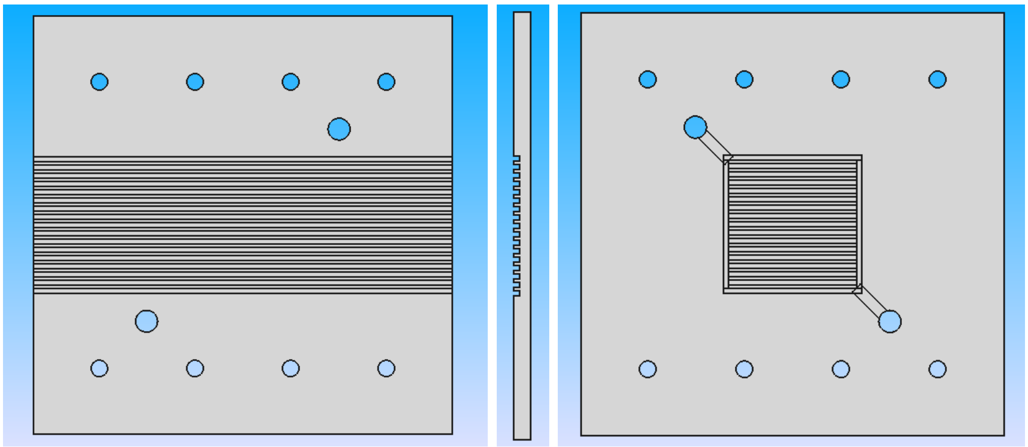
21.2.2.6 Membrane of FC stack

19042024_MEA Redesign.FCStd



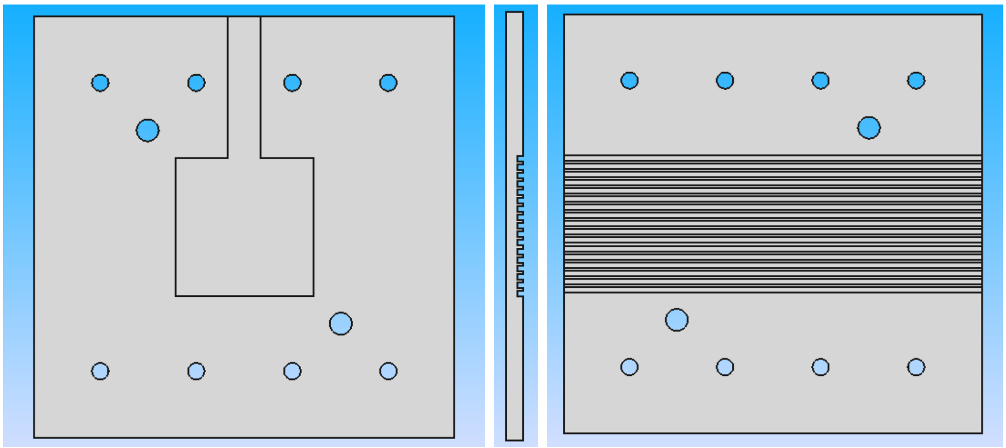
21.2.2.7 BBP graphite plate of FC stack

18042024_BBP
redesign.FCStd



21.2.2.8 Air graphite plate of FC stack

18042024_Graphite
plate of Air or O2.FC



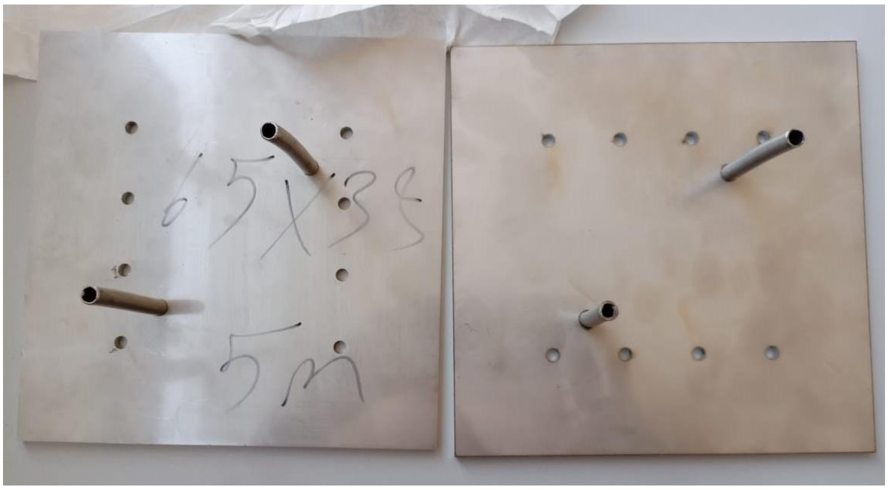
21.2.3 Sizing of FC design

This file contains all proposals and the suggested measurements for a pilot project application

13052024_Fuel cell
Sizing details.pptx

21.3 Materials of FC stack

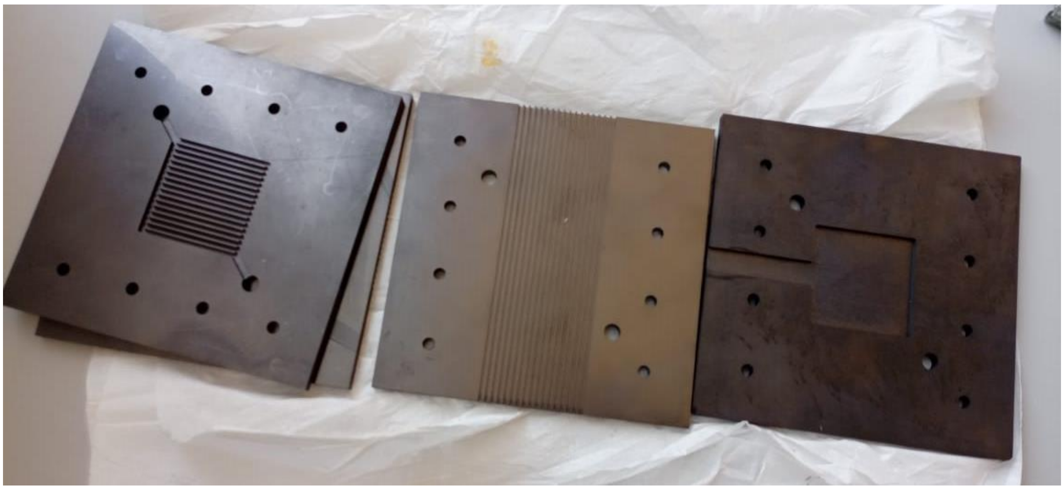
21.3.1 End plates



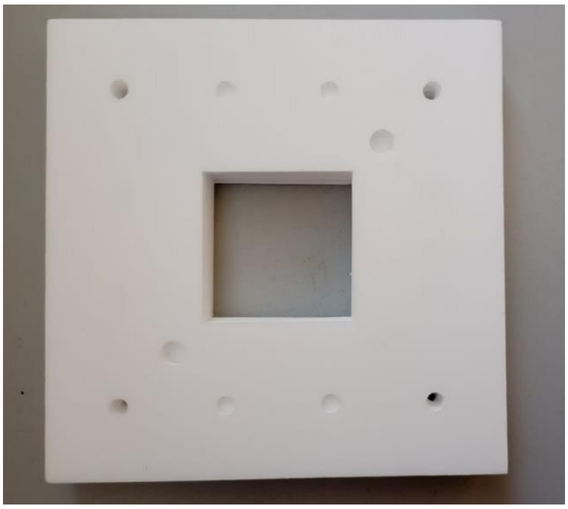
21.3.2 Current plates

21.3.3 Gasket behind the current plate

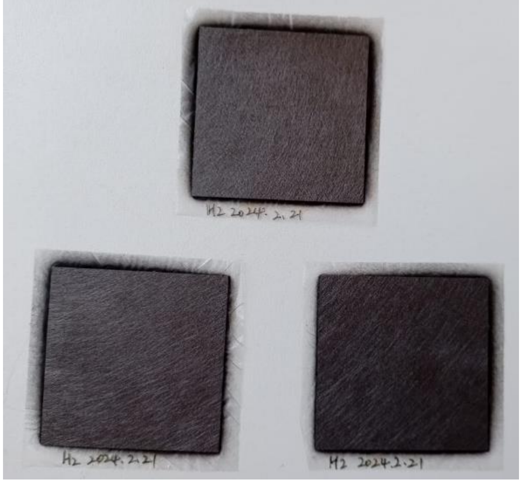
21.3.4 H_2,BPP, and Air graphite plate



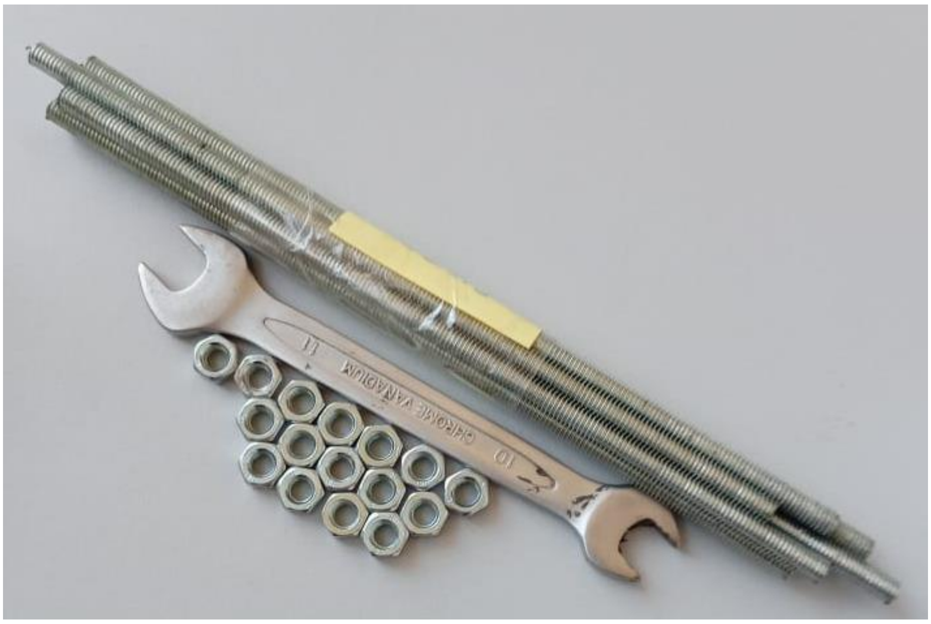
21.3.5 Gasket plate



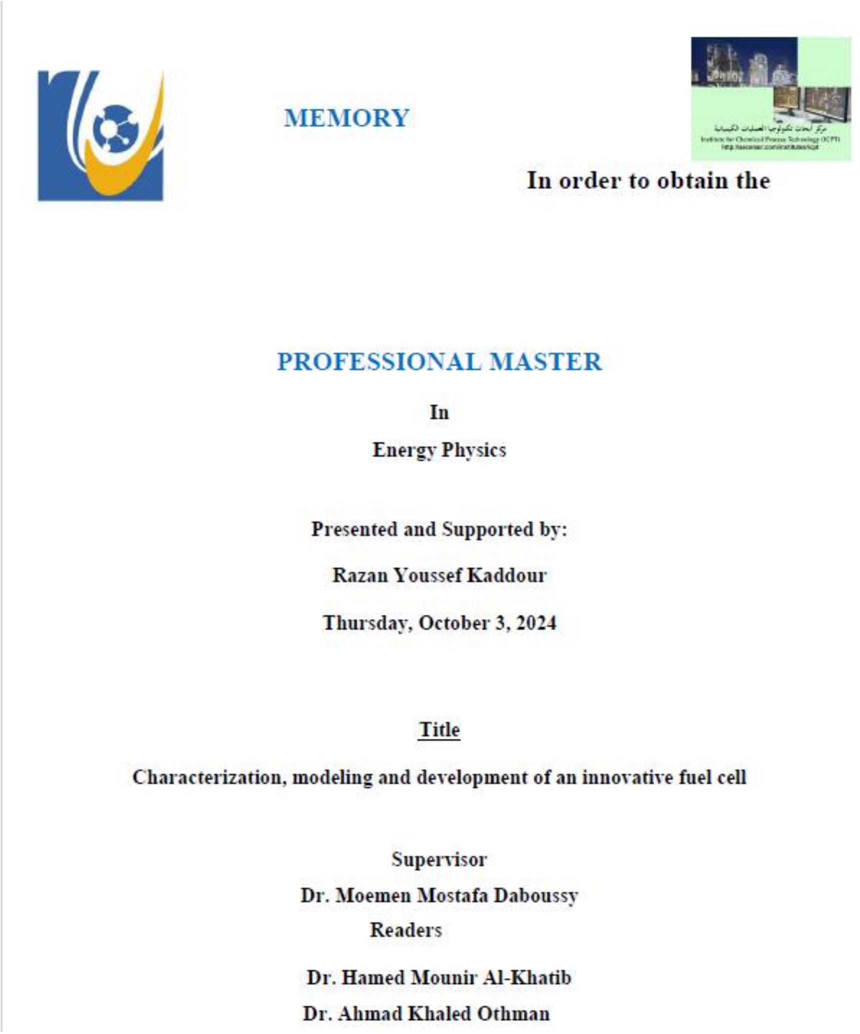
21.3.6 Membrane plate (MEA)



21.3.7 Bolts & nuts



21.4 Characterization, modeling, and development of an innovative Fuel Cell[91]



MEMORY

In order to obtain the

PROFESSIONAL MASTER

In

Energy Physics

Presented and Supported by:

Razan Youssef Kaddour

Thursday, October 3, 2024

Title

Characterization, modeling and development of an innovative fuel cell

Supervisor

Dr. Moemen Mostafa Daboussy

Readers

Dr. Hamed Mounir Al-Khatib

Dr. Ahmad Khaled Othman

Pdf file of Master Thesis:

https://aecenar.com/index.php/downloads/send/18-icpt-intitute/1790-memory-razan-kaddour

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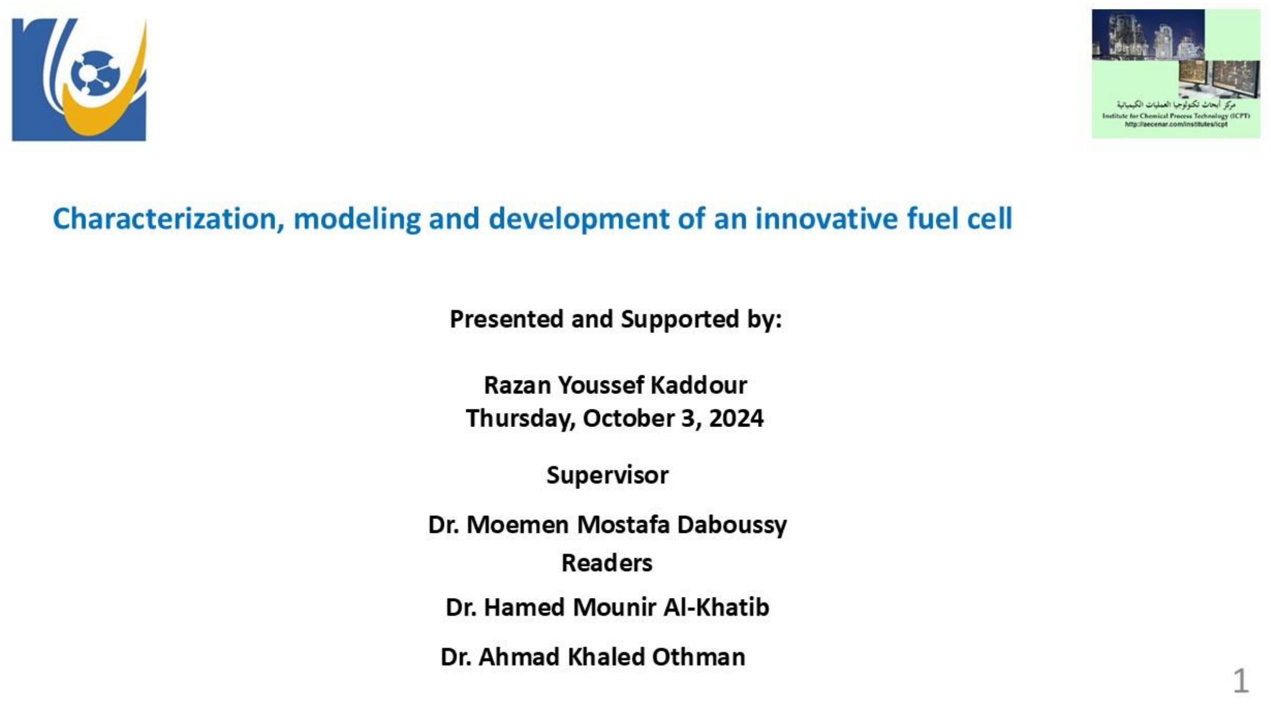
[91] From: Razan Abdulkader, Master Thesis, 2024, Lebanese University, Energetic Physics, work was done at AECENAR, supervisor: Dr. Moemen Dabbousy (Lebanese Univ. (LU))

21.4.1 Presentation on 3.10.24 at LaSeR facility



Characterization, modeling and development of an innovative fuel cell

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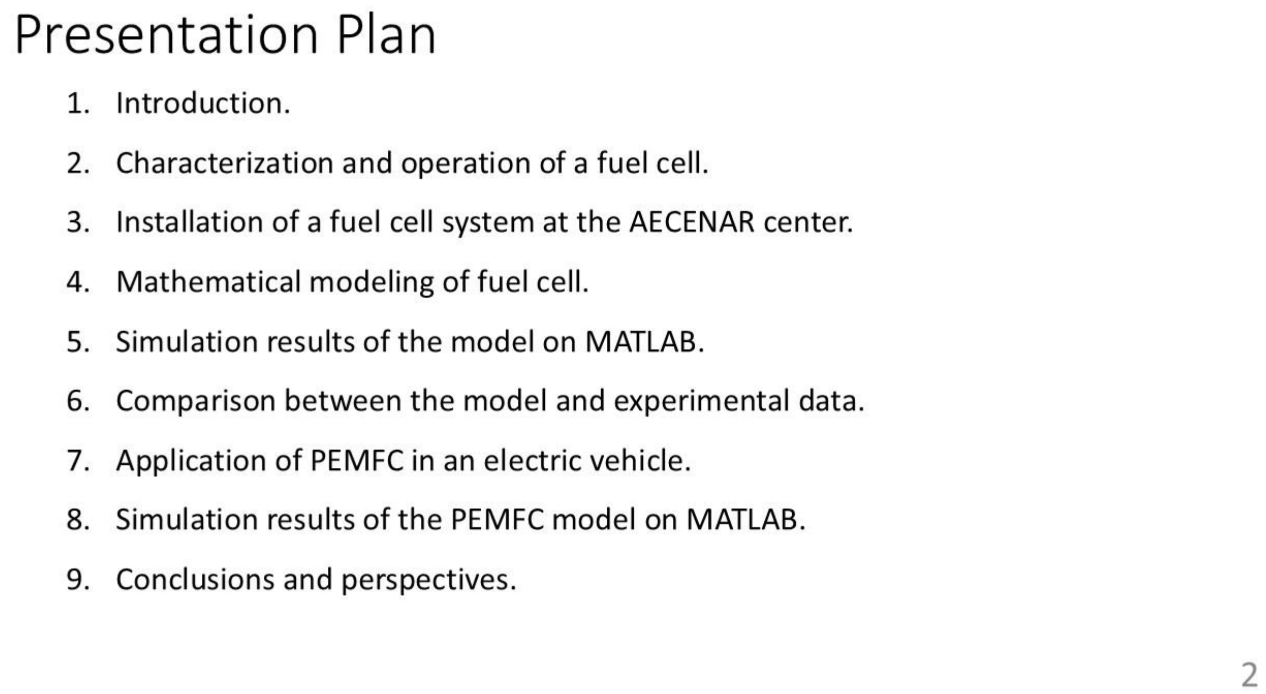


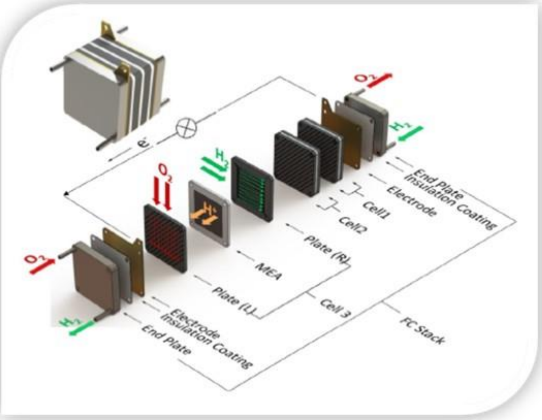
Presentation Plan

1. Introduction.
2. Characterization and operation of a fuel cell.
3. Installation of a fuel cell system at the AECENAR center.
4. Mathematical modeling of fuel cell.
5. Simulation results of the model on MATLAB.
6. Comparison between the model and experimental data.
7. Application of PEMFC in an electric vehicle.
8. Simulation results of the PEMFC model on MATLAB.
9. Conclusions and perspectives.

