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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)	

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Table of Contents

Preface

Thank be to Allah the Almighty.

In this report the system definition & design and the so far mechanical realization of all parts of NLAP-WEDC (Waste to Energy Demonstration Cycle) except the Incineration power plant is described.

1 Posters

1.1 NLAP-WEDC Overview

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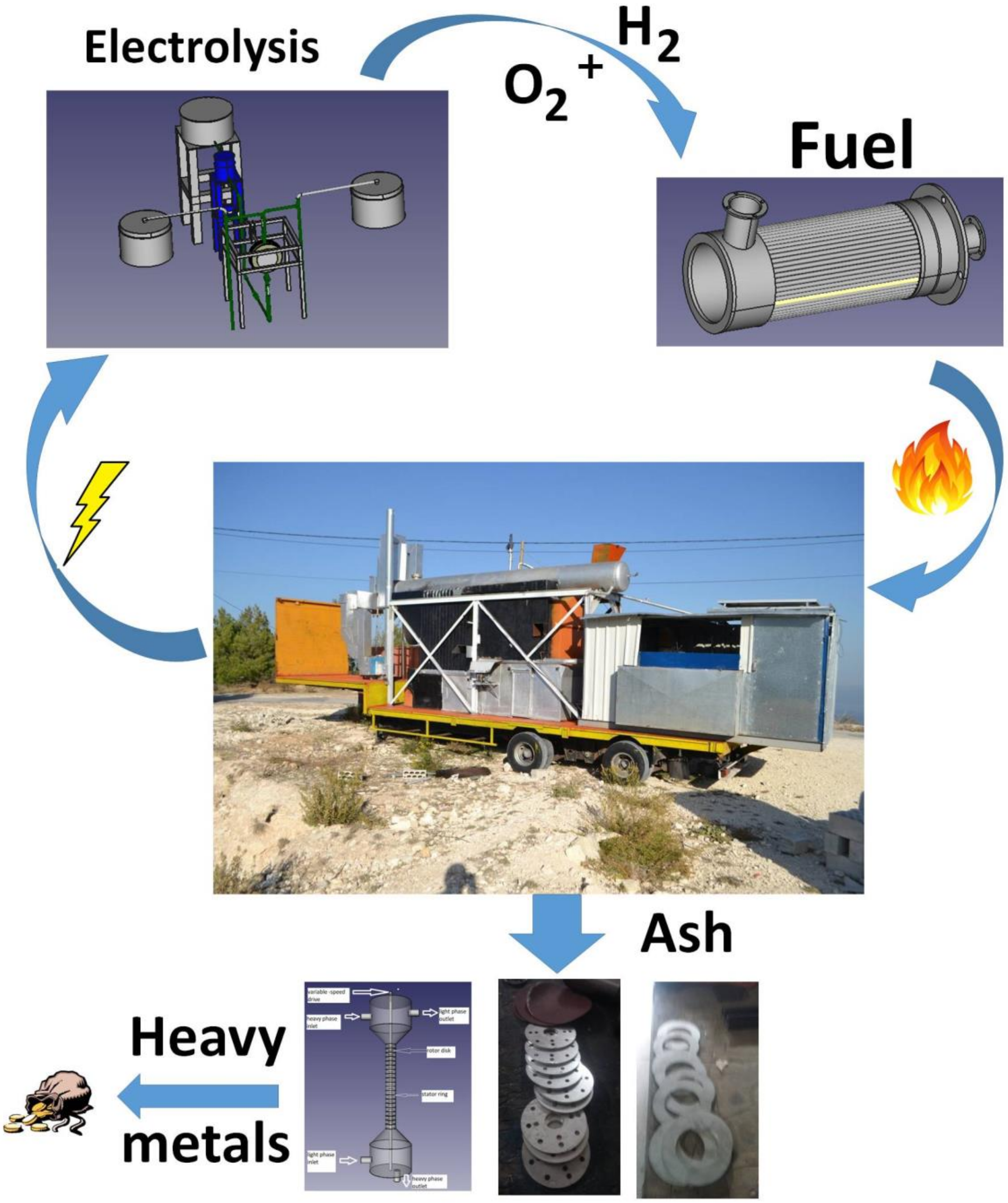
طاقة الشمال

North Lebanon Alternative Power

NLAP-WEDC Waste to Electricity

Demonstration cycle



1.2 NLAP-IPP (Incineration Power Plant)

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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.

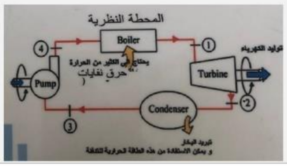
Control system نظام التحكم

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)**

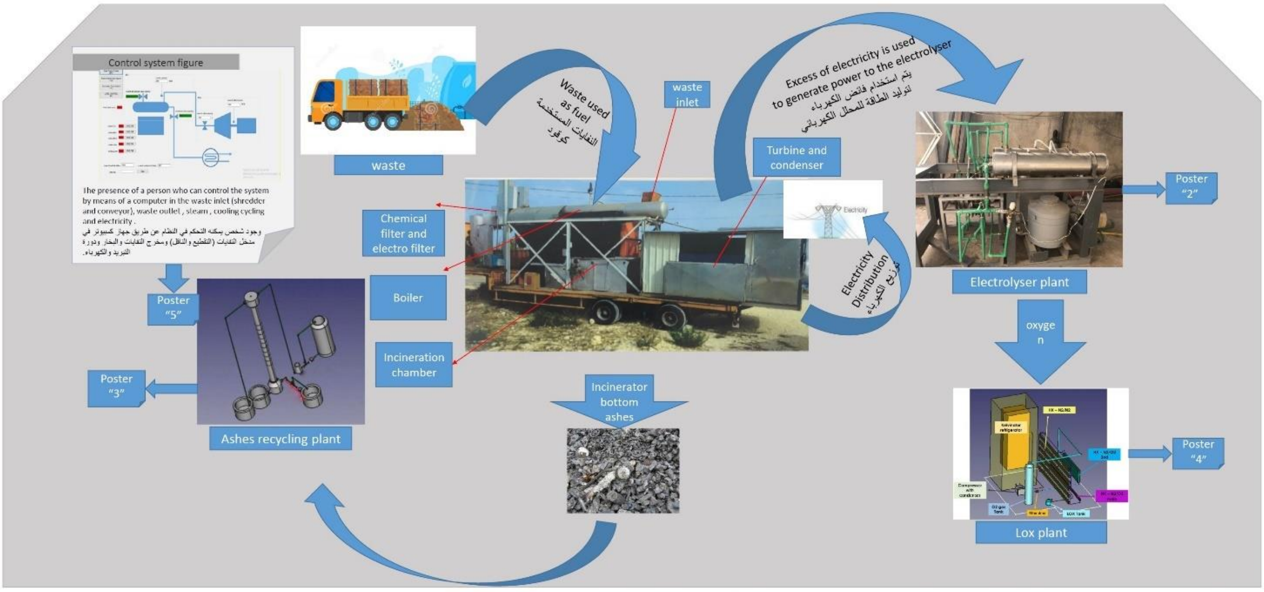
تتعدد مساوئ تحويل النفايات إلى طاقة وأصبحت أكثر وضوحًا في السنوات الأخيرة. وهي تشمل التلوث والجسيمات التي تولدها ، وتدمير المواد المفيدة ، وإمكانية تثبيط حلول إدارة النفايات الأكثر استدامة ومصادر الطاقة المتجددة.

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 (**المعالجات 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 بمكنه التحكم في النظام عن طريق جهاز كمبيوتر في مدخل النفايات (التقطيع والناقل) ومخرج النفايات والبخار ودورة التبريد والكهرباء.

Nidaa Fatfat/ Mounira Sayah ,AECENAR@November 2021

1.2.1 Process Control System of NLAP-IPP

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Poster 5

NLAP-IPP Process Control System

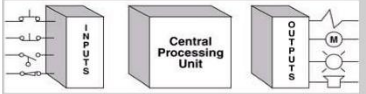
Introduction مقدمة

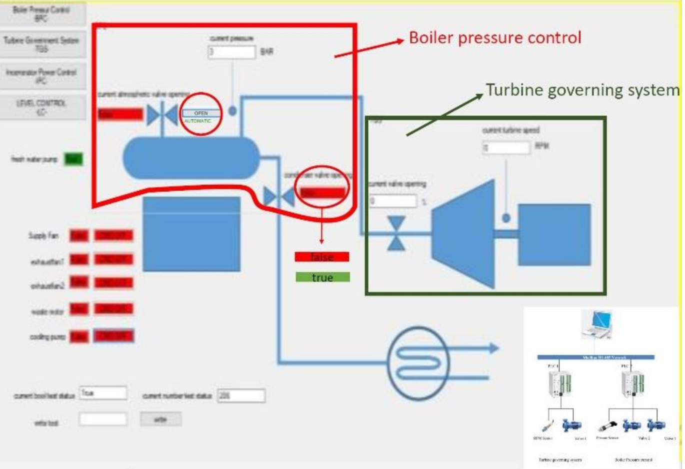
A programmable logic controller (PLC) is an industrial computer control system computer that has been ruggedized and adapted for the control of manufacturing processes, and that continuously monitors the state of input devices and makes decisions based upon a custom program to control the state of output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

- **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

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

Incinerator Regulating System نظام تنظيم المحارق

Boiler Level control التحكم في المستوى

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))

- 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))

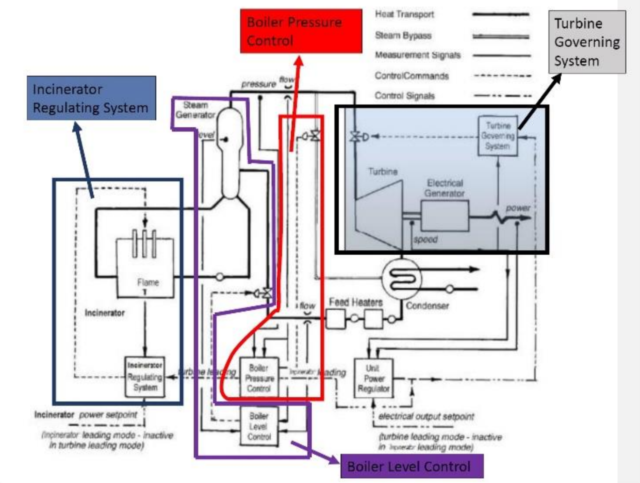
-Green→True/ON Command is send (the state field should also be green (ON))

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.



Mounira Sayah, Nidaa Fatfat/ AECENAR@November 2021

1.3 Water Electrolysis

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www.aecenar.com

بسم الله الرحمن الرحيم

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

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 :

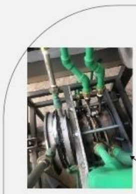
'الإلكتروليزر' او المحلّل الكهربائي هو نظام يستخدم الكهرباء لتقسيم الماء إلى "هيدروجين"و"أكسجين" ضمن عمليّة تسمّى 'الإلكتروليزيس' أو التحليل الكهربائي.

الإلكتروليزيس :

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

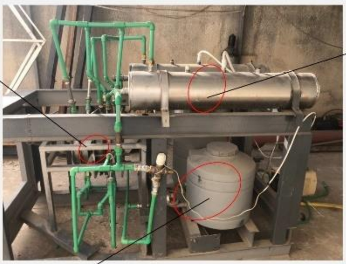
يُخَزّن كلٌّ من ال"اكسجين"و ال"هيدروجين" ضمن مستوعبات بعد مرور بمكثّف للتخلص من الماء الزّائد.

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

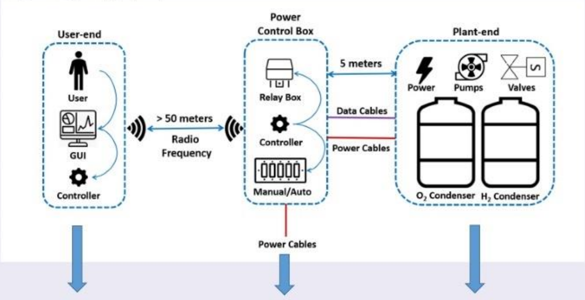
ELECTROLYTE:
An electrolyte is a substance that produces an electrically conductive solution when dissolved in a polar solvent, such as water.

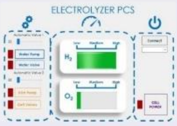
الإلكتروليت هو مادة تنتج محلول موصل كهربائي عند إذابته في مذيب قطبي ، مثل الماء

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.

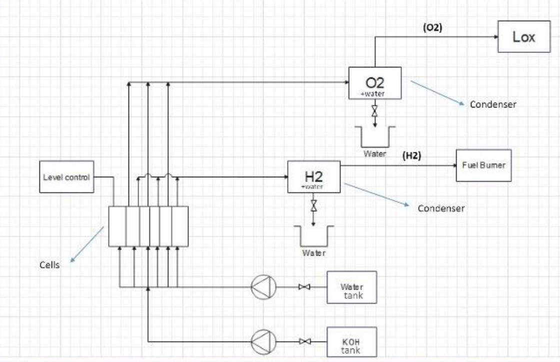


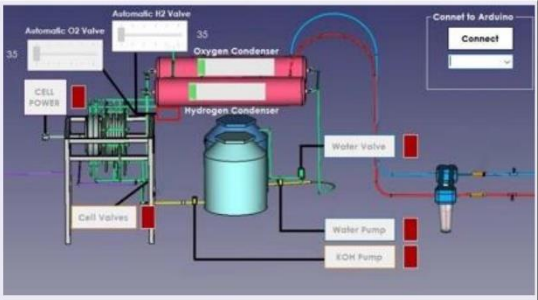


GUI

PLC

PLANT_END





GUI

“Mohamad NAAMAN, Ali DIB”@AECENAR November 2021

1.3.1 Single Stage Water Electrolysis

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in the Euro-Asian and North-African Region

بسم الله الرحمن الرحيم

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

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)

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

صورة لجميع قطع المنظومة (Picture of all parts electrolysis)

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

يمكن أن تحتوي هذه الخلية على حوالي 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 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

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	

الخطوة الرابعة: بعد عملية تحلل المياه ، سيبدأ الغاز في الطفو داخل الأنابيب ، 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)

1.3.2 Cascaded Multi-Stage Water Electrolysis

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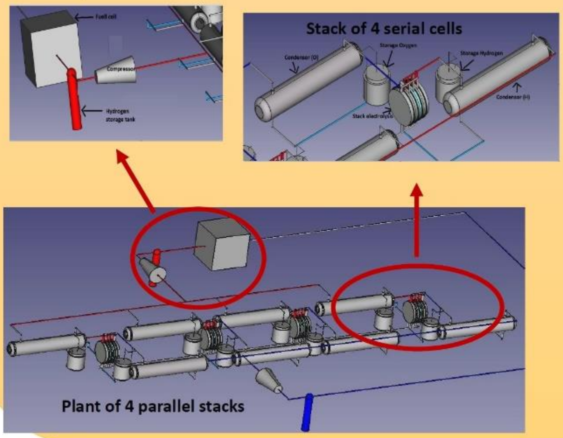
(Alkaline Electrolysis) منظومة التحليل الكهربائي للماء

I. Electrolysis design

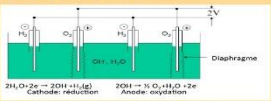
A. Introduction

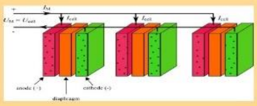
The single cell alkaline electrolysis is generated low amount of hydrogen gas per a minute. Hence, it is important to design alkaline electrolysis stack in order to produce high amount of hydrogen gas. Thus, we focuses on the designing of bipolar configuration of alkaline electrolysis stack.



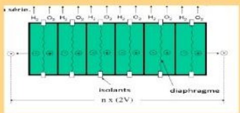
B. Technologies: Monopolar and bipolar structures

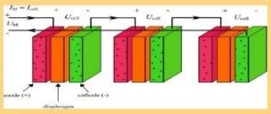
In monopolar configuration, each electrolysis cells are connected in parallel to form a large module of electrolysis stack as shown in figure below. Hence, the voltage between individual pairs of electrodes is directly equal to the total cell voltage and the sum of cell current is equal to the total 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.





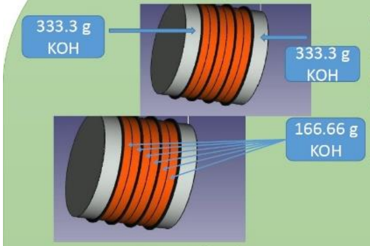
In bipolar configuration, each electrolysis cells are connected in series to form a large module of electrolysis stack as shown in Figure. Hence, the sum of all the voltages between individual pairs of electrodes is equal to the total cell voltage and the cell current is directly equal to the current 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.



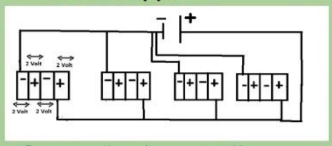


II. Electrolysis calculation

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,

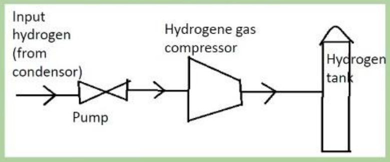
$$V_{H_{2(g)}} = \frac{n_{H_2}RT}{P}$$
$$= \frac{0.023\,mol/\min * 0.082\,Latm\,K^{-1}mol^{-1} * 298\,K}{1\,atm}$$

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

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

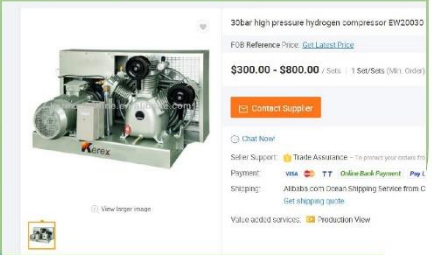
When Hydrogen gas exits from the condenser, it is pumped to the compressor at 30 bar then it storage in hydrogen tank



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)

Contact Supplier

Chat Now!

Seller Support: Trade Assurance – To protect your orders fro

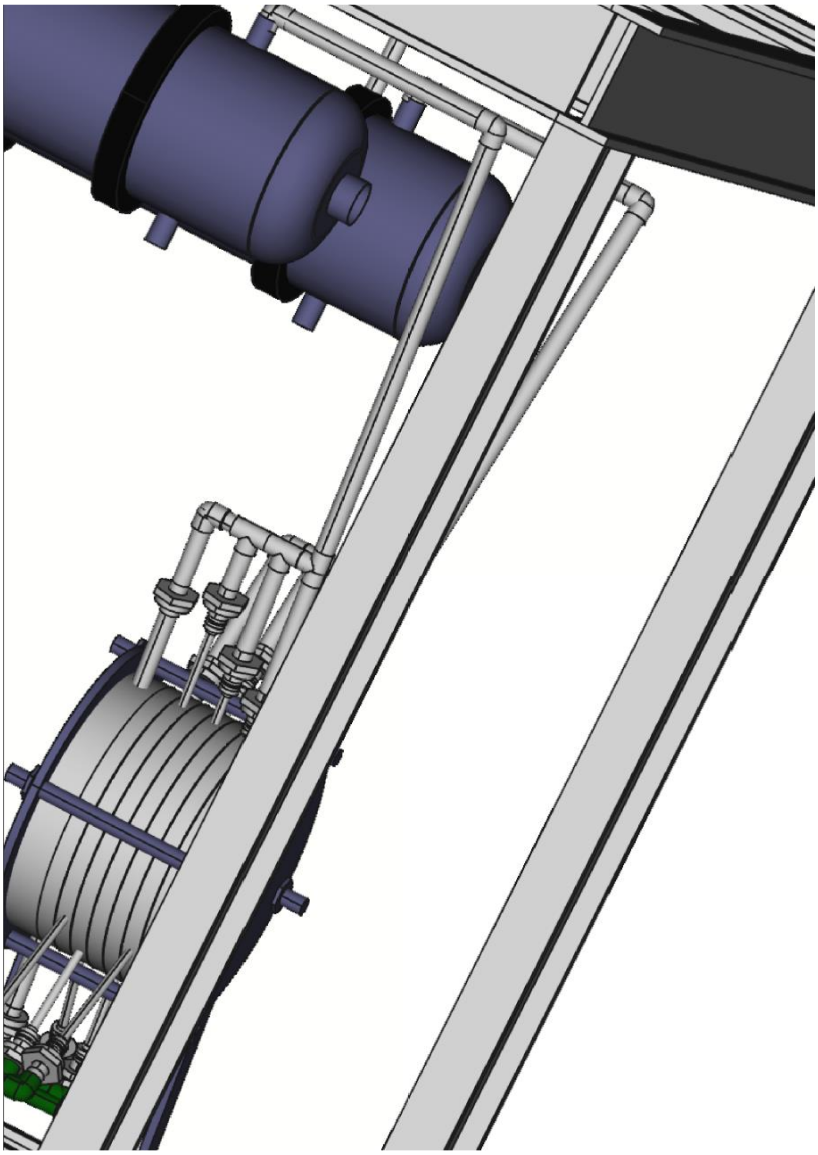
Payment: VISA TT Online Bank Payment Pay L

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

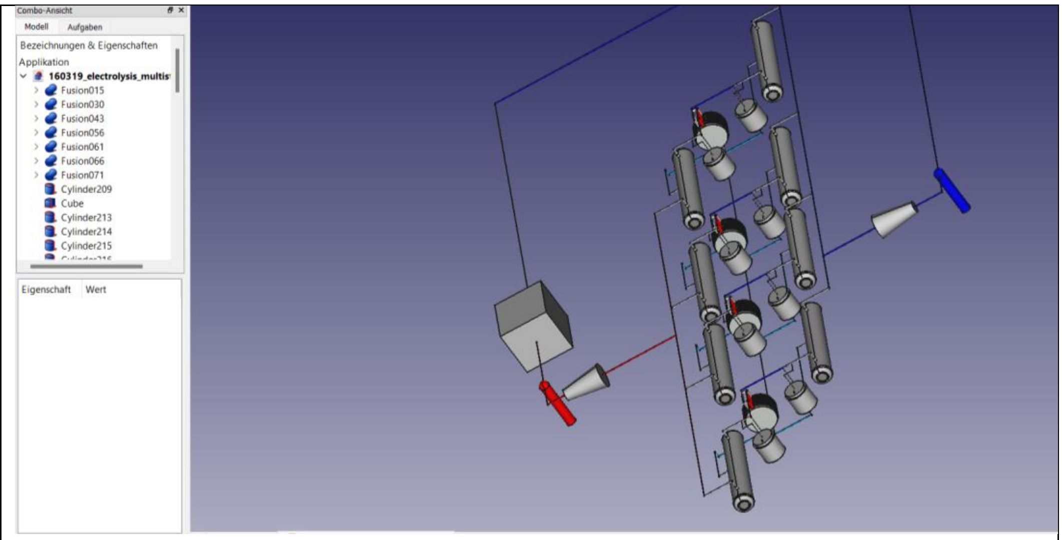
Value added services: Production View

View larger image

Siham Aisha/ AECENAR March 2019

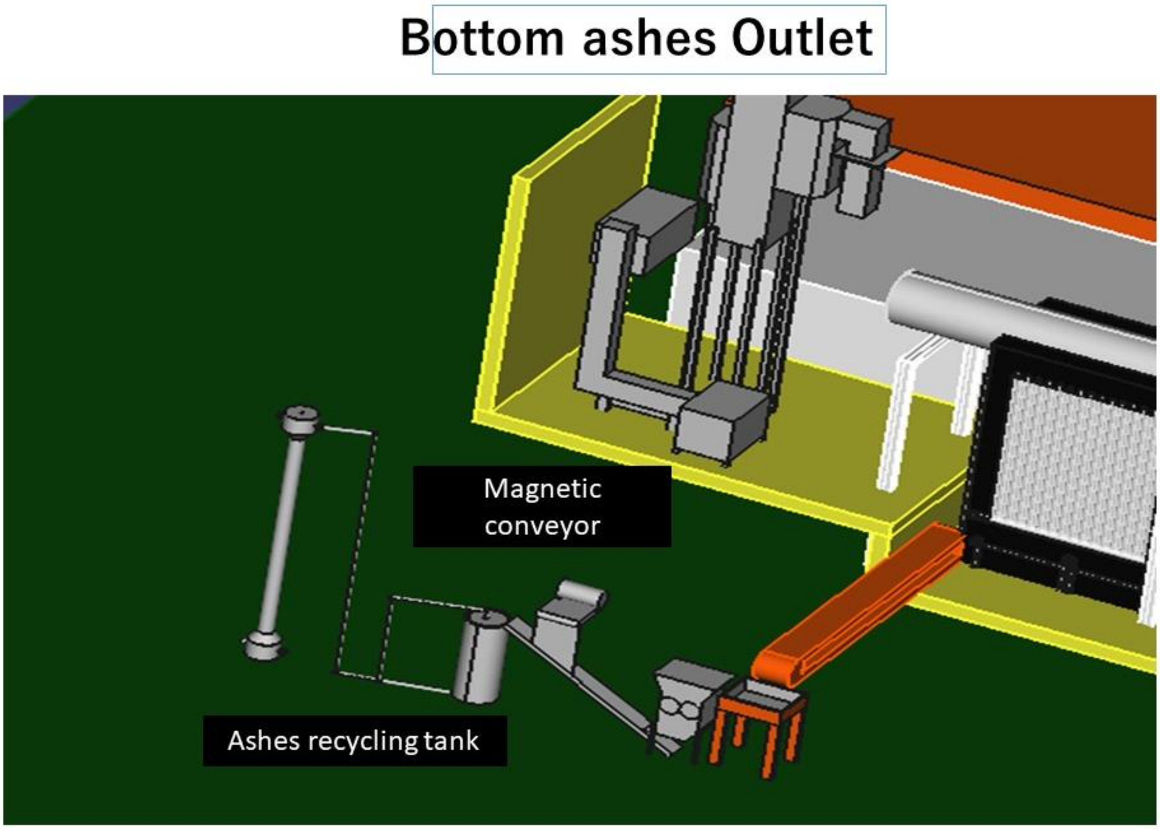


160319_electrolysis_multistack.FCStd



1.3.3 Hydrogene Storage

1.4 Ashes Recycling



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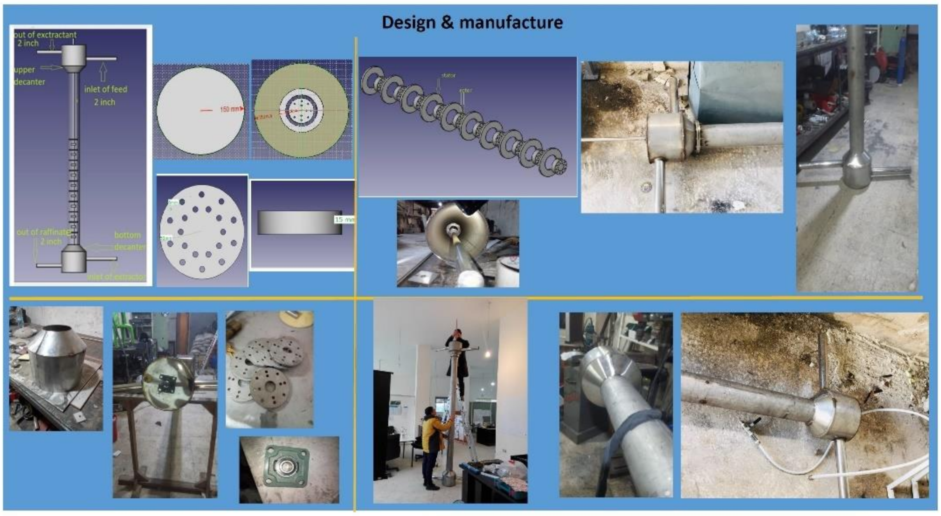
Heavy Metals Recycling Unit for NLAP-IPP Demonstration Plant

Lists of metals (mg/kg)

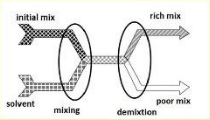
Element bottom ash	Bottom ash	Fly ash	Dry / quasi-dry	wet
Al	22.000-73.000	49.000 - 90.000	12.000-83.000	21.000-39.000
Cd	0.3-70	50-450	140-300	150-1.400
Cu	190-8.200	600-3.200	16-1.700	440-2.400
Fe	4.100-1500	12.000 - 44.000	2.600-71.000	20.000-97.000
Hg	0,02-8	0,7-30	0,1-51	2,2-2.300
Mo	2-280	15-150	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:

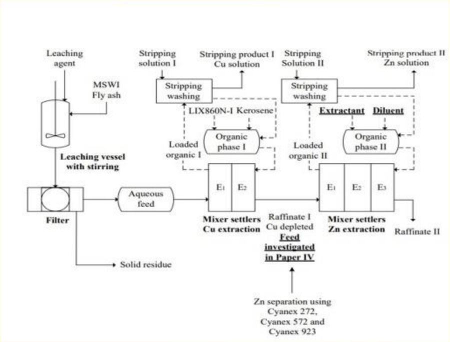
1. LIX® 984N
A mixture of 2-hydroxy-5-nonylacetophenone oxime and 5-nonylsalicylaldoxime in a high flash diluent. The acetophenone oxime modifies the aldoxime and also performs as an extractant in its own right. Molecular Weight:262.393 g/mol.

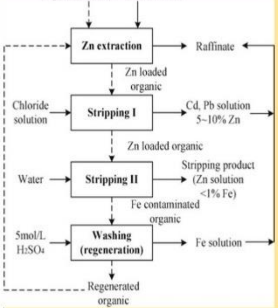
2. Acorga® M5640
5-Nonylsalicylaldoxime modified with an ester, 2,2,4-Trimethyl-1,3-pentanediol Diisobutyrate (TXIB) in a high flash diluent.

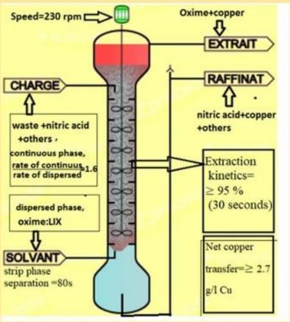
3. LIX® 622N
5-Nonylsalicylaldoxime modified with tridecyl alcohol in a high flash diluent.
Each of the extractants marketed by the major chemical suppliers has been designed for a specific type of PLS with regard to pH and copper tenor. Used under the conditions for which they were designed they all 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





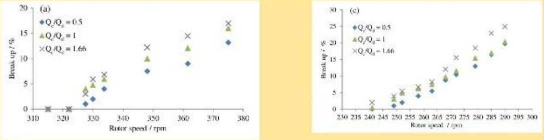


Extraction kinetics= ≥ 95 % (30 seconds)

Net copper transfer=≥ 2.7 g/l Cu

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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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

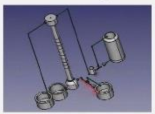


Figure 2: Ashes recycling plant

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.

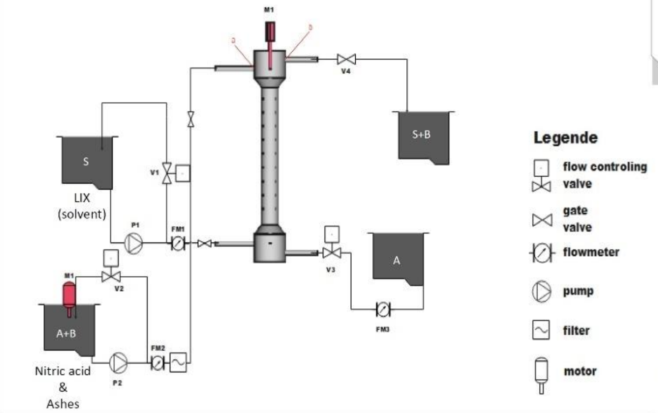
يتم أخذ عينات من رماد القاع الطازج من المحارق وتجفيفها عند 25 درجة مئوية ثم فصل الأجزاء غير المحترقة يدويًا مثل اللولب والأسلاك والبلاستيك. يتم تصغير العينة إلى حجم 500 ميكرومتر باستخدام آلة التقطيع لإزالة المحتوى المغناطيسي (إزالة الحديد). تم إخضاع عينات رماد القاع (المخلفات والمركزات) لاختبارات الترشيح 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



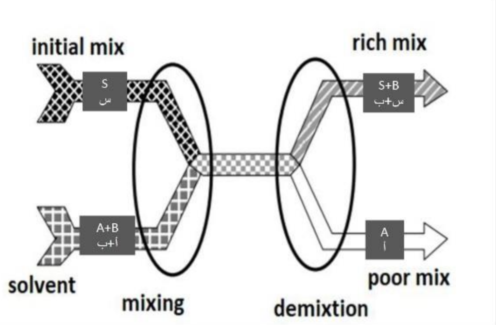


Figure 3: Principle of a separationstage by obtaining a balance

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

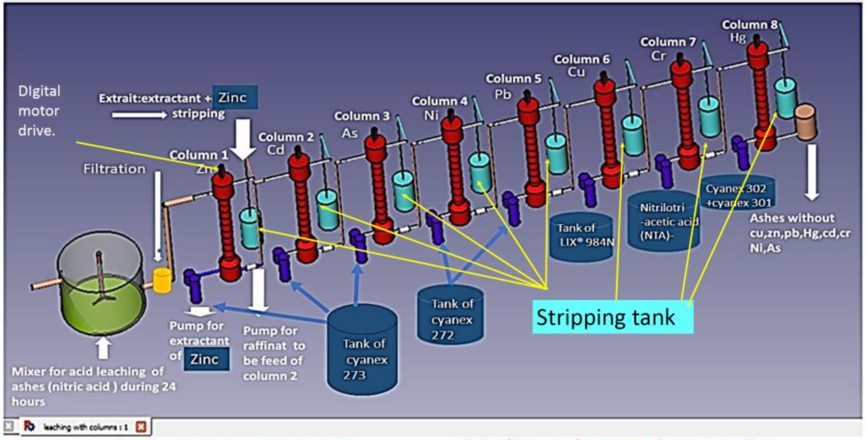
Leaching

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)

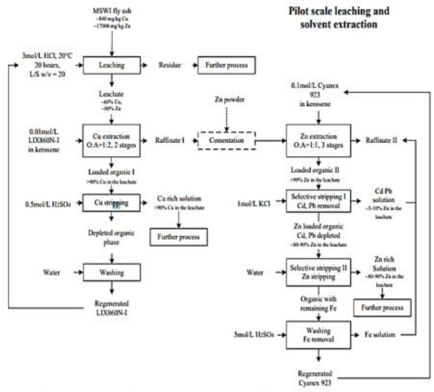
Leaching reagent	Final pH	Al	Ca	Fe	Cu	Zn	Pb
Citric acid	3.13	100	93.1	67.0	100	100	96.9
Malic acid	3.07	99.7	100	80.2	100	100	97.0
Acetic acid	3.02	88.4	100	23.2	100	100	70.1
Lactic acid	3.06	92.2	100	40.7	100	100	62.0
Oxalic acid	3.09	43.3	0.41	46.5	45.8	44.9	2.7
Tartaric acid	2.98	30.3	6.7	24.4	32.7	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.

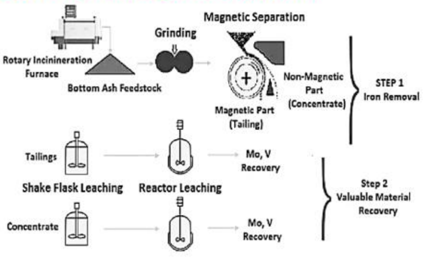


Leaching and solvent extraction plant



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 ساعةَ.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



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)

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.