1. Introduction

A fuel cell is a device that produces electricity from the chemical reaction between a fuel and an oxidant.

In a fuel cell, the fuel, often hydrogen, and the oxidant, usually oxygen from the air, are fed into the cell, where they react to generate water, heat, and electricity.

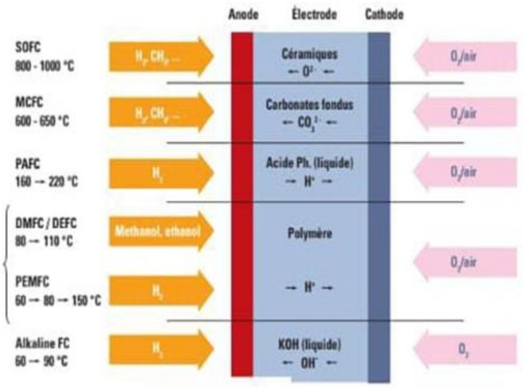


2. Characterization and operation of fuel cell

- **Fuel cell type:**

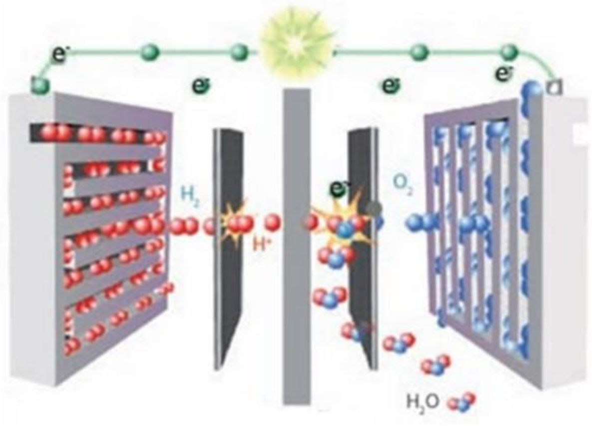
There are six main types of fuel cells, which are distinguished by the nature of their electrolyte (solid, acid, etc.)

- ➢ the proton exchange membrane fuel cell (PEMFC).
- ➢ methanol fuel cell (DMFC).
- ➢ the alkaline fuel cell (AFC).
- ➢ the phosphoric acid fuel cell (PAFC).
- ➢ the molten carbonate fuel cell (MCFC).
- ➢ the solid-state fuel cell (SOFC).



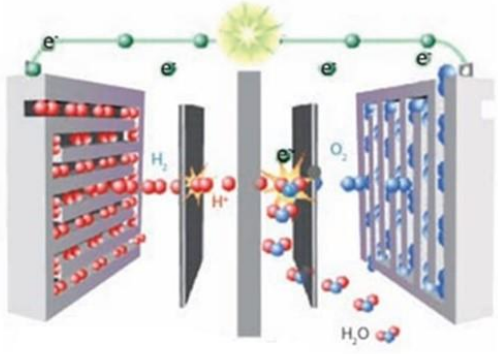
2. Characterization and operation of fuel cell

- **How a PEM fuel cell works**
  - The H2 molecule splits into 2 H+ ions and 2 electrons upon contact with the catalyst.
  - Electrons flow through the anode.
  - They travel through the external circuit and return to the cathode.



2. Fuel cell characterization

- **How a PEM fuel cell works**
  - Two oxygen atoms, each negatively charged , are formed.
  - These charges attract H+ ions across the membrane.
  - H+ ions combine with oxygen and electrons to form water (H2O) .



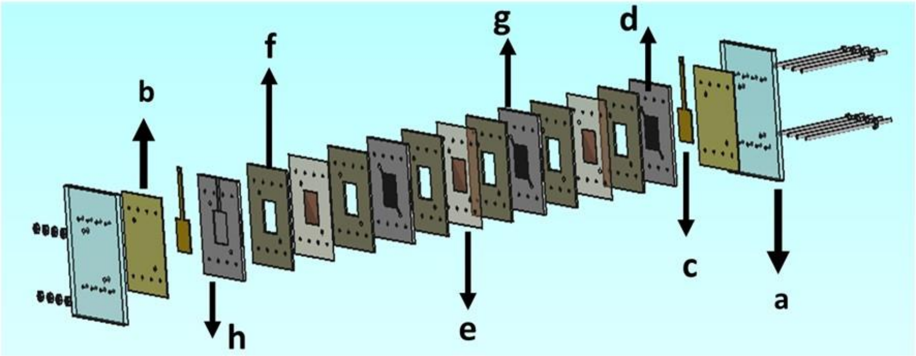
$$H_{2}(g) + \frac{1}{2}O_{2}(g) \rightarrow H2O\ (\text{liquid}) + \text{Electricity} + \text{Heat}$$

3. Installation of a fuel cell system at the AECENAR center

❖Fuel cell system design(free cad)

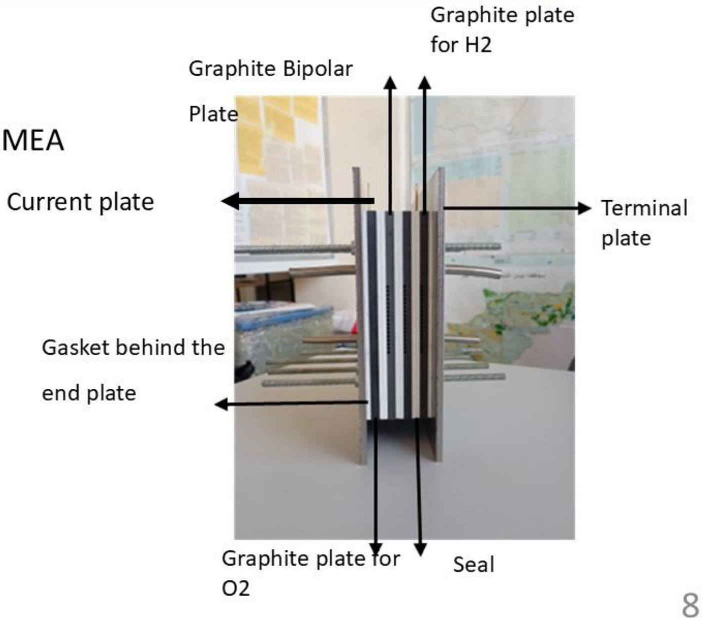
PAC components:

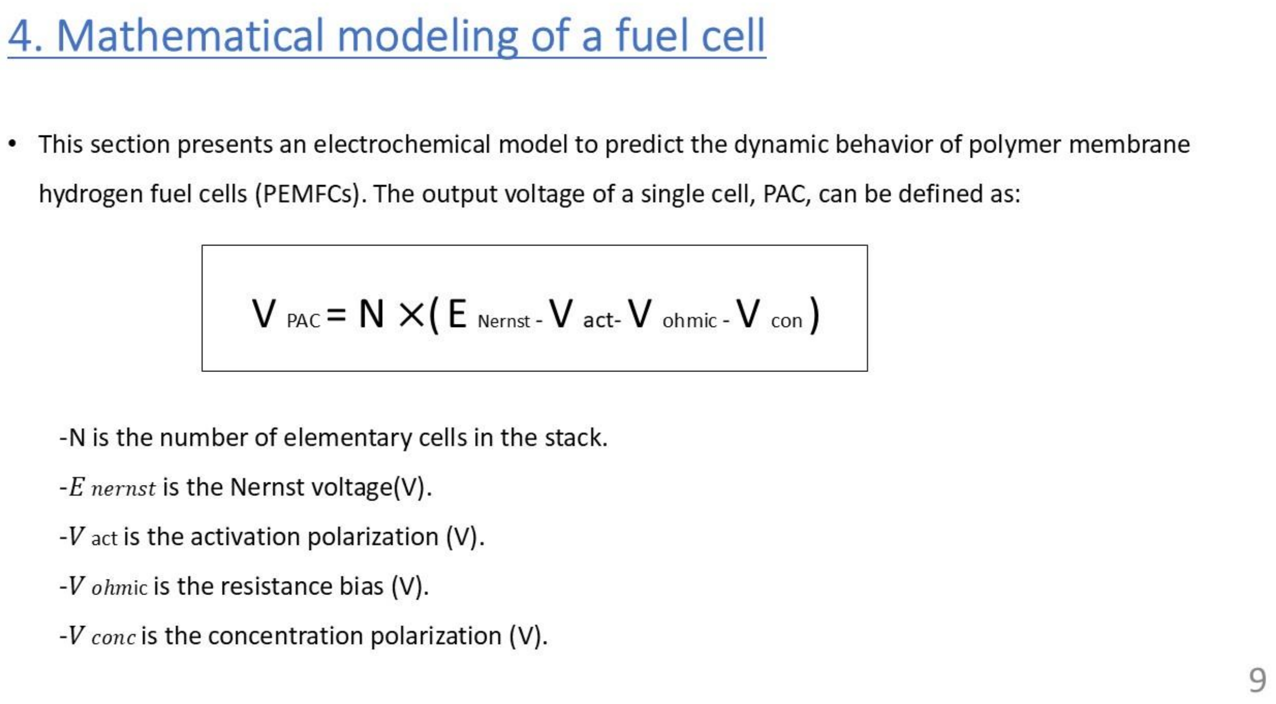
- a) Terminal plate
- b) Joint behind the end plate
- c) Current plate
- d) Graphite plate for H2
- e) MEA
- f) Joint
- g) Graphite Bipolar Plate
- h) Graphite plate for O2



3. Installation of a fuel cell system at the AECENAR center

The image shows the components needed to assemble a fuel cell, including plates with etched patterns to manage gas flow, as well as separators for the electrodes.





4. Mathematical modeling of a fuel cell

- This section presents an electrochemical model to predict the dynamic behavior of polymer membrane hydrogen fuel cells (PEMFCs). The output voltage of a single cell, PAC, can be defined as:

$$V_{PAC} = N \times (E_{Nernst} - V_{act} - V_{ohmic} - V_{con})$$

-N is the number of elementary cells in the stack.

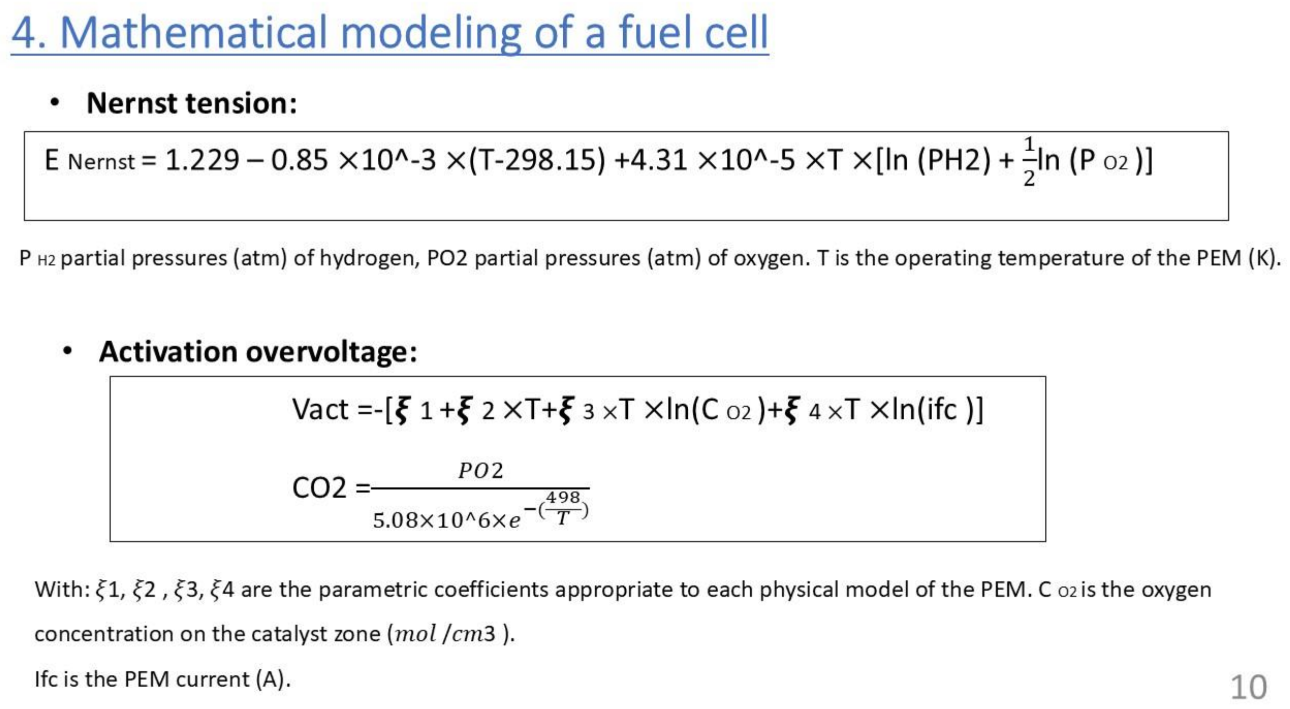
-E_{nernst} is the Nernst voltage(V).

-V_{act} is the activation polarization (V).

-V_{ohmic} is the resistance bias (V).

-V_{conc} is the concentration polarization (V).

9



4. Mathematical modeling of a fuel cell

- **Nernst tension:**

$$E_{Nernst} = 1.229 - 0.85 \times 10\text{^}{-3} \times (T-298.15) + 4.31 \times 10\text{^}{-5} \times T \times [\ln (P_{H2}) + \frac{1}{2} \ln (P_{O2})]$$

P_{H2} partial pressures (atm) of hydrogen, PO2 partial pressures (atm) of oxygen. T is the operating temperature of the PEM (K).

- **Activation overvoltage:**

$$V_{act} = -[\xi_1 + \xi_2 \times T + \xi_3 \times T \times \ln(C_{O2}) + \xi_4 \times T \times \ln(i_{fc})]$$

$$C_{O2} = \frac{PO2}{5.08 \times 10\text{^}6 \times e^{-(\frac{498}{T})}}$$

With: $\xi 1$, $\xi 2$, $\xi 3$, $\xi 4$ are the parametric coefficients appropriate to each physical model of the PEM. C_{O2} is the oxygen concentration on the catalyst zone ($mol/cm3$).

Ifc is the PEM current (A).

10

4. Mathematical modeling of a fuel cell

- **Ohmic overvoltage:**

$$V_{ohm} = ifc \times (R_m + R_c)$$

$$R_m = ƒ_m \times \frac{l}{A}$$

$$ƒ_m = \frac{181.6 \times [1+0.03 \times (ifc/A) + 0.062 \times (T/303)\text{^}2 \times (ifc/A)\text{^}2.5]}{[\Psi - 0.634 - 3 \times (ifc/A) \times e^{(4.18 \times (\frac{T-303}{T}))}]}$$

R is the contact resistance equivalent to the conduction of electrons (Ω).

R m is the equivalent resistance of the membrane to proton conduction (Ω).

l is the membrane thickness (μm), A is the active area of the PEM (cm),

ƒm is the qualitative resistivity of the membrane ($\Omega.\,cm$). Ψ is the parametric coefficient .

4. Mathematical modeling of a fuel cell

- **Concentration surge**

$$V_{con} = -B \times \ln\left(1 - \frac{J}{Jmax}\right)$$

J: current density ($A\ /cm$^2). $Jmax$: maximum density (A/cm^2). B is the electrochemical constant (dependent on cell type [V]).

- **Molar flow rate of hydrogen (H_2)**

$$n_{h2} = \frac{(ifc \times N)}{(2 \times F)}$$

F is the Faraday constant which is expressed as [C]

- **Mass of hydrogen (H_2)**

$$mh2 = \int nh2 \times Mh2\ dt$$

Mh2 is the molar mass of h2 which is expressed in [kg/mol].

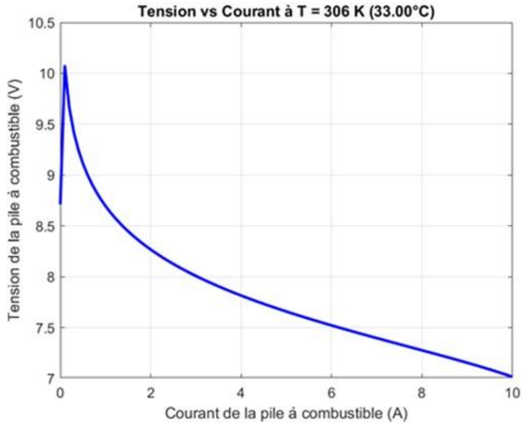
5. Model simulation results on MATLAB

The operating conditions of the mathematical model of the fuel cell are as follows :

1) Number of cells = 10 6) Partial pressure of oxygen P $_{O2}$ =0.2095[atm]
2) Partial pressure of hydrogen P $_{H2}$ =1[atm] 7) Constant dependent on cell type B=0.016
3) Temperature = 33°C (306 Kelvin) 8) Contact resistance R $_c$ =0.0003 [Ohm]
4) Parametric coefficient Ψ(si)=23 9) Maximum current density J $_{max}$ =469*10 $^{-3}$ [A/cm²]
5) Membrane thickness l= 27*10 $^{-6}$ (m)

❖Voltage versus current curve:

- The voltage peaks at 10.1 V upon initial activation.
- It drops quickly to 8.5 V because of the activation bias.
- The drop becomes gradual to 7 V at 10 A, due to ohmic and concentration losses.



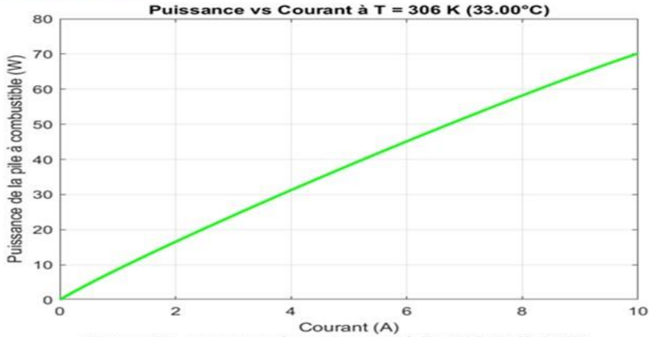
5. Model simulation results on MATLAB

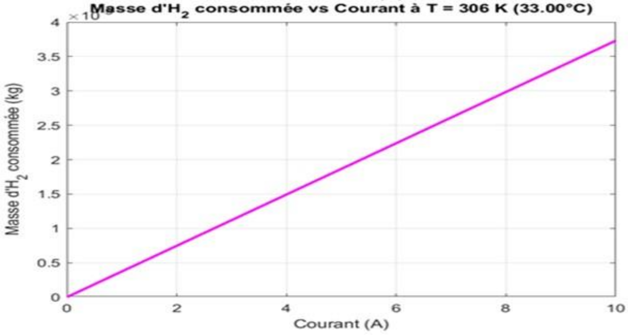
❖ Power curve as a function of current :

- It reaches 70 W at 10 A.
- The linear relationship shows a proportional increase in power.
- This indicates stable operation of the battery within this current range.

❖ H2 Mass Curve as a Function of Current:

- At low current, consumption remains low.
- Growth is almost linear.

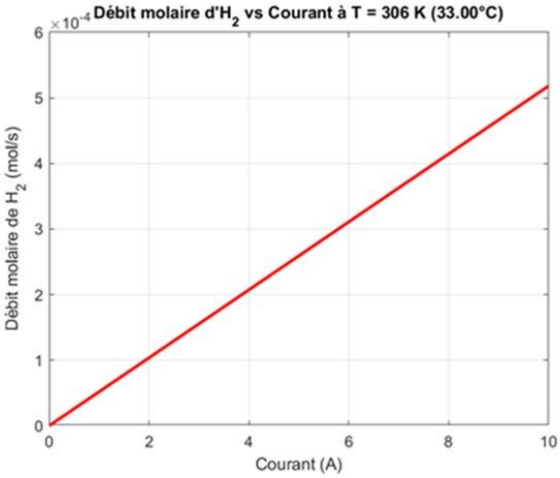




5. Model simulation results on MATLAB

❖ H2 molar flow rate curve as a function of current:

- At 10 A, the molar flow rate reaches about 5.1×10^{-4} mol/s.
- This behavior follows Faraday's law, linking hydrogen consumption to electric current.

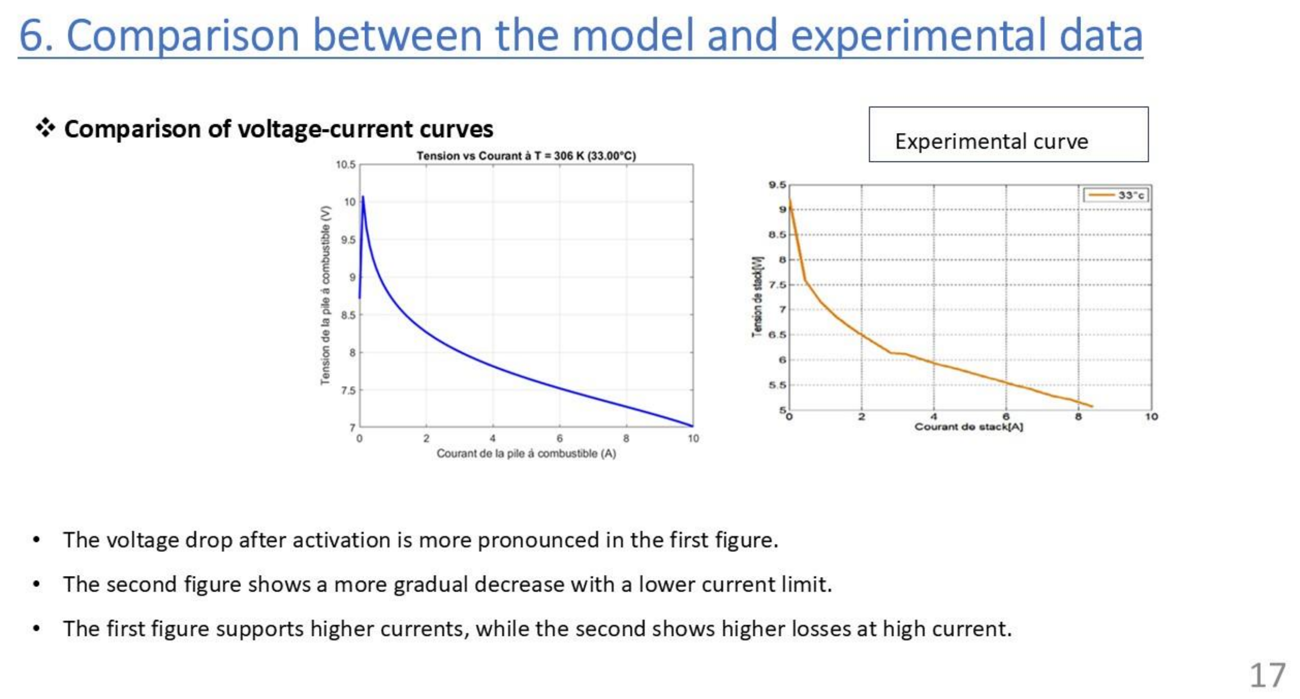


6. Comparison between the model and experimental data

In AECENAR center, we installed three PEM cells. However, due to the absence of the hydrogen bottle, it was not possible to test this system after installation. We took the real tests carried out at the Electrical Engineering Laboratory (LAGE) of the Scientific Research Center of Kasdi Merbah Ouargla University (Algeria).

Operating conditions of the experimental part:

i. Number of cells = 10
ii. Membrane thickness 27 [µm]
iii. Nominal anode pressure [bar] 0.6 +/- 0.1
iv. I max=10A
v. Raw sectional cell 25 cm^2.



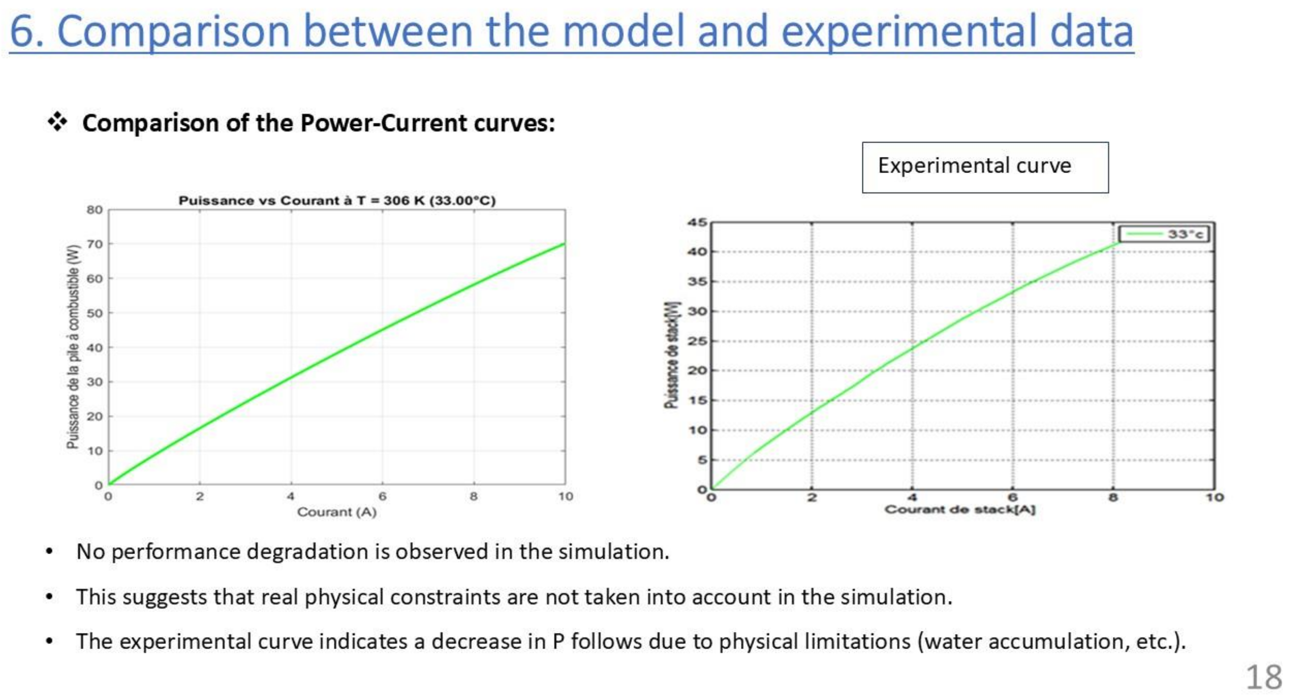
6. Comparison between the model and experimental data

❖ **Comparison of voltage-current curves**

Experimental curve

- The voltage drop after activation is more pronounced in the first figure.
- The second figure shows a more gradual decrease with a lower current limit.
- The first figure supports higher currents, while the second shows higher losses at high current.

17



6. Comparison between the model and experimental data

❖ **Comparison of the Power-Current curves:**

Experimental curve

- No performance degradation is observed in the simulation.
- This suggests that real physical constraints are not taken into account in the simulation.
- The experimental curve indicates a decrease in P follows due to physical limitations (water accumulation, etc.).

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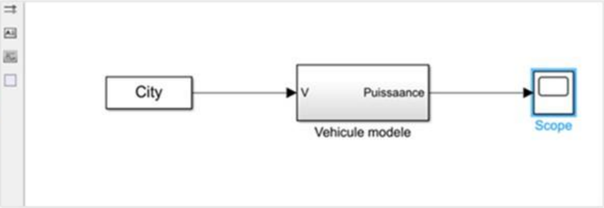
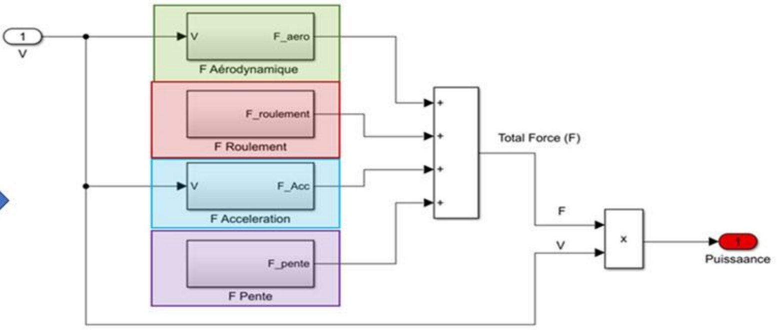
7.Application of PEMFC in electric vehicle.

- The forces acting on a vehicle include rolling resistance, slope resistance, aerodynamic force, acceleration force, and slope force .

Vehicle model in Simulink



F(N) = F _aérodynamique + F _roulement + F _accélération + F _pente



7.Application of PEMFC in electric vehicle.

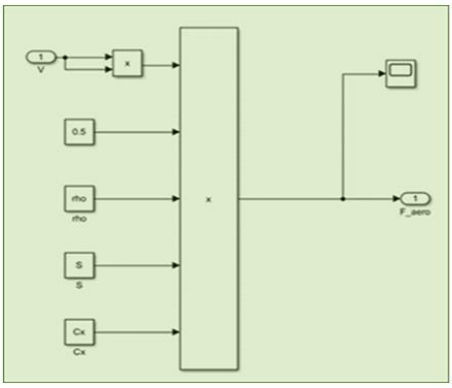
1. F _aerodynamic = $0.5 \times \rho \times S \times C_x \times V^2$

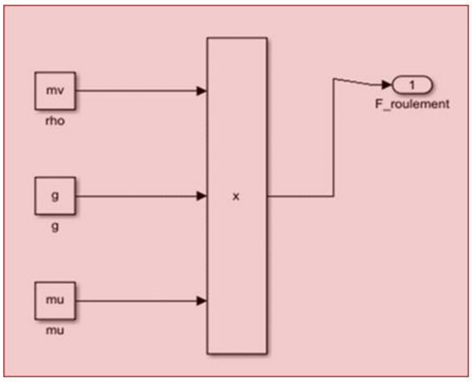
With :
V = vehicle speed [m/s]
ρ = air density ($\approx$1.2 kg/m ^{3})
S = surface (frontal area) of the vehicle [m ^{2}]
C_x = drag coefficient.

2. F _rolling = $m_v \times g \times \mu$

With :
g = acceleration of gravity [9.81 m/s ^{2}]
μ = coefficient of friction [$\approx$0.01]
m_v = mass of the vehicle.

Model in Simulink



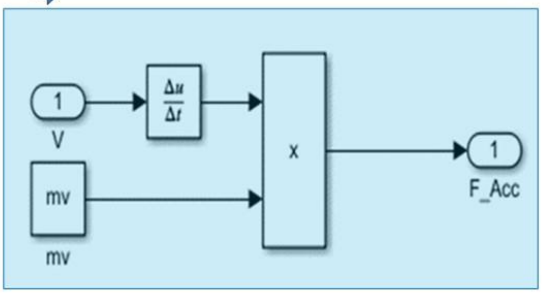


7.Application of PEMFC in electric vehicle.

3. $F\_acceleration = m_v \times a$

With :

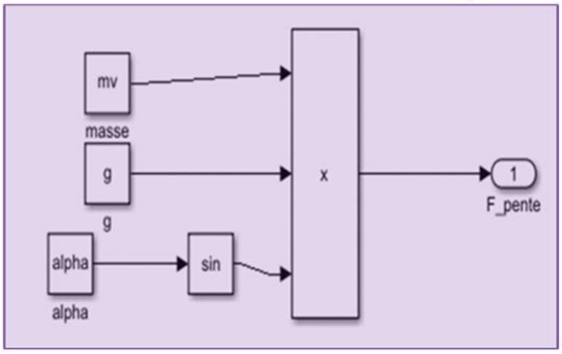
a = vehicle acceleration



4. $F\_slope = m_v \times g \times \sin \alpha$

With :

α = slope [rad]



7.Application of PEMFC in electric vehicle

❖ PAC Feature:

- **PAC current** $I_{fc} = \frac{Pfc}{Vfc}$;

P_{fc}: PAC power[W]

V_{fc}: PAC voltage [V]

- **Molar flow rate**

$\dot{n}_{H2\text{-}stack} = \frac{Ifc}{2*F} \times n_c$

F: Farad constant

nc: number of cells in the stack

- **Hydrogen mass**

$m_{H2} = \int \dot{n}_{h2} \times M_{H2}\, dt$

$M_{h2} = 2 \times 10^{-3}$ Molar mass H_2 [kg/mol]

- **Cell voltage [V]**

i. $V_c = 1.031 - 2.45 \times 10^{-4} \times j - 0.03 \times \ln(d+3) - 2.11 \times 10^{-5} \times e^{(8\times 10^{-3}\times j)}$

j: Current density [mA/cm ^{2}] ; $j = \frac{Ifc}{Sfc}$ With: S_{fc} = 480 cm ^{2} : The surface area of a cell

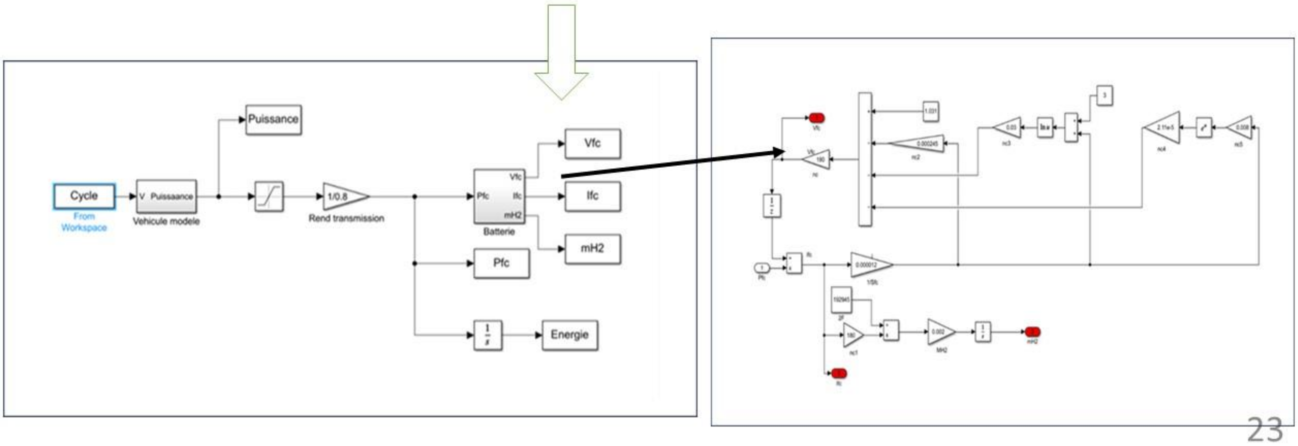
ii. $V_{FC} = V_c \times n_c$ The total battery voltage [V].

V_c : The cell voltage [V]. n_c the number of cells.

7.Application of PEMFC in electric vehicle

By integrating the vehicle's power as an input, the battery can be regulated in real time, thus optimizing energy management and system efficiency while responding to variations in energy needs.

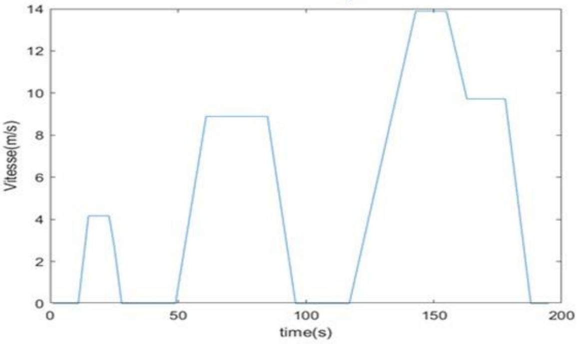
PEMFC model in MATLAB/SIMULINK



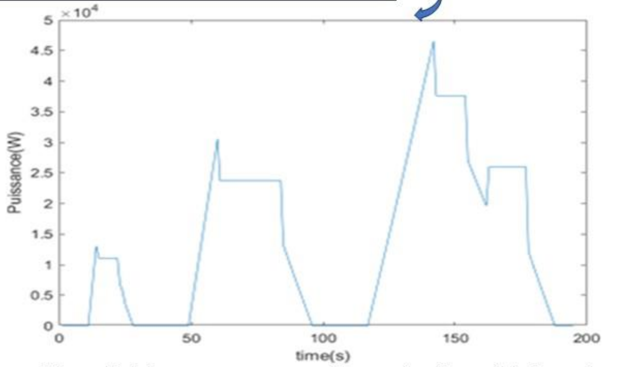
8. Results of the PEMFC model on MATLAB

Electric vehicle characteristics: ρ = air density rho=1.2(kg/m^3); S = vehicle surface area S=2.11(m2); Drag coefficient C x =0.28; Vehicle mass mv=1465(Kg); v. Gravity acceleration g=9.81 m/s2 ; vi. Friction coefficient µ =0.01; vi; alpha=10; time:0 to195s.

Electric Vehicle Curves Results



The electric vehicle speed curve simulated in MATLAB provides a detailed analysis of the vehicle's dynamic performance as a function of time.



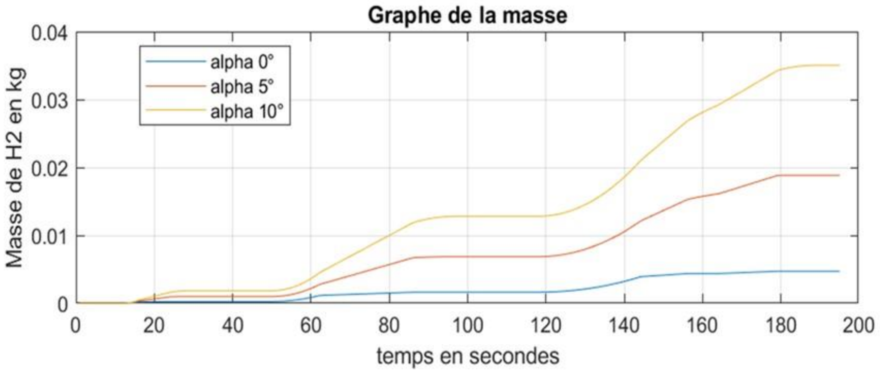
The vehicle's power curve over time makes it possible to analyze the evolution of the energy delivered by the electric propulsion system .

8.Result of PEMFC model on MATLAB

PAC Feature:

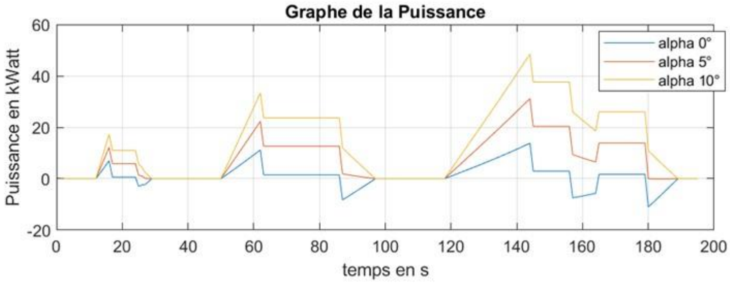
1) Nc =180 The number of cells in the stack 2) rtransmission =80 Transmission efficiency [%]
3) e = 1.602 *10^-19 Elementary electric charge [C] 4) Sfc =480 The surface area of a cell [cm^2]
5) N_A : Avogadro's number = 6.022 * 10^23 mol^-1 6) t = 195 time [s]
7) MH2 = 2*10^-3 The molar mass of dihydrogen [kg/mol] 8) α =0°; α =5°; α =10°;

•**Mass** : Increase due to internal chemical reactions.

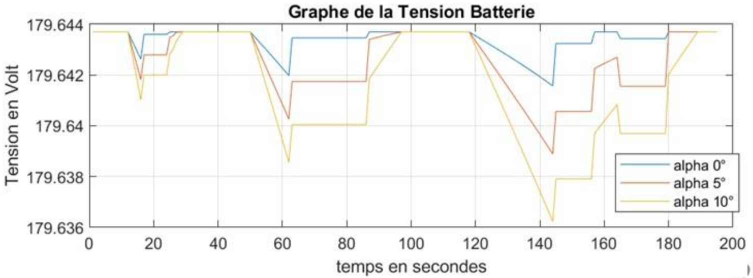


8.Result of PEMFC model on MATLAB

Power : Oscillations linked to the charge/discharge phases, varying according to the “alpha” slope.

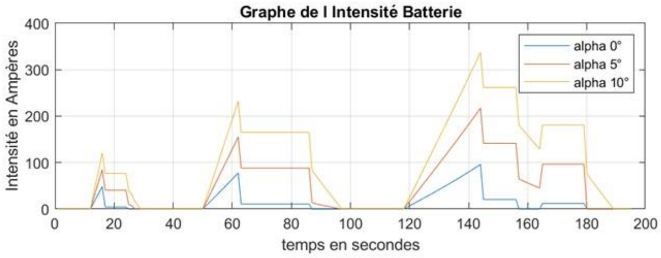


Tension : Gradual decrease, faster with high “alpha”.