Maysaa kamaredine
24 -04-2019

1.5 Liquefication of Oxygen

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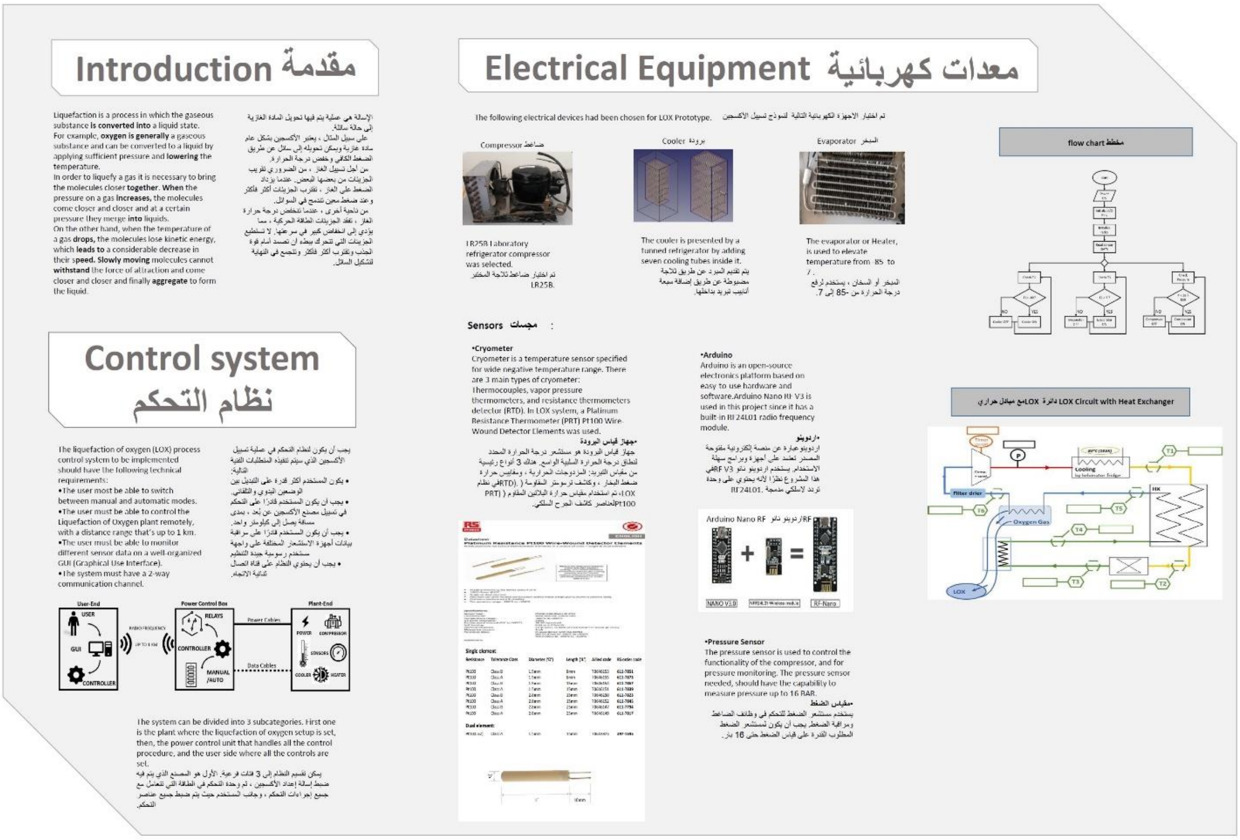
Air Liquefaction and Cryogenic



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 و التلقائي.
- 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 الأكسجين

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 او 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.

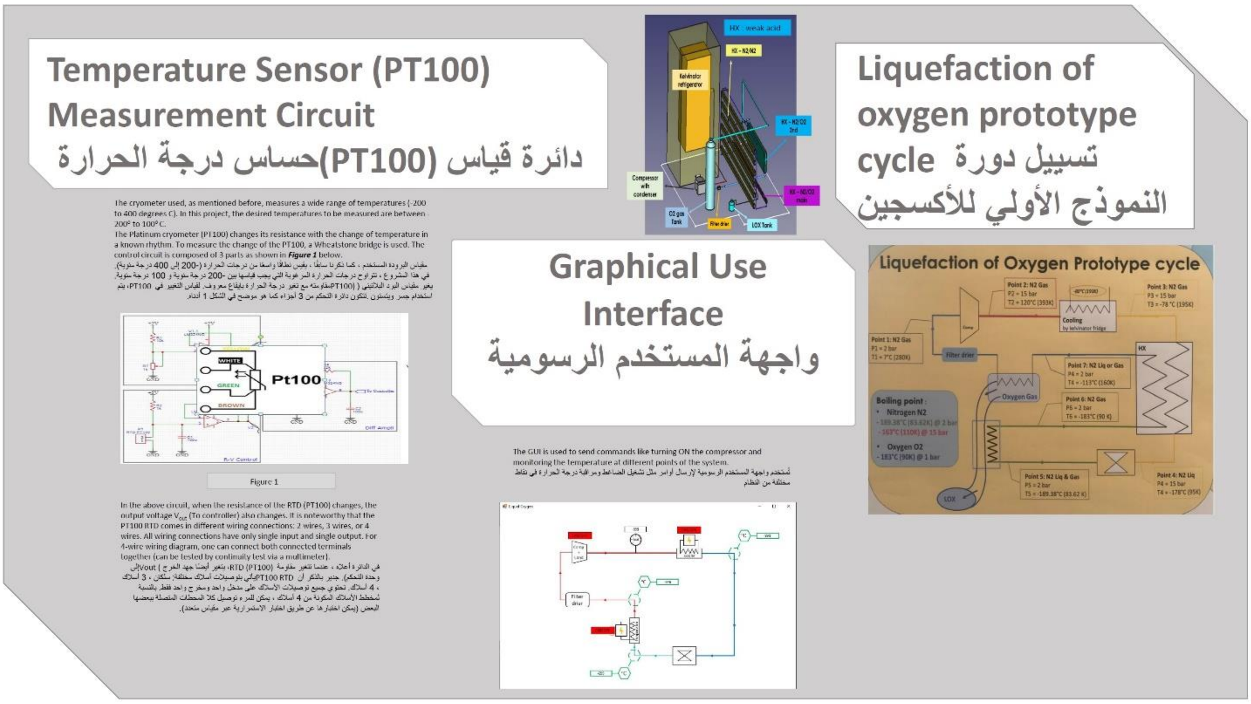
Arduino Nano RF اردوينو نانو/RF

•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 LOXمع 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).

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

Liquefaction of oxygen prototype cycle تسييل دورة النموذج الأولي للأكسجين

Liquefaction of Oxygen Prototype cycle

Nidaa Fatfat Mounira Sayah
/Aecenar November 2021

بسم الله الرحمن الرحيم

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طاقة الشمال
North Lebanon Alternative Power
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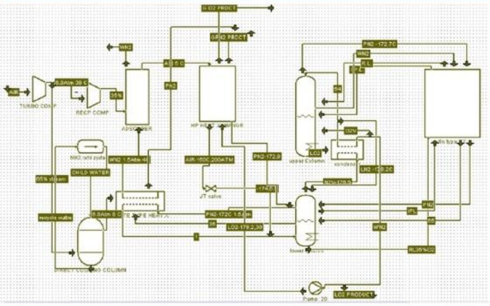
Liquefaction of air(oxygen)

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%.

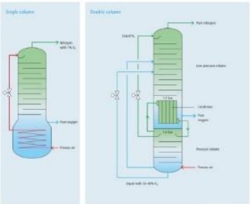


TABLE 5.6a: Specification sheet for Compressor

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

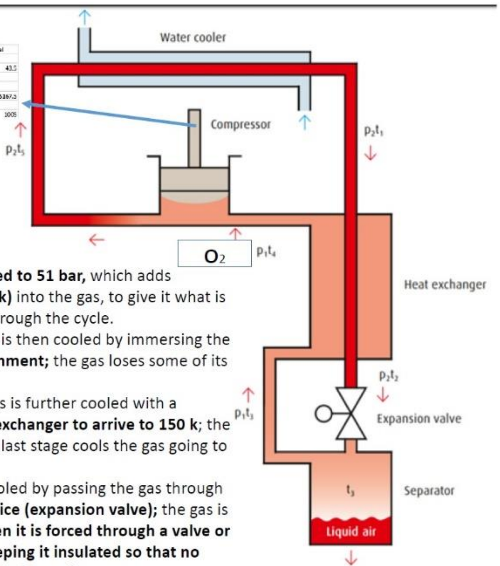
fin thickness(t)	30mm
fin frequency (f)	0.7425 fin per meter
fin length (l)	250mm
fin height (h)	50mm
fin spacing (s)	110mm
plate thickness (b)	80mm
free flow area (Aff)	4000mm^2
frontal area (A)	11200mm^2
heat transfer area (As)	83000mm^2
fin area (Af)	28000mm^2
equilibrium diameter (Dh)	48.19mm
fin 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 (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 = 45.20	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	1006



- 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]

	Work			Thermal Energy	Electricity	
Substance	cal/mole	J/mole	Btu/lb	(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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بسم الله الرحمن الرحيم

Liquefaction of Oxygen

مركز أبحاث تكنولوجيا العمليات الكيميائية
Institute for Chemical Process Technology (ICPT)
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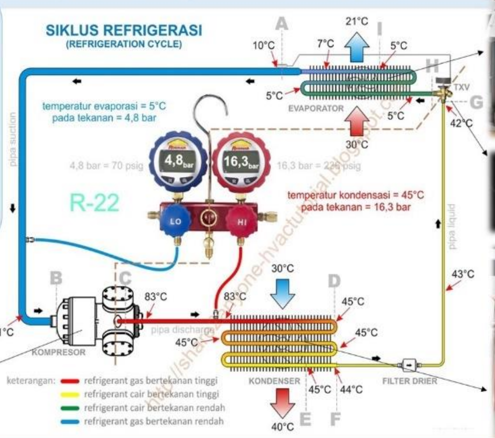
Simple refrigeration cycle

R-22
- **Nomenclature:** *Chlorodifluoromethane*
- **Symbol:** *$CHClF_2$*
- **Boiling point :**

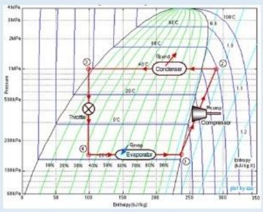
T= - *40.7°C* *(232.5 K)* ***@ 1 bar***

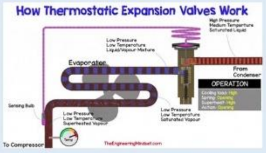
T= *4.9°C* (278.05 K) **@ 4.8 bar**

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.

R-502 (Higher stage)
- **Chemical formula:** $C_3HCl_2F_7$
- **Boiling point:**

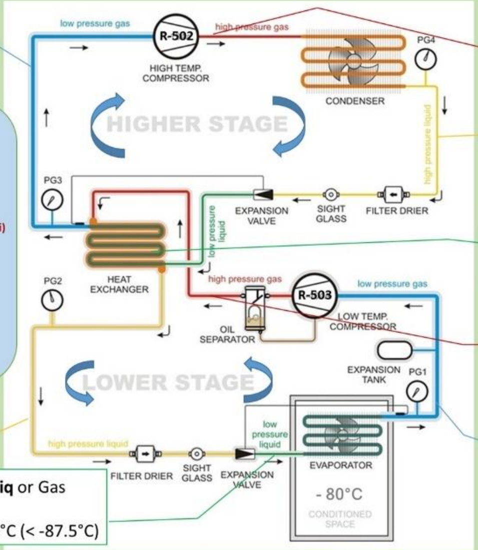
- 45.5°C @ 1 bar

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

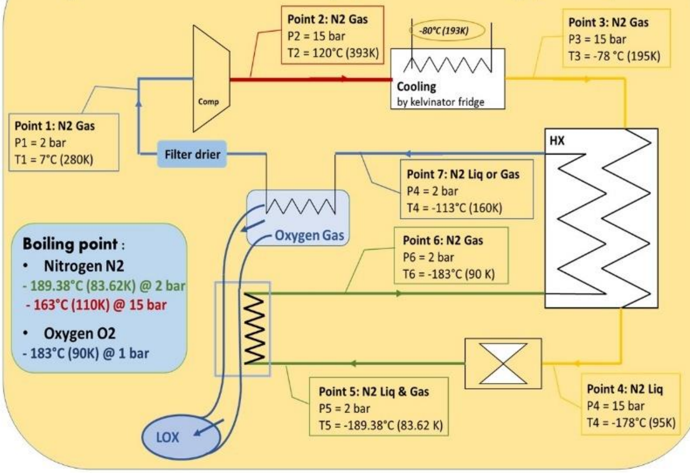
Point B: Liq
PB= 25.85 bar
TB= -30 (< -20 °C)

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

Point 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**

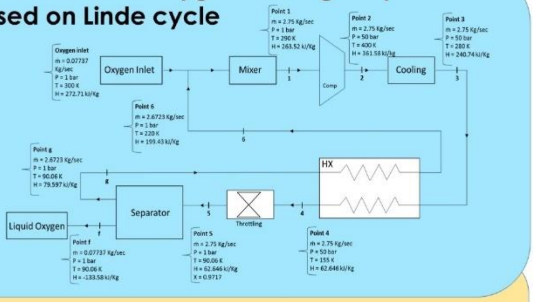
- 189.38°C (83.62K) @ 2 bar

- 163°C (110K) @ 15 bar

- **Oxygen O2**

- 183°C (90K) @ 1 bar

Liquefaction of Oxygen in a big shape based on Linde cycle



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).

Maryam EL-REZ @AECENAR/May 2021

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Institute for Chemical Process Technology (ICPT)
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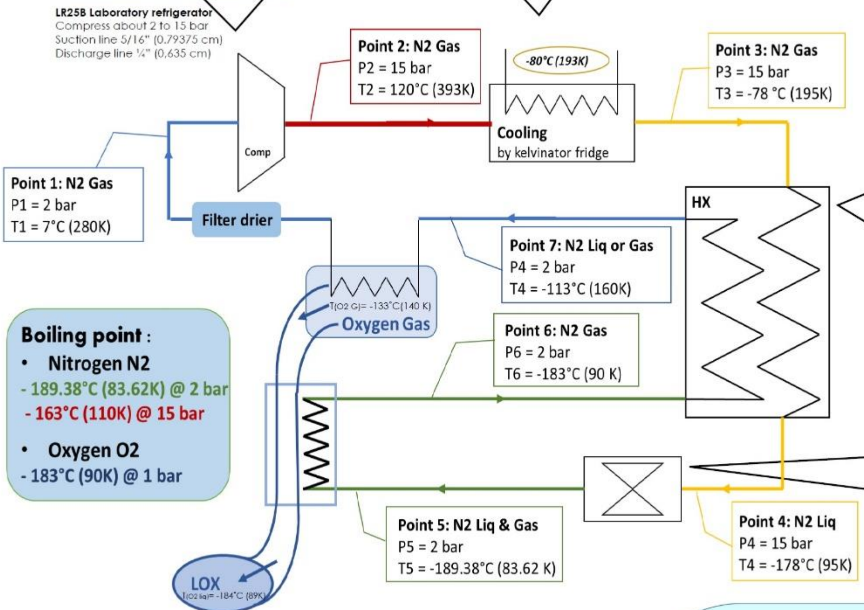
Prototype of Oxygen liquefaction



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)

-80°C (193K)
Cooling
by kelvinator fridge

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

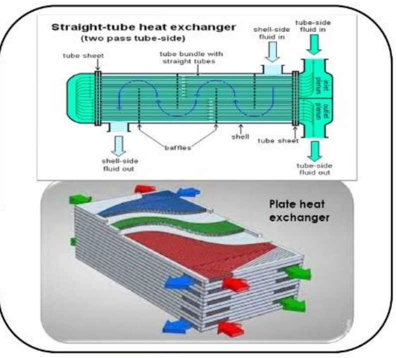
Point 4: N2 Liq
P4 = 15 bar
T4 = -178°C (95K)

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

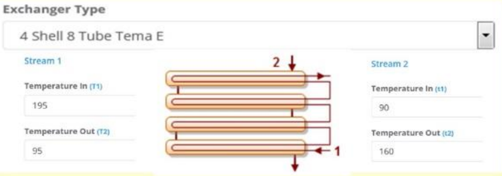


Gas flow rate of compressor : 25 Kg/hr = 6.9 g/s in condition of:
Condensing temperature: 55°C
Evaporating temperature: 7°C

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:**



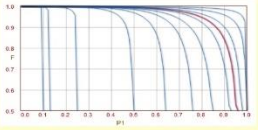
Exchanger Type: 4 Shell 8 Tube Tema E

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

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

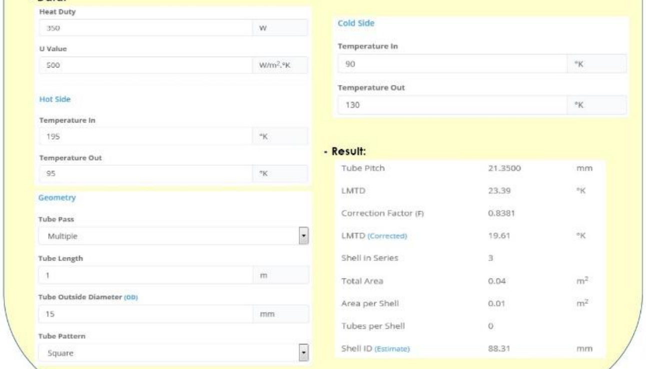
- **Result:**

```
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:**

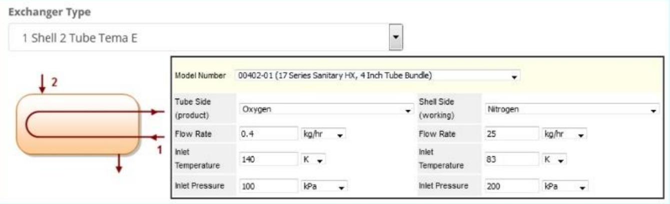
Tube Pitch	21.3500	mm
LMTD	23.39	°K
Correction Factor (F)	0.8381	
LMTD (Corrected)	19.61	°K
Shell in Series	3	
Total Area	0.04	m²
Area per Shell	0.01	m²
Tubes per Shell	0	
Shell ID (Estimate)	88.31	mm

Maryam EL-REZ @AECENAR/May 2021

Prototype Heat exchanger (HX - N_2/O_2)

LMTD Correction Factor Charts

- **Data:**



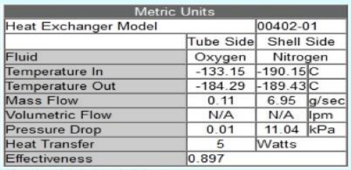
Exchanger Type: 1 Shell 2 Tube Tema E

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
```

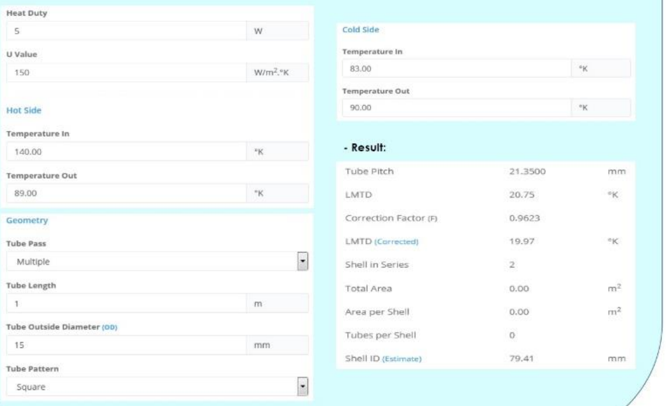


Metric Units			
Heat Exchanger Model		00402-01	
	Tube Side	Shell Side	
Fluid	Oxygen	Nitrogen	
Temperature In	-133.15	-190.15	C
Temperature Out	-184.29	-189.43	C
Mass Flow	0.11	6.95	g/sec
Volumetric Flow	N/A	N/A	lpm
Pressure Drop	0.01	11.04	kPa
Heat Transfer	5	Watts	
Effectiveness	0.897		

* 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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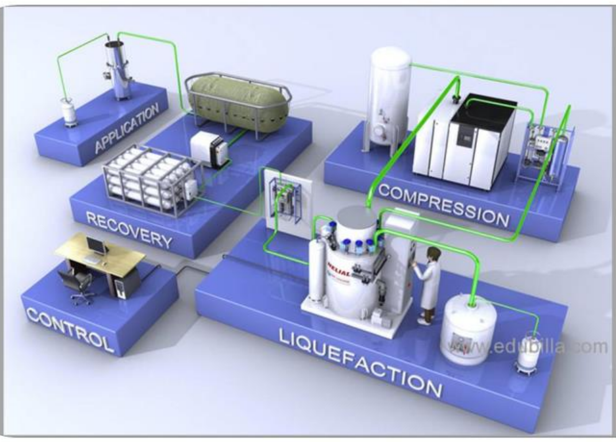
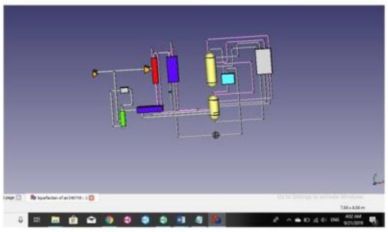
Heidelberg / Germany

LSA
Lebanese Scientific Accosiation
الجمعية العلمية اللبنانية
Tripoli / Lebanon

AIR LIQUEFACTION

Principle of Production





1.6 Fuel Cell

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Fuel Cell system

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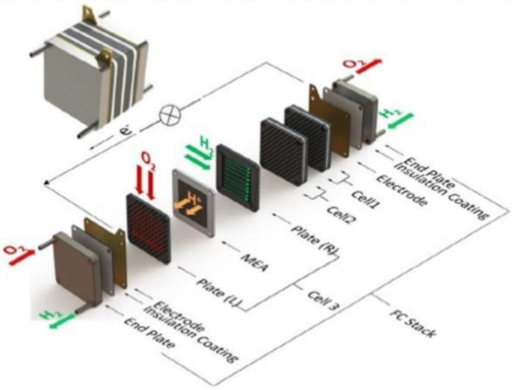
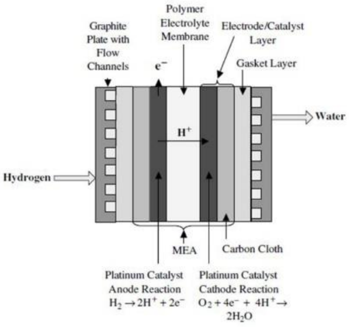


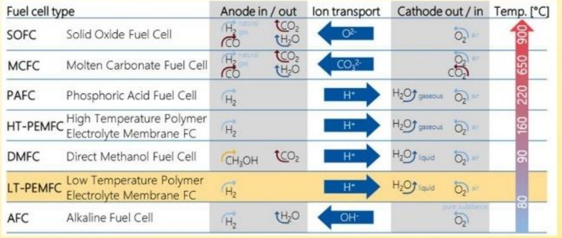
Generalized schematic of a single fuel cell

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 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***

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

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.

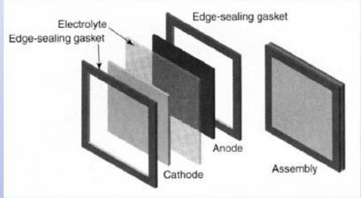
$$A = \frac{I}{J} = \frac{4.63}{0.55} = 8.42 \text{ cm}^2$$

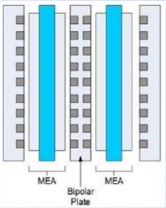
Step 3: Estimation of H2 needed per day

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

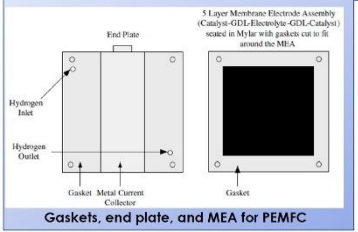
Constructing the Fuel Cell

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

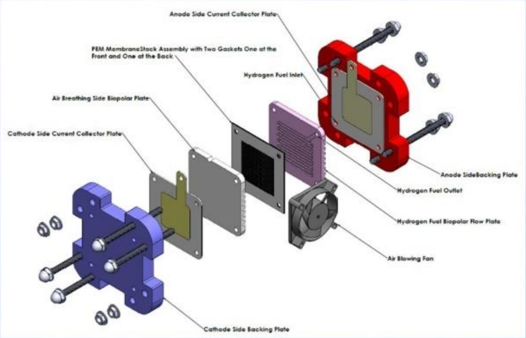




Typical fuel cell stack configuration (a two-cell stack)



Gaskets, end plate, and MEA for PEMFC

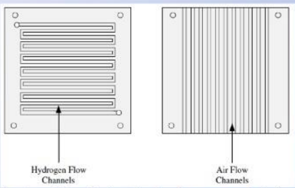


The Fuel Cell stack (PEMFC)

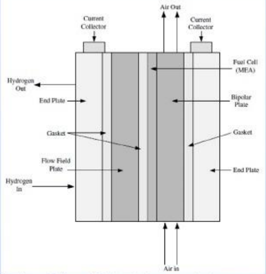
Physical characters of proton exchange membrane fuel cell (PEMFC)

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

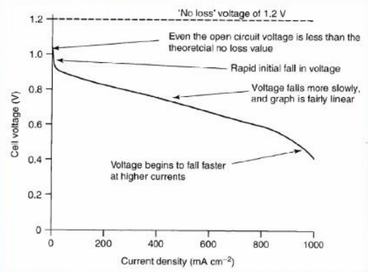
Fuel cell system	Proton exchange membrane fuel cell (PEMFC)
Operating Temperature	Room temperature to 100°C
Operating Pressure (atm)	1 to 3
Major Contaminants	CO < 100 ppm, sulfur, dust
Maximum Fuel Cell Efficiency (current)	~58%
Primary Applications	Stationary, portable, and vehicular



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

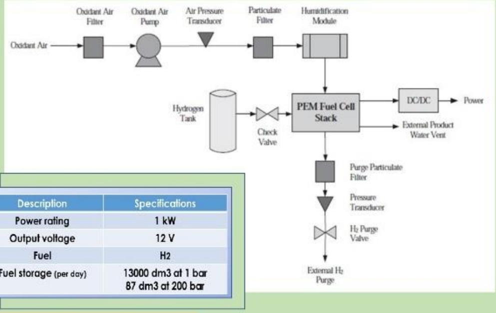


End and flow field plates, gaskets, current collectors, and MEA for a single-cell PEMFC stack



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**

1.7 Fuel Burner

بسم الله الرحمن الرحيم

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

1.7.1 Fuel Burner Mixing Test Rig

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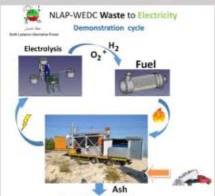
طاقة الشمال
North Lebanon Alternative Power

Fuel Burner Mixing Testrig

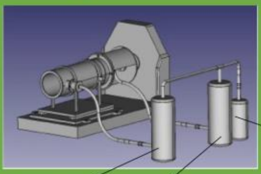
1. Introduction

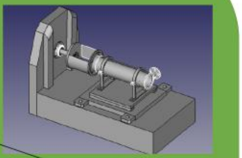


To be able to operate the NLAP Waste to Electricity Demonstration Cycle by Night without incinerating municipal waste, an electrolysis unit produces by day O2 and H2. O2 is liquefied to LOX. This is the oxidizer for the fuel burner.

The fuel can be liquefied Methane (liquefied waste gas from landfill) or propan gas *(غاز البيوت)*.

2. Testrig mechanical system design



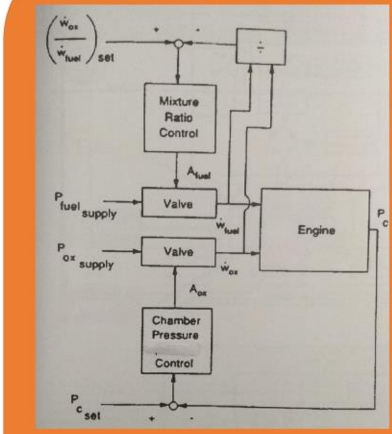


The methane and oxygen are mixed together, and from high pressure gas supply tank (He), a feed mechanism to force the the fuel and the oxidizer from the tanks into the burning chamber

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

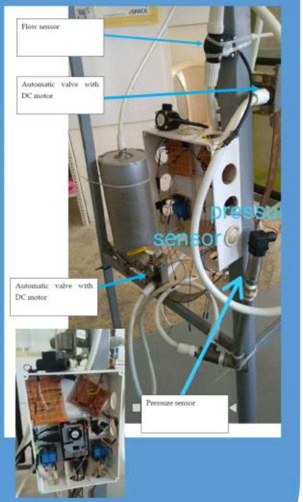
Flowmeter

Automatic valve with DC motor

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

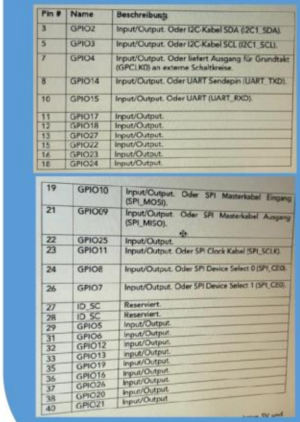
pressure sensor

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*

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

Water Electrolysis

---

2 Single Stage Electrolysis (`ICPT-WE (single)`)

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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 يَتَعدى 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

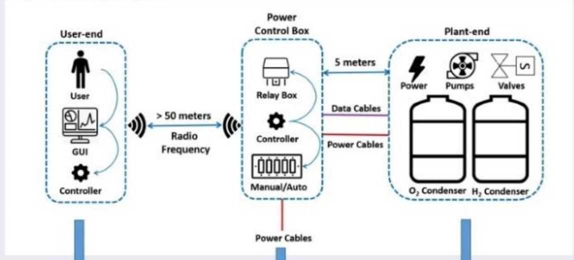
ELECTROLYTE:
An electrolyte is a substance that produces an electrically conductive solution when dissolved in a polar solvent, such as water.

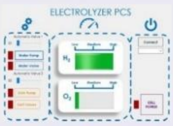
الإلكتروليت هو مادة تنتج محلول موصل كهربائي عند إذابته في مذيب قطبي ، مثل الماء

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.

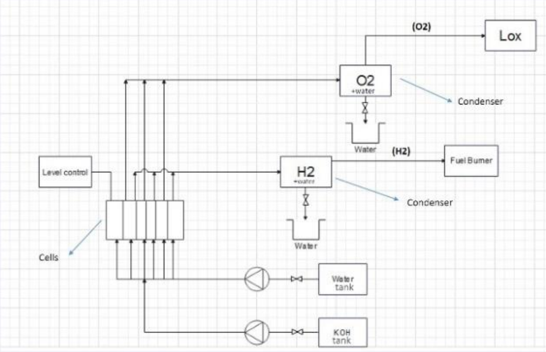


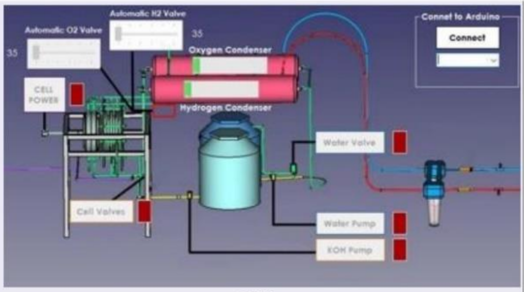


GUI

PLC

PLANT_END





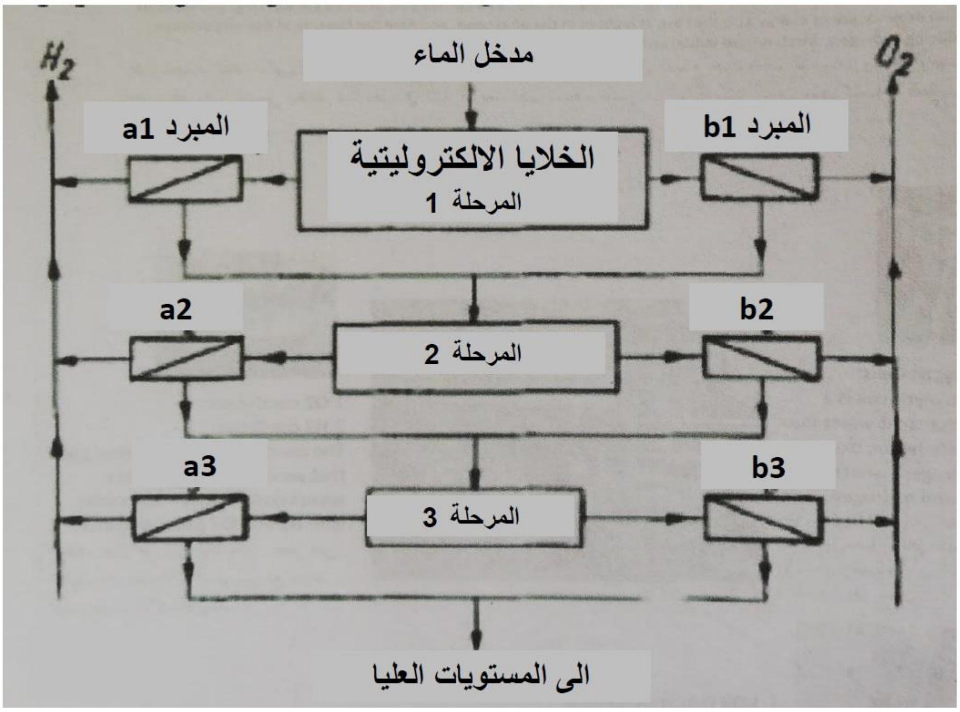
GUI

"Mohamad NAAMAN, Ali DIB"@AECENAR November 2021

3 Multistage ICPT-WE

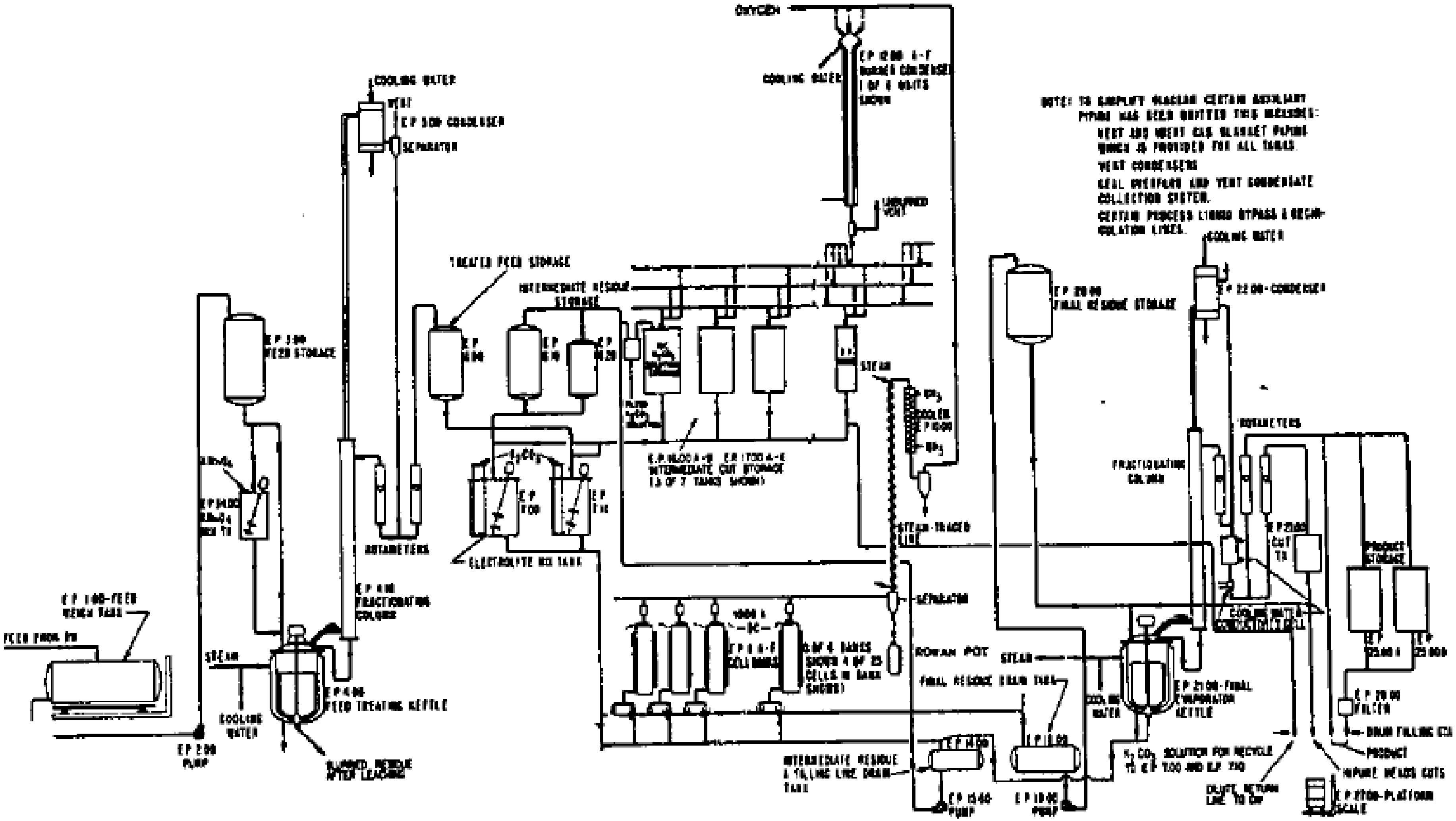
3.1 Stages 1-9

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 المبردات a1 و b1 يذهب إلى خلايا المرحلة 2. يتم تغذية المرحلة 3 بواسطة المبردات a2 و b2 وما إلى ذلك. ينخفض معدل النقل كلما ارتفعت المرحلة.