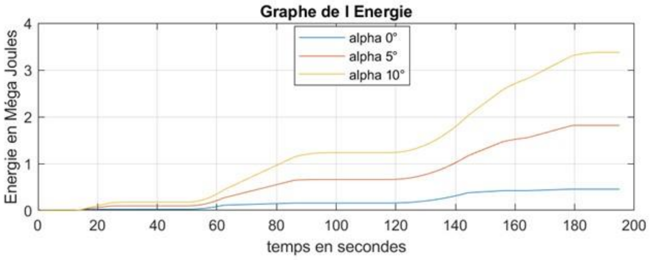


8.Result of PEMFC model on MATLAB

Intensity : Peaks similar to power, linked to the charge/discharge phases.



Energy : Charge/discharge cycles similar to those of power.



9. Conclusion and perspectives

•**Modeling and validation** of a PEM fuel cell system for electric vehicles.

•**Implementation in MATLAB/Simulink** to simulate dynamic stack behavior.

•**Successful comparison** of simulation results with experimental data.

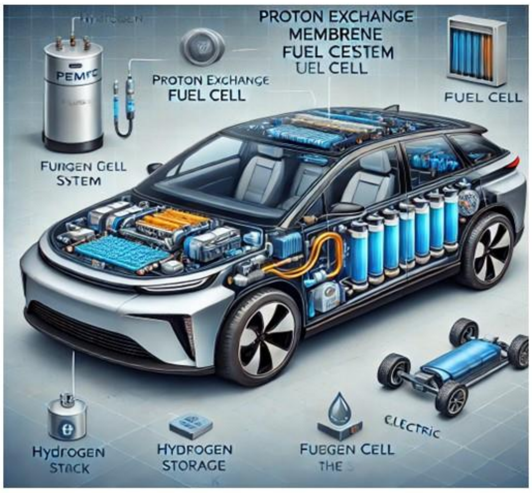
Perspectives:

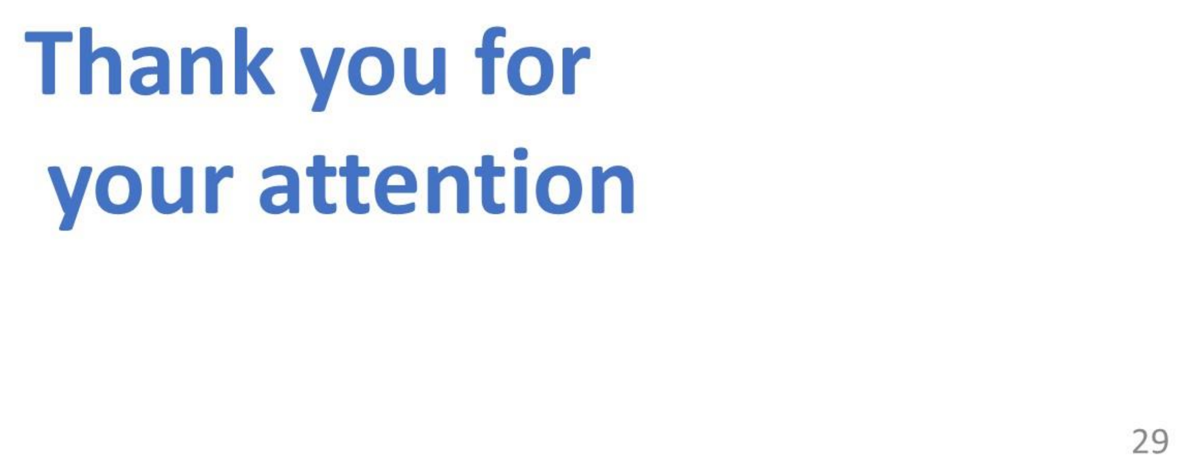
. Continue the installation of an experimental battery bench within the AECANAR center to collect experimental data.

•**Optimization of operating conditions** : hydration, temperature, pressure.

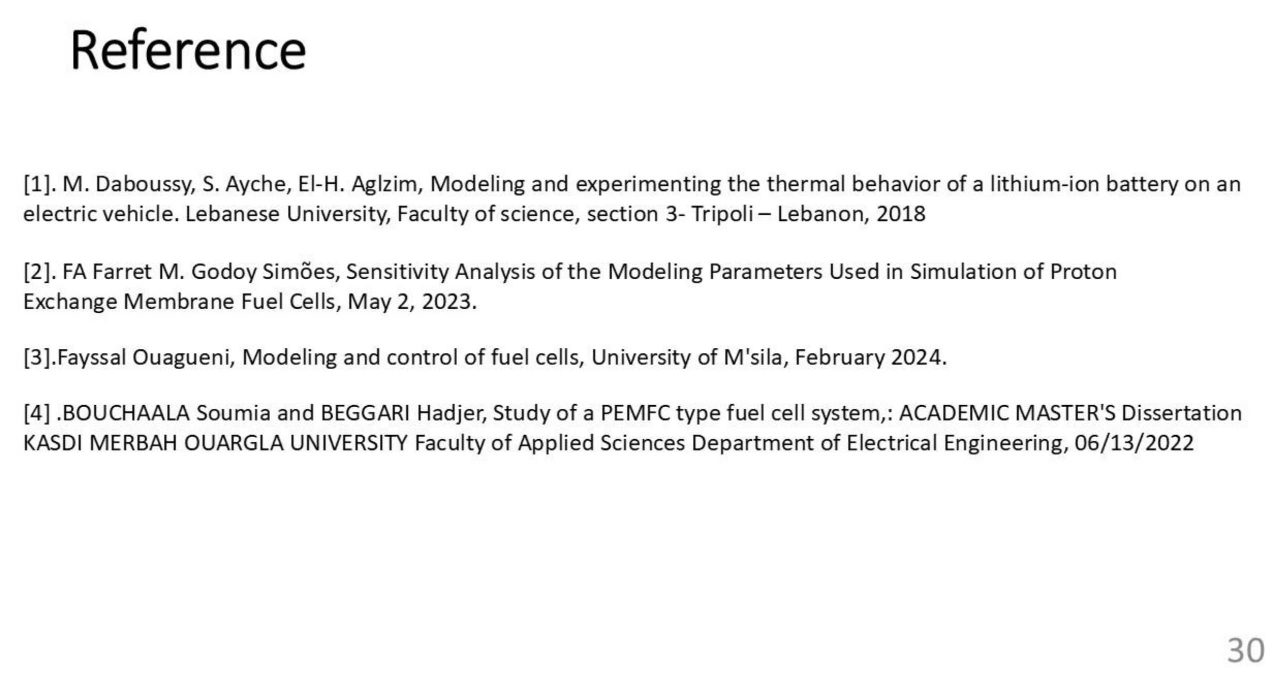
•**Study of hybrid systems** combining hydrogen fuel cells and batteries.

•**Improved modeling** for more accurate simulations.





Thank you for your attention



Reference

[1]. M. Daboussy, S. Ayche, El-H. Aglzim, Modeling and experimenting the thermal behavior of a lithium-ion battery on an electric vehicle. Lebanese University, Faculty of science, section 3- Tripoli – Lebanon, 2018

[2]. FA Farret M. Godoy Simões, Sensitivity Analysis of the Modeling Parameters Used in Simulation of Proton Exchange Membrane Fuel Cells, May 2, 2023.

[3].Fayssal Ouagueni, Modeling and control of fuel cells, University of M'sila, February 2024.

[4] .BOUCHAALA Soumia and BEGGARI Hadjer, Study of a PEMFC type fuel cell system,: ACADEMIC MASTER'S Dissertation KASDI MERBAH OUARGLA UNIVERSITY Faculty of Applied Sciences Department of Electrical Engineering, 06/13/2022

21.4.2 Fuel Cell Modeling (Master Thesis Razan, Chapter 2)

21.4.2.1 Introduction

The PEMFC fuel cell attracts the attention of researchers due to its many advantages. It generates electricity, water and heat, using the oxygen in the air and the hydrogen, which must be produced. Its production is a key issue for the adoption of these cells. This chapter presents the mathematical modeling of the cell, the test bench and its performance, as well as the design and installation of the fuel cell system, the components and their operation.

21.4.2.2 Mathematical modeling of fuel cell

The theoretical thermodynamic potential of a PEMFC is about 1.23 V at atmospheric pressure and a temperature of 25°C. However, when the fuel cell is connected to a load, the actual voltage decreases compared to the theoretical voltage due to polarization phenomena. There are three types of polarization: activation polarization, ohmic (resistance) polarization, and concentration polarization. The VPAC fuel cell voltage can be expressed as follows:

$$V_{PAC}= N \times (E_{Nernst} - V_{act} - V_{ohmic} - V_{con}) \quad \textit{[21]} \qquad (\acute{E}q\ 2,1)$$

N is the number of elementary cells in the stack.

E $nernst$ is the Nernst voltage (V).

V act is the activation bias (V).

V ohm is the resistance bias (V).

V $conc$ is the concentration bias (V).

Supply voltage

The supply voltage is a reversible thermodynamic potential of each fuel cell. It represents the no-load voltage of the PEM. This voltage is expressed as follows:

$$E_{Nernst} = \frac{\Delta G}{2\times F} - \frac{\Delta S}{2*F} \times (T-T_{ref}) + \frac{R\times T}{2\times F} * [\ln (P_{H2}) + \frac{1}{2} \ln (P_{O2})] \qquad \textit{[21]}$$

Where ΔG is the free energy change (J/k.mol),

Δs is the entropy change (J/k.mol),

F is the Faraday constant (C/k.mol),

T is the PEM operating temperature (k),

$Tref$ is the reference temperature (k), and

R is the universal gas constant (J/k.mol).

PH2 partial pressures (atm) of hydrogen, and PO2 partial pressures (atm) of oxygen.

When we substitute the standard value temperature and pressure, the equation becomes simplified as follows [21]:

$$E_{Nernst} = 1.229 - 0.85\times10^{-3} \times (T-298.15) + 4.31\times10^{-5}\times T\times [\ln (P_{H2}) + \frac{1}{2} \ln (P_{O2})] \qquad (\acute{E}q\ 2,3)$$

Activation overvoltage

At low current densities, due to the activation energy required to initiate the reaction between gases, especially oxygen at the cathode, the relationship between activation losses and current density is expressed as follows:

$$V_{act}=-[\xi_1+\xi_2\times T+\xi_3\times T\times \ln(C_{O2})+\xi_4\times T\times \ln(i_{fc})] \ ; \qquad (\acute{E}q\ 2,4)$$

$$C_{O2}=\frac{PO2}{5.08\times 106\times e^{-(\frac{498}{T})}} \qquad (\acute{E}q\ 2,5)$$

$\xi_1, \xi_2, \xi_3, \xi_4$ are the parametric coefficients appropriate to each physical model of the PEM. C O2 is the oxygen concentration on the catalyst zone (*mol* /*cm*3).

I_{fc} is the operating current of the PEM (A). [21]

Ohmic Overvoltage

For average current densities, ohmic losses result from the electrical resistance of the various components of the proton exchange membrane (PEM) fuel cell, such as the electrolyte and electrodes. These losses can be expressed using Ohm's law, according to the following equation:

$$V_{ohm} = i_{fc}\times(R_M+R_c) \qquad (\acute{E}q\ 2,5)$$

$$R_m = ƒ_m\times l/A \qquad (\acute{E}q\ 2,6)$$

$$ƒ_m=\frac{181.6\times[1+0.03\times\left(\frac{ifc}{A}\right)+0.062\times\left(\frac{T}{303}\right)^2\times\left(\frac{ifc}{A}\right)^{2.5}}{[\Psi-0.634-3\times\left(\frac{ifc}{A}\right)\times\exp\,[4.18\times(\frac{T-303}{T})]]} \qquad (\acute{E}q\ 2,7)$$

R is the contact resistance equivalent to electron conduction (Ω).

Rm is the equivalent resistance of the membrane to proton conduction (Ω).

l is the membrane thickness (μ*m*),

A is the active area of the PEM (*cm*),

ƒm is the qualitative resistivity of the membrane (Ω. *cm*).

Ψ is the parametric coefficient. [21]

Concentration overvoltage

Concentration overvoltage is also called concentration polarization, it occurs at high current densities and is caused by the variation of the concentration of reactants (hydrogen or oxygen) at the electrodes, especially at the cathode. The following relation can describe these losses:

$$V_{con} = -B\times\ln\left(1-\frac{J}{Jmax}\right) \qquad (\acute{E}q\ 2,8)$$

J is the current density (*A* /*cm*2). *Jmax* is the largest current density (*A*/ *cm*2).

B is the electrochemical constant (dependent on cell type [V]). [21]

Molar flow rate of hydrogen (H_2) in a PEM fuel cell

The molar flow rate represents the amount of moles of hydrogen consumed per unit time in the cell, usually expressed in moles per second (mol/s). This flow rate is crucial in a proton exchange membrane (PEM) fuel cell to power the electrochemical reaction. The following relationship:

$$n_{h2}=\frac{(ifc\times N)}{(2\times F)} \qquad (\acute{E}q\ 2,9)$$

F is the Faraday constant which is expressed in [C].

Hydrogen (H_2) mass in a PEM cell:

Together with the molar flow rate, it plays a key role in the autonomy of the cell, determining how long it can operate before the hydrogen tank needs to be refilled. In a PEM cell, a small mass of hydrogen is required to produce a significant amount of energy, making it a very efficient fuel source. According to the following relationship:

$$m_{h2} = \int nh2 \times Mh2 \, dt \qquad (\acute{E}q\ 2{,}10)$$

Mh2 is the molar mass of h2 expressed in [kg/mol].

In this study, several critical parameters were defined to model the behavior of the proton exchange membrane (PEM) fuel cell in MATLAB/Simulink. These parameters directly influence the simulation performance and results. A thorough understanding of these parameters is essential to optimize the system design.

Detailed calculations on MATLAB can be found in Appendix 1.[92]

---

[92] Appendix 1: **PAC parameter in MATLAB**

```
clear all ;
close all ;
clc;
n = 10; % Number of cells used in the stack
A = 25; % Active cell surface area of a cell [cm²]
l = 27e-6; % Membrane thickness [m]
T_K = 306; % Cell operating temperature [K]
T_C = T_K - 273.15; % Temperature in degrees Celsius
Po2 = 0.2095; % Partial pressure of oxygen [atm]
Ph2 = 1; % Partial pressure of hydrogen [atm]
Rc = 0.0003; % Contact resistance [Ohm]
B = 0.016; % Cell type dependent constant [V]
zeta11 = -0.853; % Parametric coefficient (fixed to a single value)
zeta3 = 7.6e-5; % Parametric coefficient
zeta4 = -1.93e-4; % Parametric coefficient
if = 23; % Parametric coefficient
Jn = 3e-3; % No-load current density [A/cm²]
Jmax = 469e-3; % Maximum current density [A/cm²]
F = 96485; % Faraday constant [C/mol]
Mh2 = 0.002; % Molar mass of H2 [kg/mol]
% Current range definition
current_range = 0:0.1:30; % Current from 0 to 30 A with a step of 0.1 A
num_current = length(current_range);
% Operation time (eg 1 hour)
t_op = 3600; % Time in seconds
for i = 1:num_current
```

```
ifc = current_range(i);
% Thermodynamic potential of each unit cell
E_N = 1.229 - (0.85*10^-3)*(T_K - 298.15) + (4.31*10^-5)*T_K*(log(Ph2) + 0.5*log(Po2));
% CO2 calculation
co2 = Po2 / (5.08*10^6 * exp(-498 / T_K));
zeta2 = 0.00286 + 0.0002*log(A) + (4.3*10^-5)*log(co2);
if ifc == 0
Vact = -(zeta11 + zeta2*T_K + zeta3*T_K*log(co2));
else
Vact = -(zeta11 + zeta2*T_K + zeta3*T_K*log(co2) + zeta4*T_K*log(ifc));
end
rom=181.6*(1+0.03*(ifc/A)+0.062*(T_K/303)^2*(ifc/A)^2.5)/((si-0.634-3*(ifc/A))*exp (4.18*((T_K-303)/T_K)));
Rm = rom * l / A;
Vohmic = ifc * (Rm + Rc);
if ifc == 0
J = Jn; 67

else
J = ifc / A; % [A/cm²]
end
Vcon = -B * log(1 - (J / Jmax));
Vfc = n * abs(E_N - Vact - Vohmic - Vcon);
Vfc_total(i) = Vfc;
Pfc = ifc * Vfc;
Pfc_total(i) = Pfc;
nh2 = (ifc * n) / (2 * F); % [mol/s]
nh2_total(i) = nh2 ;
mh2 = nh2 * Mh2 * t_op; % [kg]
mh2_total(i) = mh2;
end
color_voltage = 'b' ; % Blue
color_power = 'r' ; % Red
color_flow = 'g' ; % Green
color_mass = 'm' ; % Magenta
figure(1);
plot(current_range, Vfc_total, 'b-' , 'LineWidth' , 2);
xlabel( 'Fuel cell current (A)' );
ylabel( 'Fuel cell voltage (V)' );
title([ 'Voltage vs Current at T = ' num2str(T_K) ' K (' num2str(T_C, '%.2f' ) '°C)' ]);
grid on ;
%2. Power vs Current
figure(2);
plot(current_range, Pfc_total, 'r-' , 'LineWidth' , 2);
xlabel( 'Current (A)' );
```

21.4.2.3 Fuel cell design (Free cad)

A fuel cell consists of graphite catalytic electrodes, a proton exchange membrane for the passage of ions, and bipolar plates to ensure uniform gas distribution and efficient water evacuation, all designed to maximize electrochemical efficiency and optimize thermal management.

- Fuel cell components:

a) Terminal plate

b) Gasket behind the terminal plate

c) Current plate

d) Graphite plate for H2

e) MEA

f) Gasket

g) Graphite bipolar plate

h) Graphite plate for O2

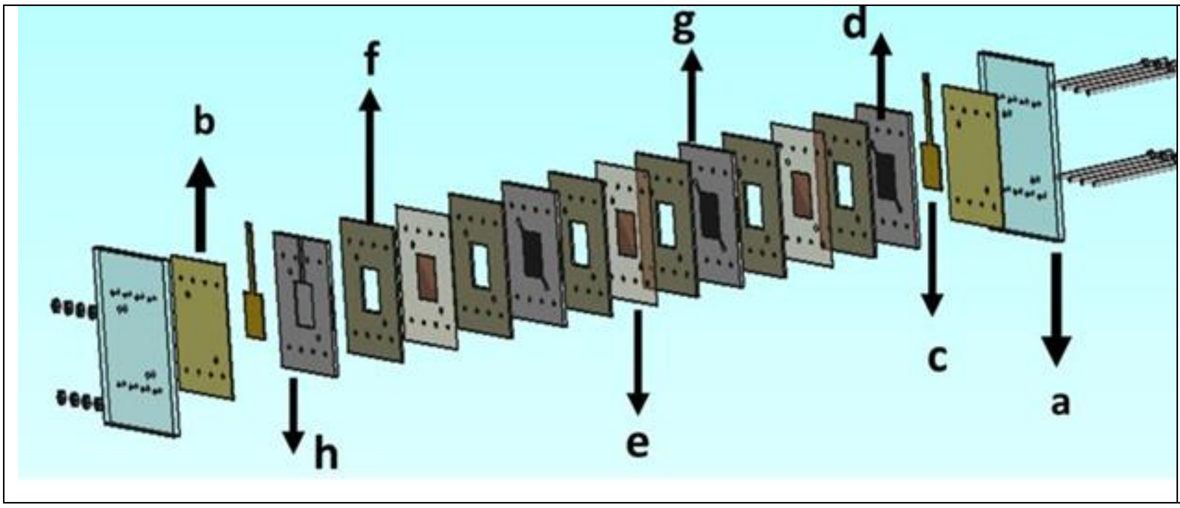


Figure 2.27: Exploded 3-cell fuel cell (Free cad)

```
ylabel( 'Fuel cell power (W)' );
title([ 'Power vs Current at T = ' num2str(T_K) ' K (' num2str(T_C, '%.2f' ) '°C)' ]);
grid on ;
figure(3);
plot(current_range, nh2_total, 'g-' , 'LineWidth' , 2);
xlabel( 'Current (A)' );
ylabel( 'Molar flow rate of H_2 (mol/s)' );
title([ 'Molar flow rate of H_2 vs Current at T = ' num2str(T_K) ' K (' num2str(T_C, '%.2f' ) '°C)' ]);
grid on ;
figure(4);
plot(current_range, mh2_total, 'm-' , 'LineWidth' , 2);
xlabel( 'Current (A)' );
ylabel( 'Mass of H_2 consumed (kg)' );
title([ 'Mass of H_2 consumed vs Current at T = ' num2str(T_K) ' K (' num2str(T_C, '%.2f' ) '°C)' ]);
grid on ;
```

Here is a more concise version of the description of the components of the PAC design (3-cell fuel cell)

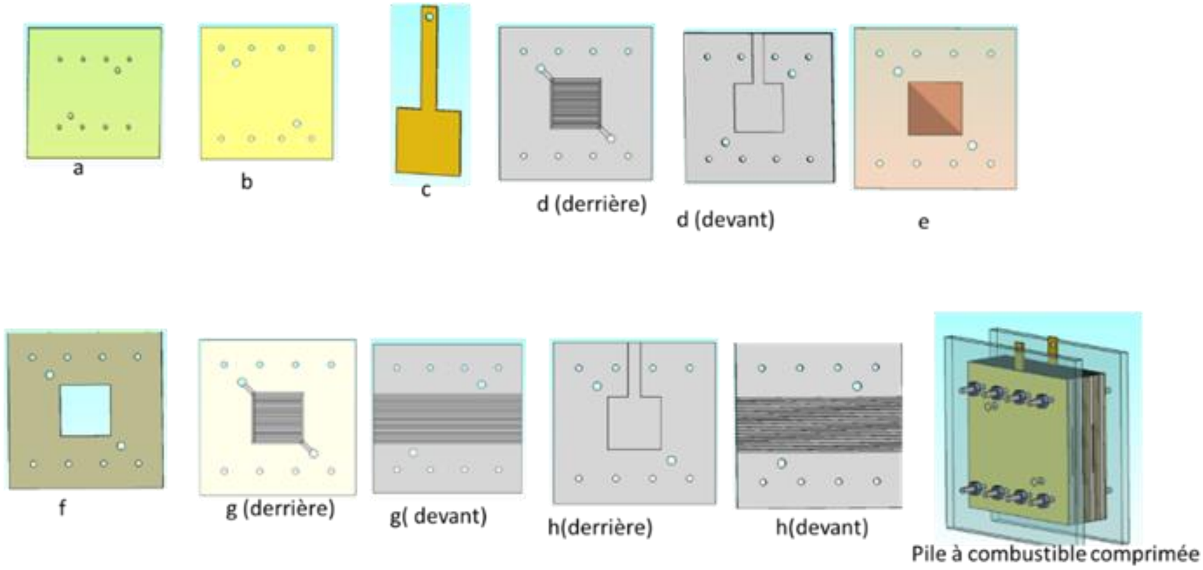


Figure 2.28: Design of each cell (FreeCAD)

Table 3: Components of the 3 cells

2 End plates	2 Gaskets behind the end plates
2 Current plates	1 graphite plate for H_2 (Anode)
3 MEA (Membrane Electrode Assembly)	6 Gaskets
2 Bipolar plates (BBP)	2 Graphite plates for O_2 (Cathode)

21.4.2.4 Fuel Cell System Installation

In the NLAP lab, we have been installing the fuel cell-cell plates. The installation of these plates is essential for the assembly and overall efficiency of the fuel cell system.

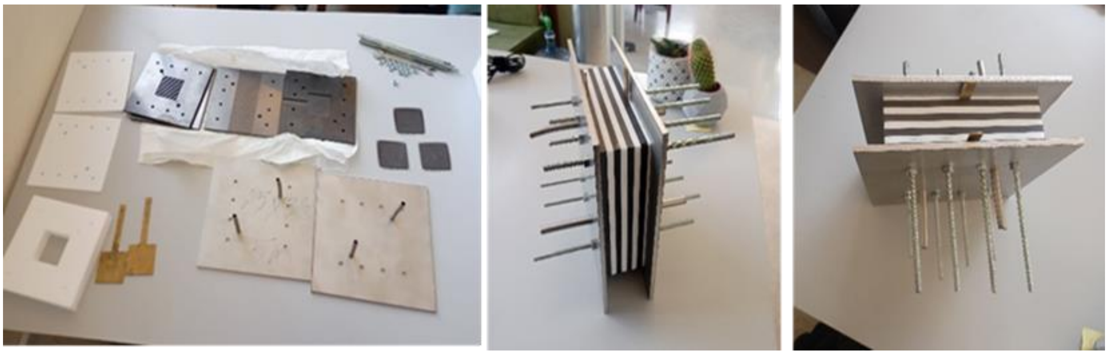


Figure 2.29: Fuel cell system

In the laboratory, we installed three PEM cells. However, due to the absence of the hydrogen bottle, it was not possible to test this system after installation.

We decided to adjust the number of cells in the simulation to test different configurations. This approach will allow us to analyze the performance of the system by changing the number of cells and comparing them with the expected results of the experimental part. We took the real tests carried out at the Electrical Engineering Laboratory (LAGE) of the Scientific Research Center of Kasdi Merbah Ouargla University (Algeria) [20].

Finally, comparing the simulated results with the experimental data will validate the reliability and accuracy of the model, ensuring that it faithfully reproduces the behavior of the real system.

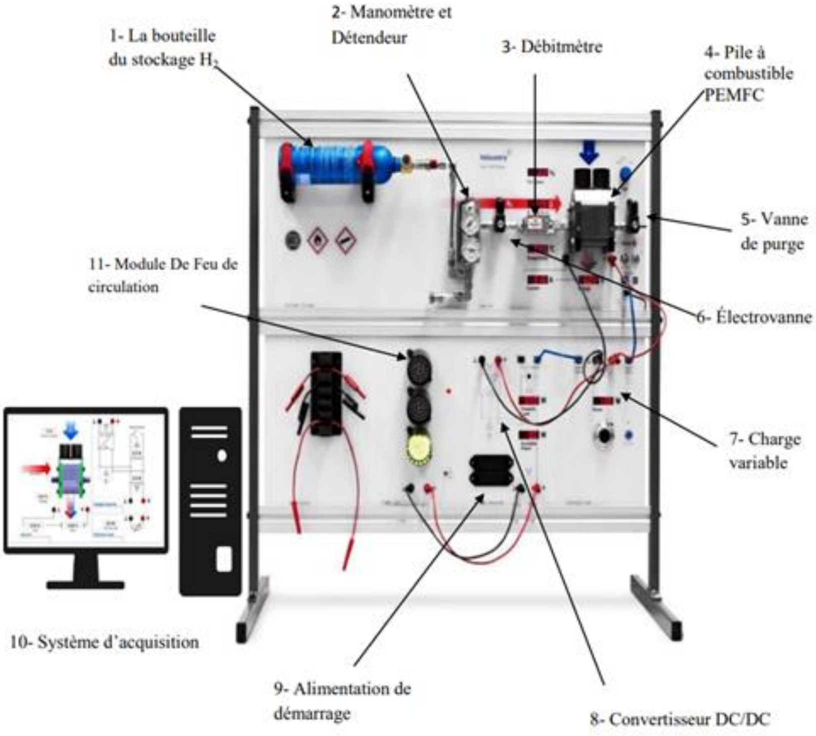
21.4.2.5 Experimental Data Analysis (LAGE)

The experimental fuel cell system (26 cells) stands out for its advanced technical features and its ability to simulate real operating conditions. Thanks to its modular and flexible design, this system allows experimenting with various configurations, facilitating the detailed study of PEM cell performance under different conditions. It integrates an intuitive user interface that simplifies the control and monitoring of critical parameters such as temperature, voltage, and current.

The system contains:

- 50 W PEM fuel cells (air-cooled, open cathode).
- USB interface.
- Displays to view all quantities.
- Intuitive and educational software.
- Automatic mode for recording.
- Instantaneous values and display of curves.
- Manual mode for point-by-point recording.
- Complete educational materials.

The system presented in Figure (2.34) is a system designed to produce electrical energy using a 50 W PEMFC fuel cell. The latter is powered by solar hydrogen [20].



Acquisition System: The software is designed to facilitate system control, data acquisition and graphical representation of the collected data.

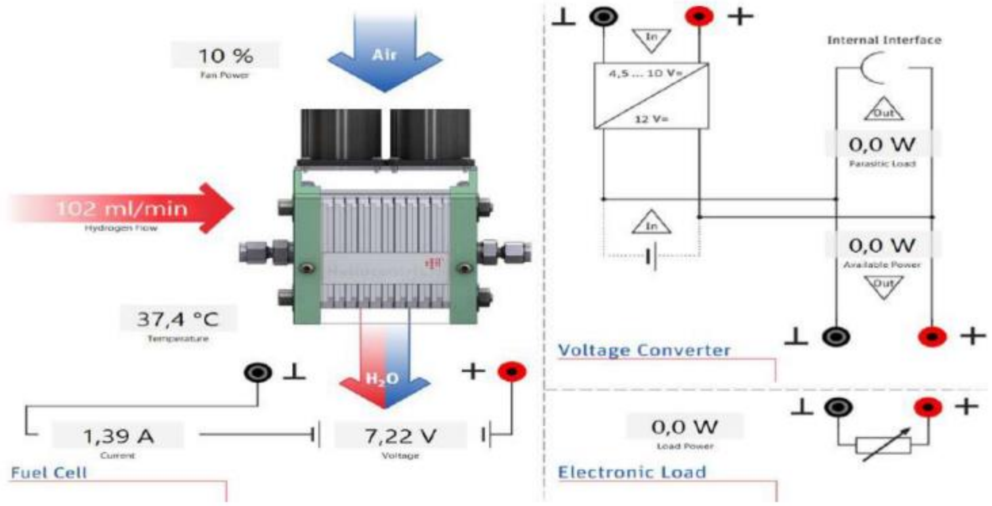


Figure 2.31: Fuel cell software interface

Comparing the results of the fuel cell (FC) model in MATLAB with the experimental data is essential to validate the accuracy of the model in the previous chapter. This step allows to verify whether the model correctly simulates the real performances of the cell, in particular in terms of voltage, current, power and hydrogen consumption. In case of significant deviations, adjustments can be made to the model to refine its predictions. When the simulated and experimental results are sufficiently close, the model is considered reliable and can be used to predict the performances under different conditions, thus reducing the need for repeated physical experiments.

21.4.2.6 Application of PEMFC in Electric Vehicle

Problem

The limitation of natural resources and climate change, aggravated by polluting vehicles that emit large amounts of CO2, require an urgent change in individual transportation modes. The automotive industry, in particular, contributes significantly to these environmental and energy problems. In response to this, hybrid electric vehicle technologies are increasingly perceived as one of the most promising solutions.

These vehicles, which combine an internal combustion engine with an electric motor, not only reduce greenhouse gas emissions but also improve energy efficiency by reducing fuel consumption. Moreover, by using renewable energy sources for electricity, these technologies contribute to decreasing dependence on fossil fuels, making the transportation system more sustainable in the long term. Thus, the adoption of hybrid vehicles could be a key element in addressing the environmental and energy challenges posed by the current automotive industry.

Electric Vehicle Characteristic

The forces acting on a vehicle include rolling resistance, grade resistance, aerodynamic force, acceleration force, and grade force. Rolling resistance comes from the friction between the tires and the road, while grade resistance and gravitational force influence the vehicle's movement on a slope.

Aerodynamic force opposes the movement due to friction with the air. Acceleration force occurs when the vehicle changes speed.

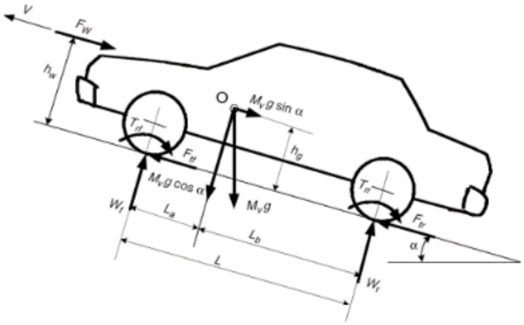


Figure 2.32: Forces acting on the car

$F(N) = F_{\text{aerodynamic}} + F_{\text{rolling}} + F_{\text{acceleration}} + F_{\text{slope}}$ (Eq *2,11)*

Aerodynamic force

Aerodynamic force, also called aerodynamic drag, is the resistance force exerted by the air on a moving object. It opposes the direction of movement of the object and is due to the interaction between the air and the surface of the object. This force increases proportionally to the speed of the object, making high-speed movements more energy-intensive, and is expressed as follows:

$F_{\text{aerodynamic}} = 0{,}5 \times \varrho \times S \times C_x \times V^2$ (Eq 2.12)

With:

V = vehicle speed [m/s]

ϱ = air density (≈1.2 kg/m^3)

S = vehicle frontal area [m^2]

C_x = drag coefficient

Rolling force

Rolling force (or rolling resistance) is the force that opposes the movement of a vehicle due to the contact between the wheels and the road surface. This force results from the deformation of the tires and the road surface, as well as the energy losses related to this phenomenon. It is expressed as follows:

$F_{\text{rolling}} = m_v \times g \times \mu$ (Eq 2.13)

With:

g = acceleration of gravity [9.81 m/s^2]

μ = coefficient of friction [≈0.01]

m_v = mass of the vehicle

Acceleration force

The acceleration force is the force applied to increase the speed of a vehicle. It is expressed as follows:

F _acceleration =mv×a (Eq 2.14)

With:

a = acceleration of the vehicle

Slope force

The slope force (or gravitational force on a slope) is the component of the gravity force that acts on a vehicle when it moves on an inclined surface (uphill or downhill). According to the following relationship:

$F_{slope} = mv \times g \times Sin\alpha$ (Eq 2.15)

With:

α = slope [rad]

And we must calculate the vehicle power:

$P = F \times V$ (Eq 2.16)

V: Vehicle speed. F: Forces applied to the vehicle

21.4.2.7 Vehicle Parameters in MATLAB

The purpose of the time and speed variables in MATLAB is to plot the curve of variation of the vehicle speed as a function of time. The results obtained will be presented in the previous chapter.

The vehicle parameters are:

i. ϱ = air density rho=1.2(kg/m^3);

ii. S = surface (frontal area) of the vehicle S =2.11(m^2);

iii. Drag coefficient C_x=0.28;

iv. Mass of the vehicle m_v=1465(Kg);

v. Gravity acceleration g=9.81 m/s^2;

vi. Friction coefficient μ =0.01;

vii. alpha=10°;

viii. Time from 0 to 195 seconds;

The calculation is detailed in Appendix 2[93]

[9393] Appendix 2: Vehicle Parameter in MATLAB

```
rho=1.2;
S=2.11;
Cx=0.28;
mv=1465;
g=9.81;
mu=0.01;
alpha=10;
```

21.4.2.8 Vehicle model in Simulink

The vehicle model used in this study includes the following characteristics: a total weight of 1465 kg, an aerodynamic drag coefficient of 0.28, and a frontal area of 2.11 m². This model is simulated in MATLAB/Simulink to analyze the vehicle dynamics as a function of speed, acceleration, and acting forces such as rolling resistance, aerodynamic drag, and gravitational force. The results of this simulation provide a better understanding of the energy efficiency of the vehicle equipped with a fuel cell system.

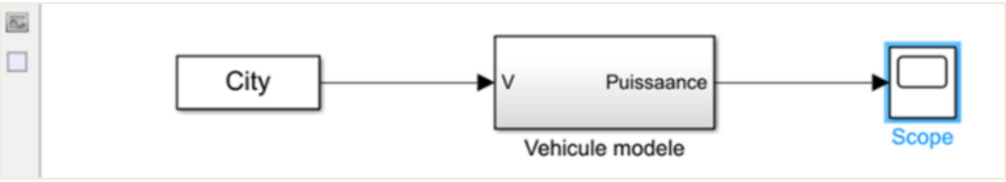


Figure 2.33: Entering and exiting a vehicle

```
City =[
1.0000 0
2.0000 0
3.0000 0
4.0000 0
5.0000 0
:
:
195.0000 0
];
t=City(:,1) %time [s]
V=City(:,2) %speed [m/s]
simtemps = length(t);
% Calculate forces
F_Aerodynamic = 0.5 * rho * S * Cx * V.^2; % Aerodynamic force
F_rolling = mv * g*mu; % Rolling force
F_Slope = mv * g * sin(deg2rad(alpha))*ones(size(V)); % Slope force
% Calculate acceleration
a = [diff(V) ./ diff(t); 0]; % Acceleration (m/s^2)
F_Acceleration = mv * a; % Acceleration force
% Calculation of total forces
F = F_Aerodynamic + F_rolling + F_Acceleration + F_Slope;
P = F .* V; % Power (W)
plot(t, V);
xlabel( 'time(s)' );
ylabel( 'Speed(m/s)' );
figure;
plot(t, P);
xlabel( 'time(s)' );
ylabel( 'Power(W)' );
```

In this Simulink model, the "Vehicle Model" block (which is a subsystem), representing the forces acting on the vehicle.

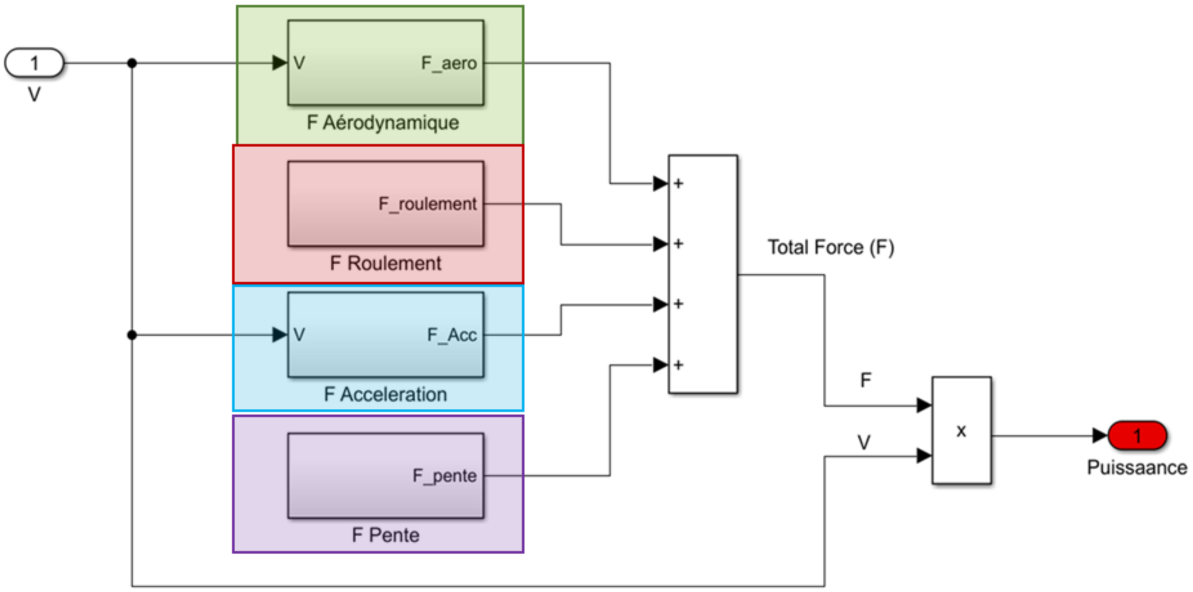


Figure 2.34: Forces acting on vehicle

Here is a picture of the aerodynamic, rolling, acceleration and slope forces blocks (which is a subsystem) in the Simulink model.