3.2 Stages 10-14



NOTE: TO SIMPLIFY DIAGRAM CERTAIN AUXILIARY PIPING HAS BEEN OMITTED THIS INCLUDES:

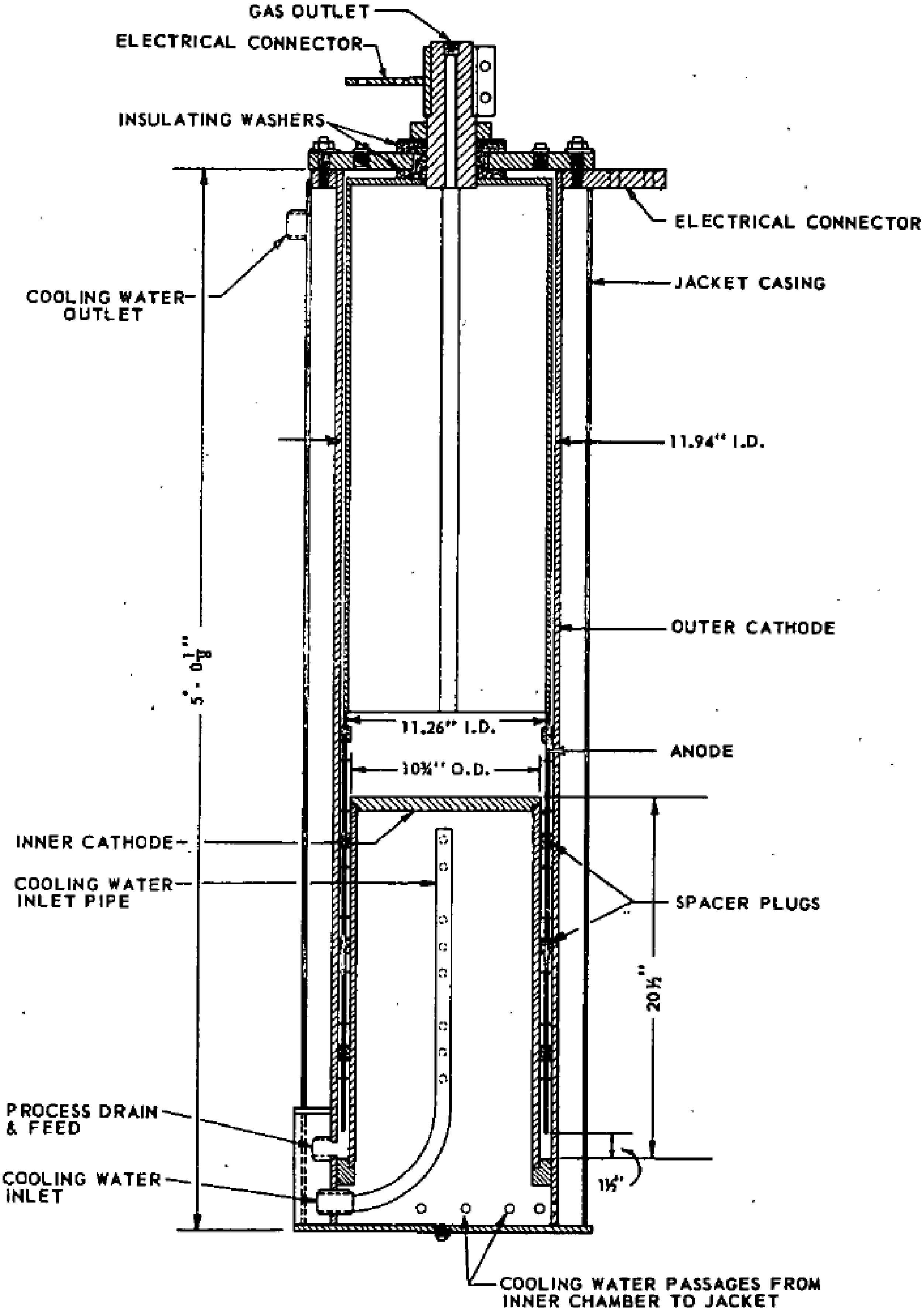
VENT AND INERT GAS BLANKET PIPING WHICH IS PROVIDED FOR ALL TANKS.

VENT CONDENSERS

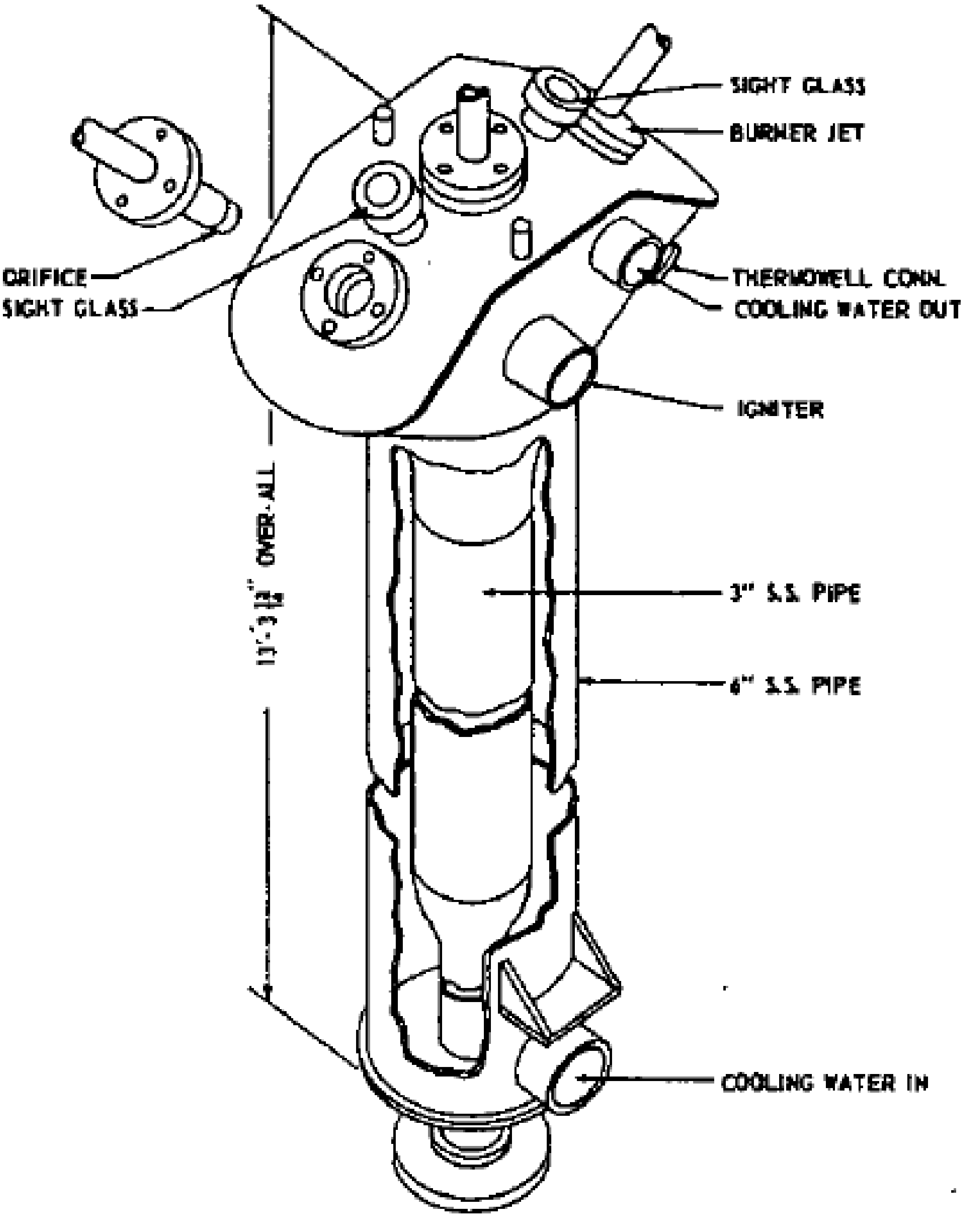
SEAL OVERFLOW AND VENT CONDENSATE COLLECTION SYSTEM.

CERTAIN PROCESS LIQUID BYPASS & RECIRCULATION LINES.

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.

Ashes Recycling

See See NLAP-WEDC Final Report (2012-2020)

Air Liquefaction and Cryogenics – Part I: Basics

Air Liquefaction and Cryogenics – Report 1 (2021)

Part I : Basics

Last update: 30.07.2021

Author: Mariam El Rez

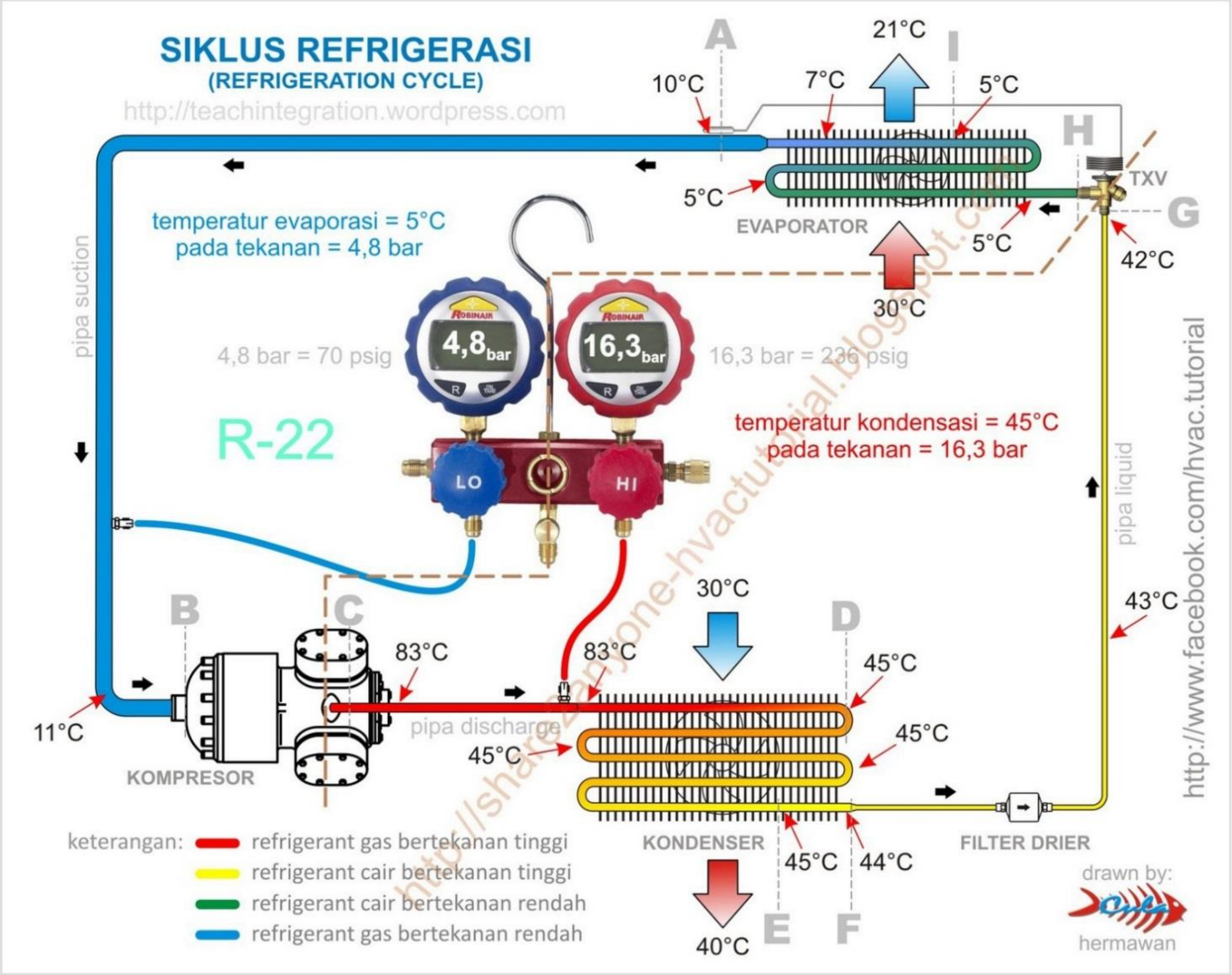
Editor: Samir Mourad

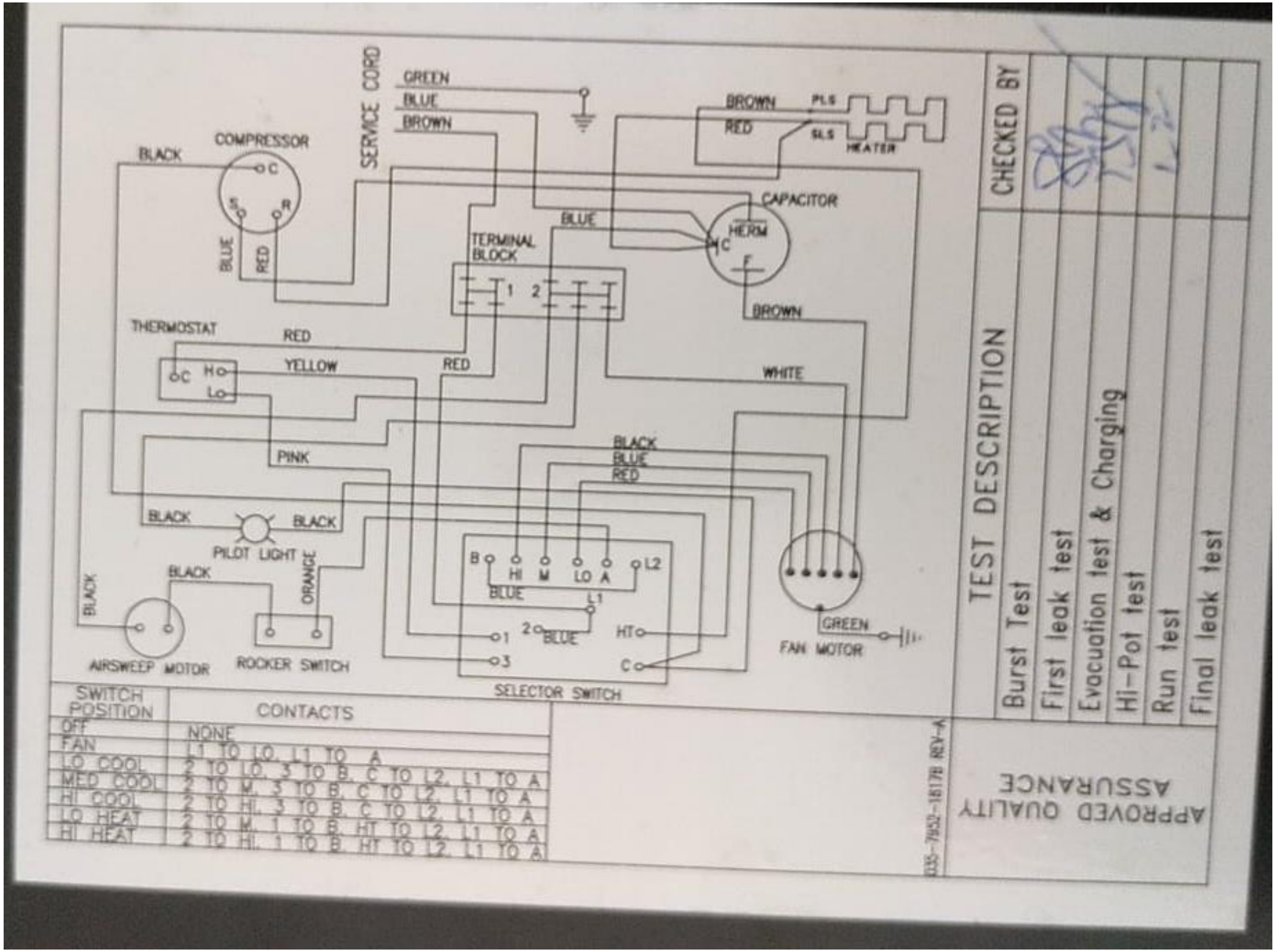
Contents

114

....115

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:
DB72201390
SASO
Made in Saudi Arabia





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	

...... 118

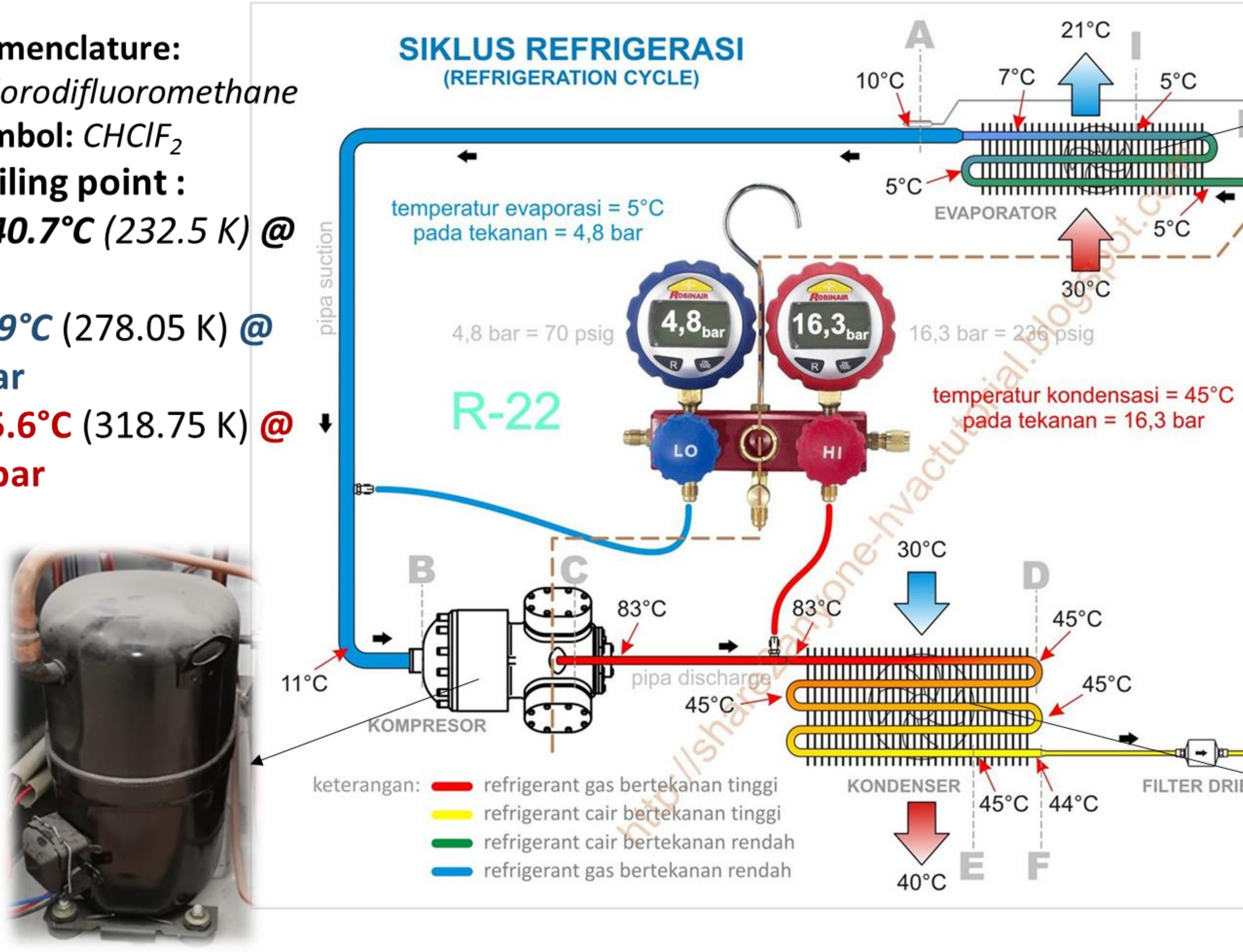
R-22

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

T= - *40.7°C* *(232.5 K)* @ *1 bar*

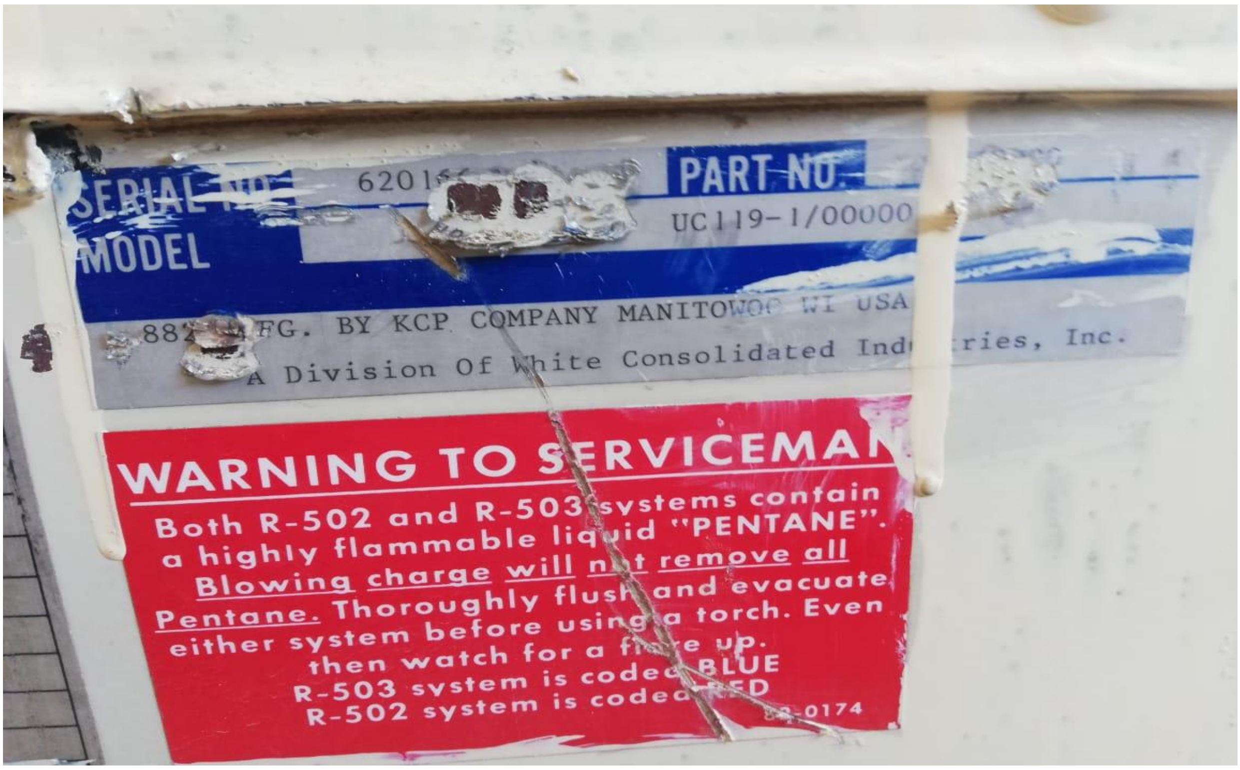
T= *4.9°C* (278.05 K) **@ 4.8 bar**

T= 45.6°C (318.75 K) **@ 16.3 bar**



		HIGH STAGE			[illegible] STAGE		
[illegible]SURE	L.S.	162			12		
	H.S.	375					
REFRIGERANT		502	9.5	OZ.	503	5	OZ.
CHARGE				OZ.			OZ.
	PENTANE	35		C.C.	35		C.C.
AMPERES	RATED LOAD						
	LOCKED ROTOR						
	FANS						
	COND. HTR.						
	TOTAL CAB.	12					
	H.P.						
	VOLTA	230					
		50					

120

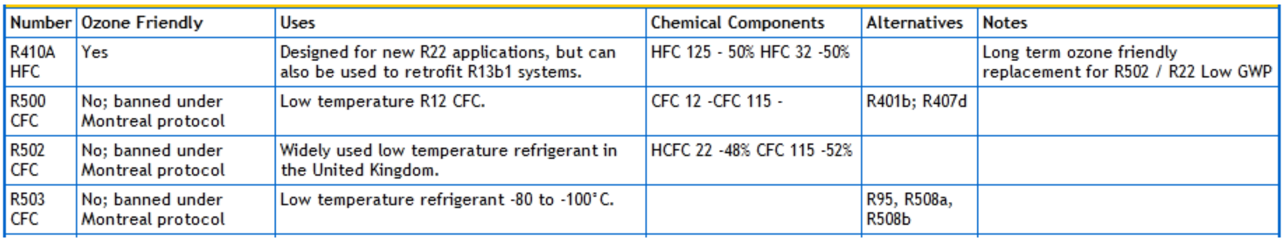


SERIAL NO. 620 1[illegible]
MODEL
PART NO. UC119-1/00000
88[illegible] FG. BY KCP COMPANY MANITOWOC WI USA
A Division Of White Consolidated Indu tries, Inc.

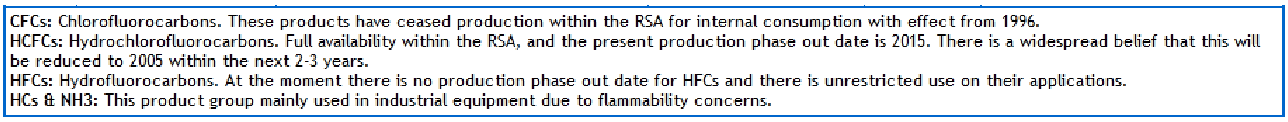
WARNING TO SERVICEMAN

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
88-0174

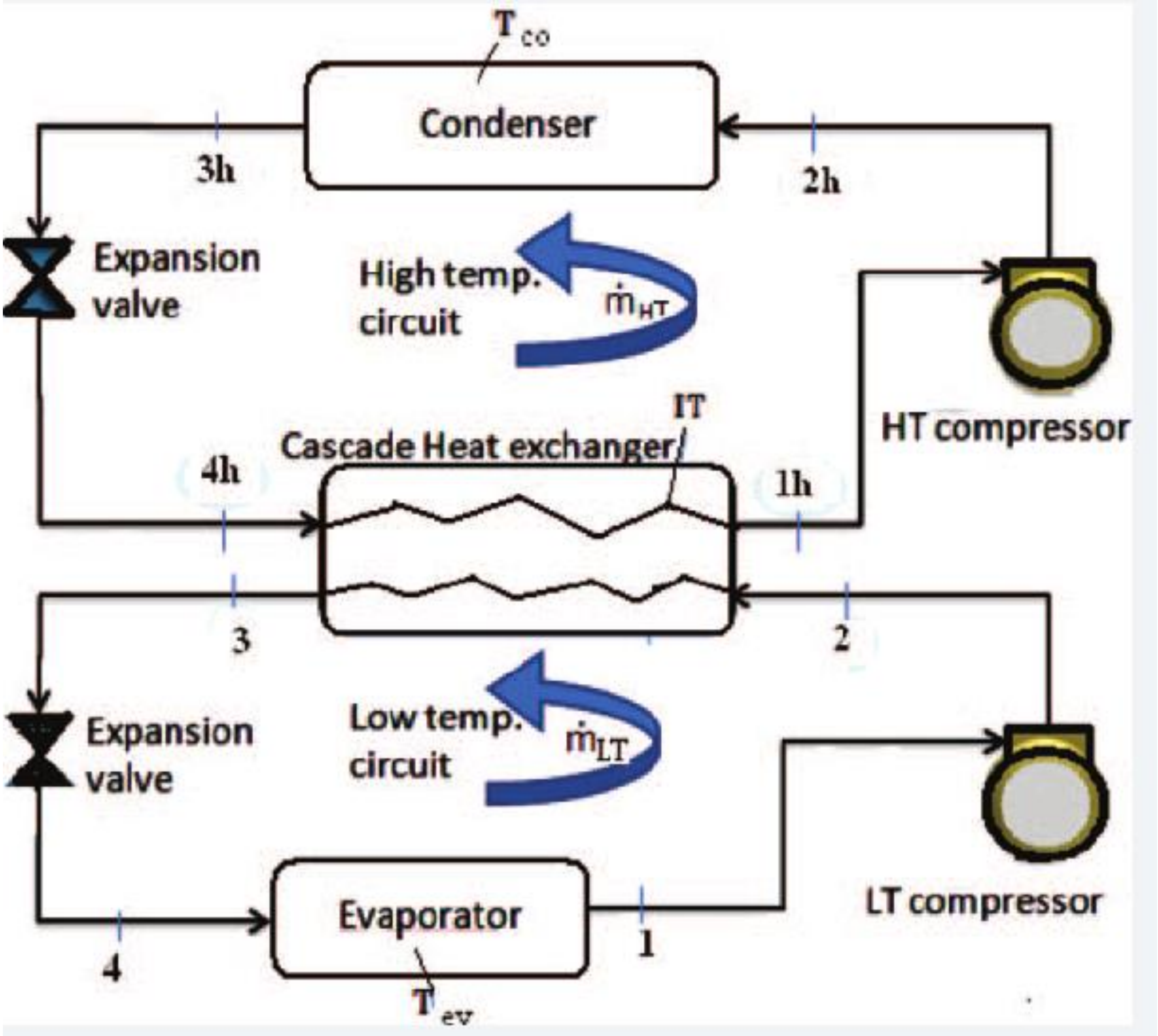
121



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.


T co
Condenser
3h
2h
Expansion valve
High temp. circuit
ṁHT
HT compressor
IT
Cascade Heat exchanger
4h
1h
3
2
Expansion valve
Low temp. circuit
ṁLT
LT compressor
Evaporator
4
1
T ev

122

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**

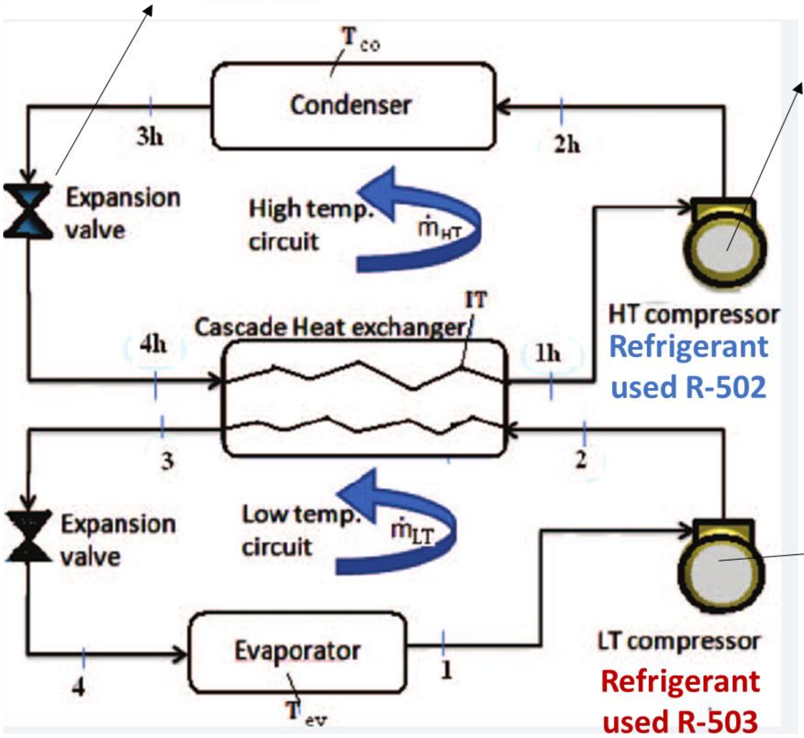
T= 61.5°*C* (334.7 K) **@ 25.85 bar**

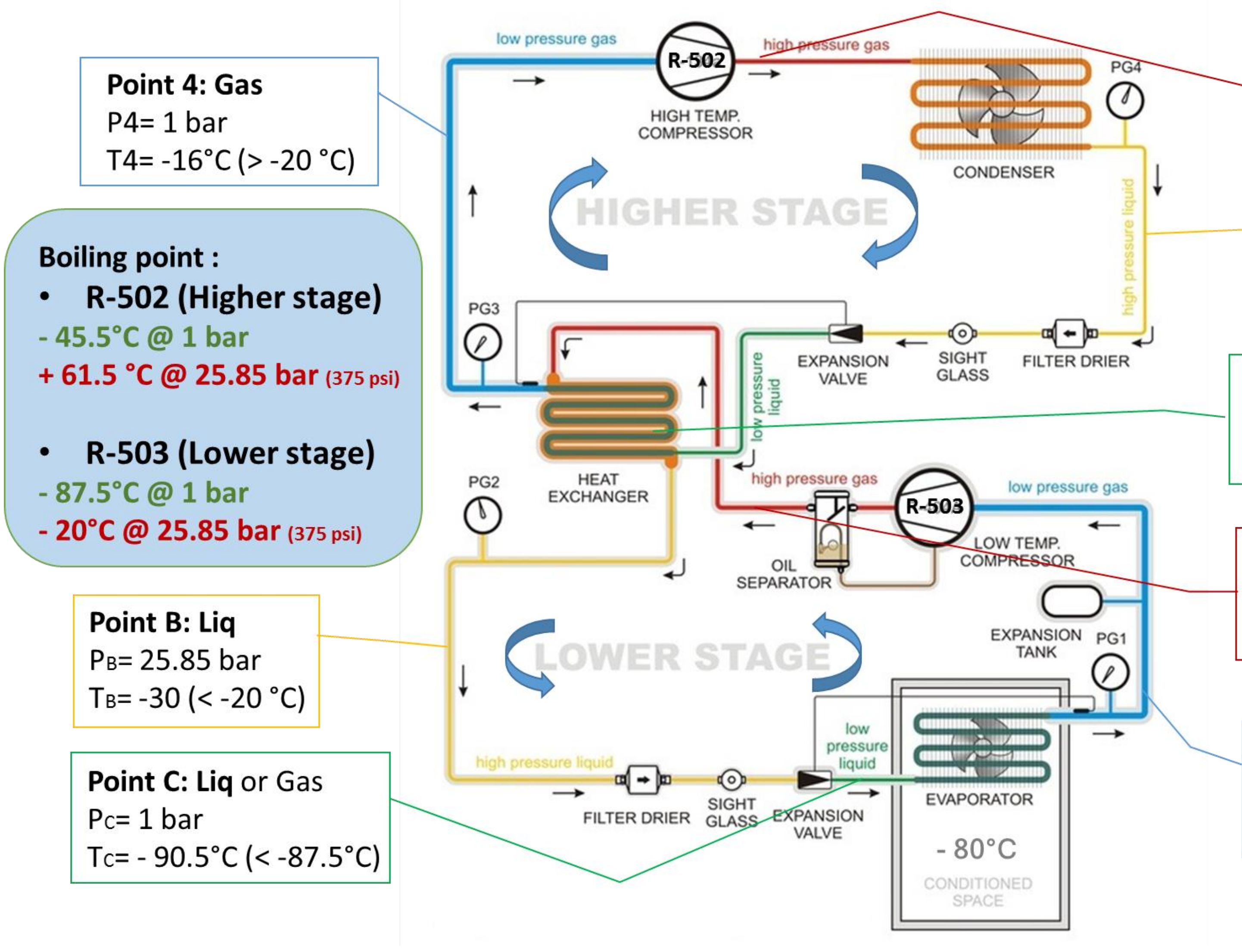
R-503 (Low stage)