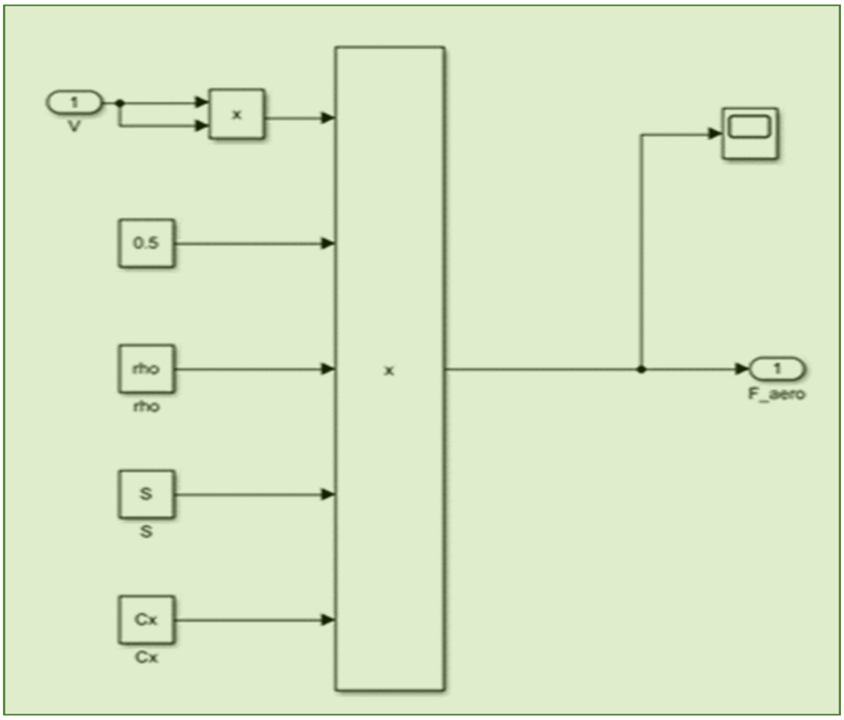


Figure 2.35: Aerodynamic force block

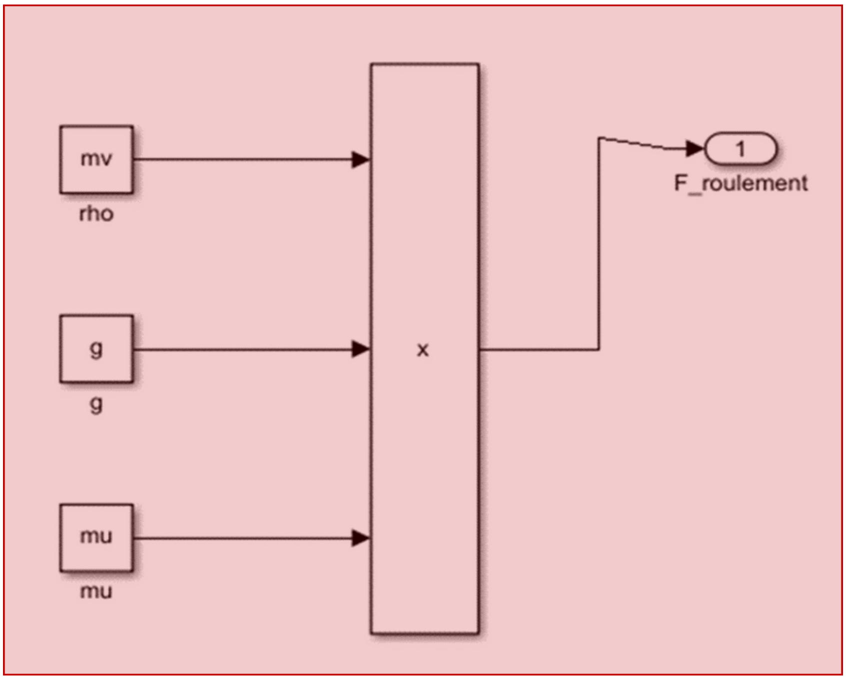
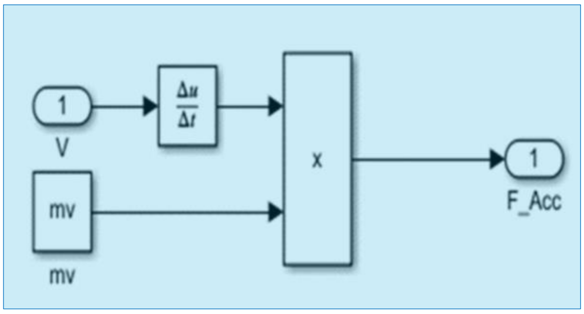


Figure 2, 36: Rolling force block



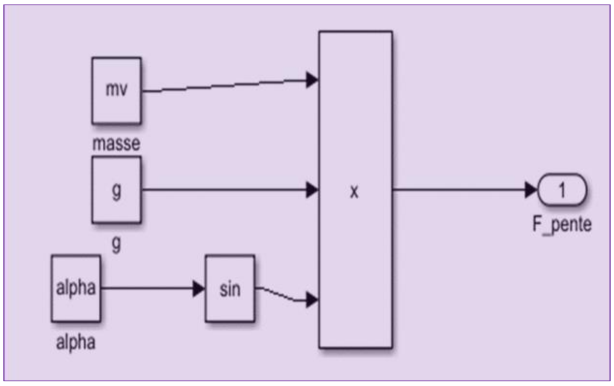


Figure 2.38: Acceleration Force block

Figure 2,3: Slope Force block

21.4.2.9 Fuel Cell (PAC) Model

The simulation of proton exchange membrane fuel cells (PEMFC) is a valuable tool for the development and large-scale testing of new alternative energy sources. In order to develop a relevant PEMFC model, capable of analyzing fuel cell-based power generation systems, it is essential to accurately determine a set of specific modeling parameters.

Fuel cell characteristics

Fuel cell current

The current of a fuel cell is the flow of electrical charge resulting from the electrochemical reactions in the cell. It transforms the chemical energy of the fuel, such as hydrogen, into electrical energy, thus powering devices such as electric motors. According to the following equation:

$I\_fc = \frac{Pfc}{Vfc}$ (Eq *2,17)*

With P_{fc} : power of FC [W], and V_{fc} : voltage of FC [V]

Molar flow rate

The molar flow rate of hydrogen (H_2) in a fuel cell represents the amount of hydrogen consumed per unit of time, generally expressed in moles per second (mol/s).

The molar flow rate of dihydrogen [mol/s] in the stack;

$$\dot{n}_{H2\text{-}stack} = \frac{Ifc}{2*F} \times n_c \qquad (\text{Éq } 2{,}18)$$

With:

F: Faraday constant(C)

n_c: number of cells in the stack

Hydrogen Mass

The mass of hydrogen (H_2) in a fuel cell refers to the total amount of hydrogen used or available for electrochemical reactions within the cell.

The mass of H2 [kg];

$$m_{H2} = \int \dot{n}_{h2} \times M_{H2}\, dt \qquad (\text{Éq } 2{,}19)$$

With:

M_{H2} = 2 × 10-3 kg/mol The molar mass of dihydrogen [kg/mol]

Fuel Cell voltage

The fuel cell voltage corresponds to the difference in electrical potential between its electrodes, measured during its operation. It is an essential indicator of the performance and energy efficiency of the system. Optimizing this voltage is fundamental to maximizing electricity production [22].

The cell voltage [V] ;

$$V_c = 1{,}031 - 2{,}45 \times 10^{-4} \times j - 0{,}03 \times \ln(j+3) - 2{,}11 \times 10^{-5} \times \exp(8 \times 10\text{-}3 \times j) \qquad (\text{Eq } 2{,}20)$$

With:

j : Current density [mA/cm2];

$$j = \frac{Ifc}{Sfc} \qquad (\text{Eq } 2{,}21)$$

S_{fc} = 480 cm^2: The surface area of a cell [cm^2]

$$V_{FC} = V_c \times n_c \qquad (\text{Eq } 2.22)$$

With

V_c: Cell voltage [V]

V_{FC}: Total battery voltage [V]

n_c : the number of cells

△ **In this fuel cell model, it is essential to use the power demanded by the vehicle as the main input. This power determines the energy demand, directly influencing the electricity production of the fuel cell.**

By integrating the vehicle power as an input parameter, it becomes possible to regulate the operation of the stack in real time, thus ensuring optimal energy management and maximum system efficiency, while responding to variations in the vehicle's energy needs.

Among the following operating conditions:

i. N_A = 6.022*10^23 Avogadro's number [mol^-1]
ii. e = 1.602 *10^-19 Elementary electric charge [C]
iii. t =195 time[s]
iv. M_{H2} = 2*10^-3 Molar mass of dihydrogen [kg/mol]
v. N_c =180 Number of cells in the stack
vi. S_{fc} = 480 Surface area of a cell [cm^2]
vii. $r_{transmission}$ = 80 Transmission efficiency [%]

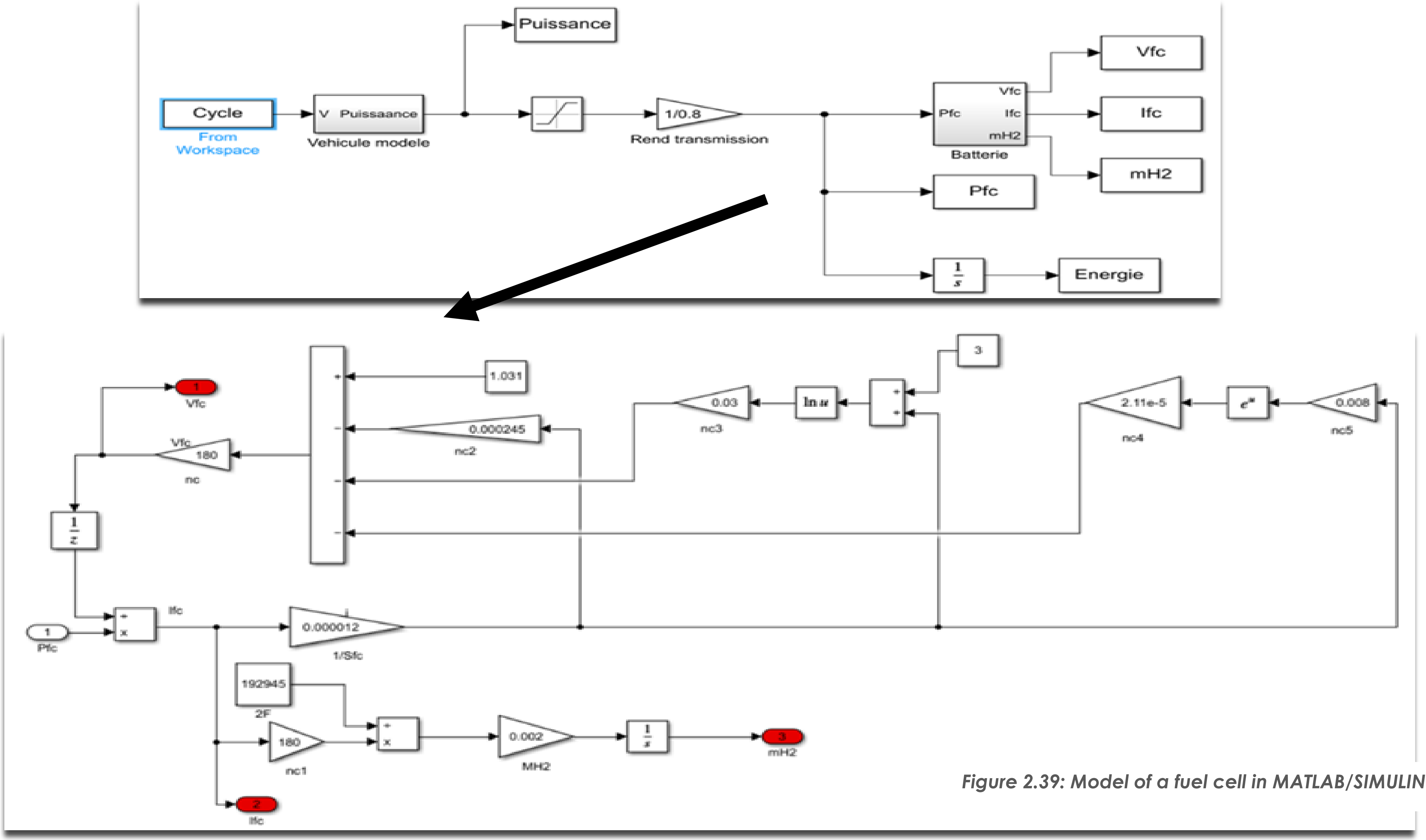


Figure 2.39: Model of a fuel cell in MATLAB/SIMULINK

21.4.2.10 Conclusion

This chapter has outlined the key steps in the development of a fuel cell (FC) system for electric vehicles. Mathematical modeling has established fundamental relationships between the main FC parameters, such as voltage, current, power, and hydrogen consumption.

The implementation of this model in MATLAB/Simulink has allowed simulating the dynamic behavior of the fuel cell under different operating conditions, providing essential simulation results for performance analysis.

This approach has not only highlighted the ability of fuel cells to meet the energy requirements of electric vehicles, but also paved the way for future optimizations. Thus, this chapter demonstrates the promising application of fuel cells in electric vehicles, highlighting their potential as a key solution for clean and sustainable mobility, while contributing to the transition to greener transportation systems.

21.4.3 Results and Discussion (Master Thesis Razan, Chapter 3)

21.4.3.1 Introduction

Once the model is validated, it is integrated into the Simulink simulation environment, which facilitates dynamic analysis and optimization of PAC performance in real conditions, particularly in the context of automotive applications.

In this chapter, we present the results of mathematical modelling characteristic curves in MATLAB and compare them with the experimental part.

In addition, the results from simulations performed with MATLAB/SIMULINK to evaluate the performance of the fuel cell (FC) in electric vehicles.

These electric vehicle simulations allow to generate the speed curve as a function of time and the power that must be used as input into PAC. In addition to the PAC simulation, the voltage, current, power, hydrogen molar flow (H_2) and the mass of H_2 consumed curves are all calculated at multiple alpha values.

21.4.3.2 Fuel cell (PAC) characteristic curve in MATLAB

The operating conditions of the mathematical model of the fuel cell are as follows:

- Number of cells = 10
- Temperature = 33°C (306 Kelvin)
- Cell surface A= 25 (cm2)
- Membrane thickness l= 27*10-6(m)
- Cell type dependent constant B=0.016
- Oxygen partial pressure PO2 =0.2095[atm]
- Hydrogen partial pressure PH2=1[atm]
- Contact resistance Rc=0.0003 [Ohm]
- Parametric coefficient Ψ(si)=23
- No-load current density Jn=3*10-3 [A/cm^2]
- Maximum current density Jmax=469*10-3[A/cm^2]
- Faraday constant F=96485[C/mol]
- Molar mass of H2 Mh2=0.002 [kg/mol]

Voltage-current characteristic curve

Figure (2.27) shows the result of the simulation of voltage as a function of current.

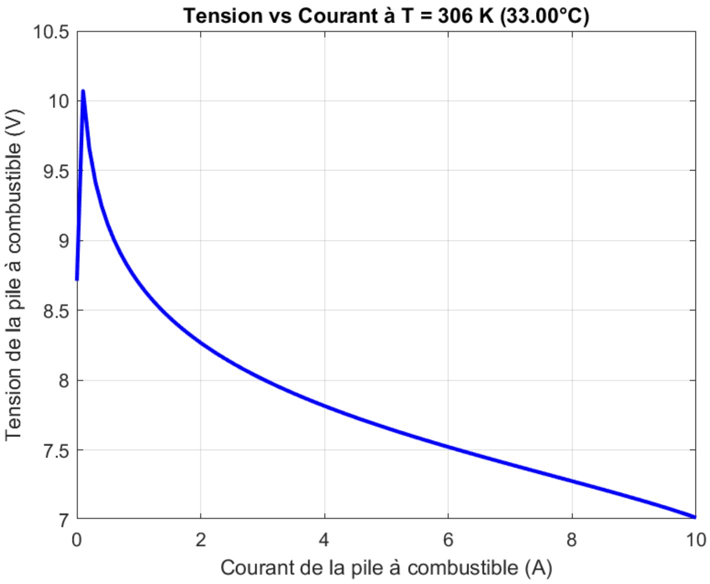


Figure 3.40: Voltage versus current curve

It presents an open circuit voltage (i=0) experiences a slight sudden increase, reaching a peak around 10.1 V. This phase corresponds to the activation zone of the fuel cell, marking the beginning of the electrochemical reaction.

After the initial peak, the voltage decreases rapidly with increasing current, it drops to about 8.5 V.

This decrease is due to the activation polarization, which corresponds to the loss of energy necessary to overcome the activation barriers of the reactions.

From this point, the curve shows a more gradual decrease in voltage as the current increases, going down to about 7 V at a current of 10 A.

This part represents the ohmic losses and the concentration losses, where the internal resistance of the cell and the limited availability of reactants cause a more linear decrease in voltage.

Power-current characteristic curve

The results of the curve represent power as a function of current.

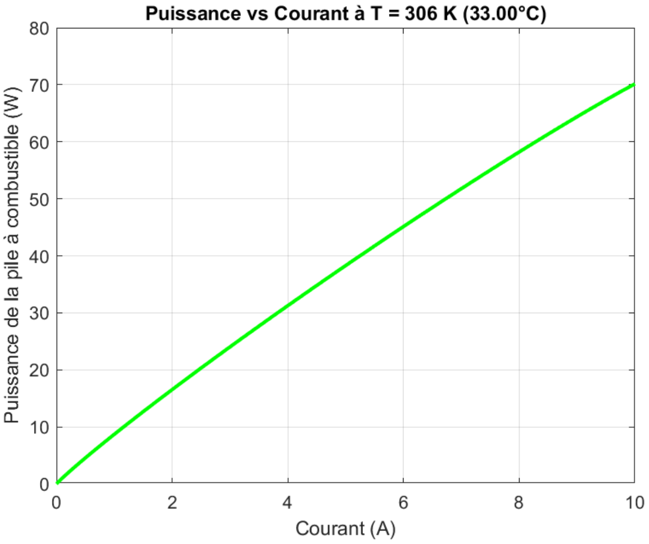


Figure 3.41: Power curve as a function of current

We notice that the power of a fuel cell increases progressively with increasing current, reaching 70 W at a current of 10 A. This linear relationship shows that the fuel cell provides increasing power as a function of current, without saturation or noticeable decrease over the interval shown. This means that for each increase in current, there is a proportional increase in power, suggesting a stable and efficient operation of the fuel cell in this current range.

Flow rate and mass H2-current characteristic curve

We then show the simulation results representing the molar flow rate H2 and the mass H2 as a function of the current.

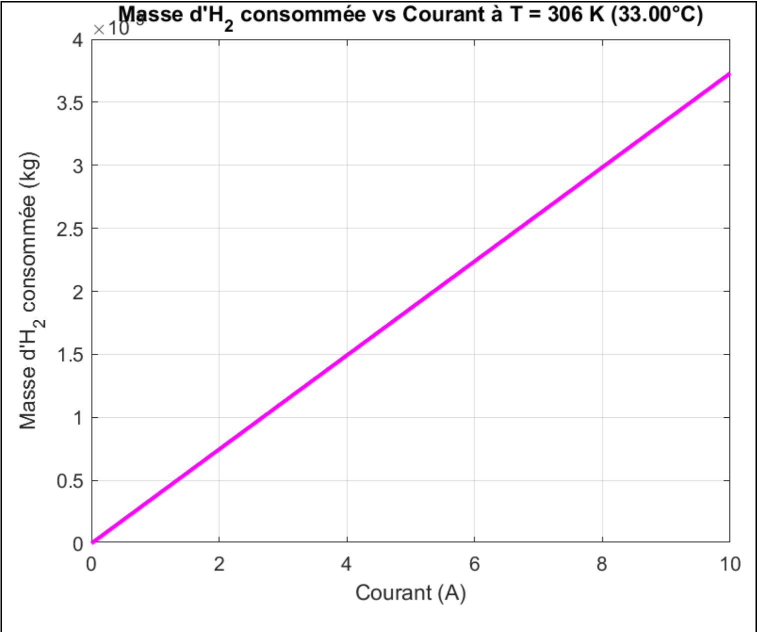


Figure 3.42: H_2 mass curve as a function of current

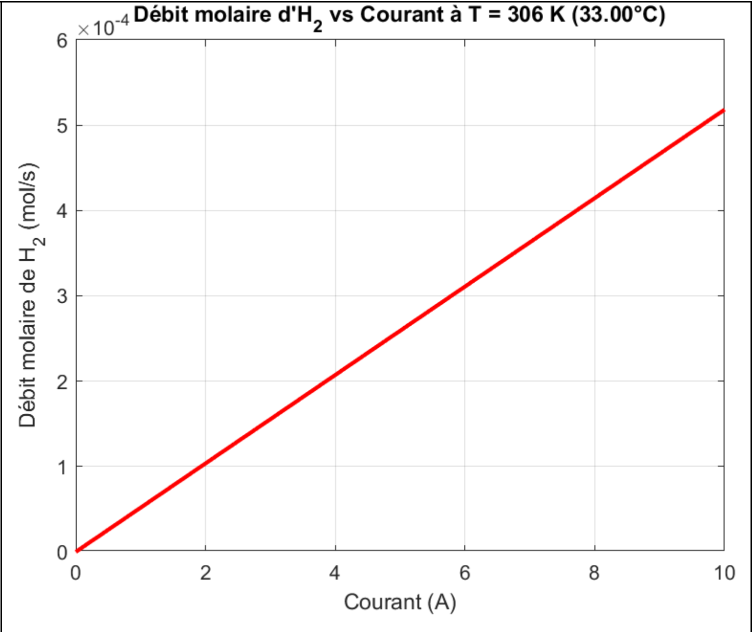


Figure 3.43: H2 flow rate curve as a function of current

The curve in Figure (3.42) showing the mass of hydrogen consumed by the fuel cell shows a steady increase as the current increases. As the current increases, the cell requires more hydrogen to power the electrochemical reactions.