- **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**





Point 4: Gas
P_4= 1 bar
T_4= -16°C (> -20 °C)

Boiling point :

- **R-502 (Higher stage)**

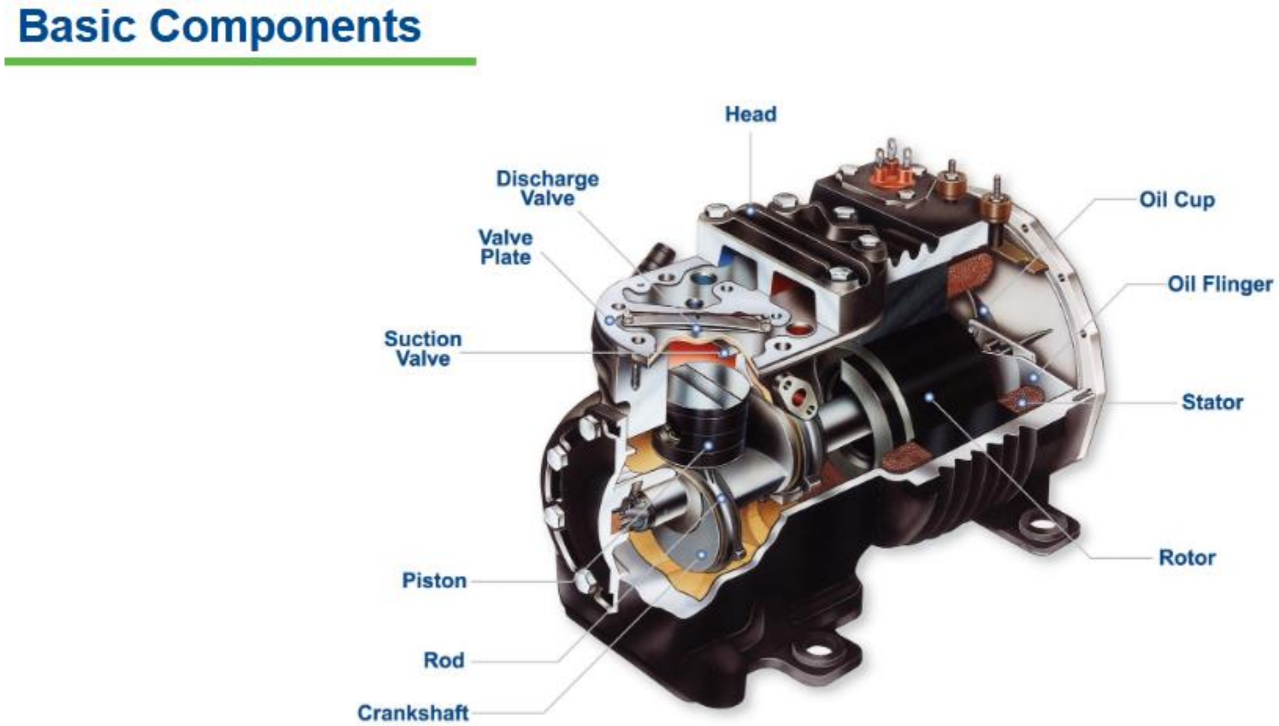
- 45.5°C @ 1 bar
+ 61.5 °C @ 25.85 bar (375 psi)

- **R-503 (Lower stage)**

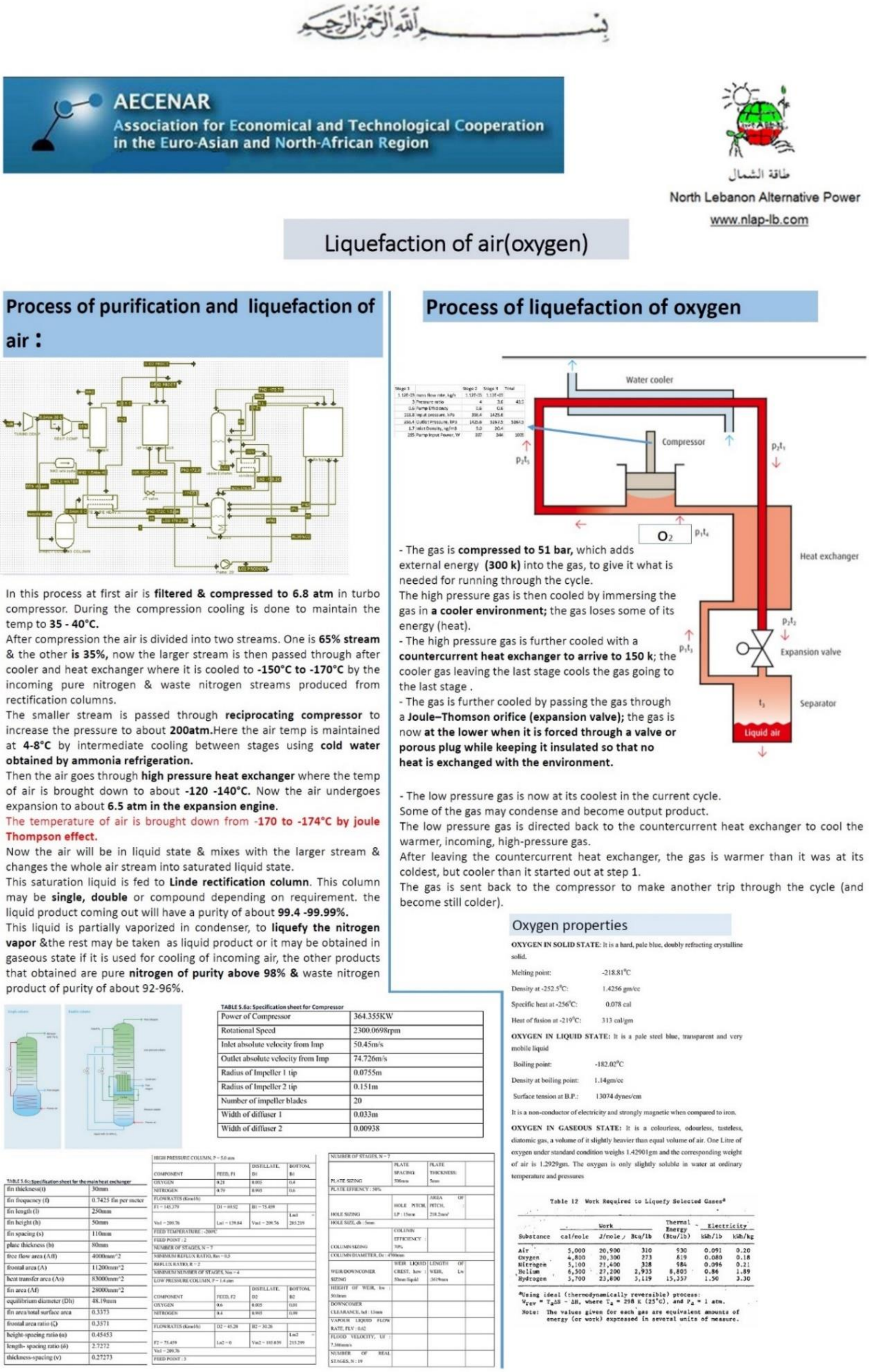
- 87.5°C @ 1 bar
- 20°C @ 25.85 bar (375 psi)

Point B: Liq
P_B= 25.85 bar
T_B= -30 (< -20 °C)

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


Basic Components
Head
Discharge Valve
Valve Plate
Suction Valve
Piston
Rod
Crankshaft
Oil Cup
Oil Flinger
Stator
Rotor

4 Starting point December 2020 (Work of Maysaa Kamareddine 2019)



بسم الله الرحمن الرحيم

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

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

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 = 45.28	B2 = 30.28	
F2 = 75.459	Ln2 = 0	Vm2 = [illegible]	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 : 7.300mm/s			
NUMBER OF REAL STAGES, N : 19			

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 12 Work Required to Liquefy Selected Gases[a]

	Work			Thermal Energy	Electricity	
Substance	cal/mole	J/mole	Btu/lb	(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.

---

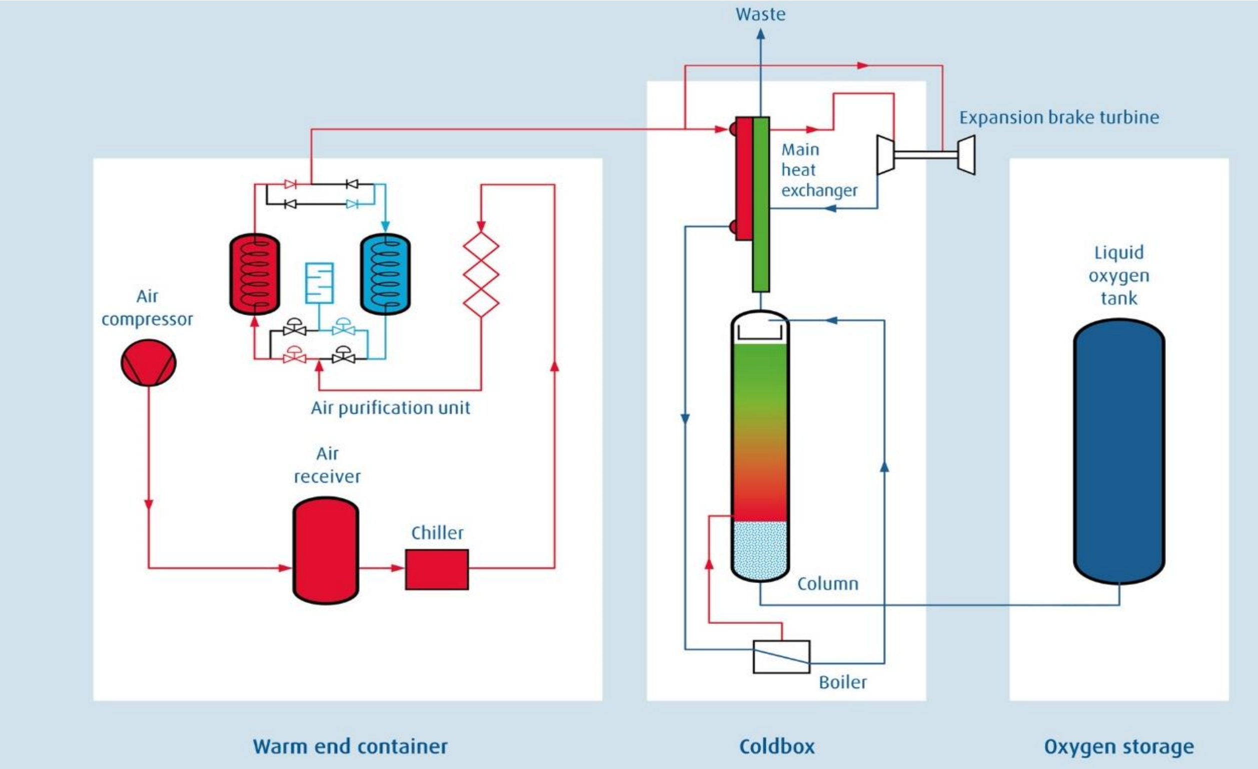
5 Cryogenic air plant principle

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.

5.1 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

5.2 Plant modules

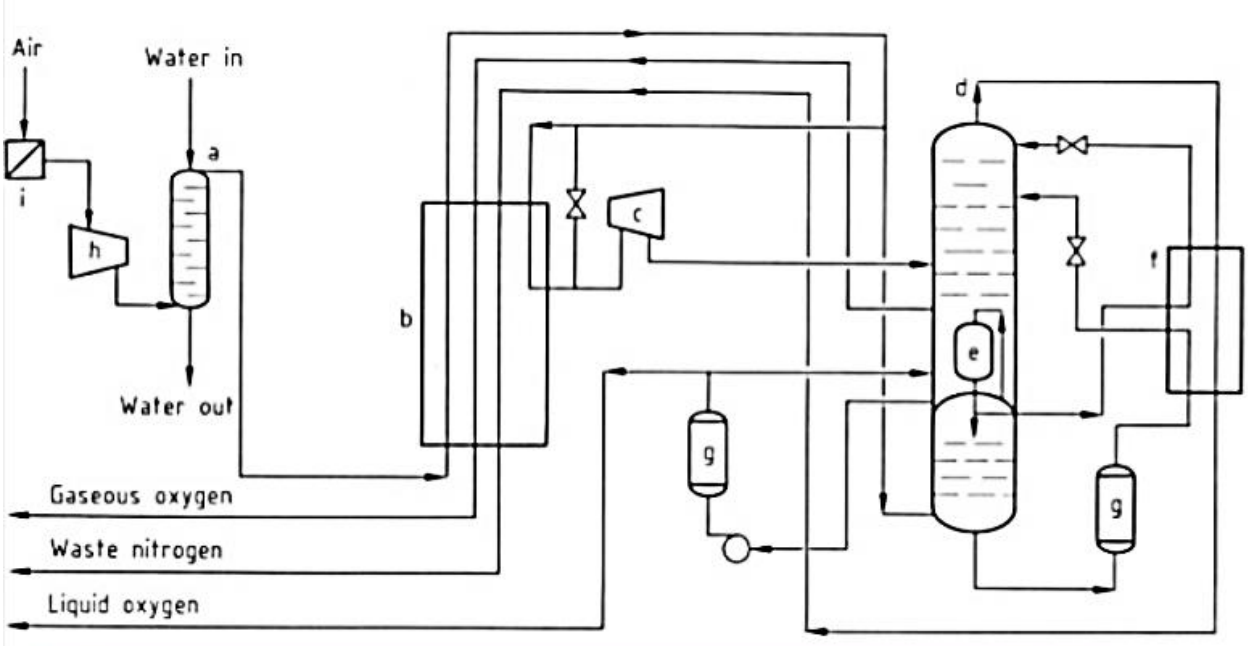


A cryogenic air plant comprises:

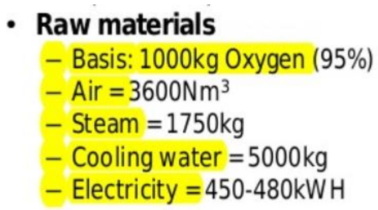
- Warm end (W/E) container
    - Compressor
    - Air receiver
    - Chiller (Heat exchanger)
    - Pre-filter
    - Air purification unit (APU)
- Coldbox
    - Main heat exchanger
    - Boiler
    - Distillation column

  - Expansion brake turbine
- Storage
  - Liquid oxygen tank
  - Vaporizer
  - Filling station

5.2.1 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

5.3 Linde’s Method of liquefaction of gases.[1]

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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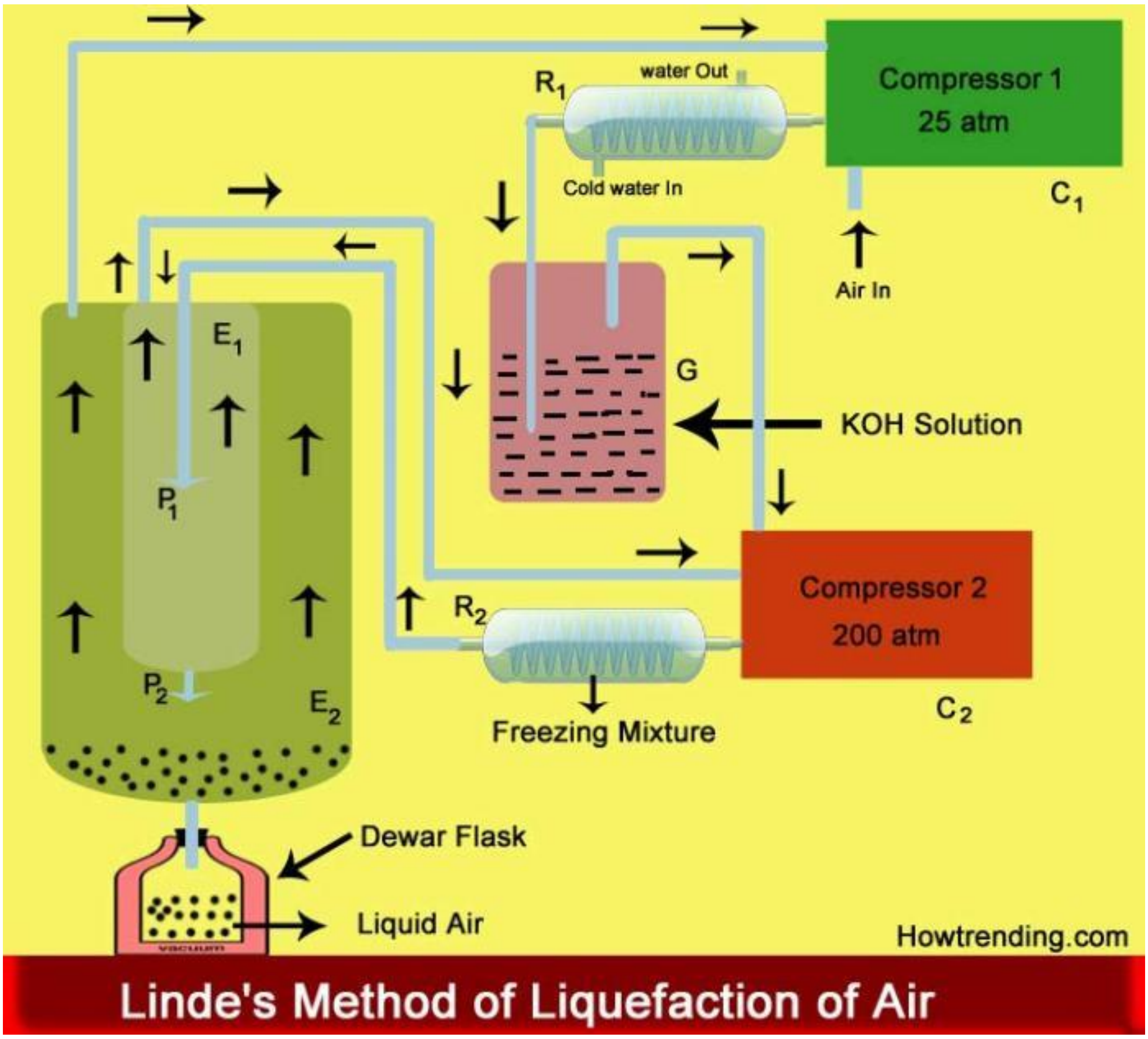
[1] https://www.howtrending.com/liquefaction-of-gases/



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.

5.3.1 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.

Cryogenic air plant principle

5.3.2 Principle

Linde's process of liquefaction is work on the principle of the **Joule Thomson effect** coupled with **regenerative cooling**.

5.3.3 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.

5.4 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.

4

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.

Cryogenic air plant principle

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

6

6 Large Scale Factory study

6.1 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 $	**حسب موقع alibaba.com**
	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			

6.2 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*

6.3 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			

6.4 Costs of modules

6.4.1 Air receiver tank

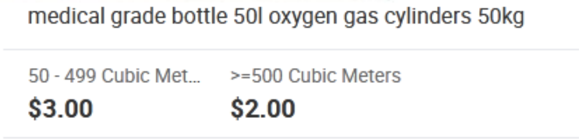
Air Receiver Tank 0.8Mpa 1.0Mpa 1.3Mpa 1.6Mpa 2.5Mpa 3.0Mpa 4.0Mpa 6.0Mpa

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)

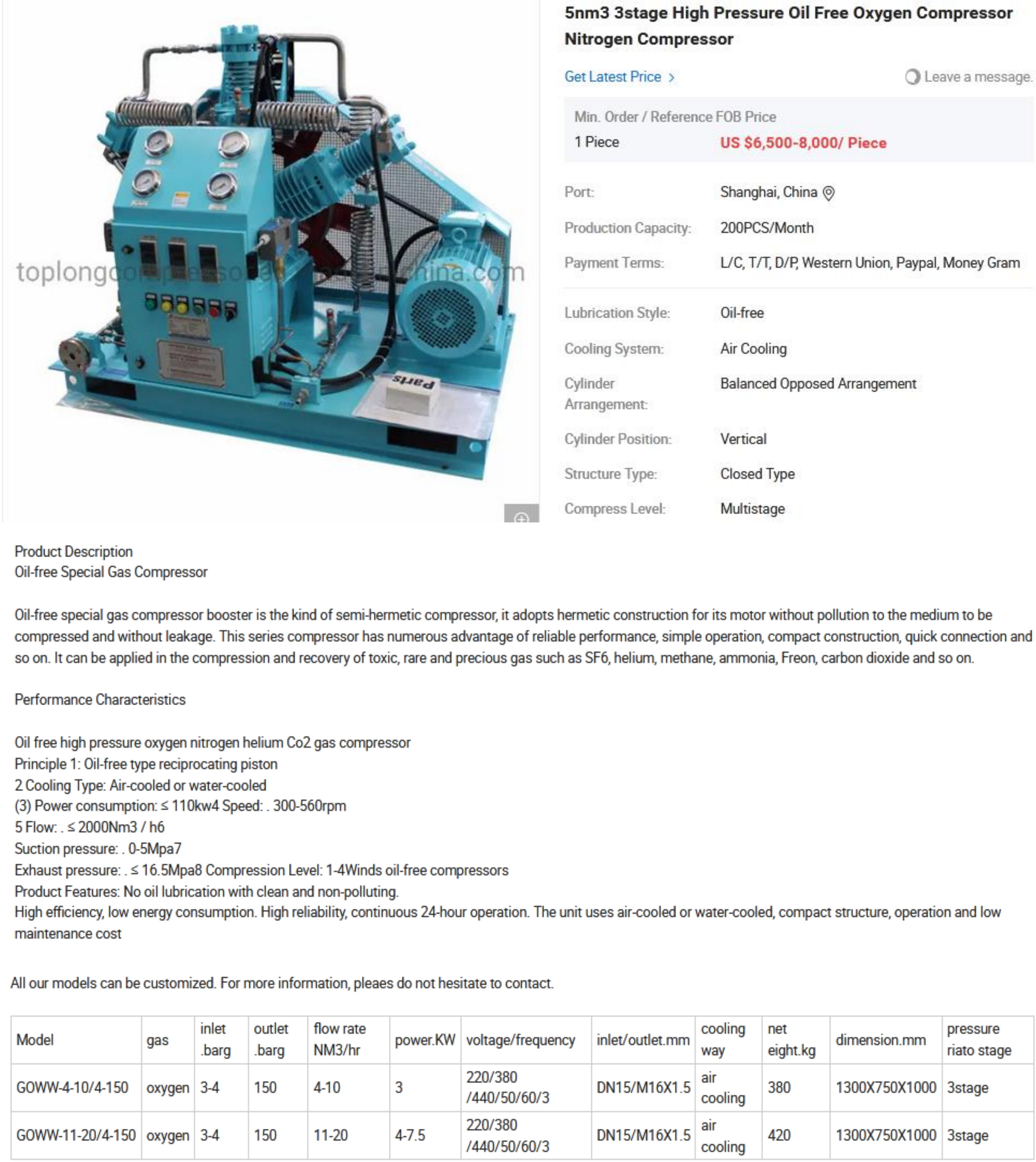
Guangzhou Jielv Environment Technology Co., Ltd. > CN 3 YRS

93.9% Taux de réponse US $440,000+ in 81 Transaction (s)

6.4.2 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

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

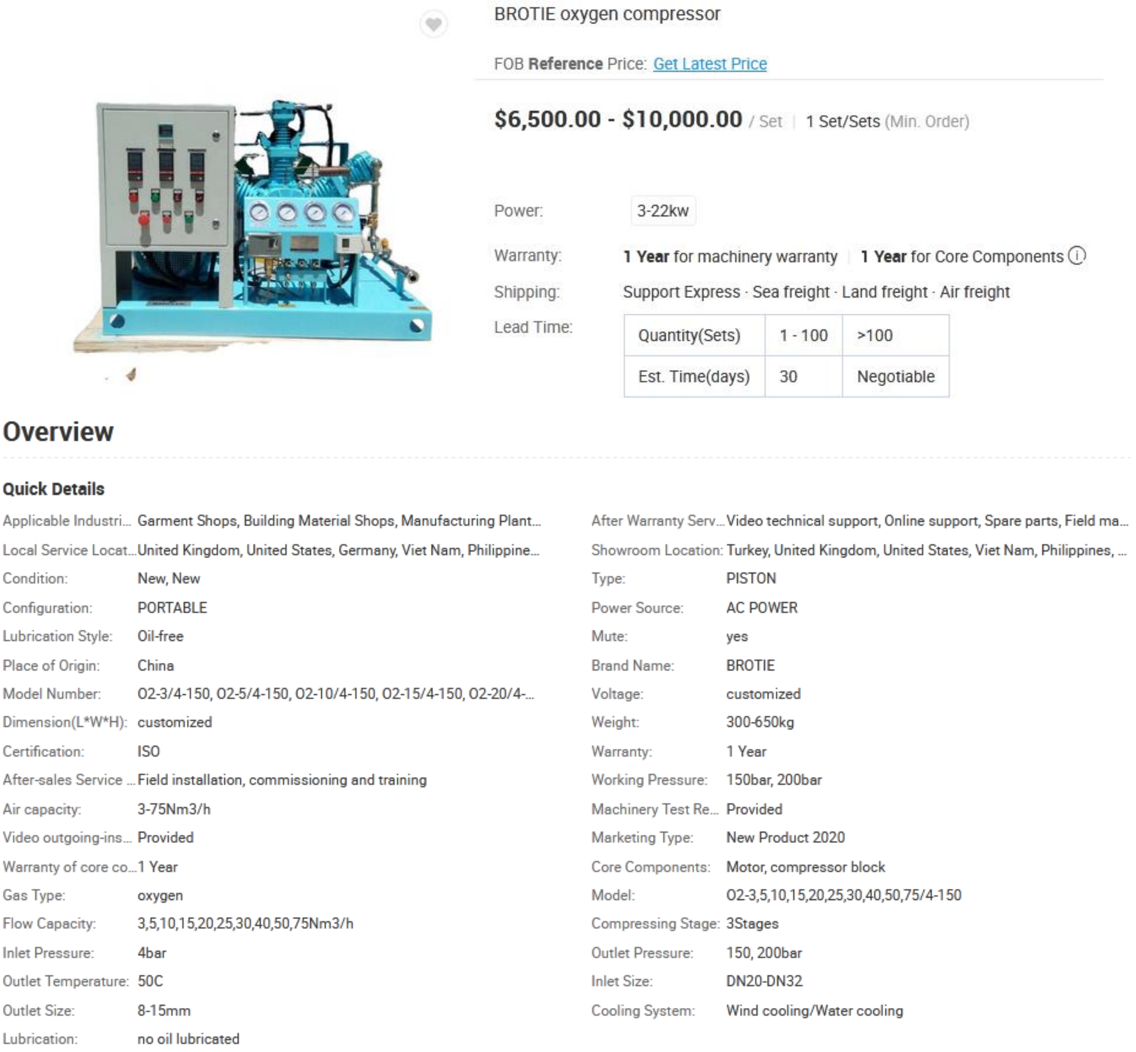
All our models can be customized. For more information, pleaes do not hesitate to contact.

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:

Large Scale Factory study

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:	

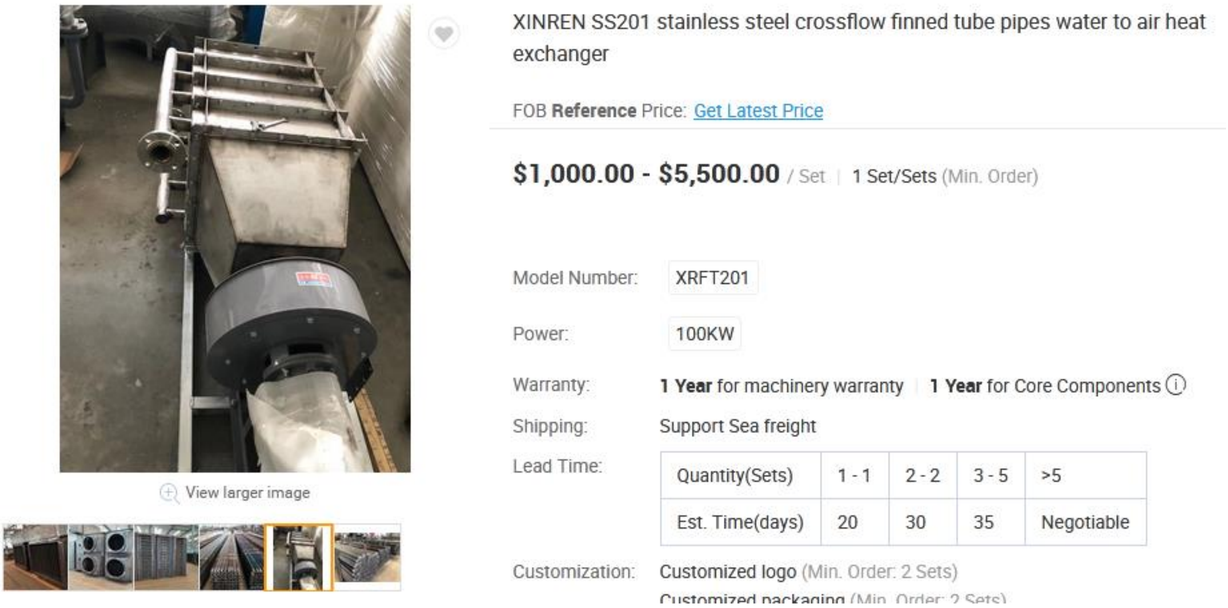
Quantity(Sets)	1 - 100	>100
Est. Time(days)	30	Negotiable

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		

6.4.3 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

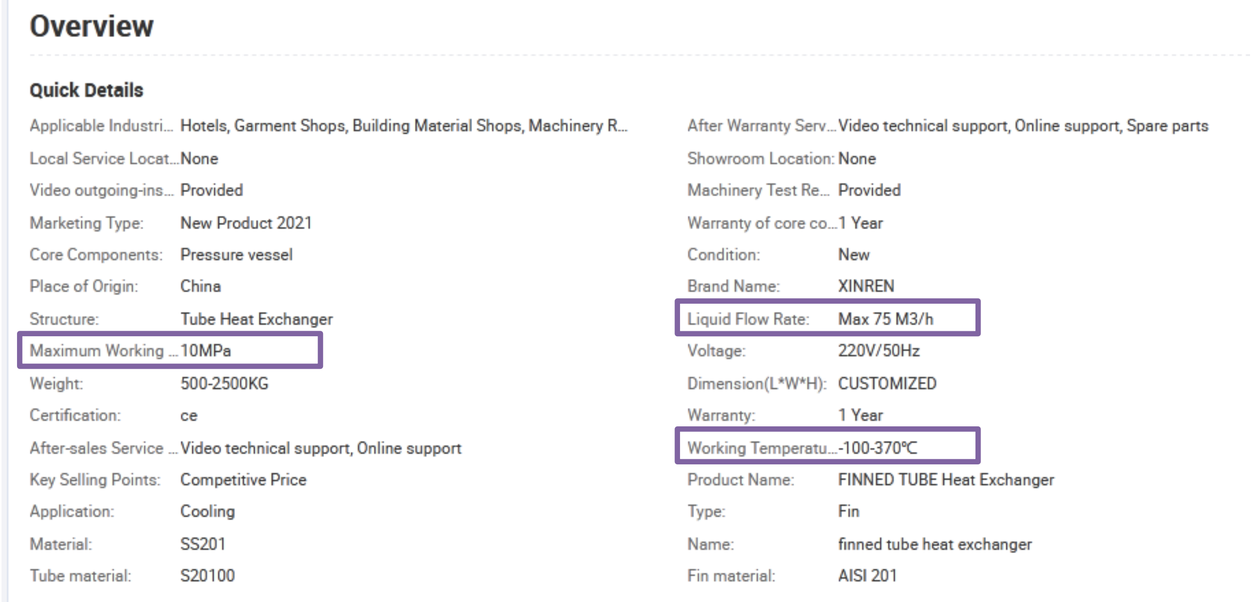
Warranty: **1 Year** for machinery warranty | **1 Year** for Core Components

Shipping: Support Sea freight

Lead Time:

Quantity(Sets)	1 - 1	2 - 2	3 - 5	>5
Est. Time(days)	20	30	35	Negotiable

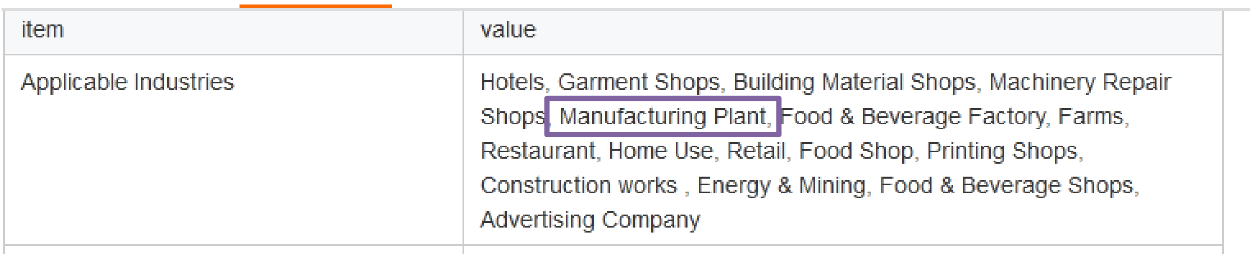
Customization: Customized logo (Min. Order: 2 Sets)
Customized packaging (Min. Order: 2 Sets)



Overview

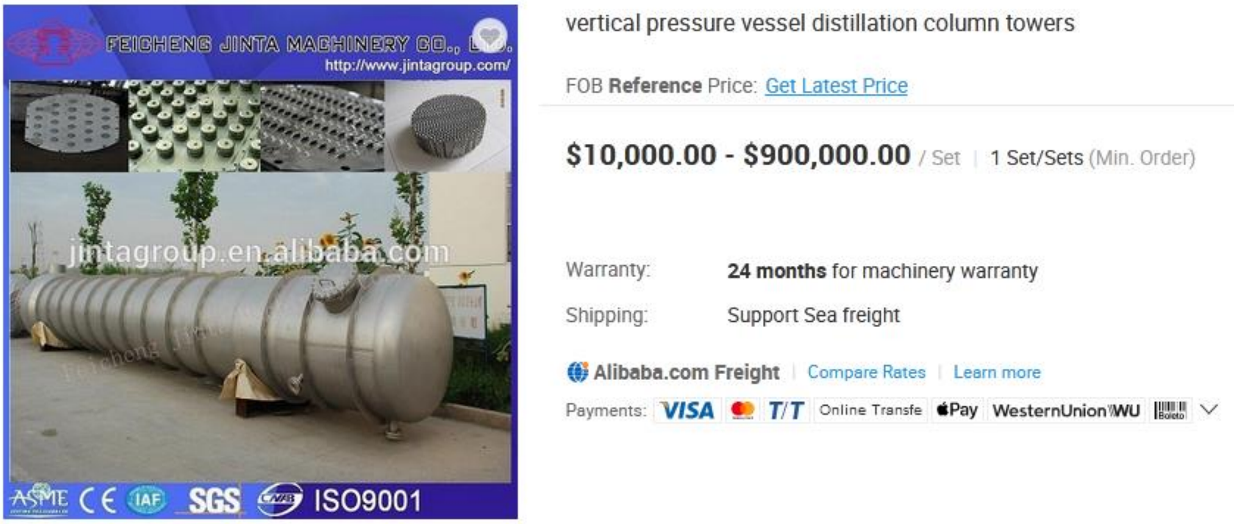
Quick Details

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

6.4.4 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)

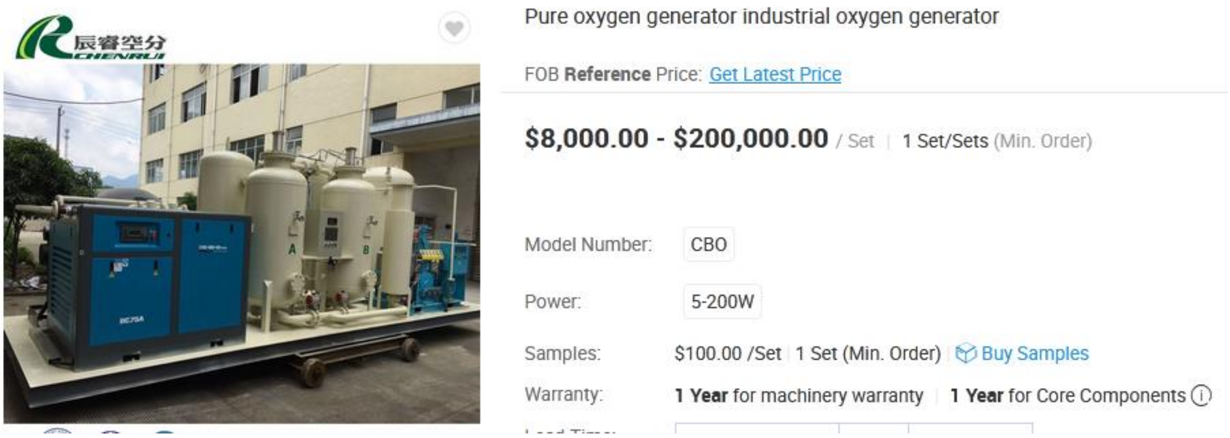
Warranty: **24 months** for machinery warranty

Shipping: Support Sea freight

Alibaba.com Freight | Compare Rates | Learn more

Payments: VISA T/T Online Transfe Pay WesternUnion WU

6.4.5 Industrial oxygen generator (whole system)



Pure oxygen generator industrial oxygen generator

FOB **Reference** Price: Get Latest Price

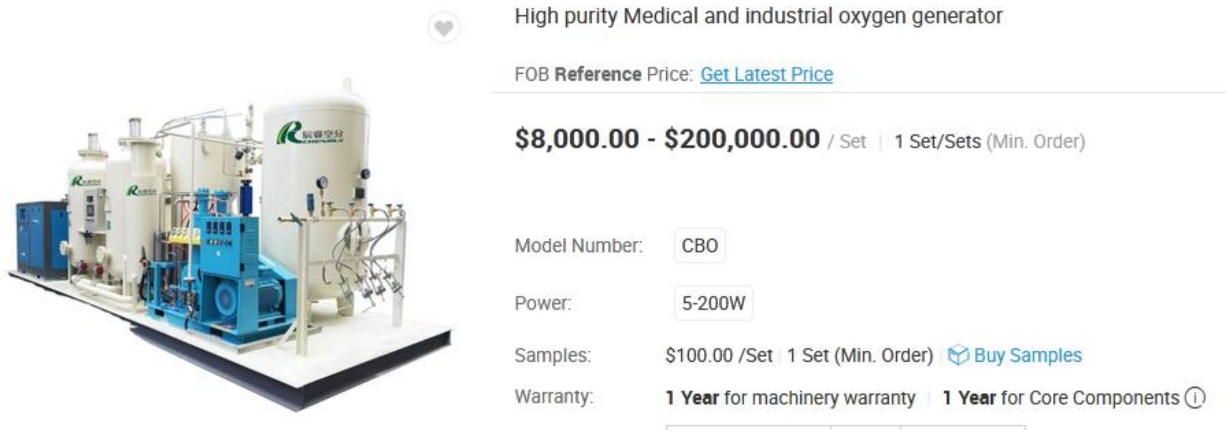
$8,000.00 - $200,000.00 / Set | 1 Set/Sets (Min. Order)

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

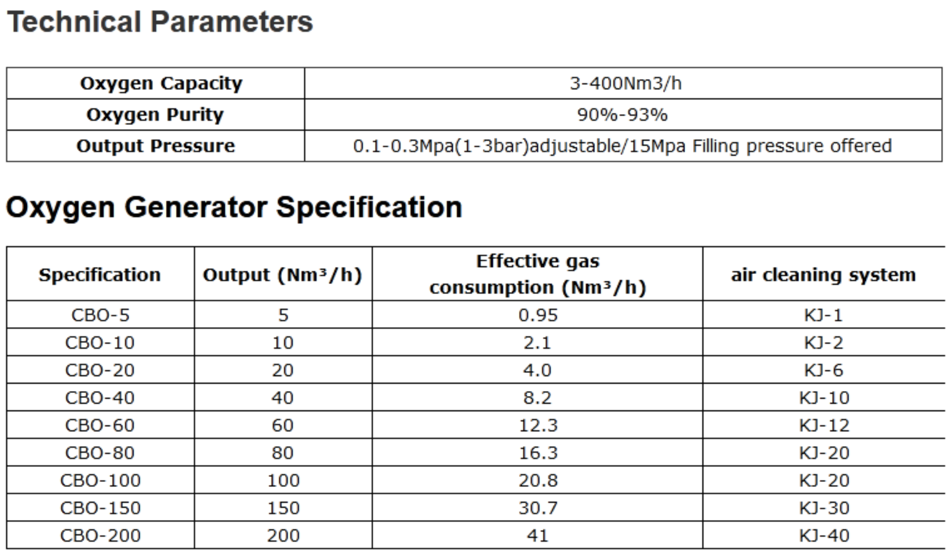
$8,000.00 - $200,000.00 / Set | 1 Set/Sets (Min. Order)

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



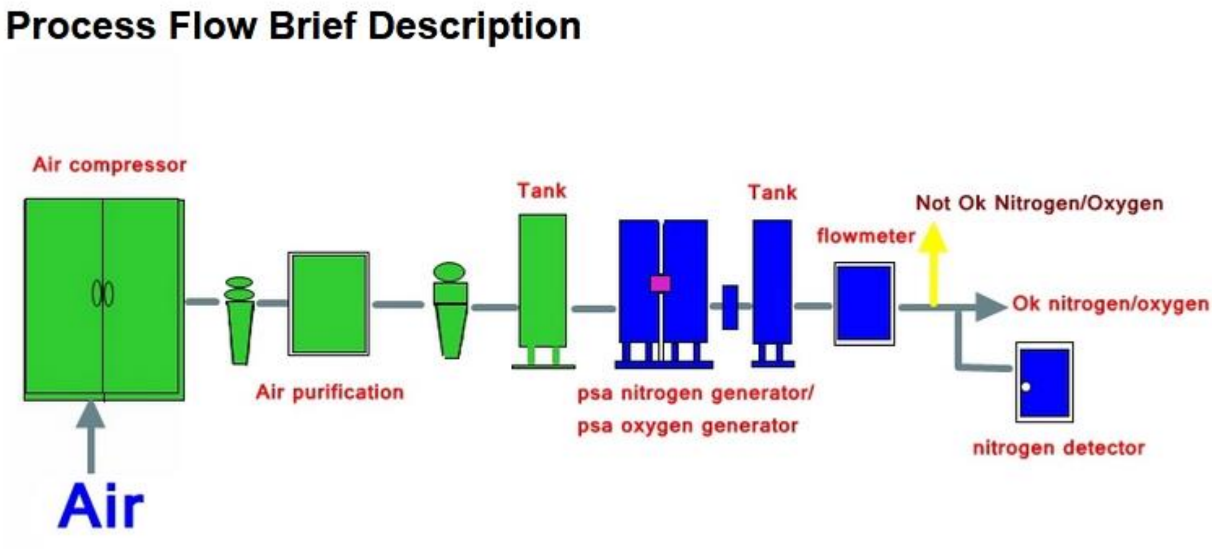
Technical Parameters

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 (Nm^3/h)	Effective gas consumption (Nm^3/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

7 Process Flow Brief Description



7.1 ملخص_الهواء في حالة سائلة

7.2 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 K 90.17، 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 [2] .

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[3] .

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[2] World Encyclopedia

[3] Encyclopedia Mypedia

8 توليد النيتروجين (N2) باستخدام تقنية الامتزاز بالضغط المتأرجح (PSA)

https://www.atlascopco.com/ar-eg/compressors/wiki/compressed-air-articles/what-is-nitrogen

8.1 توليد النيتروجين باستخدام تقنية الأغشية

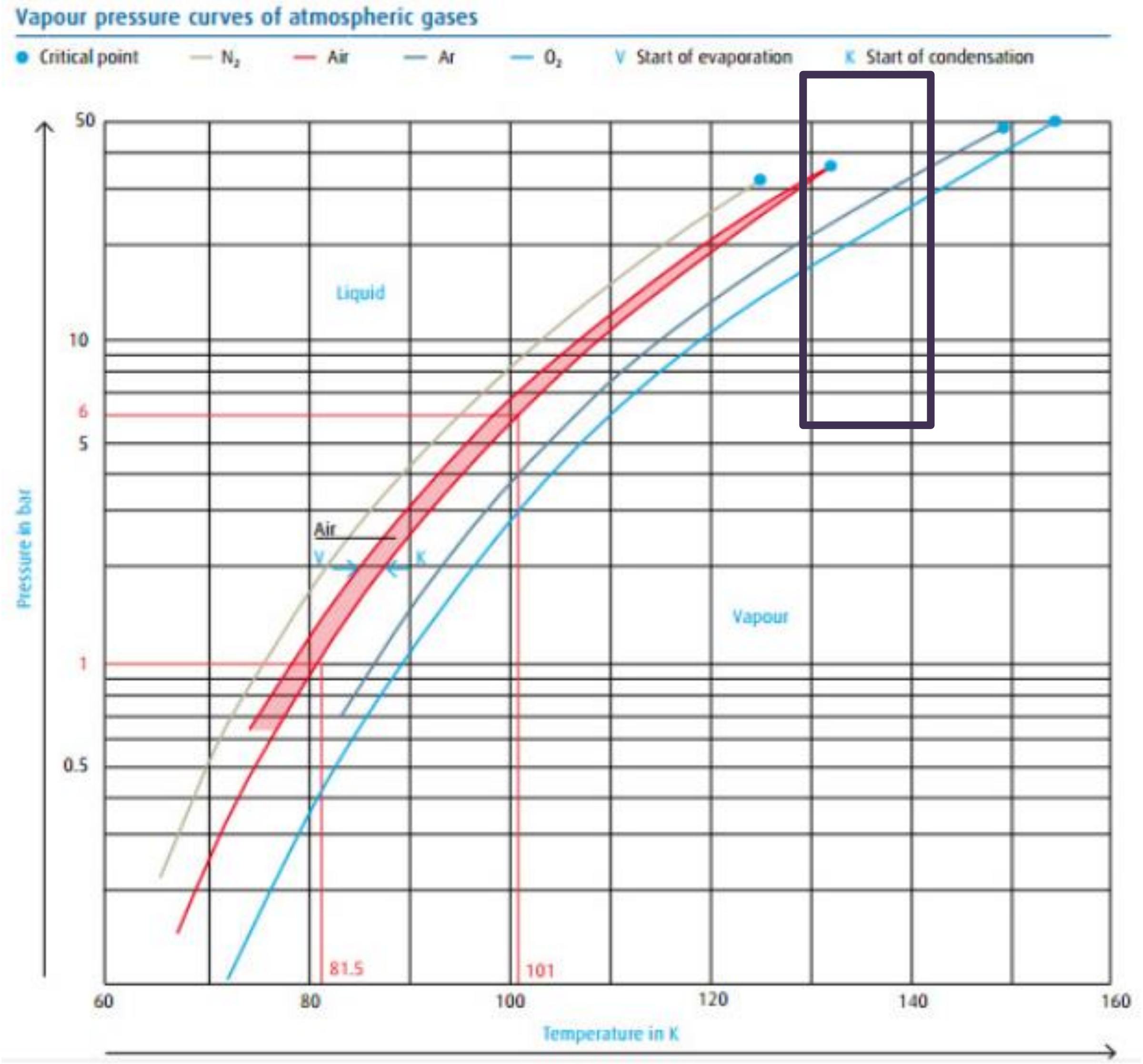
https://www.atlascopco.com/ar-eg/compressors/wiki/compressed-air-articles/generating-nitrogen-membrane

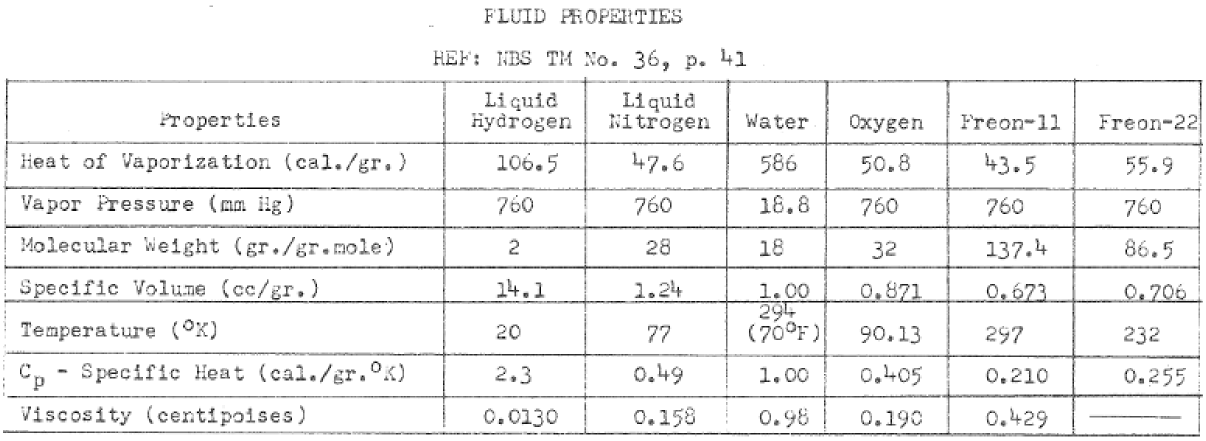
	غشائي	الامتزاز بالضغط المتأرجح (PSA)
النقاء الذي يمكن تحقيقه	كفاءة تصل إلى 99.9%	كفاءة تصل إلى 99.999%
الكفاءة	عالية	أعلى
الأداء مقابل درجة الحرارة	أعلى عند درجة الحرارة المرتفعة*	أقل عند درجة الحرارة المرتفعة
تعقيد النظام	منخفض	متوسط
كثافة الصيانة	منخفضة للغاية	منخفض
استقرار الضغط	ثابت	دخل/خرج متقلب
استقرار التدفق	ثابت	دخل/خرج متقلب
سرعة بدء التشغيل	ثوانٍ	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

9 Parameters of Liquefaction of Oxygen

9.1 Properties of Oxygen

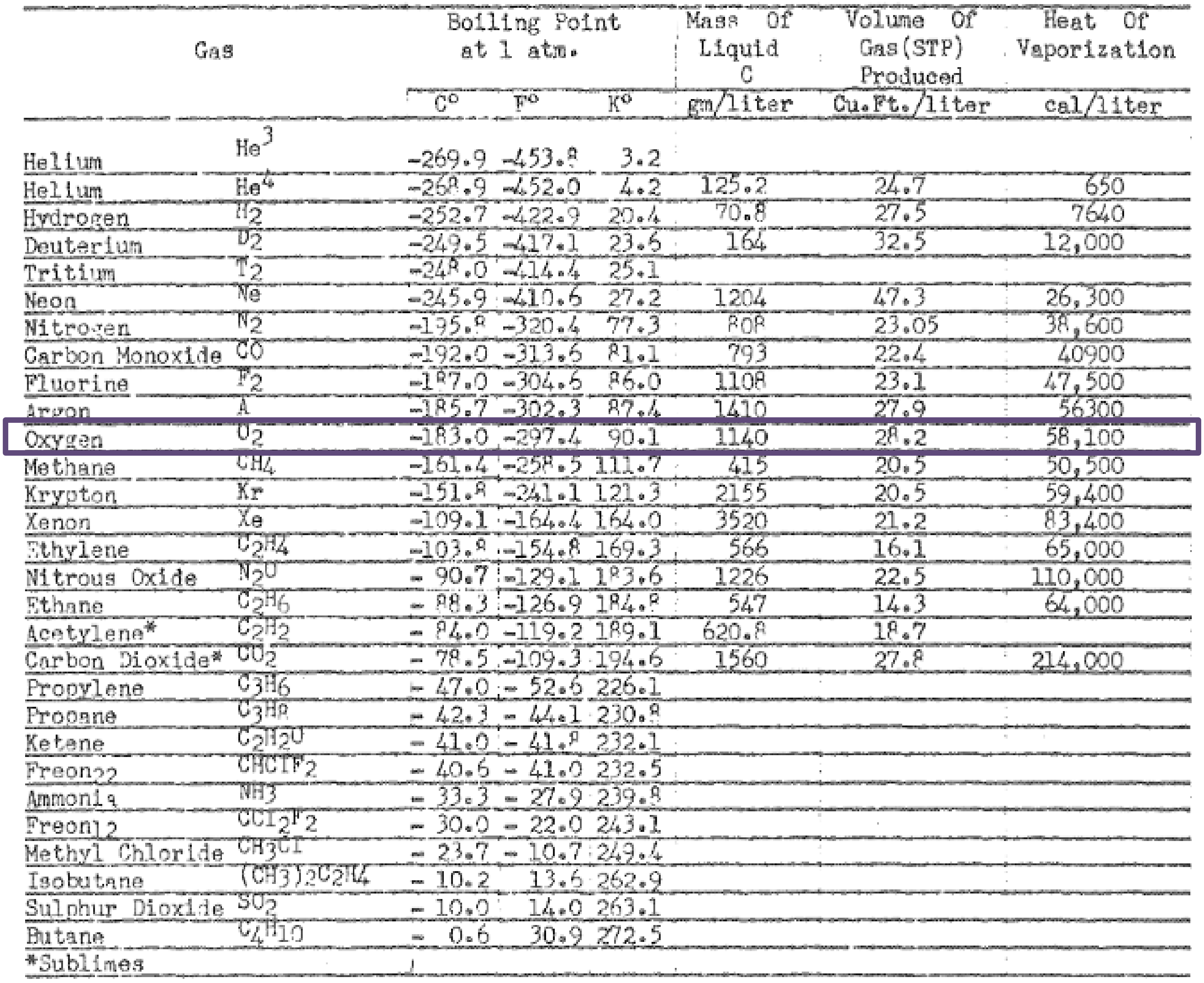



FLUID PROPERTIES

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	———

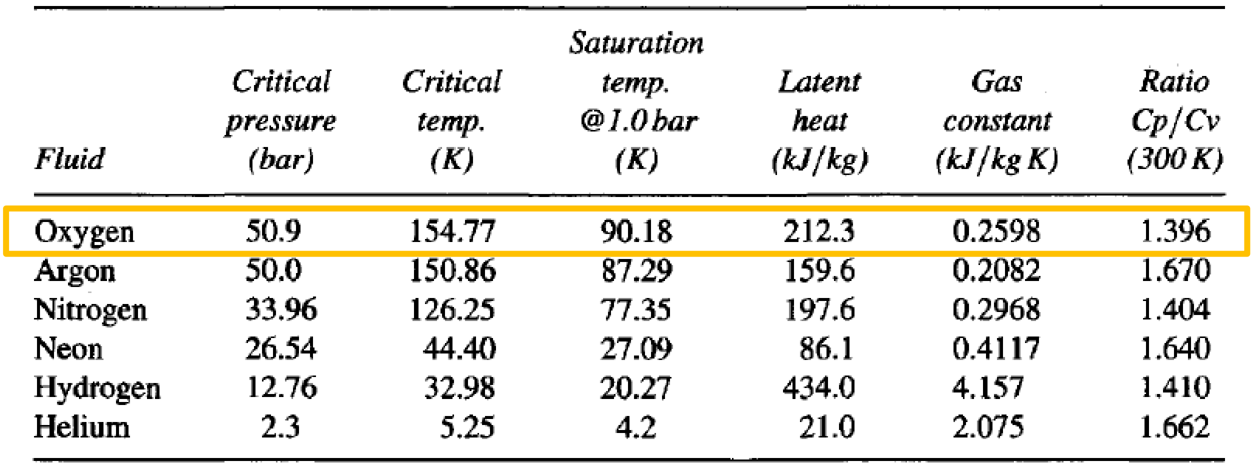
BOILING POINTS OF GASES



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

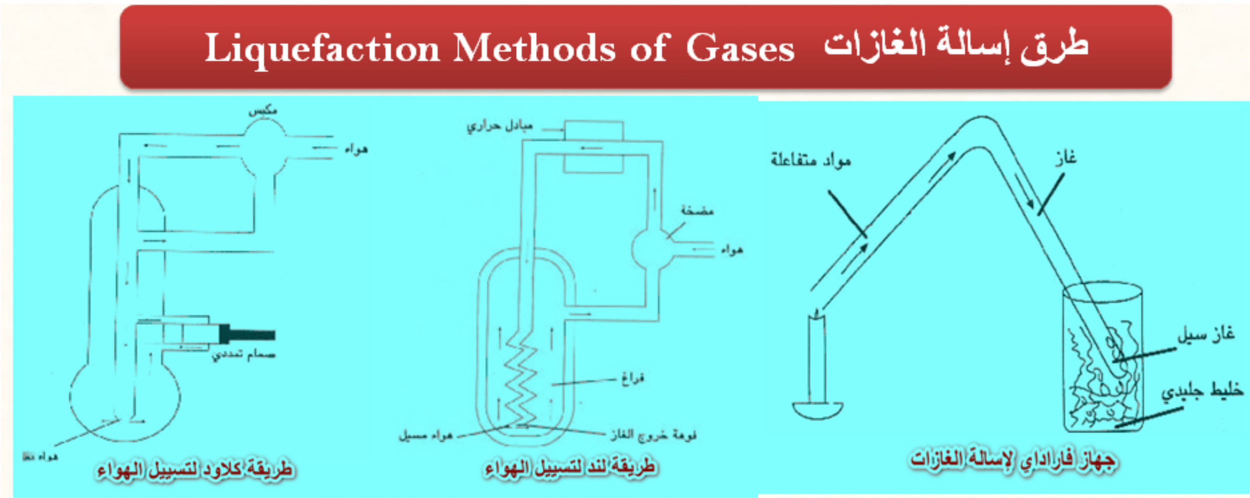


Fluid	*Critical pressure (bar)*	*Critical temp. (K)*	*Saturation temp. @1.0 bar (K)*	*Latent heat (kJ/kg)*	*Gas constant (kJ/kg K)*	*Ratio Cp/Cv (300 K)*
Oxygen	50.9	154.77	90.18	212.3	0.2598	1.396
Argon	50.0	150.86	87.29	159.6	0.2082	1.670
Nitrogen	33.96	126.25	77.35	197.6	0.2968	1.404
Neon	26.54	44.40	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

9.2 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.

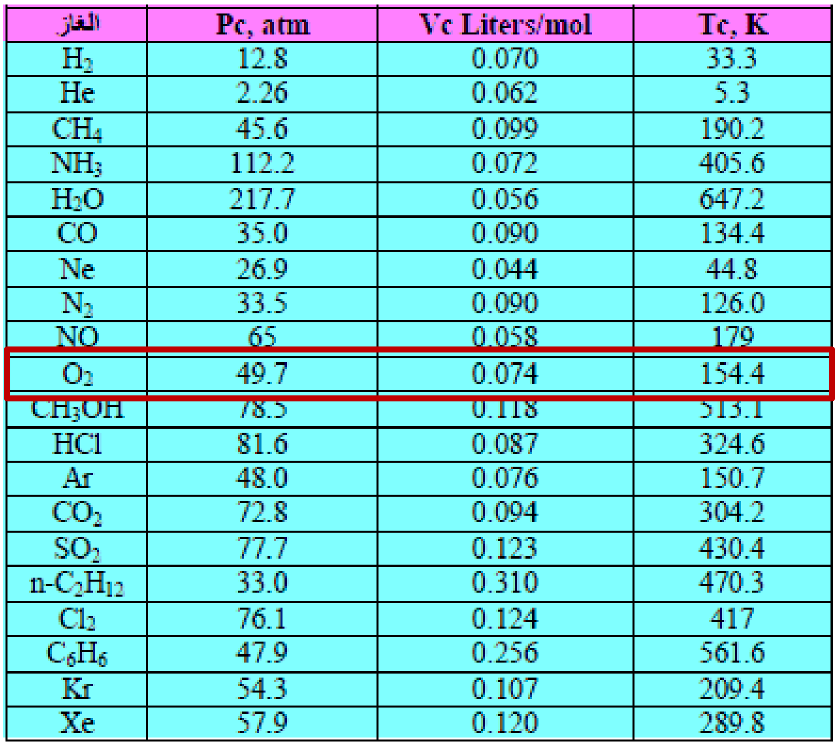
القيم الحرجة لإسالة الغازات

– 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



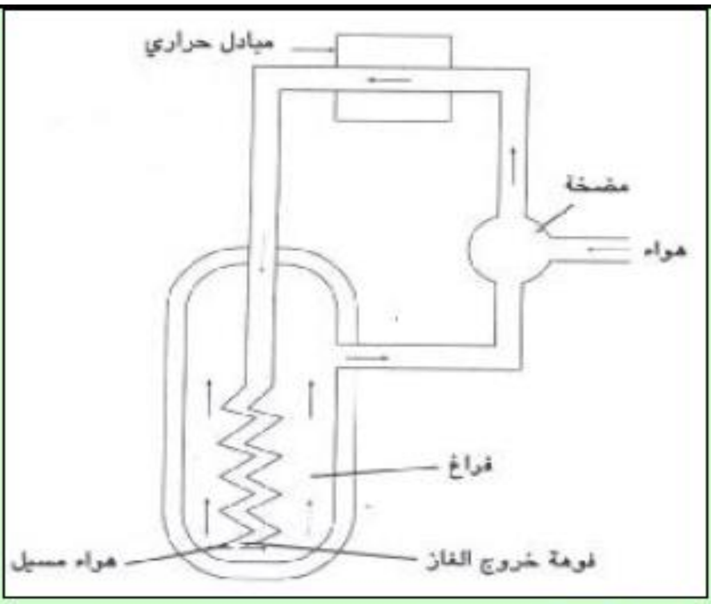
الغاز	Pc, atm	Vc Liters/mol	Tc, K
H_2	12.8	0.070	33.3
He	2.26	0.062	5.3
CH_4	45.6	0.099	190.2
NH_3	112.2	0.072	405.6
H_2O	217.7	0.056	647.2
CO	35.0	0.090	134.4
Ne	26.9	0.044	44.8
N_2	33.5	0.090	126.0
NO	65	0.058	179
O_2	49.7	0.074	154.4
CH_3OH	78.5	0.118	513.1
HCl	81.6	0.087	324.6
Ar	48.0	0.076	150.7
CO_2	72.8	0.094	304.2
SO_2	77.7	0.123	430.4
n-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

9.2.1.1 الطريقة الأولى لتسييل الغازات: طريقة ليند و هامبسون Lind-Hampson’s Method

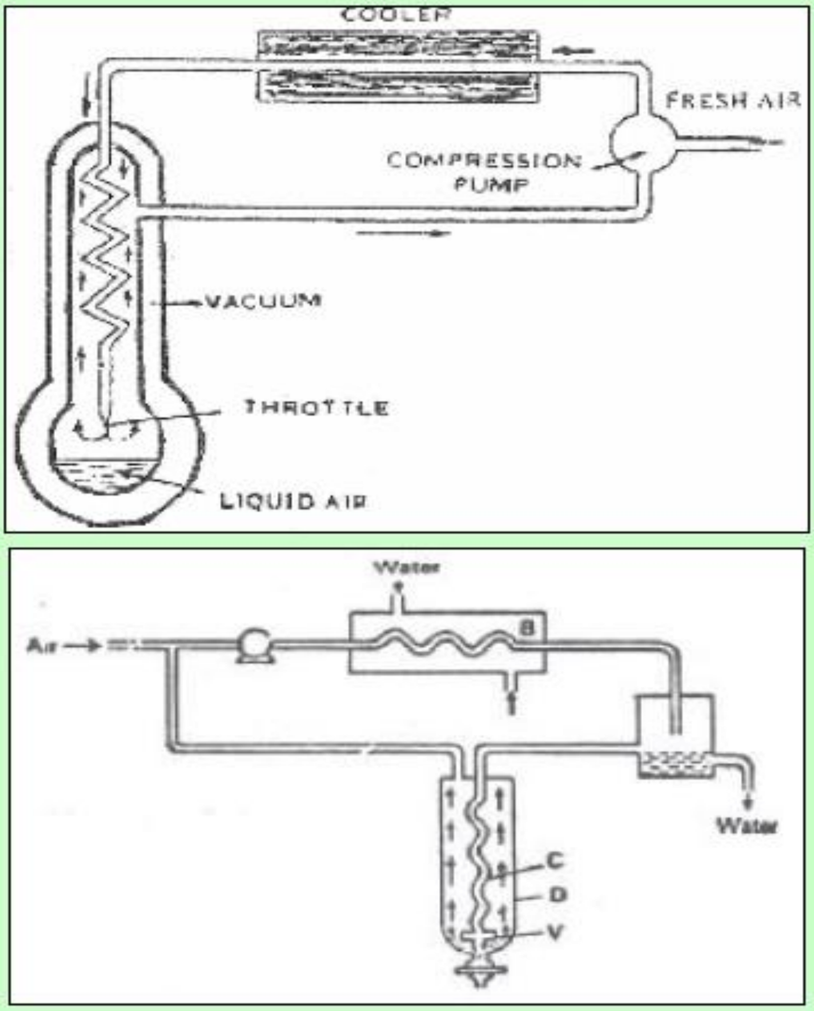
-تعتمد طريقة ليند وهامبسون على تأثير جول- طومسون والذي ينص على أنه:

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 .

9.3 خطوات العمل 4

(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 حوالي (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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[4] https://learnchemistry12.com/2019/02/liquefaction-methods-of-gases.html

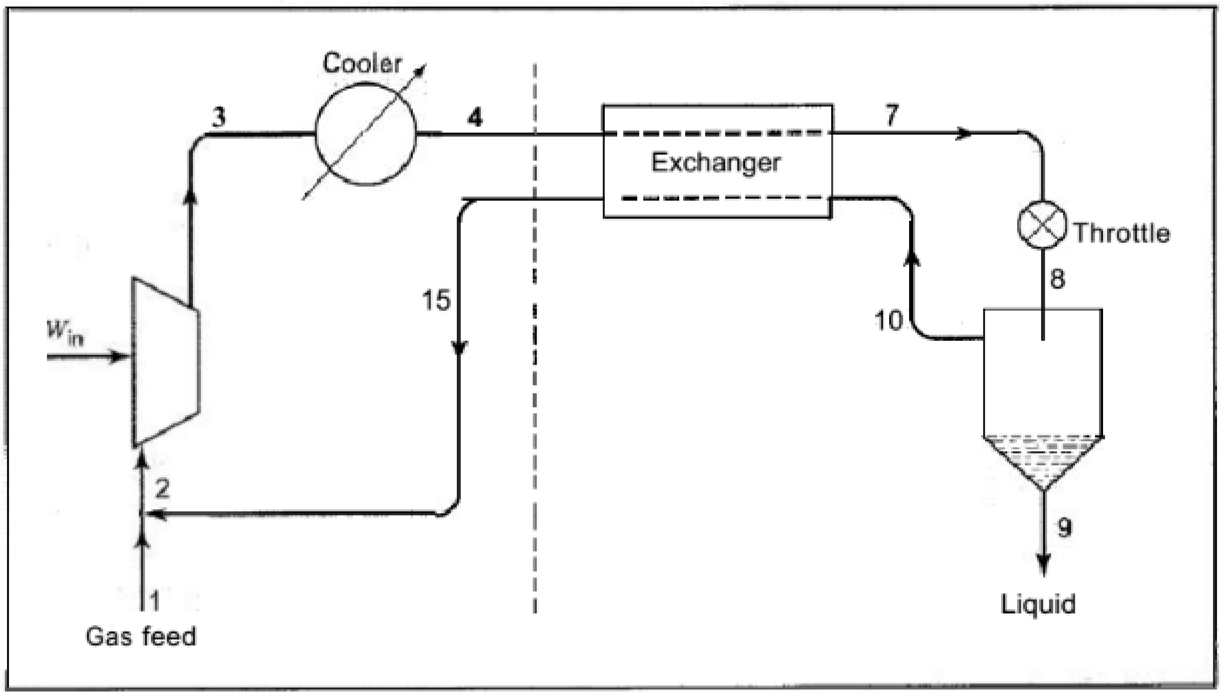


Figure 9.6 Linde liquefaction process

10 Static Analysis

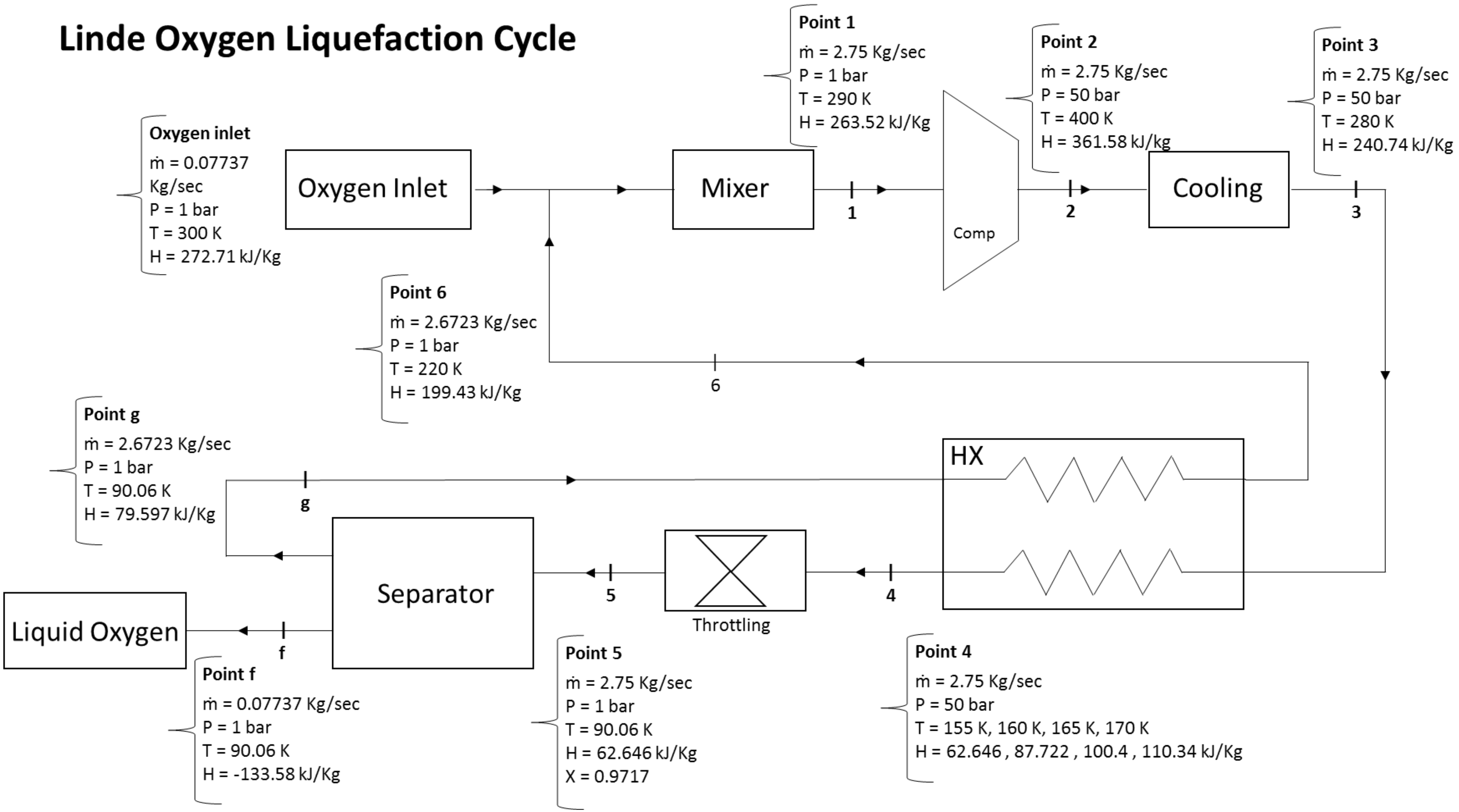
At the start of the first cycle, the oxygen gas passes from the oxygen inlet towards the compressor at the ambient temperature (300 K, 1 bar), through the mixer. It is at this stage that the mixer plays the role of the tank. The oxygen gas comes out hot from the compressor (400 K, 50 bar) in the direction 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.