For low currents, the mass of hydrogen consumed remains relatively low. As the current increases, the mass of hydrogen follows an almost linear growth. When the current reaches a higher value, the mass of hydrogen consumed reaches about 3.7×10-3 Kg.

Figure (3.43) of the molar flow rate of hydrogen shows a steady increase as the current generated by the fuel cell increases.

Initially, for low currents, the molar flow rate is relatively low, but it increases almost linearly with increasing current. When the current reaches higher values (10A), the molar flow rate reaches about 5.1× 10⁻4 mol/s. This behavior illustrates the direct relationship between the cell current and the amount of hydrogen consumed, in accordance with Faraday's law which relates the amount of reactants used to the electric current.

21.4.3.3 Operating conditions of the experimental part

i. Temperature=33°C

ii. Number of cells =10

iii. Membrane thickness 27 [µm]

iv. Nominal anode pressure [bar] 0.6 +/- 0.1

v. I max=10A

vi. Gross sectional cell 25 cm2

vii. Maximum power 50 [W]

Voltage-current characteristic curve

Using the data stored in the acquisition system, the voltage-current characteristics (V-I) of the fuel cell were plotted as shown in:

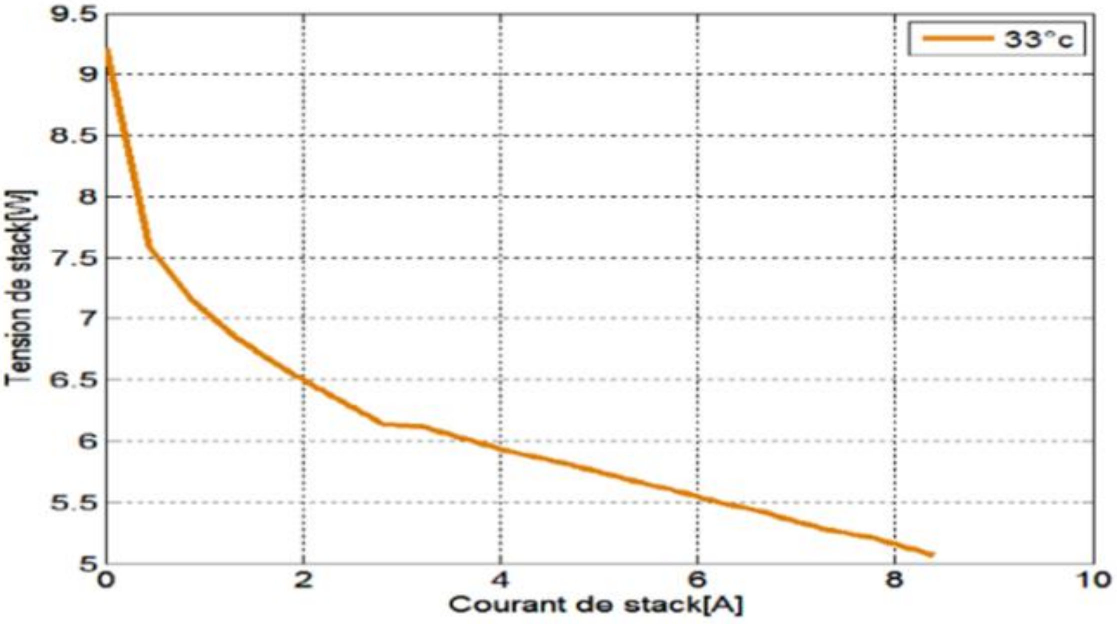
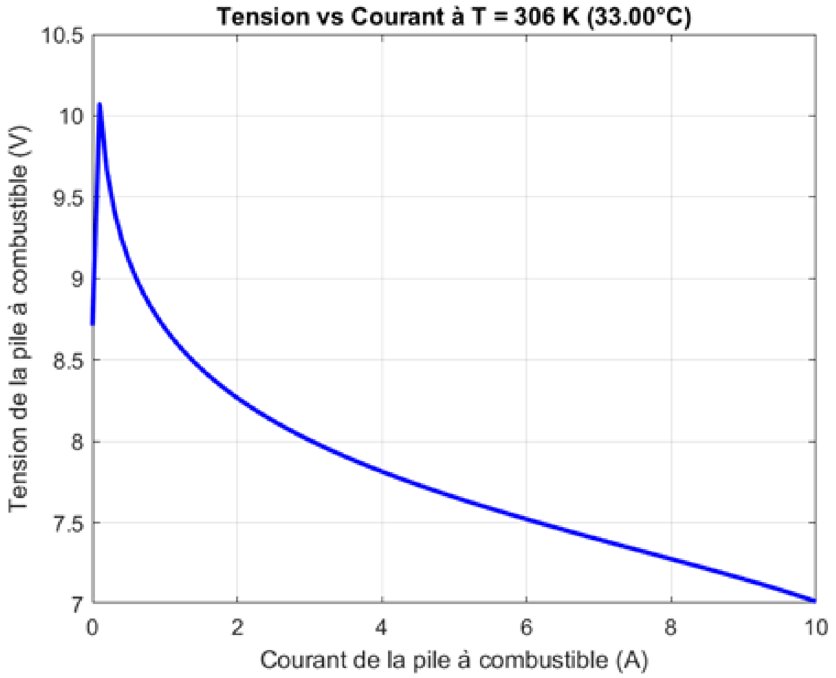


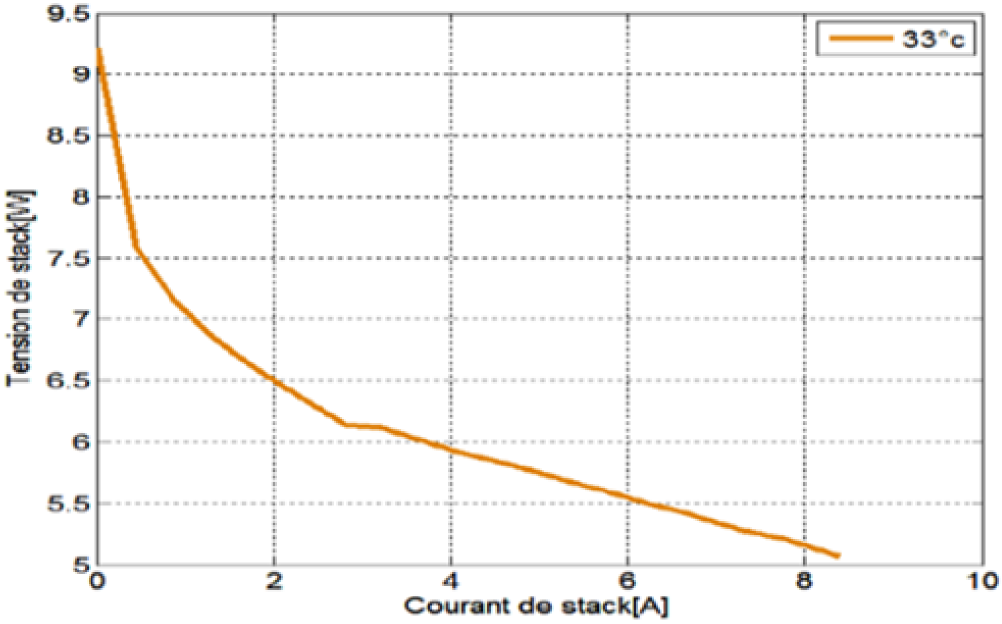
Figure 3.44: Voltage curve as a function of current (from the experimental part)

Figure (3.44) shows an open circuit voltage of about 9.21 V. It is observed that the cell voltage decreases inversely proportional to the current due to internal losses. The characteristic curve of the PEMFC cell highlights three distinct polarization zones:

- From 0 to 0.44 A, there is the activation polarization zone, caused by the transfer of charges at the electrode/electrolyte interface, linked to the slowness of the chemical reaction on the surface of the electrode.
- From 0.44 to 2.81 A, we identify the resistance polarization zone, which results from the electrical resistance of the various components of the cell, in particular the electrolyte.
- From 2.81 to 8.39 A, we enter the diffusion polarization zone, influenced by the concentration of the electrolyte around the electrodes.

□ Comparison of voltage-current curves from the theoretical part with the experimental part :





The open circuit voltage in the first figure is higher than the second figure, which could reflect differences in the materials used or the experimental conditions. In both figures, a decrease in voltage is observed after the activation phase, but this drop is more pronounced in the first figure, while the second figure shows a more gradual decrease with a lower current limit.

The second figure describes in more detail the different polarization zones, while the first shows a more regular decrease, related to ohmic and concentration losses.

In addition, the first figure shows a higher current limit, suggesting that the cell can support higher currents, unlike the second figure which shows a lower current limit, reflecting higher losses at higher currents.

Power-current characteristic curve

Using the data stored in the acquisition system, the power-current (P-I) characteristics of the fuel cell were plotted as shown in the figure:

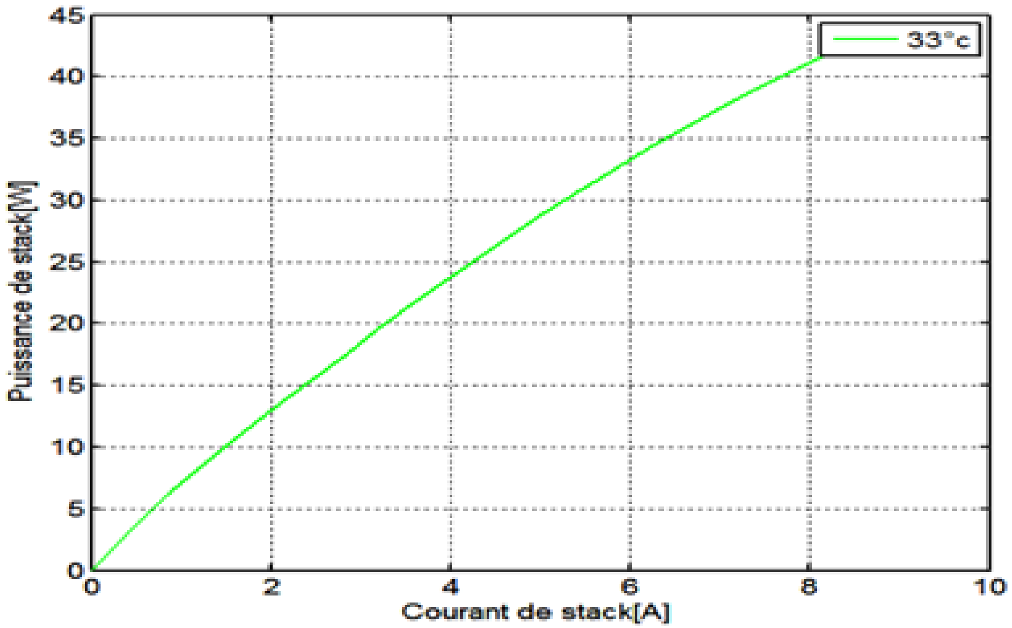
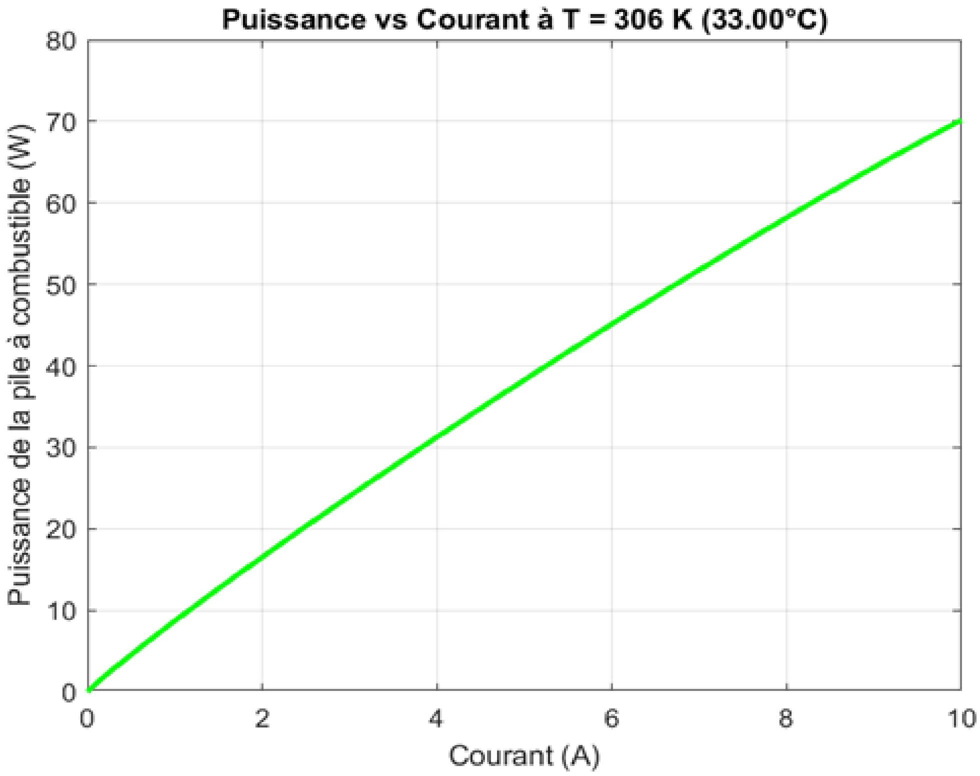


Figure 3.45: Power curve as a function of current (from the experimental part)

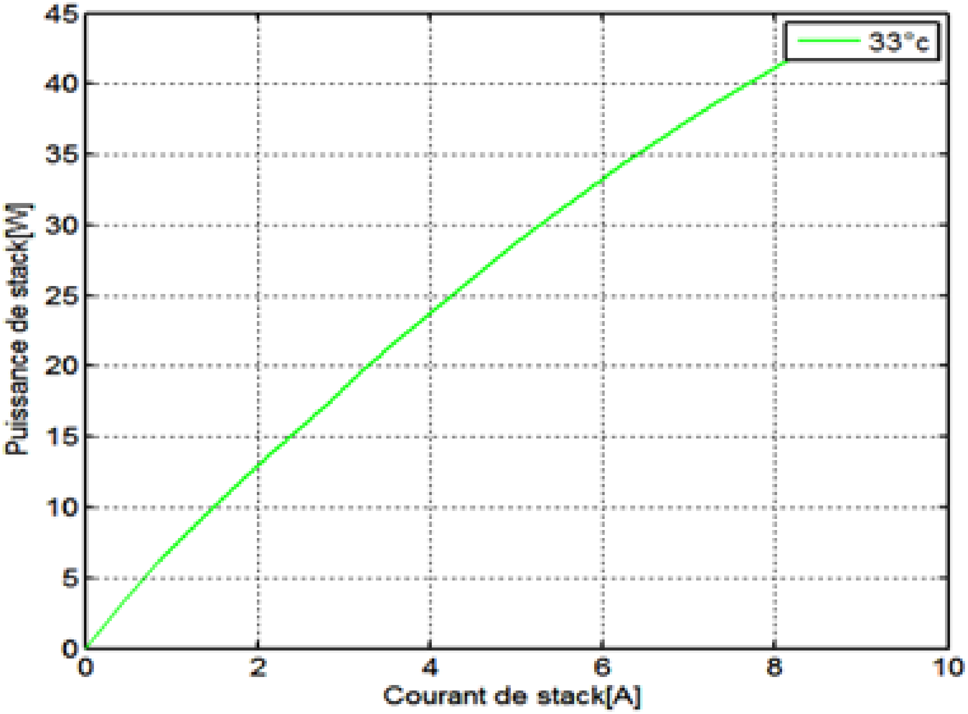
We observe that the power of a fuel cell increases gradually, reaching a maximum at a certain point, but then decreases. At a current of 8.39 A, the cell produces about 42 W. However, this maximum power point does not correspond to the optimal operating point of the cell. Indeed, it becomes difficult to maintain the cell at its maximum power due to the low efficiency of the cell, the accumulation of water and the increase in temperature, which complicates the control of the cell under these conditions.

- **Comparison of the power-current curves of the theoretical part with the experimental part:**

The comparison of the curves from the mathematical modeling and the experimental part reveals a good overall correspondence, at the same temperature (33°C). This consistency validates the modeling method used in Matlab, by demonstrating that the model results are in agreement with the experimental data, even under varied operating conditions.



Mathematical modeling results



Experimental part

The mathematical result figure shows a linear increase in power up to 70 W at 10 A, without performance degradation, suggesting a simulation without considering real physical constraints, while the experimental part curve reaches a peak of 42 W at 8.39 A, followed by a power drop due to physical limitations of the cell (water accumulation, thermal management, efficiency loss).

21.5 FC test specification

21.5.1 Test objectives:

Voltage

Current

Hydrogen (H_2) flow rate

21.5.2 Test Devices

Stack (Fuel Cell)

Voltmeter

Amperemeter

Hydrogen (H_2) tank

Connection wires

Resistor

Fan

21.5.2.1 Installation of Fuel Cell

Components:

a) End plat
b) Gasket behind the end plate
c) Current plate
d) Graphite plate for H_2
e) MEA (Membrane Electrode Assembly)
f) Gasket
g) Graphite Bipolar Plate
h) Graphite plate for O_2

21.5.3 Pre-test: Hydrogen preparation for use in a fuel cell system:

First, an exothermic reaction is initiated, where hydrochloric acid (HCl) reacts with aluminum to produce hydrogen.

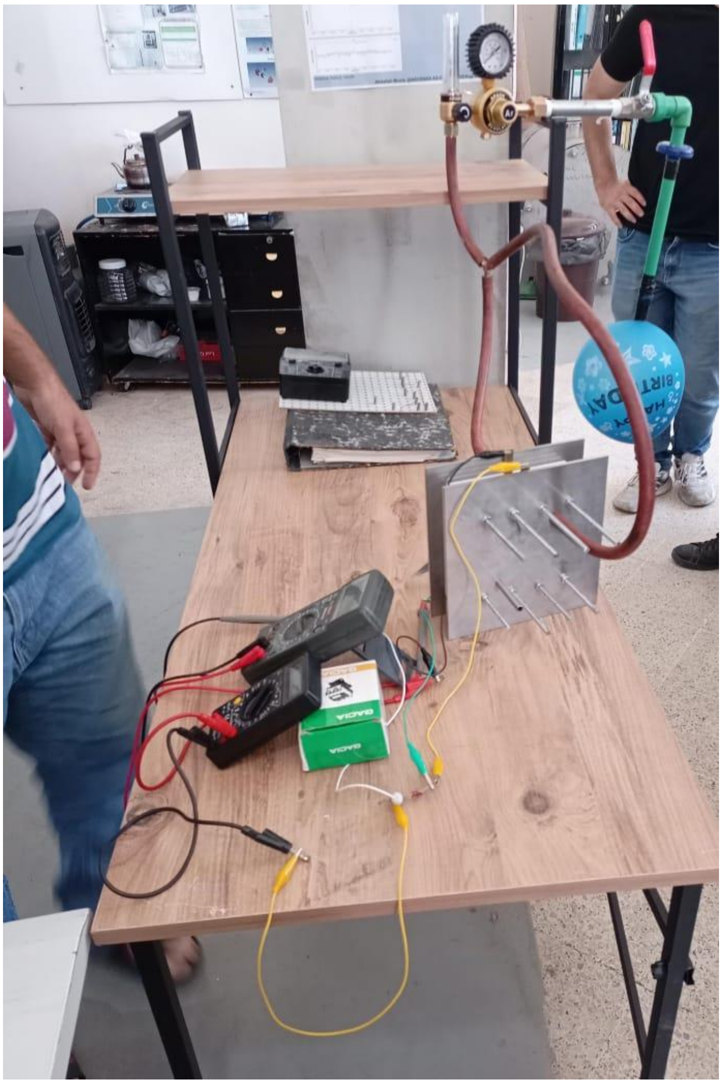
Next, the chemistry lab was set up following all appropriate safety standards.

The equipment used includes a water bottle connected to an Erlenmeyer flask via a tube. A small faucet is attached to the tube, with an uninflated balloon fixed to the end of the faucet.

A measured amount of acid was poured into the Erlenmeyer, followed by the addition of aluminum pieces. The reaction quickly accelerated, causing the balloon to inflate as it filled with hydrogen.