10.1 Schema of Linde-Hampson liquefaction cycle of Oxgene with example values



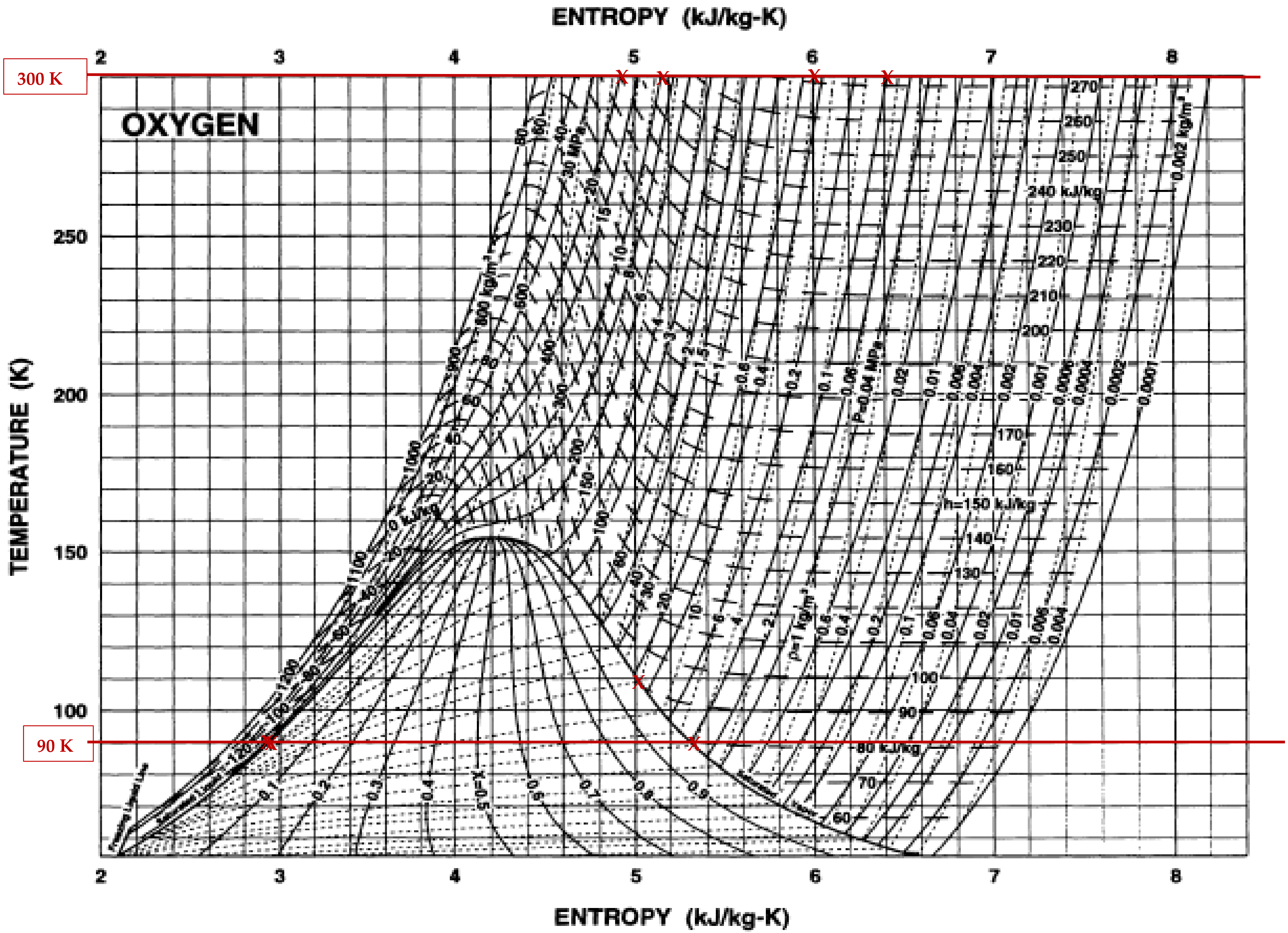


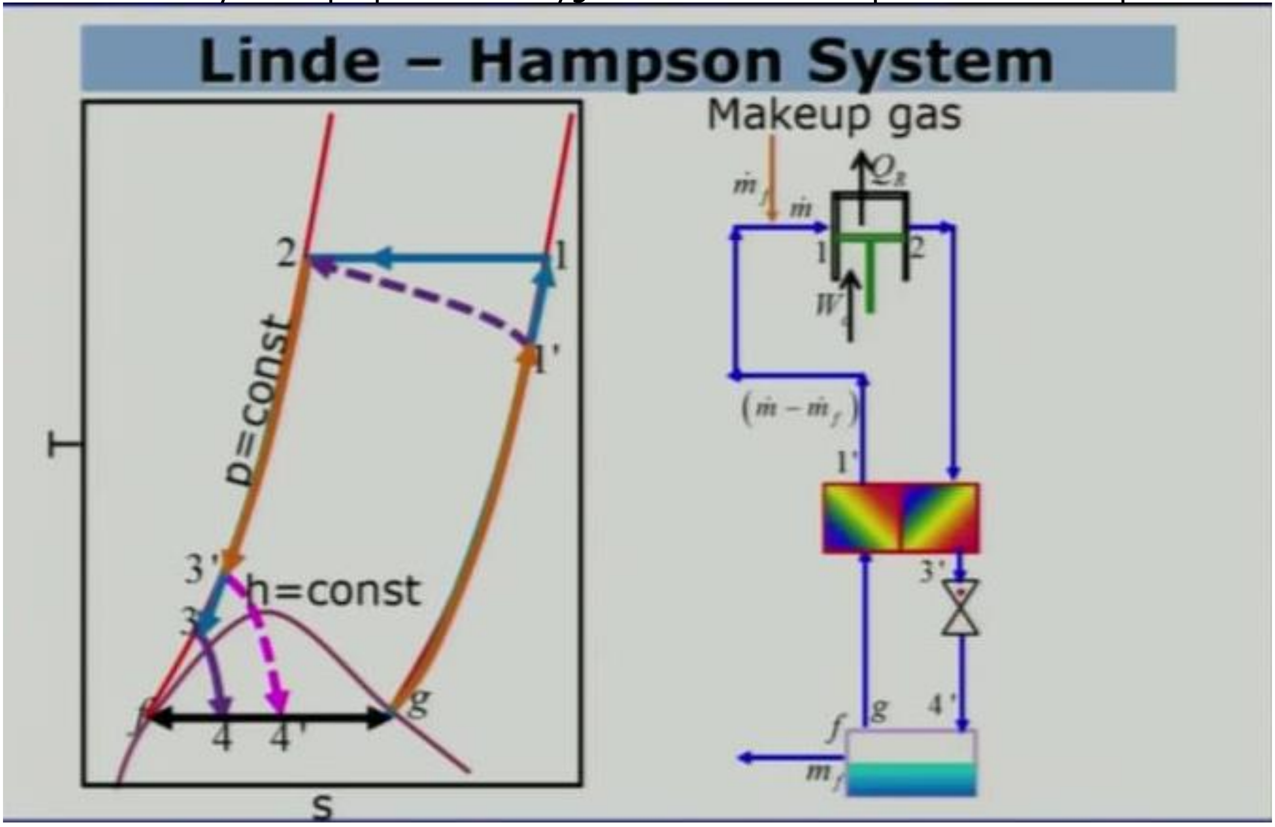
Fig. 5.30. $T-S$ diagram for oxygen ($T = 50-300$ K)

10.2 Drawing by FreeCad

Linde.FCStd

10.3 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 $\dot{m}$=2.75 Kg/s is an approximated value, a change in this value will affect Q-dot as well as $\dot{m}$f and thus yield Y.

- In steady state conditions, the first Law around the compressor gives:
  $\dot{W}$c – (Q-dot)r + $\dot{m}$(h1 –h2) = 0

The second Law around the compressor gives:

$$(\dot{Q})_r = \dot{m}\, T1\,(S1 - S2)$$

Combining, we have:

$$\dot{W}c = \dot{m}\,[T1\,(S1 - S2) - (h1 - h2)]$$

$$= (\dot{Q})_r - \dot{m}\,(h1 - h2)$$

Or $(\dot{Q})_c = \dot{m}\,(h1 - h2)$

- 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, $y = \frac{\dot{m}f}{\dot{m}} = \frac{h1 - h2}{h1 - hf}$
- 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**

10.4 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

10.4.1 Calculation of heat exchanger [5]

✍ **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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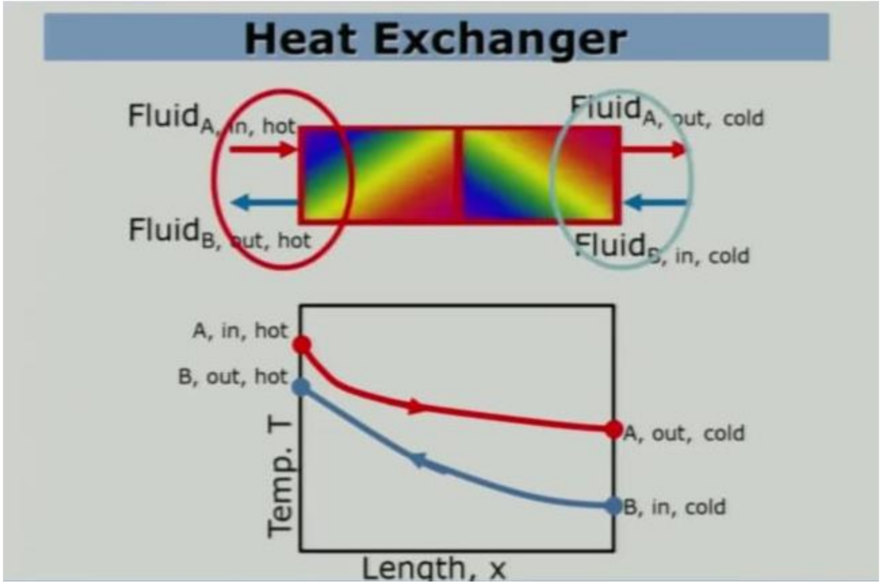
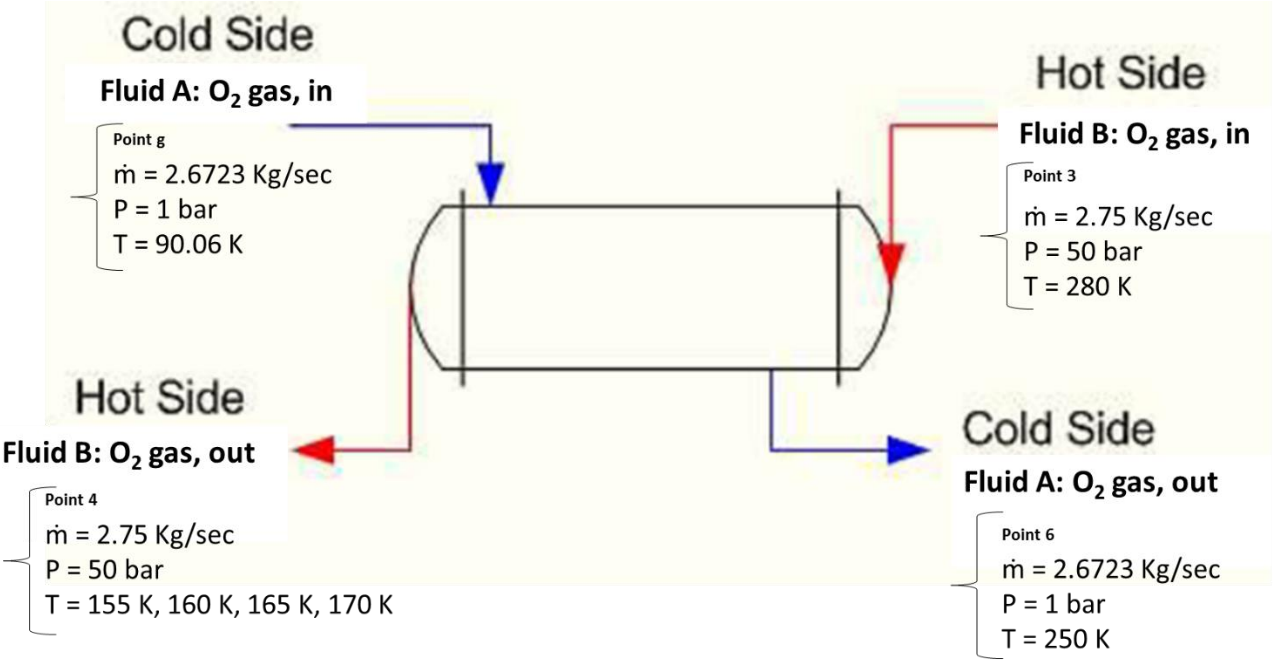
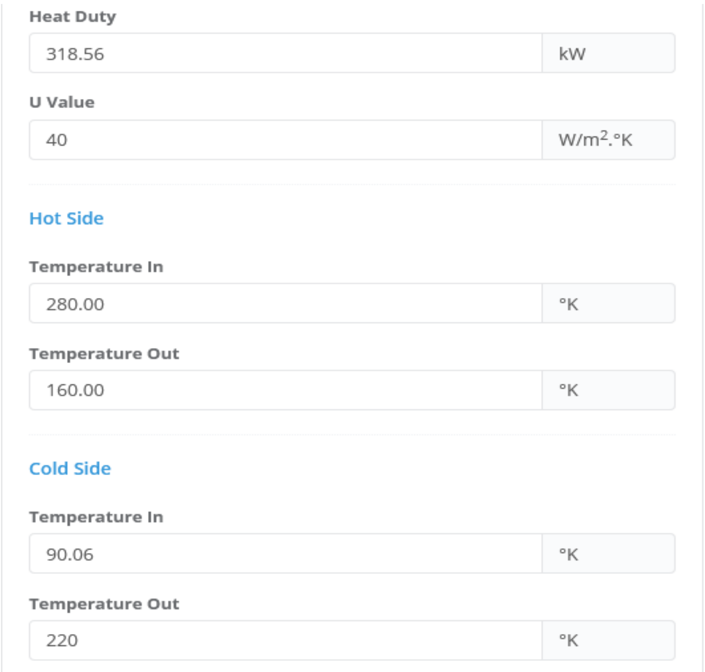
[5] https://checalc.com/solved/LMTD_Chart.html & https://checalc.com/calc/ShortExch.html


Heat Exchanger
Fluid$_{A, in, hot}$
Fluid$_{B, out, hot}$
Fluid$_{A, out, cold}$
Fluid$_{B, in, cold}$
A, in, hot
B, out, hot
A, out, cold
B, in, cold
Temp. T
Length, x


Cold Side
Fluid A: O_2 gas, in
Point g
ṁ = 2.6723 Kg/sec
P = 1 bar
T = 90.06 K
Hot Side
Fluid B: O_2 gas, in
Point 3
ṁ = 2.75 Kg/sec
P = 50 bar
T = 280 K
Hot Side
Fluid B: O_2 gas, out
Point 4
ṁ = 2.75 Kg/sec
P = 50 bar
T = 155 K, 160 K, 165 K, 170 K
Cold Side
Fluid A: O_2 gas, out
Point 6
ṁ = 2.6723 Kg/sec
P = 1 bar
T = 250 K

Static Analysis


Heat Duty
318.56 kW

U Value
40 W/m²·°K

Hot Side

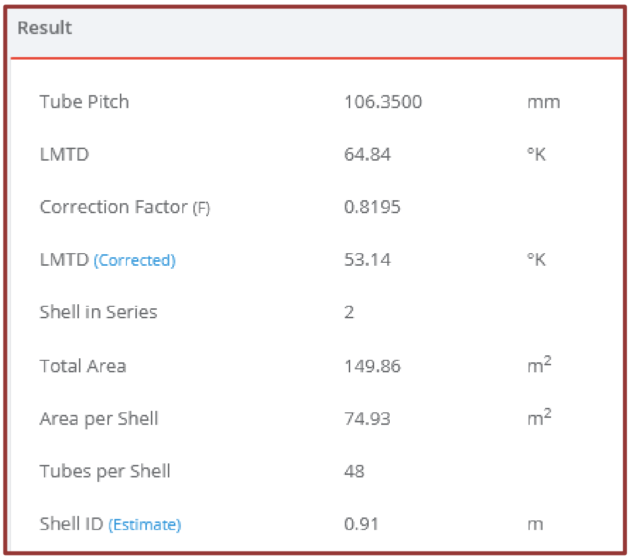
Temperature In
280.00 °K

Temperature Out
160.00 °K

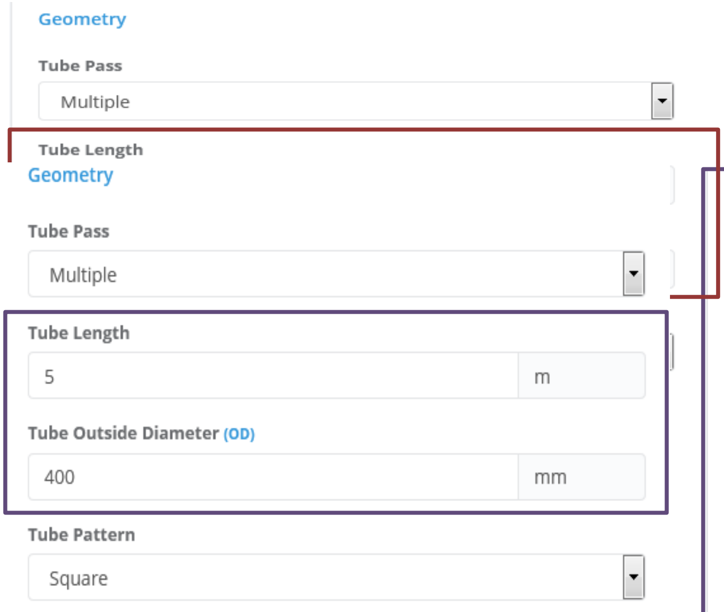
Cold Side

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	m^2
Area per Shell	74.93	m^2
Tubes per Shell	48	
Shell ID (Estimate)	0.91	m


Geometry

Tube Pass
Multiple

Tube Length

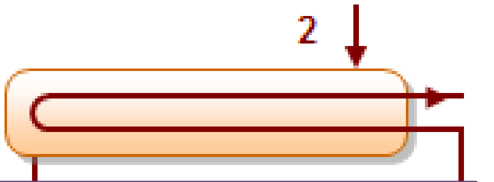
Geometry

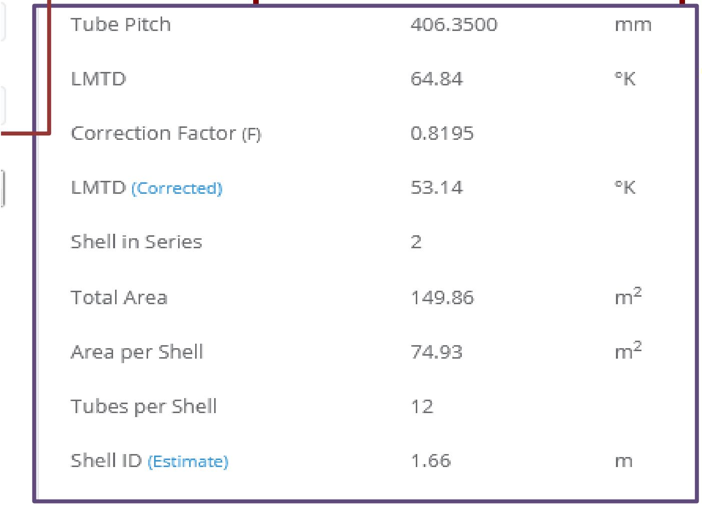
Tube Pass
Multiple

Tube Length
5 m

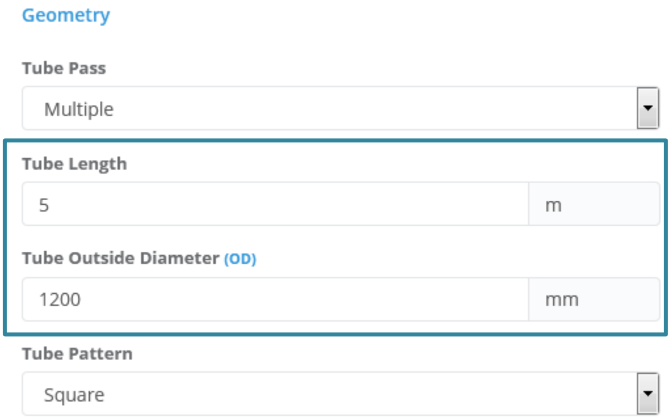
Tube Outside Diameter (OD)
400 mm

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	m^2
Area per Shell	74.93	m^2
Tubes per Shell	12	
Shell ID (Estimate)	1.66	m



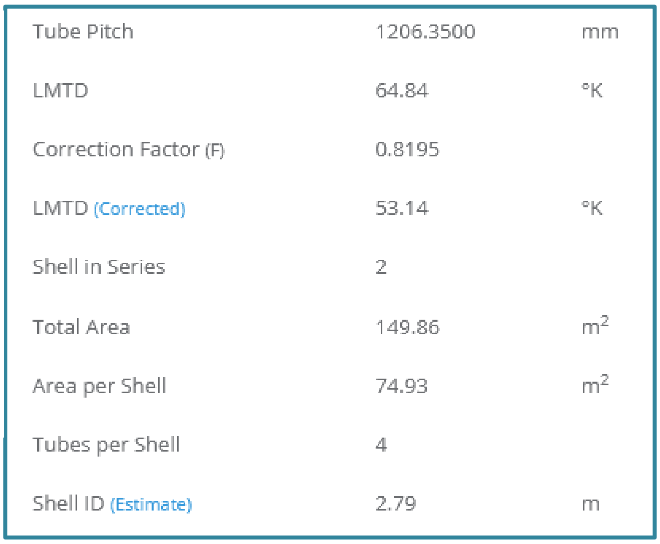
Geometry

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

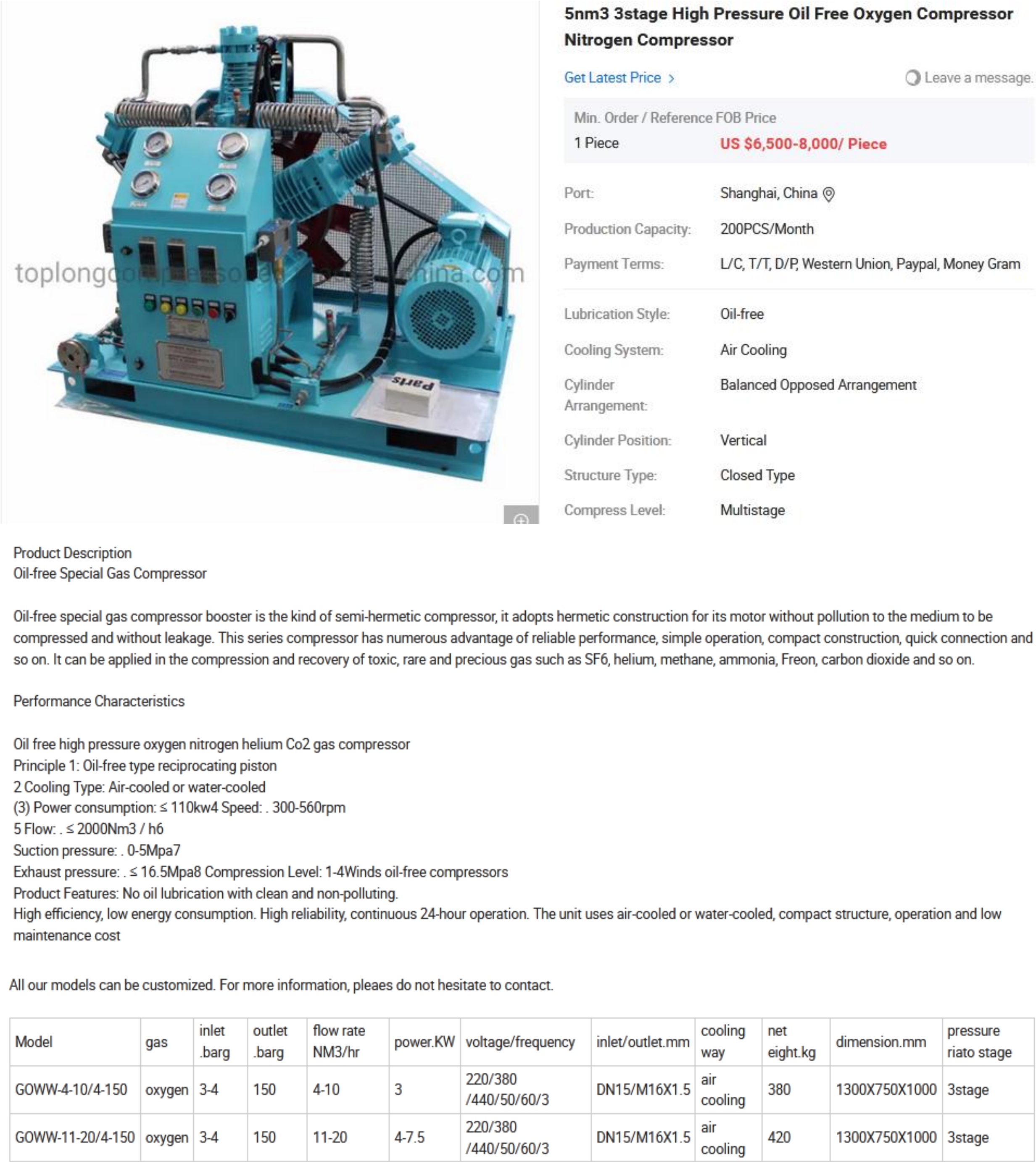
10.5 Calculation of compressor

	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

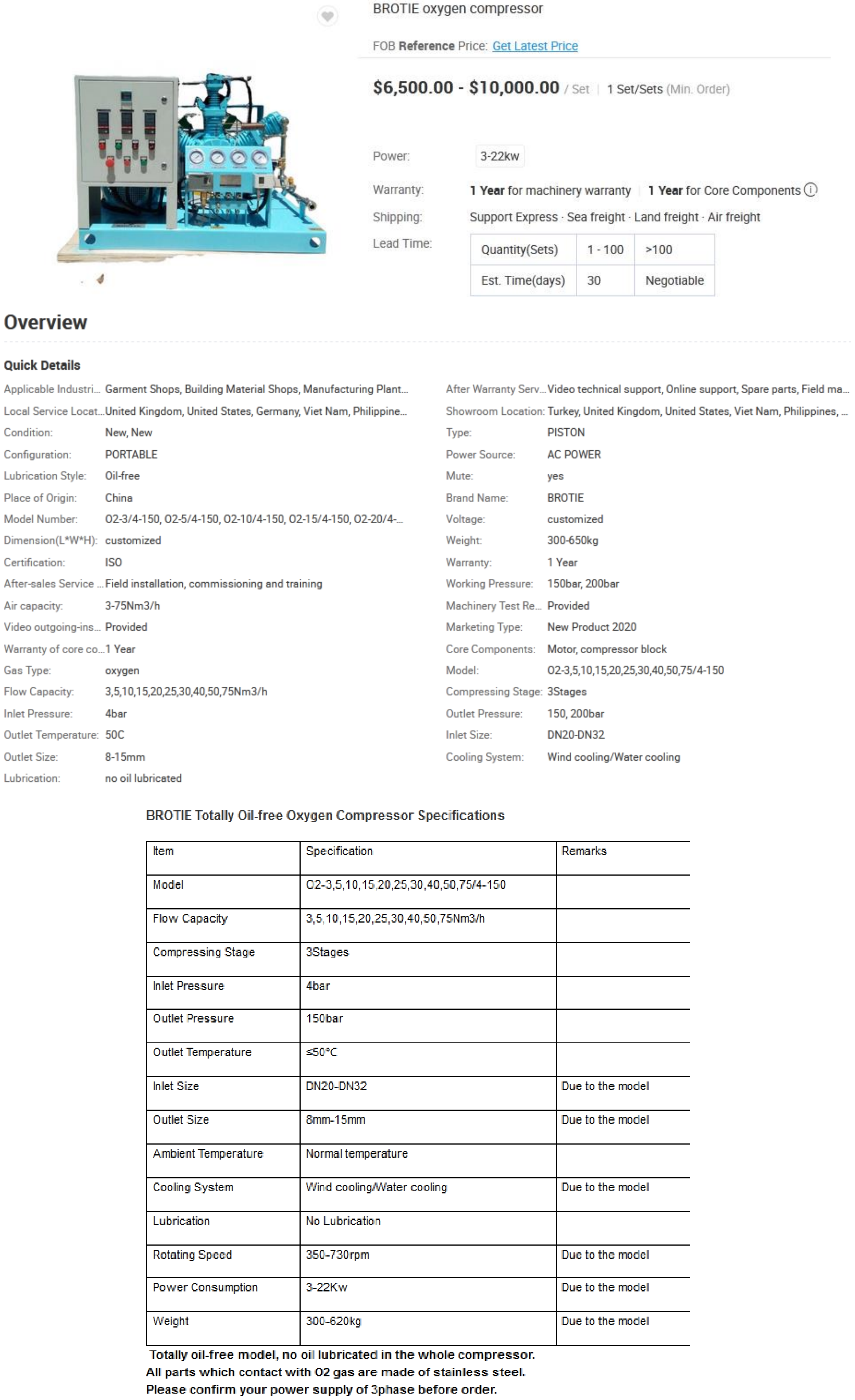
Oil free high pressure oxygen nitrogen helium Co2 gas compressor
Principle 1: Oil-free type reciprocating piston
2 Cooling Type: Air-cooled or water-cooled
(3) Power consumption: ≤ 110kw4 Speed: . 300-560rpm
5 Flow: . ≤ 2000Nm3 / h6
Suction pressure: . 0-5Mpa7
Exhaust pressure: . ≤ 16.5Mpa8 Compression 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

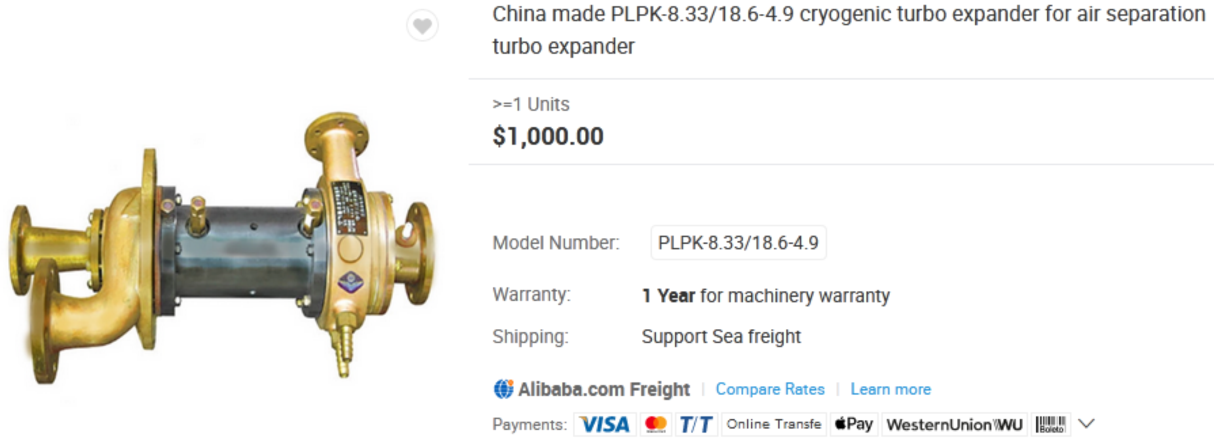
Totally oil-free model, no oil lubricated in the whole compressor.
All parts which contact with O2 gas are made of stainless steel.
Please confirm your power supply of 3phase before order.

10.6 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

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	

10.7 Materials suitable for cryogenic heat exchanger

Material link: [6]

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[6] https://www.gasparini.com/en/blog/metals-and-materials-for-low-temperatures/

10.7.1 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.

10.7.2 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.

10.7.3 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.

10.7.4 Materials suitable down to -196 °C

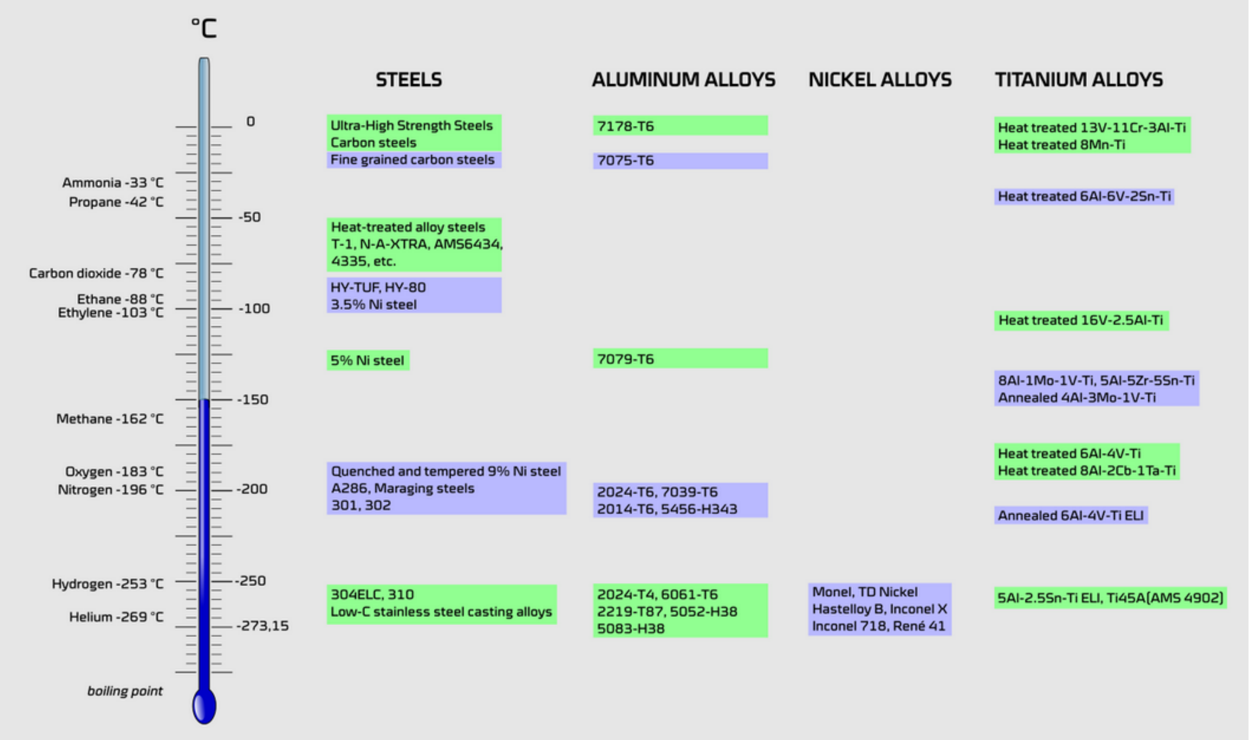
The austenitic stainless steels of the 300 series are all suitable for working in this temperature range. Maraging steels with nickel content between 20% and 25% and the addition of cobalt, molybdenum, titanium, aluminium, and niobium are also suitable. Maraging steels have excellent malleability, toughness 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.



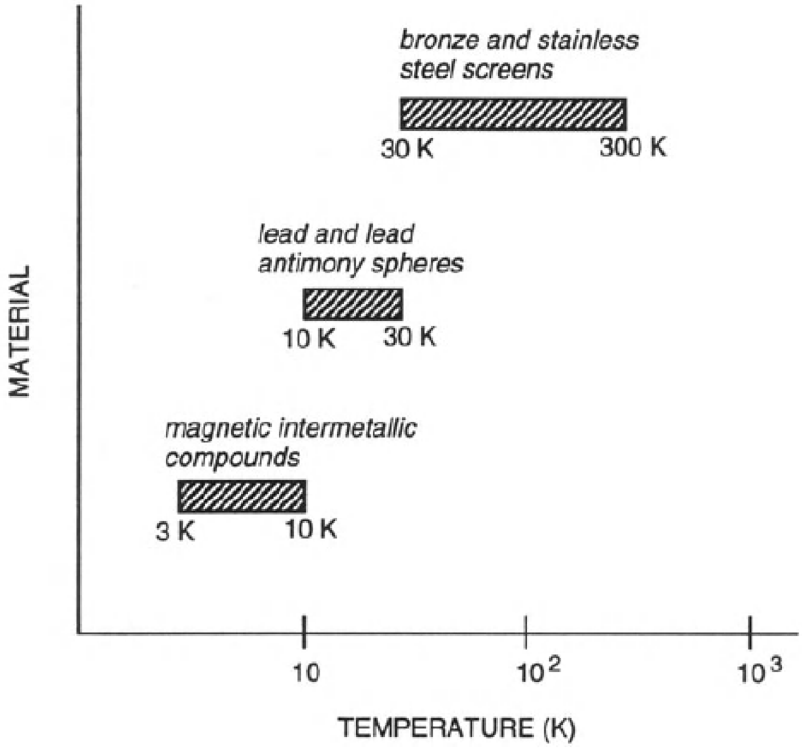


Fig. 2.16. Temperature range for commonly used regenerator materials in cryogenic refrigerators. [7]

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[7] https://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.468.3966&rep=rep1&type=pdf

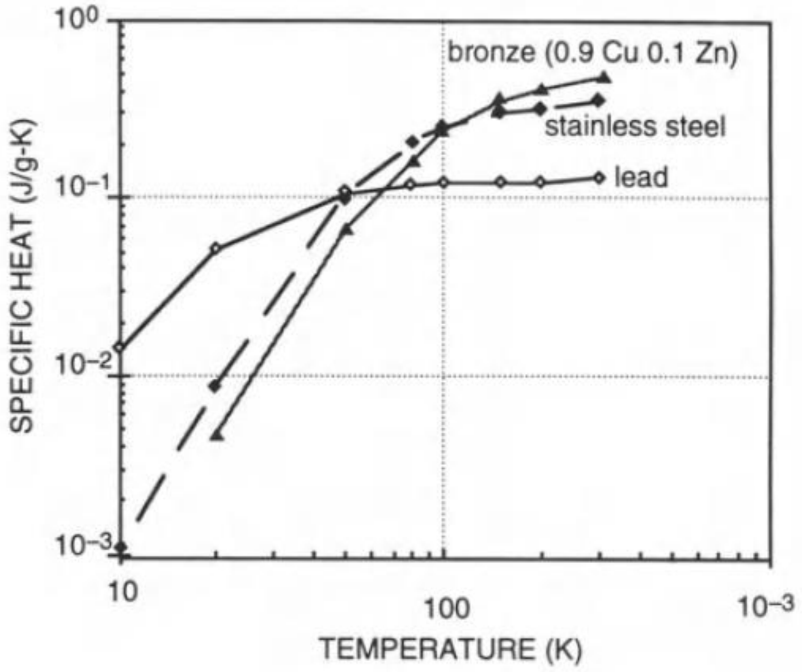

Fig. 2.17. Comparison of the specific heats for three commonly used regenerator materials. 6

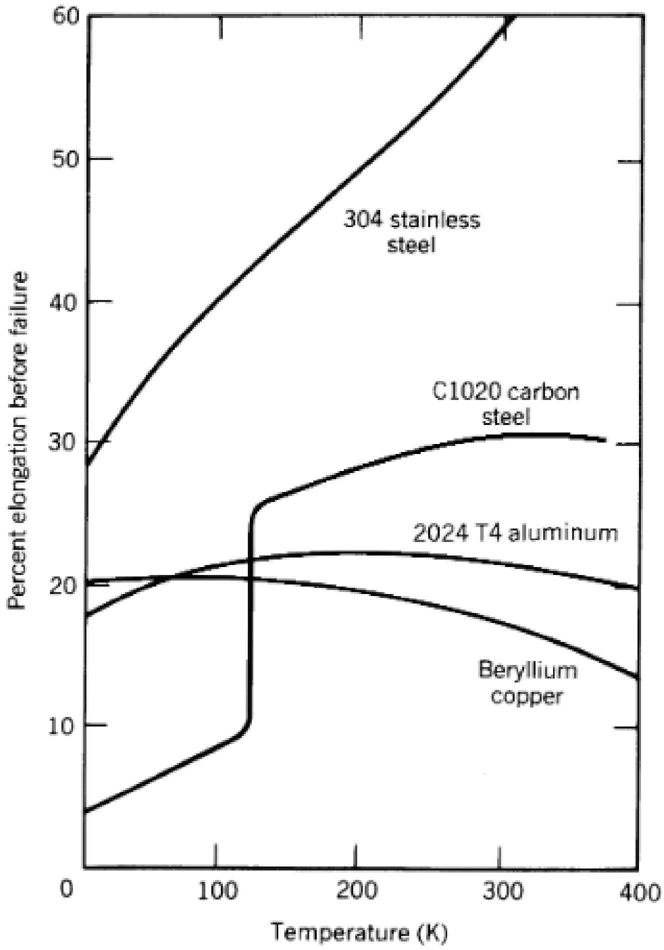

Figure 33 Percent elongation before rupture of some materials used in cryogenic service. 6

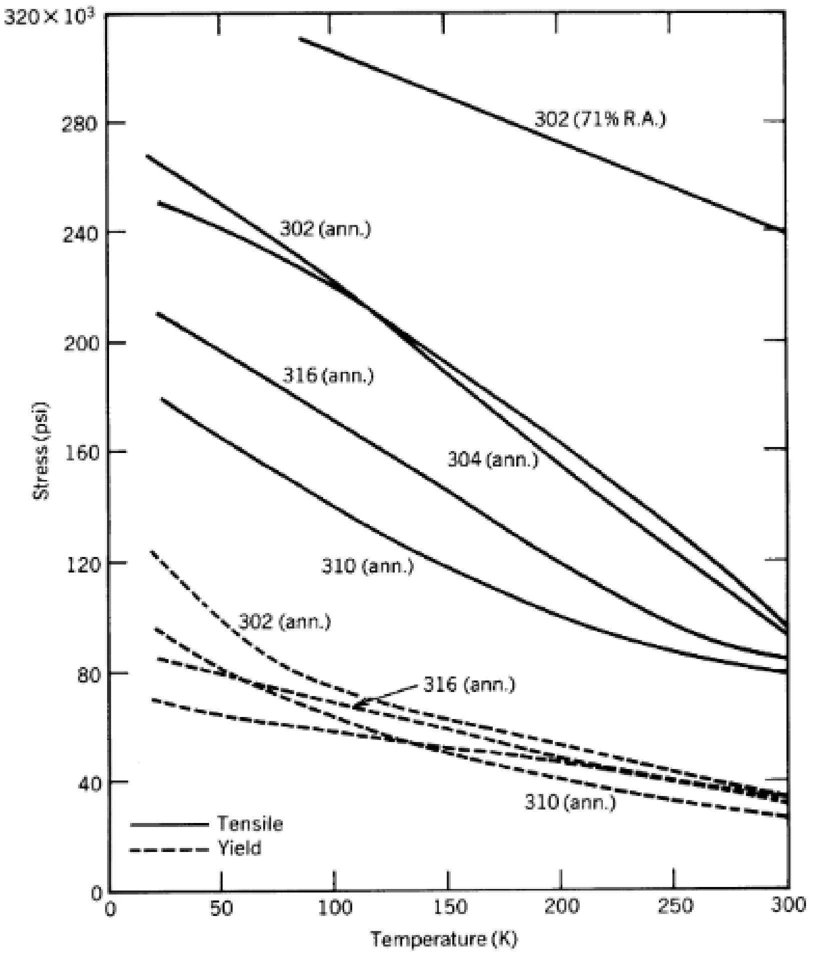

Figure 34 Yield and tensile strength of several AISI 300 series stainless steels.[33] (Courtesy American Iron and Steel Institute.)

6

Table 6 Properties of Various Multilayer Insulations (Warm Wall at 300 K)

Sample Thickness (cm)	Shields per Centimeter	Density (g/cm^3)	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.

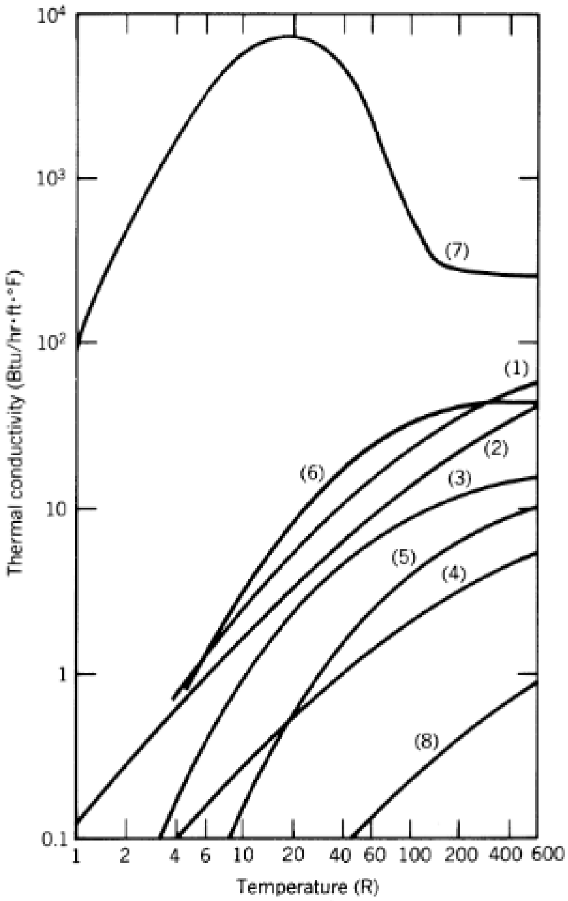

Figure 36 Thermal conductivity of materials useful in low-temperature service. (1) 2024TA aluminum; (2) beryllium copper; (3) K-Monel; (4) titanium; (5) 304 stainless steel; (6) C1020 carbon steel; (7) pure copper; (8) Teflon.[35] 6

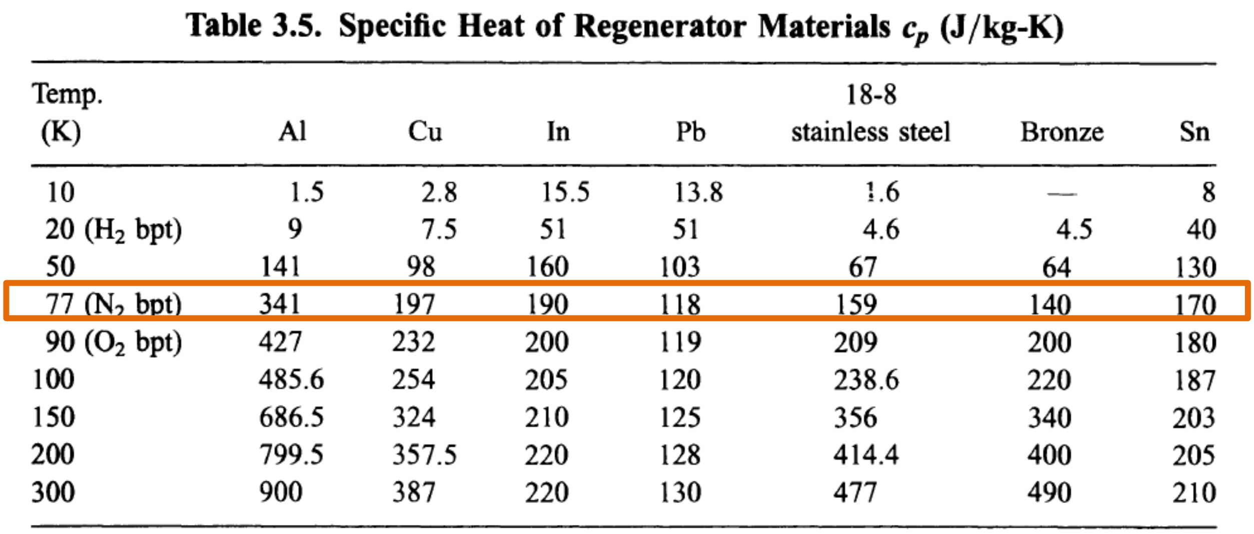

Table 3.5. Specific Heat of Regenerator Materials c_p (J/kg-K)

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

10.8 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[8]

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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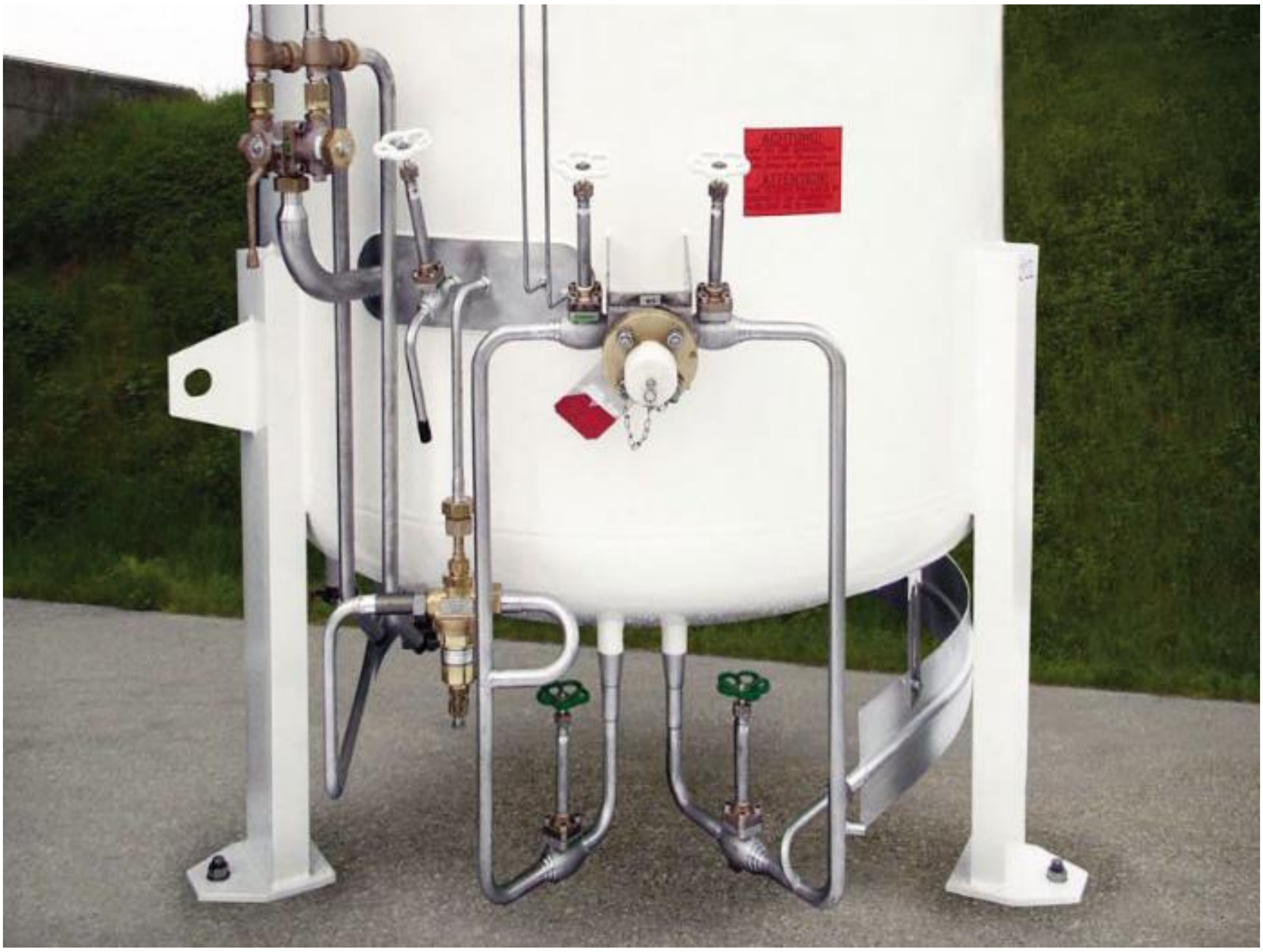
[8] http://m.zhongjie-se.com/cryogenic-tank/cryogenic-storage-tank/liquid-oxygen-tank.html

(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 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.9

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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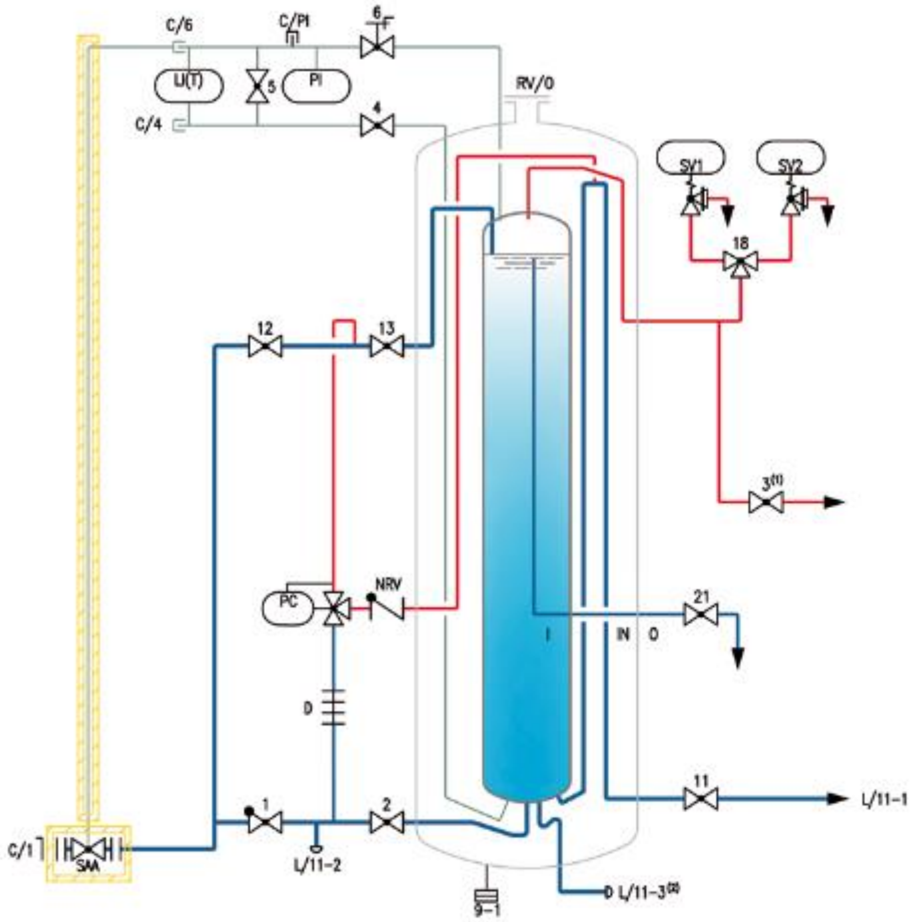
9 https://acprodbponlinebcc5.blob.core.windows.net/bp-public-files/bp_editor_div_mgs/TechnicalInformation/PMGS_LOX_Storage_Tanks_HTM_Instruction_Book_EN_8102341086.pdf



[10]

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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[10] 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[11]

- 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.

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[11] Bulk Storage Product Catalog

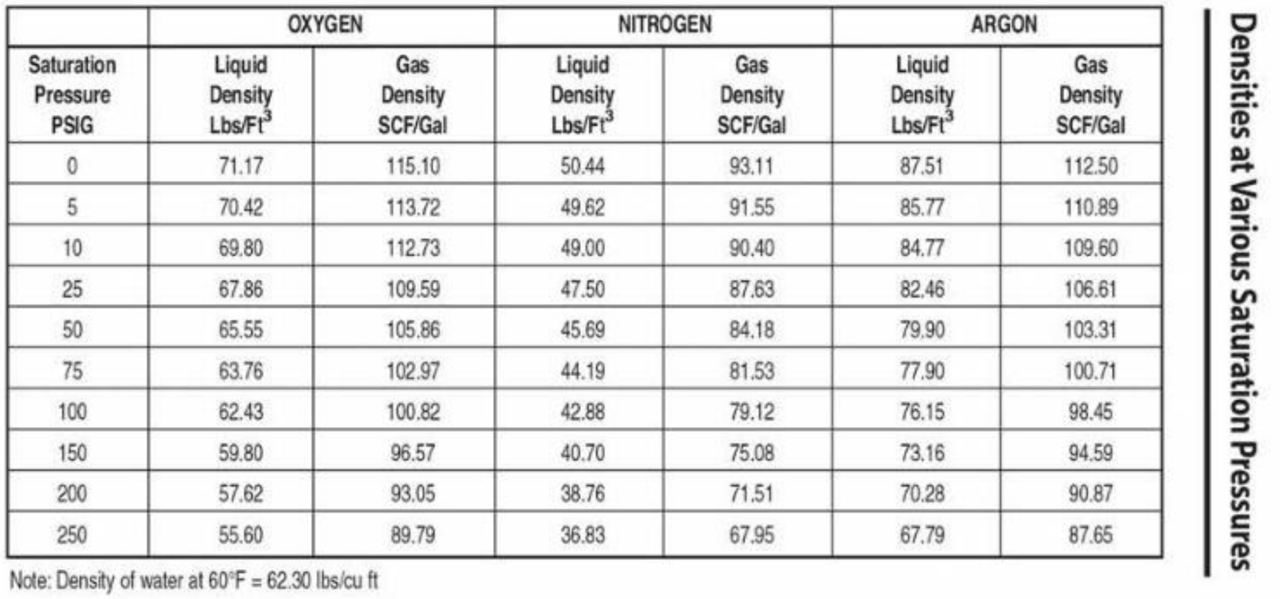
- Combination pressure building/economizer regulator for easy pressure adjustment and extended bonnet bronze control valves for ease of operation.
- Piping modules designed for ease-of-access to all operational control valves with stainless steel inter- connecting piping for improved durability.

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.

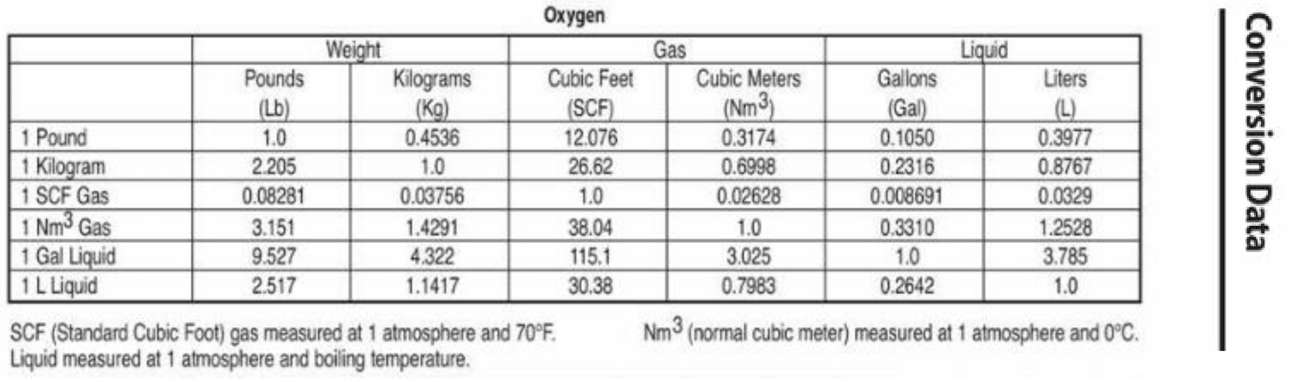
Full-trycock and economizer valves come standard with non-extended packing



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.

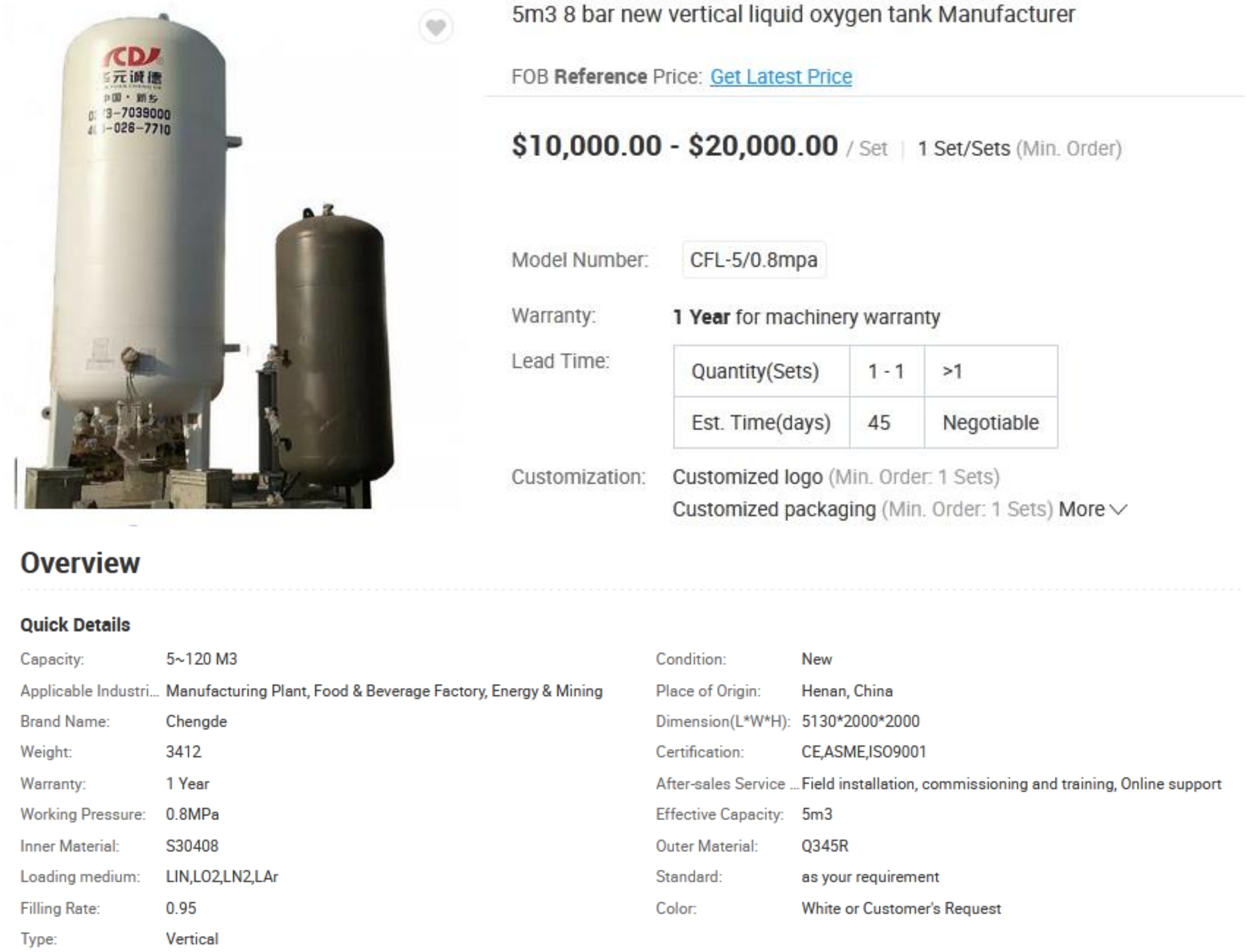
Nm^3 (normal cubic meter) measured at 1 atmosphere and 0°C.

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:

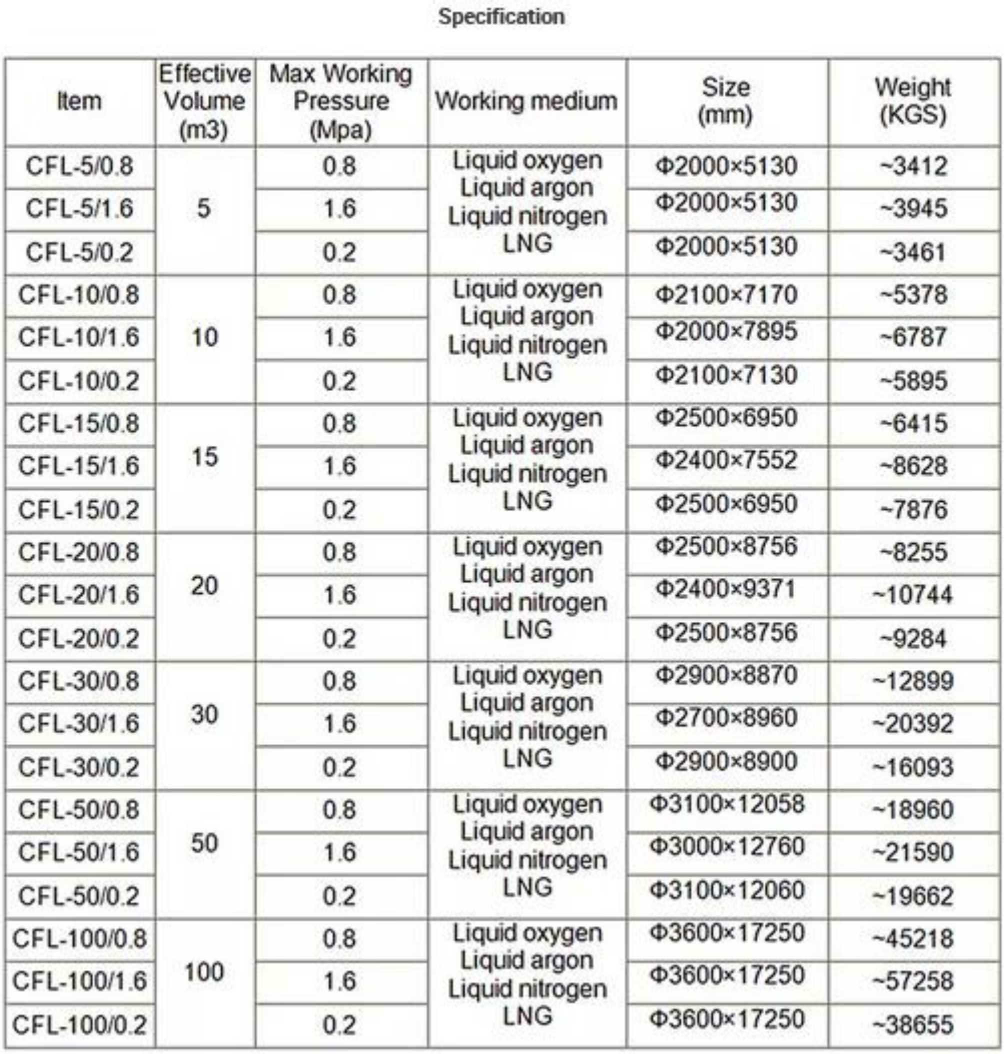
Quantity(Sets)	1 - 1	>1
Est. Time(days)	45	Negotiable

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		



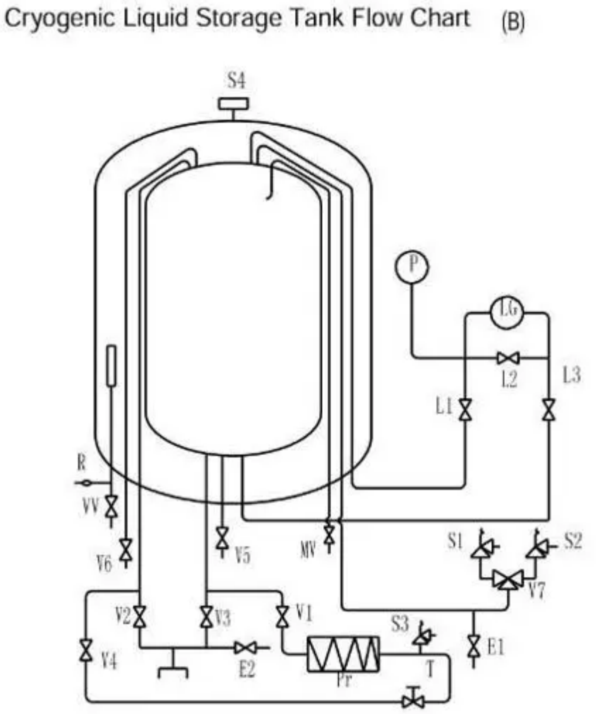
Specification

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

Phone: +86-373-2677103 Fax: +86-373-2677983

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: $20m^3$
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

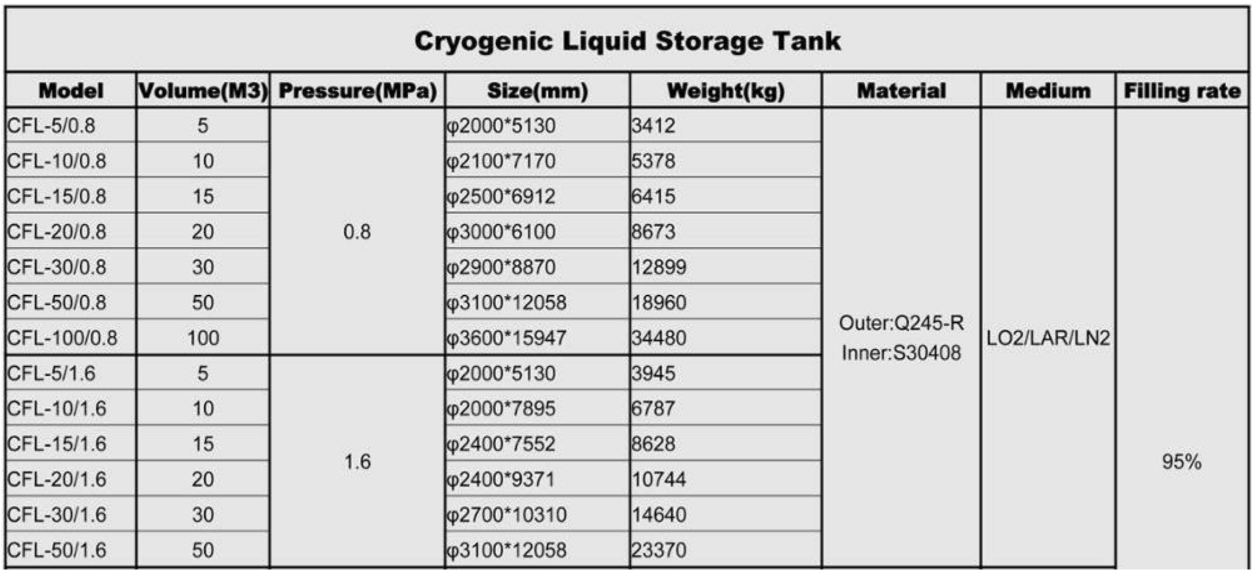
6. قذيفة المواد: سترة الخارجي: Q245-R ، الداخلية: S30408.