21.5.4 Specification for Fuel Cell System Test

Step	**Step Description**	**Expected Result**
Precondition	-System is off -The connection wires are connected -the voltmeter as well as the amperemeter are prepared. -Three resistors were used in place of a fuel cell stack, and the resistance (in ohms) was measured -Additionally, a fan was installed on the fuel cell system to use oxygen	
Open the Valve	Open the valve	The valve is open and allows the hydrogen gas to pass through.
Switch ON the system	Turn Off the global Hydrogen valve Turn On the system from the GUI	The system in general, produces water, heat, and electricity



21.6 Fuel Cell System Test

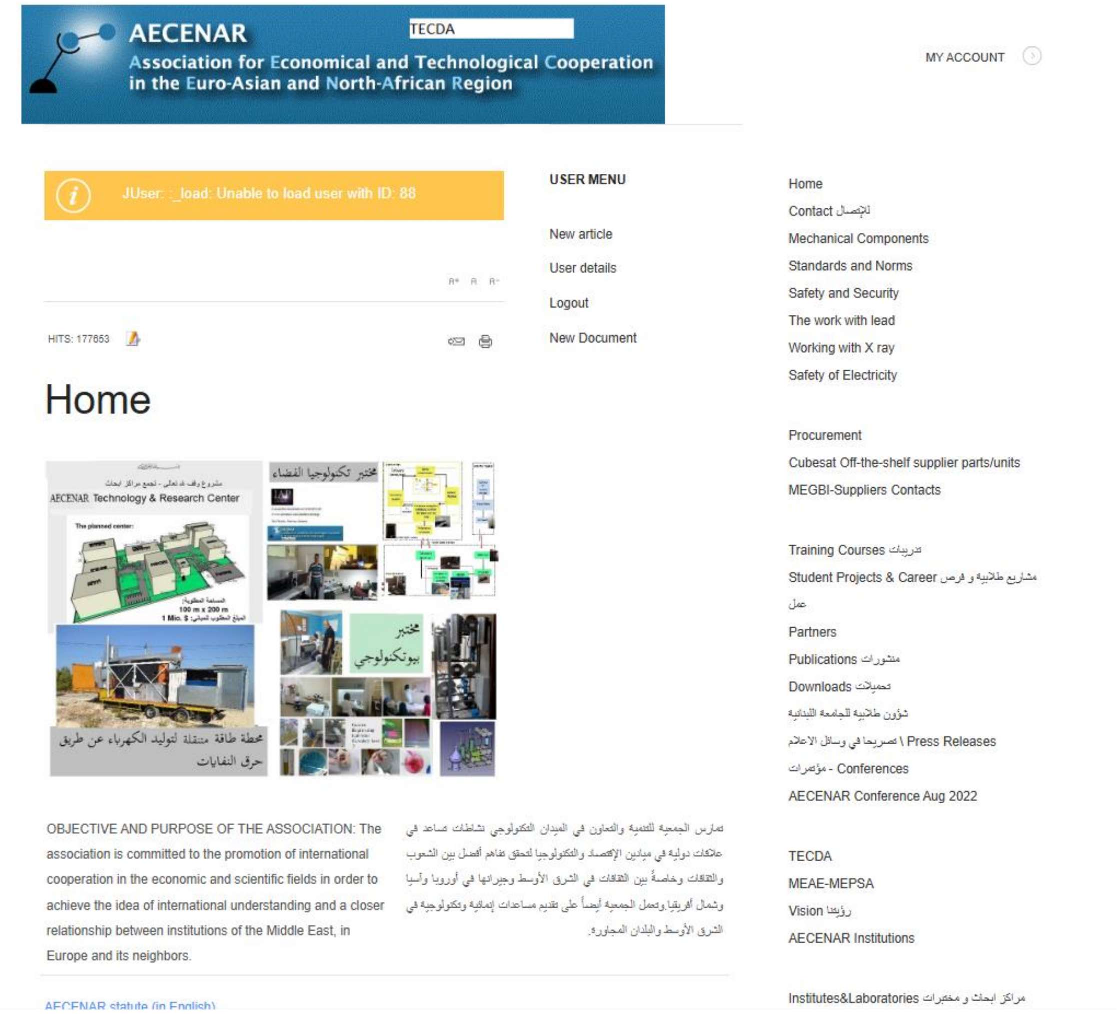
21.6.1 Test result and failure analysis

The FC did not perform as expected. It did not produce as much electricity as expected. This may be due to the need to compress the hydrogen before it is introduced into the fuel cell.

21.7 What's Next

After completing the theoretical and design part of the first part of the project, work must be done in the future to secure pure and compressed hydrogen gas to operate the fuel cell model.

References - www.aecenar.com menu



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تمارس الجمعية للتنمية والتعاون في الميدان التكنولوجي نشاطات تساعد في علاقات دولية في ميادين الإقتصاد والتكنولوجيا لتحقق تفاهم أفضل بين الشعوب والثقافات وخاصةً بين الثقافات في الشرق الأوسط وجيرانها في أوروبا وآسيا وشمال أفريقيا. وتعمل الجمعية أيضاً على تقديم مساعدات إنمائية وتكنولوجية في الشرق الأوسط والبلدان المجاورة.

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    - Lab Scale Penicillin production
      - Penicillin Quantification
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    - Pilot Plant Scale Penicillin/Aspirin Production
      - Pilot scale test specification
      - Pilot scale system test
        - WHOLE SYSTEME TEST (AUTOCLAVE TEST) 07/11/2022
        - Aspirin Production System Test (Water test) 28/11/2023
        - Aspirin Production System Test (Water test) 01/12/2023
        - Aspirin Pilot Plant Flow sensor test 6-7/12/2023
        - Aspirin Production System Test (Water test) 14/12/2023
        - Aspirin Pilot Plant Flow sensor test 14/12/2023
        - ASPIRIN PILOT PLANT TEST (AUTOCLAVE TEST) 14/12/2023
        - Aspirin Pilot Plant (Aspirin Production : TEST 1) 08/01/2024
        - ASPIRIN PILOT PLANT TEST (AUTOCLAVE TEST) ASPIRIN PILOT PLANT 29/12/2023

    - Aspirin pilot plant Mechanical Realisation
    - Requirements Aspirin Pilot Plant Production
    - pilot plant system design
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    - system desgin/system concept
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      - Aspirin/Penicillin PCS Implementation
    - Raw Materials production
  - Lab Scale Ampicillin production
    - Ampicillin trials
    - Amp quantification
    - Ampicillin Production and Quantification May2023
  - Aspirin production
    - Aspirin Identification Tests
  - The most important solutions in biology-lab
  - Ministry of Health license
  - Phenylacetic acid production(PAA-precursor)
    - PAA-Trials
  - Lab Content
- MEAE
- iap
- IEP
  - إدارة النفايات في شمال لبنان
    - معالجة النفايات في ضهر العين تشرين الاول 2023
    - متطلبات انشاء معمل لفرز النفايات الصلبة
    - وضع المحطة في الضنية – بقاعصفرين (Jul 22 - ...)
      - الصيانة بعد النقل و تجهيز المحطة
      - مشروع ادارة النفايات في بلدية بقاع صفرين
        - Possible land for Biogaz plant

  - SDM-WasteManagementNorthLebanon
  - EIA Waste to Energy Plants in North Lebanon
    - EIA for B.P.P
  - مشروع ازالة جبل النفايات في طرابلس
  - معمل ريمون مِتري في بلاط – جبيل
  - مشروع تنظيف طرابلس
    - المكبات العشوائية في طرابلس
  - ارض الاوقاف في مجدليا مرشحة لوضع المحطة وقسم من المركز
  - حملة لتنظيف الضنية
  - نقل المحطة الى كفرشلان
  - NLAP-IPP at Central Mina next to Masjid as-Salam (Sep 21-Jul 22)
  - Biogas Pilot Plant in Assoun/Dinniye - North Lebanon
    - Assoun Biogas Plant Official Papers
    - EIA assoun project
    - الجدوى الاقتصادية لمشروع الهاضم اللاهوائي
  - Waste Management for Tripoli
  - EIA Ras Nhash
  - لائحة بأسماء المطاعم في طرابلس
  - EIA Biogas Plants
  - BiogasTest 21.06.2023
  - Jezzine Biogas Plant Proposals
  - Jezzine Biogas & Compost Plant
  - Meeting at Deir Amar Municipality 28.10.24
- IEP-MEPSA
  - قطاع الطاقة الكهربائية في السعودية

  - Electricity Supply in North Lebanon Region - تغطية لبنان الشمال بالكهرباء
- SDM-EnergyEconomyIndonesia
- النظام السياسي في لبنان
- TrafficManagementSystem
  - برنامج للسكة الحديدية في الشرق الادنى
  - مبادرة اصلاح طريق العمارة عكار
  - Roads repairs cost in North LEBANON
- Water and Waste Water
- IEP-UrbanicPlanning
- نشاطات لمؤسسات اجنبية في شمال لبنان
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- عقبات اجتماعية :
- وزارات
- North Lebanon Maps
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- Oil and Gas Reserves in Lebanon
- Méthanisation: Processus, condition,étapes..
- مبادرات

    - اصلاح الطرقات وتنظيم إدارة النفايات في منطقة الجامعة اللبنانية في راس مسقا
  - قسم التنظيم المدني
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  - Lebanon economical analysis
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- Vacuum pump

    - PhysicsLab ICF Device
        - IAP-ICF light ion driver
            - Pulsed power diode accelerator Basics - Components
            - IAP-Light ion driver, Marx Generator
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                - Pulsed Diode System Test Specification
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        - system test specification of LINAC with Glass Tube 2022-2023
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        - MSE-T2 - 26.09.2024 - Distillation process with water bath
        - MSE-T3 - 10.10.2024 - Leakage of Stack #5
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  - Test 01.09.2023 - Ras Maska
  - Filtration test (18.12.2023)
  - 04272024.Test.Atomizing Nozzle Air to Fluid ratio
  - 08052024.Test.Atomizing Nozzle Air to Fluid ratio
  - Flue Gas into Water test 12.06.2024
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- Mobile Biogas Generation and Gas Turbine Testrig
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    - ICPT - GasTurbine Version 2
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    - Biogas Turbine test using Butane/Oxygen with Turbocharger on 02.04.2024
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      - ICPT-Biogas test 2 18.08.2023 : Gas extraction
      - ICPT-Biogas test 3_22082023: Digester leakage's test
      - ICPT-Biogas test 4_16012024:Enhancing Methane storage through Gas Compression

      - ICPT-Biogas test 5 18012024:Enhancing Methane storage through Gas Compression part 2
  - Pilot Project NLAP Power.plant
- AECENAR Research Center مشاريع ابحاث
- AECENAR Startup Companies Complex
  - North Lebanon Alternative Power (NLAP)
    - NLAP Reports
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      - Nakhle Biogas Plant
      - Beit El Hosh Biogas plant
      - Diyala Waste Separation & Recycling System
      - Batroun Waste Management 2024
      - Complete Waste Management 1000 tons per day (Riad)
      - NLAP Project Mirador Miniye July 2024
        - Project Mirador waste management 20 tons/day - Technical Issues
          - NLAP Mirador Incinerator
          - Automation System of Mirador Project
      - 250kg/day biowaste: Biogas Plant_RasNhash_Mr. Labib Shalak Concept
      - 4MW Abde NLAP-IPP - Proposal 2015
    - NLAP Administration
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      - E-Agriculture-TukTuk_2 Requirements
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        - AGRI-TUK 2 Tests
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            - NLAS motorized hitch controller
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    - AS-COMSAT SW&HW Repository
    - AS-COMSAT Planning&Controlling
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- AS-COMSAT Planning and Controlling 2022
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  - AS-COMSAT Office&Atelier Istanbul
- AS-COMSAT Planning & Controlling 2024

- AS-COMSAT Platforms&Devices
  - AS-COMSAT_1 (LEO Communication Satellite)
    - AS-COMSAT_1 (LEO Satellite) System Architecture
    - AS-COMSAT_1 ACS (Design&Realization&Testing)
      - AS-COMSAT_1 ACS Board STM32 SW
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    - AS-COMSAT_1 Power Management Unit (PMU)
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      - ACS_ControlCodePython
    - AS-COMSAT_1 Launching
    - AS-COMSAT_1 LEO Satellite Concepts
      - AS-COMSAT_1 COM Concept with HackRF
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            - AS-COMSAT 1 COM Software
        - AS-COMSAT 4U Cubesat Integration Concept
    - AS-COMSAT 1 LEO to GEO Orbit Change Module
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        - AS-COMSAT 1 LEO to GEO Transfer Requirements
        - AS-COMSAT 1 LEO to GEO Transfer Module Propulsion System Design&Realization
            - Regenerative Cooling for AS-COMSAT 1 OrbitChange Module
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            - AS-COMSAT 1 LEO to GEO Orbit Change Teststand - Test Specification
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            - AS-COMSAT 1 LEO to GEO Orbit Change Teststand - System Test
                - 22.12.2023 - AS-COMSAT 1 Orbit Change Teststand System Test
            - AS-COMSAT 1 Orbit Change HIL Teststand
        - AS-COMSAT 1 Orbit Change Module CFD-NC Simulation
- RF 2.4GHz Tranceiver Unit Prototype
    - RF System Implementation
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        - AS-COMSAT Patch Antenna Design & Realization
            - Basics Microchip antennas
        - Power Management Unit (PMU) Design
    - RF 2.4GHz System Design (Microchip)
    - Transceiver Design 2023 V2
        - ECS V2 System Requirements
        - ECS V2 System Design

            - Amplifier Design
            - Power Management Unit (PMU) Design
    - ICS Emergency COM System (ECS) V1 (SDR based)
    - AS-COMSAT City Network Ambulance (CNA)
        - mobile network basics
        - CNA GUI Implementation (C#)
            - CNA GUI Software Implementation (C#) - Update Versions Feb-Sep 2024 (beta versions)
        - CNA STM32 eSW (C)
        - AS-COMSAT City Network Ambulance (CNA) Hardware Requirements
        - AS-COMSAT City Network Ambulance (CNA) Software Requirements
        - System Design of CNA Communication Node
        - CNA Satellite Payload Transmitter Design
        - CNA 2 Mobile Users
        - CNA with 2 nodes and 2 mobile users
        - CNA with 1 Gateway, 3 nodes, and n fixed users
            - Users Guide, Getting Started - CNA with 1 Gateway, 3 nodes, and n fixed users
            - Developers Guide, Getting Started - CNA with 1 Gateway, 3 nodes, and n fixed users
    - AIS Specification & Use Cases
    - RF 144 MHz Transceiver Unit Prototype
        - 144MHz Modulation/Demodulation Scheme
        - 144 MHz Oscillator Circuit
- AS-COMSAT Customer Projects
    - Ambulance Emergency System (ECS CNA Trip 2024)
- DevOps CI/CD Development Environment (HW, GUI and embedded SW)
- AS-COMSAT Testbeds CNA+LEO-Sat, Antenna
    - Testing of CNA 3-1-2024
    - Reduced Testbed (Defined 8 Jan 2024)
    - Antenna Testing and Sending&Receiving Testing with gnu radio and HackRF

        - Launch Issues (SpaceX and other suppliers from India and Russia)
    - hi enterprises
        - hi enterprises Planning 2024
    - Green Chemistry
        - todos for 2024
        - Caustic Soda Production
            - market research for parts
            - Calculation
            - System design / system concept
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                    - Requirements For Acetic Anhydride Pilot Plant Production
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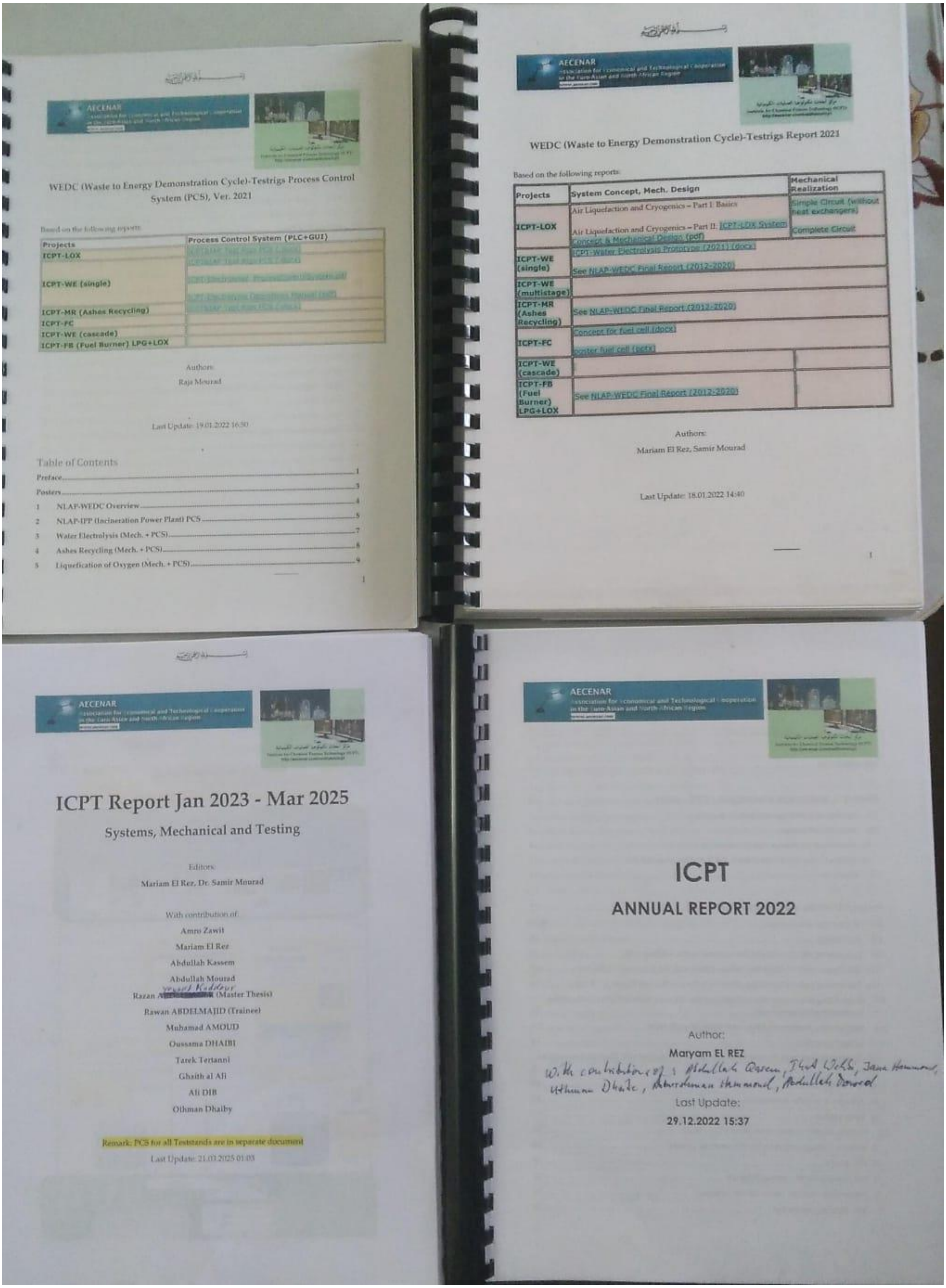
The following reports and articles (with submenues) are included:



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WEDC (Waste to Energy Demonstration Cycle)-Testrigs Process Control System (PCS), Ver. 2021

Based on the following reports:

Projects	Process Control System (PLC+GUI)
ICPT-LOX	[illegible] [illegible]
ICPT-WE (single)	[illegible] [illegible]
ICPT-MR (Ashes Recycling)	[illegible]
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Authors:

Raja Mourad

Last Update: 19.01.2022 16:50

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Association for Economical and Technological Cooperation in the Euro-Asian and North-African Region

WEDC (Waste to Energy Demonstration Cycle)-Testrigs Report 2021

Based on the following reports:

Projects	System Concept, Mech. Design	Mechanical Realization
ICPT-LOX	Air Liquefaction and Cryogenics – Part I: Basics Air Liquefaction and Cryogenics – Part II: ICPT-LOX System Concept & Mechanical Design (pdf)	Simple Circuit (without heat exchangers) Complete Circuit
ICPT-WE (single)	ICPT-Water Electrolysis Prototype (2021) (docx) See NLAP-WEDC Final Report (2012-2020)	
ICPT-WE (multistage)		
ICPT-MR (Ashes Recycling)	See NLAP-WEDC Final Report (2012-2020)	
ICPT-FC	Concept for fuel cell (docx) poster fuel cell (pptx)	
ICPT-WE (cascade)		
ICPT-FB (Fuel Burner) LPG+LOX	See NLAP-WEDC Final Report (2012-2020)	

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Last Update: 18.01.2022 14:40

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ICPT Report Jan 2023 - Mar 2025

Systems, Mechanical and Testing

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Remark: PCS for all Teststands are in separate document

Last Update: 21.03.2025 01:03

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ANNUAL REPORT 2022

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Last Update:

29.12.2022 15:37

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