7.عزل: فراغ مسحوق العزل

8.الوزن الفارغ: حوالي 6415 كجم

9. محدل التحبئة: 0.95

10.صمام الإغاثة: جميع الصمامات عبارة عن صمامات صينية عالية الجودة.[12]



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			

[13]

- ❖ Another method of Oxygen liquefaction

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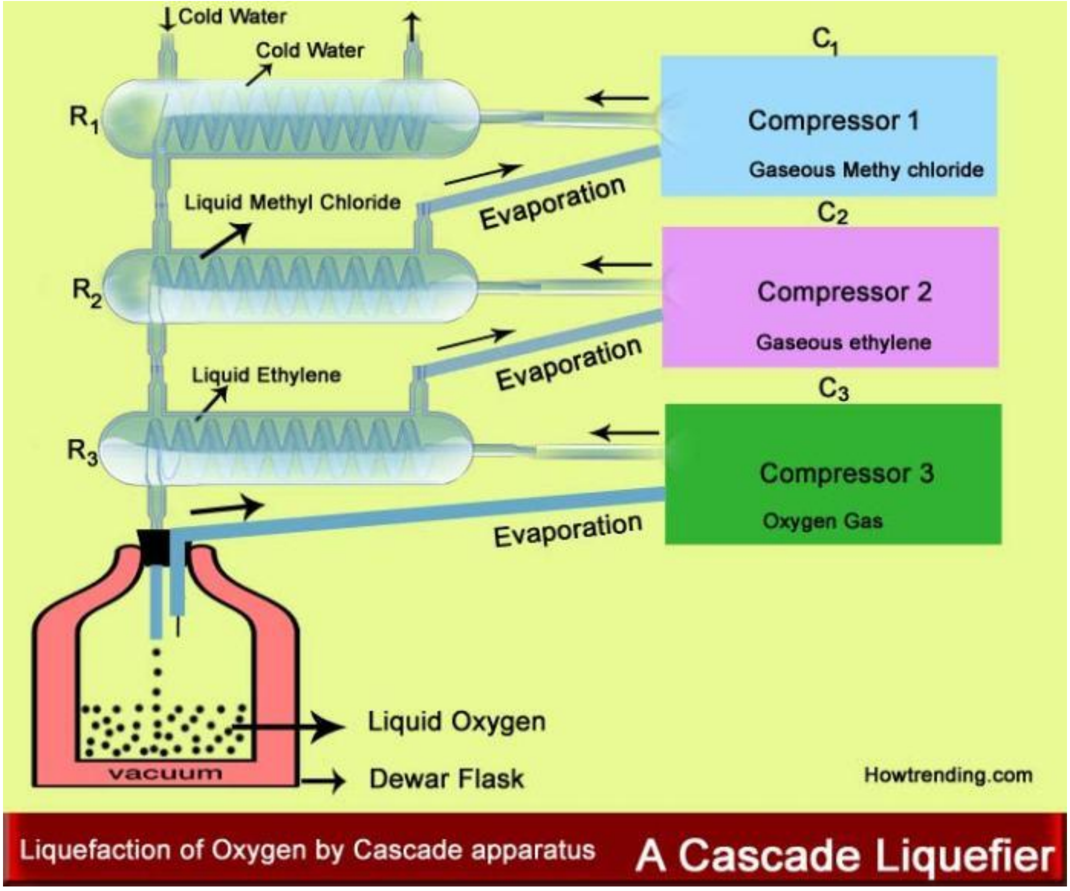
[12] http://ar.cncdtank.com/cryogenic-tank/5000l-oxygen-liquid-tank.html

[13] 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.**14**



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.

10.8.1 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.

10.8.2 Principles

This apparatus work on two principles.

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[14] 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.

10.8.3 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.

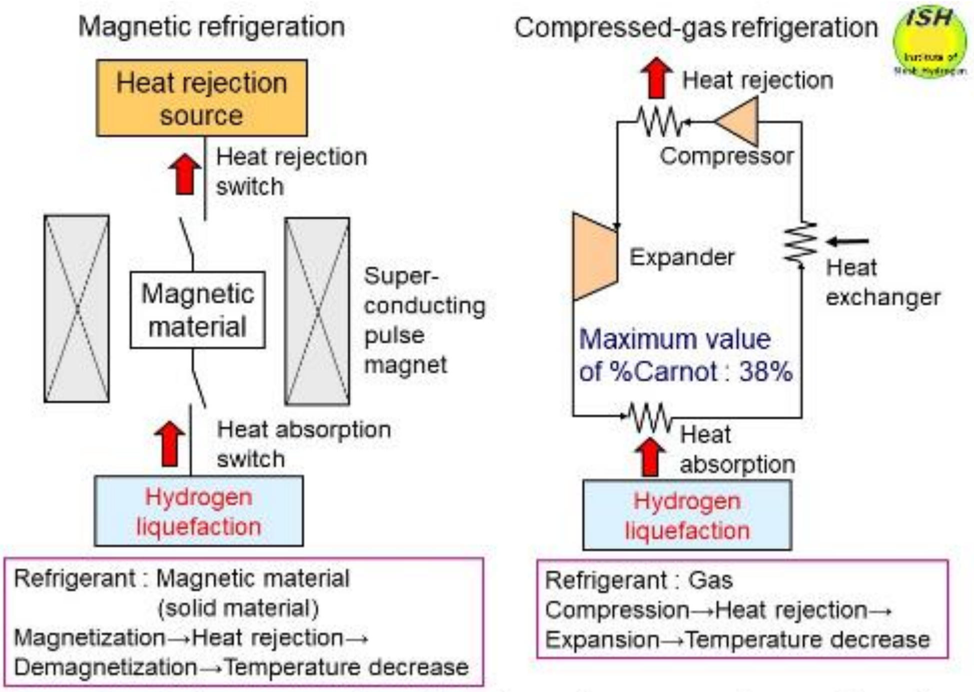
Here, likewise the previous stages, the evaporated oxygen return back to the compressor C_3 through the suction side of the compressor.

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).

10.9 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. [15]

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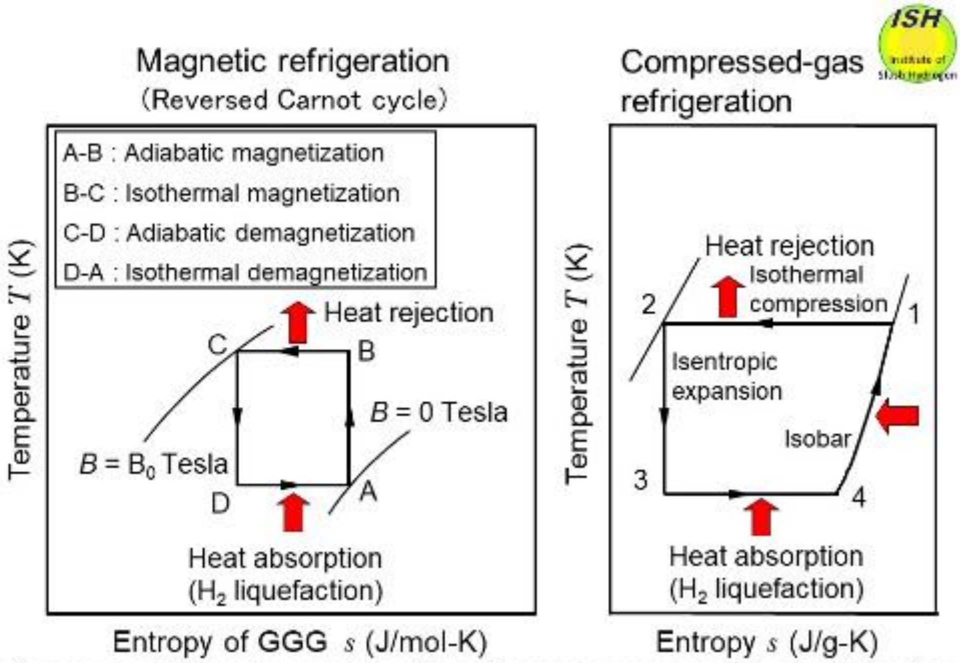
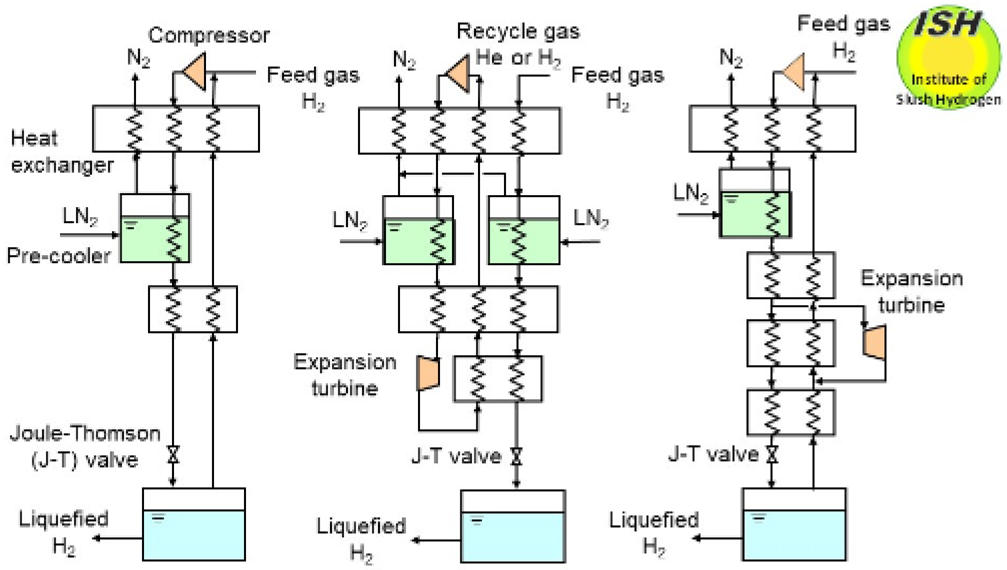
[15] https://slush-ish-mag-english.com/technology2.html



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.

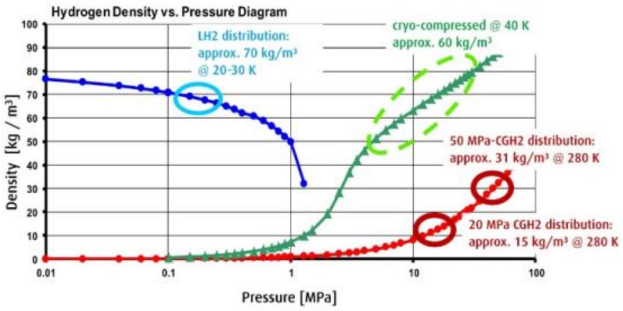
Brayton system

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.

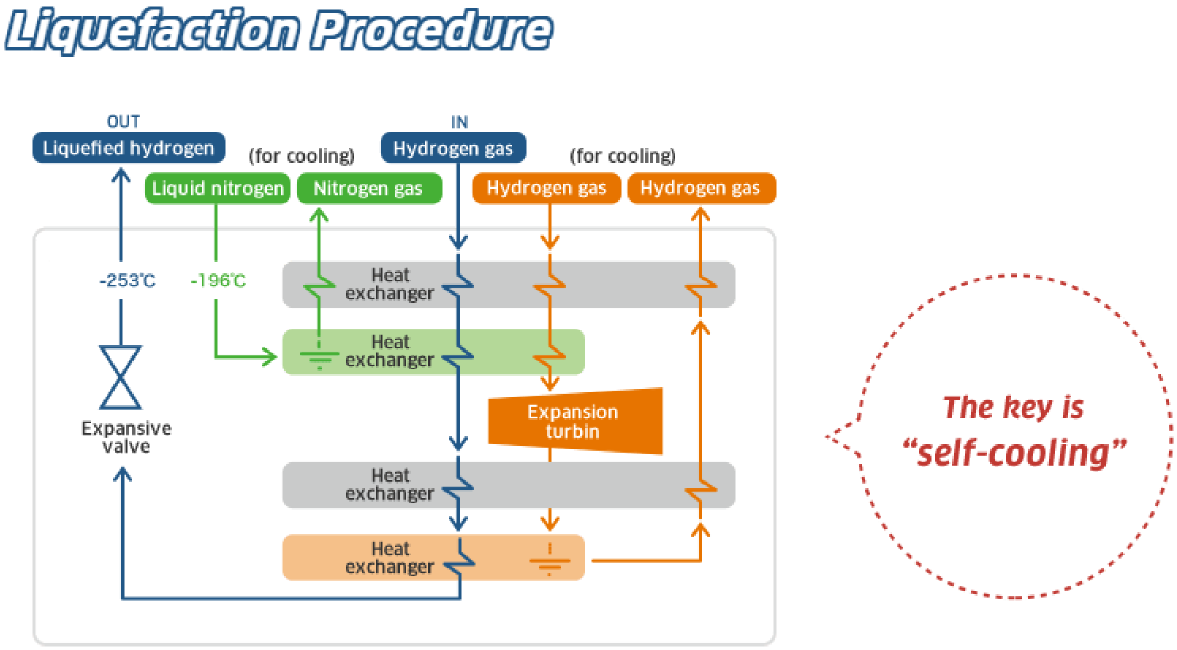


Comparison of hydrogen density in storage form of hydrogen [16]

10.9.1 Liquefaction of hydrogen by compressed-gas

http://sadanaresearch.com/liquid-helium-generator-overview/ !

https://vorbuchner.com/en/helium-liquefaction/



[17]

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[16] https://www.jstra.jp/seminar/PDF/English_Report%20of%20The%202nd%20International%20Workshop%20on%20Liquefied%20Hydrogen%20Technology.pdf

[17] 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				

10.10 Methane liquefaction

10.10.1 Characteristics of Methane

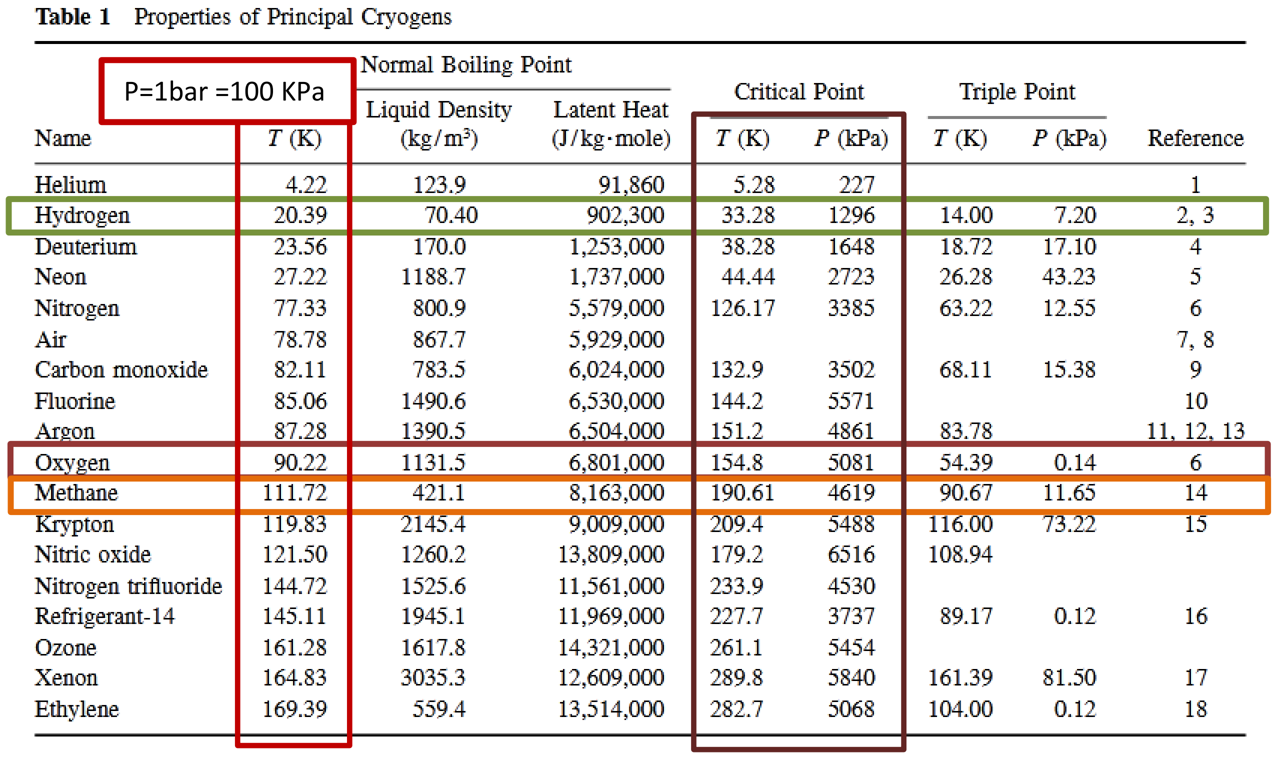

Table 1 Properties of Principal Cryogens

P=1bar =100 KPa

	Normal Boiling Point			Critical Point		Triple Point		
Name	*T* (K)	Liquid Density (kg/m³)	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

- Methane liquefaction basic cycle[18]

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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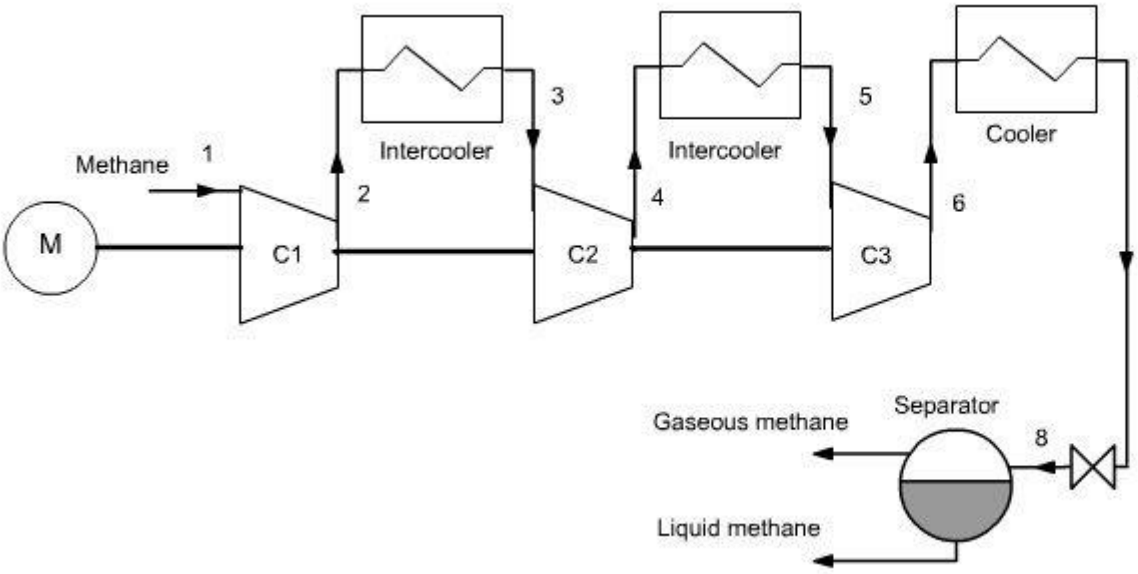
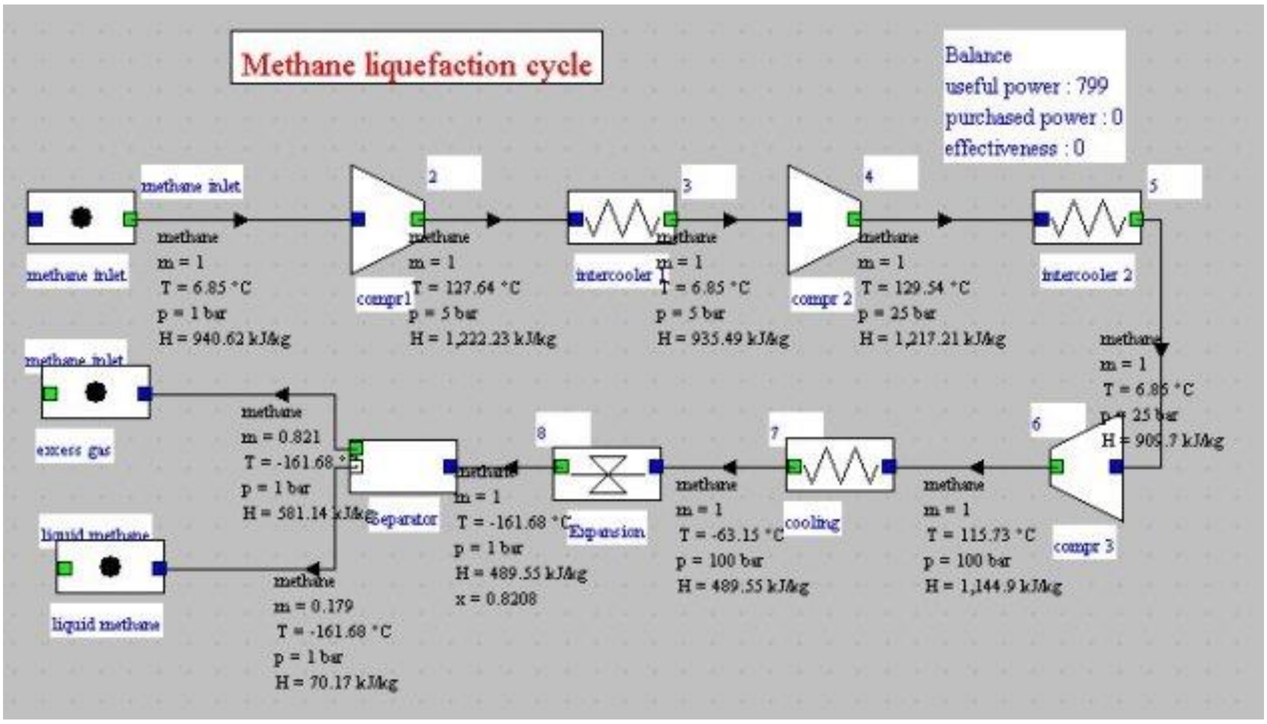
[18] https://direns.mines-paristech.fr/Sites/Thopt/en/co/cryogenie.html



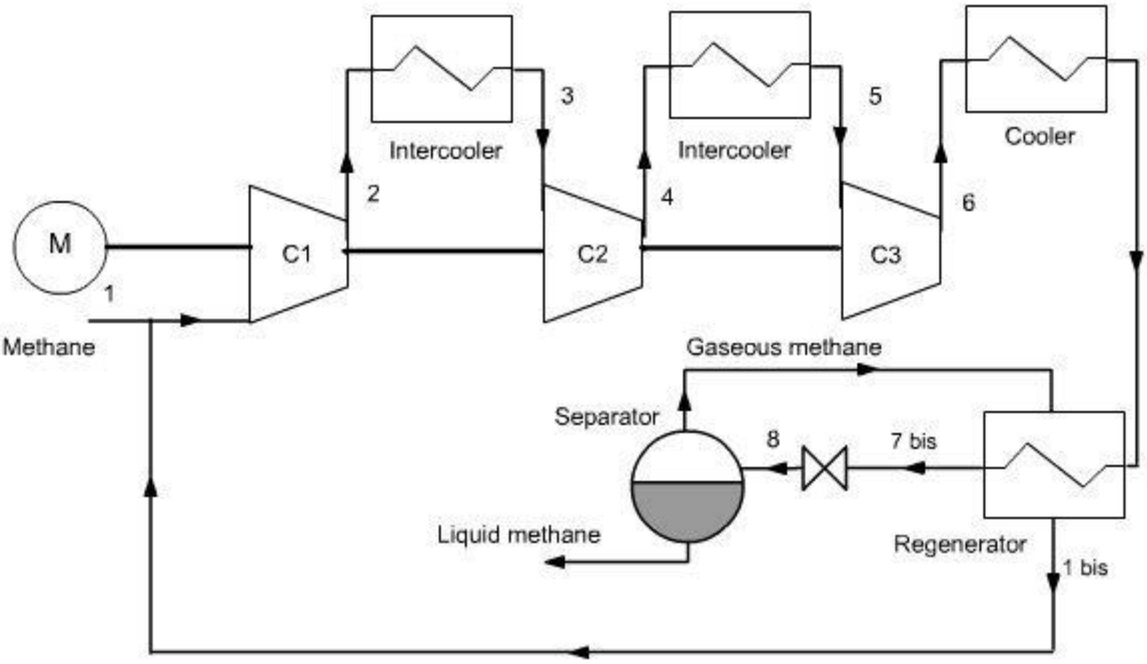


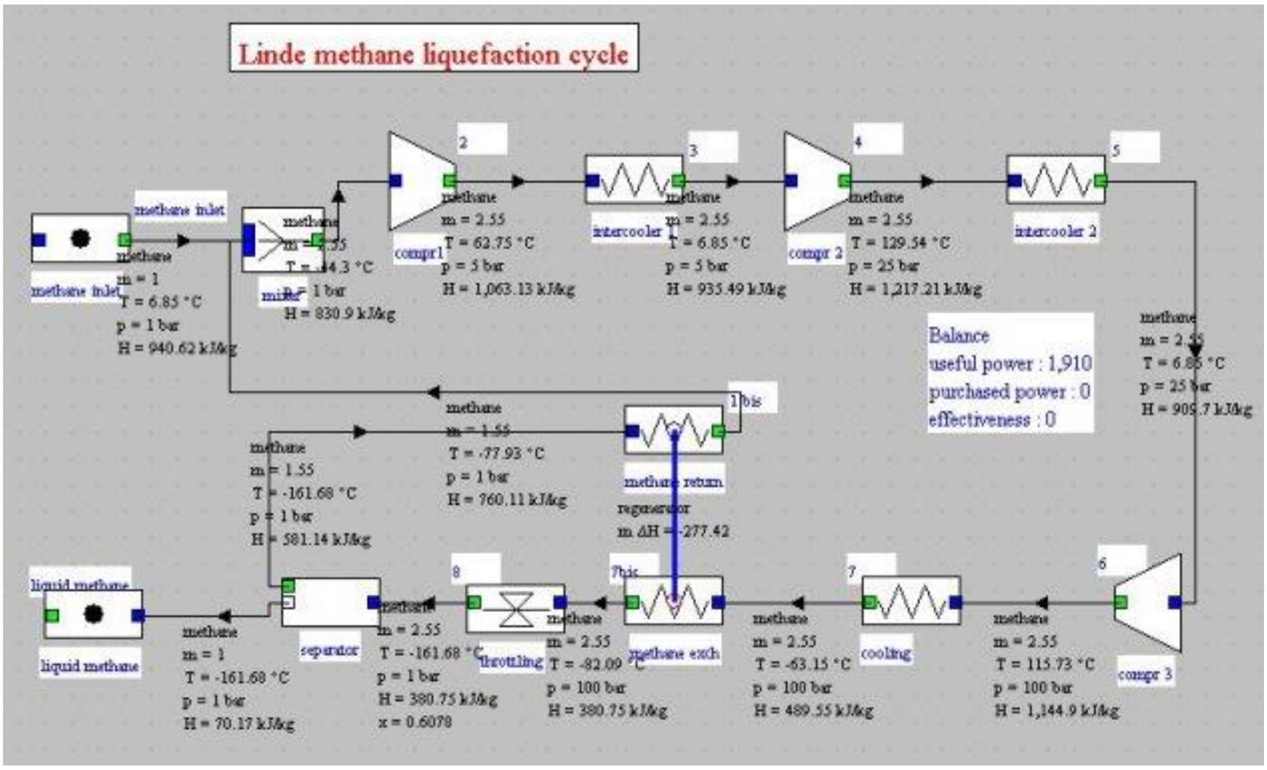
The compression work required per kilogram of methane sucked is 798.5 kJ, and 0.179 kg of liquid methane is produced, which corresponds to a work of 4.46 MJ per kilogram of liquefied methane.

- 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.





methane
m = 1
T = 6.85 °C
p = 1 bar
H = 940.62 kJ/kg

methane
m = 2.55
T = 44.3 °C
p = 1 bar
H = 830.9 kJ/kg

methane
m = 2.55
T = 62.75 °C
p = 5 bar
H = 1,063.13 kJ/kg

methane
m = 2.55
T = 6.85 °C
p = 5 bar
H = 935.49 kJ/kg

methane
m = 2.55
T = 129.54 °C
p = 25 bar
H = 1,217.21 kJ/kg

Balance
useful power : 1,910
purchased power : 0
effectiveness : 0

methane
m = 2.55
T = 6.85 °C
p = 25 bar
H = 909.7 kJ/kg

methane
m = 1.55
T = -77.93 °C
p = 1 bar
H = 760.11 kJ/kg

methane
m = 1.55
T = -161.68 °C
p = 1 bar
H = 581.14 kJ/kg

regenerator
m ΔH = -277.42

methane
m = 1
T = -161.68 °C
p = 1 bar
H = 70.17 kJ/kg

methane
m = 2.55
T = -161.68 °C
p = 1 bar
H = 380.75 kJ/kg
x = 0.6078

methane
m = 2.55
T = -82.09 °C
p = 100 bar
H = 380.75 kJ/kg

methane
m = 2.55
T = -63.15 °C
p = 100 bar
H = 489.55 kJ/kg

methane
m = 2.55
T = 115.73 °C
p = 100 bar
H = 1,144.9 kJ/kg

- 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.

11 Compressors

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.19

11.1 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

11.2 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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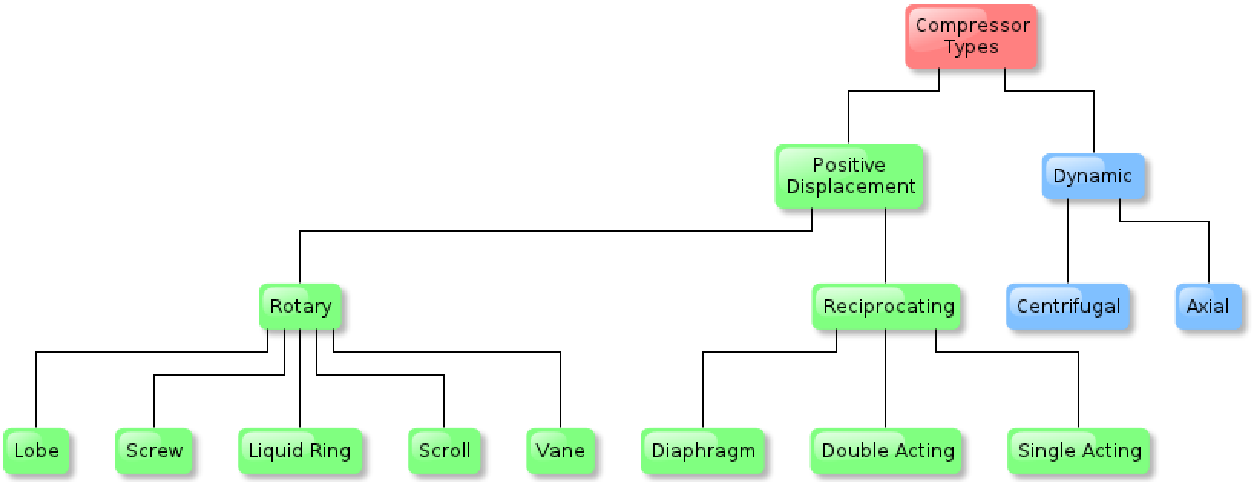
19 https://kbdelta.com/blog/main-types-of-compressors.html



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

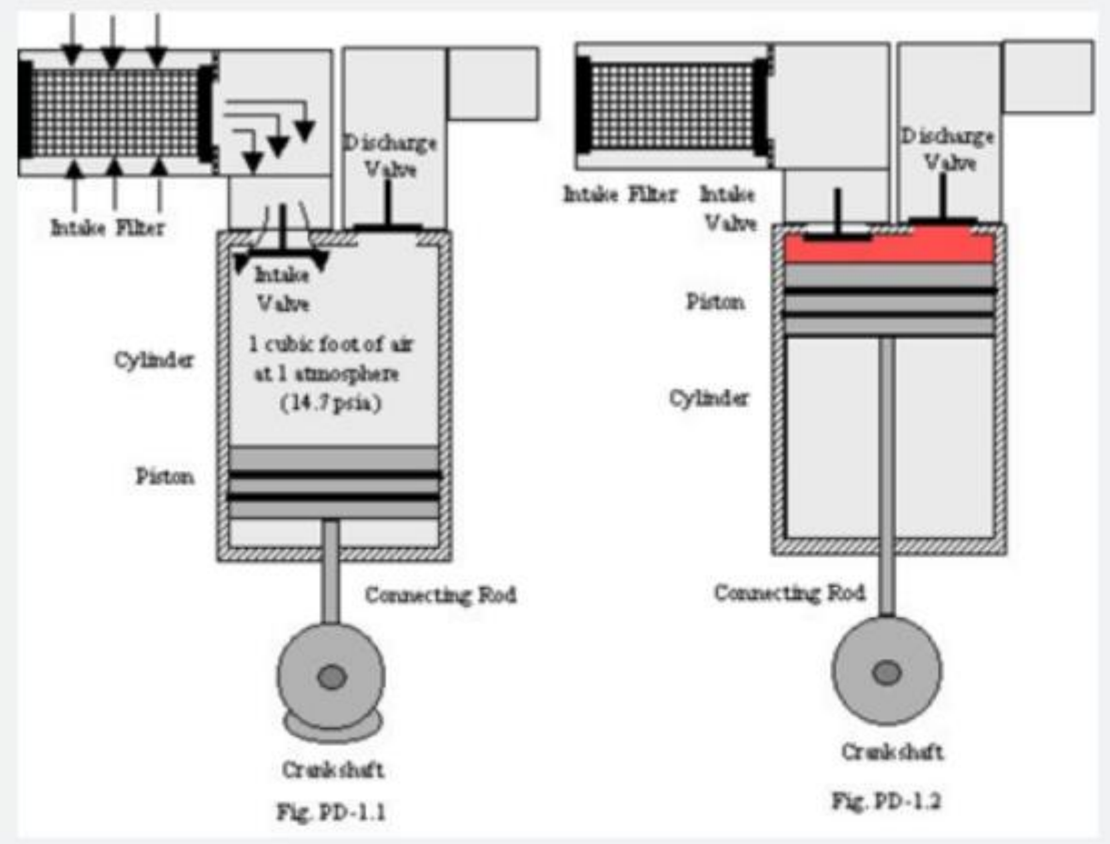
11.2.1 POSITIVE DISPLACEMENT COMPRESSORS

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.



[20]

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.

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[20] https://cascousa.com/compressed-air-101/types-of-compressors/positive-displacement-compressors/

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.

11.2.2 TYPES OF RECIPROCATING COMPRESSORS

11.2.2.1 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.

11.2.3 ROTARY COMPRESSORS

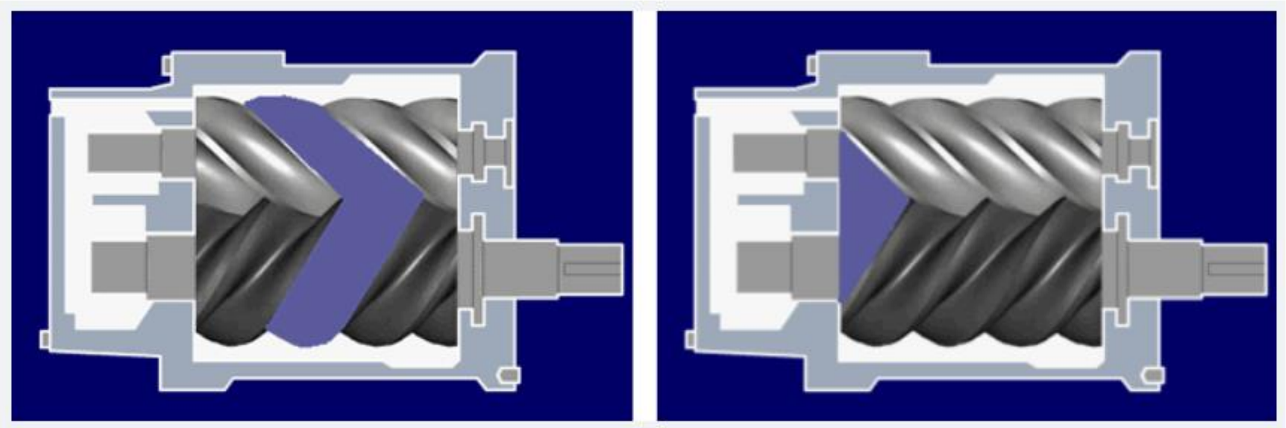
Rotary compressors also have a positive displacement. These low capacity types of equipment have applications in home freezers and refrigerators.

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:

11.2.4 - ROTARY SCREW COMPRESSORS

It uses two meshed helical screws in rotation to force the gas into a smaller space.

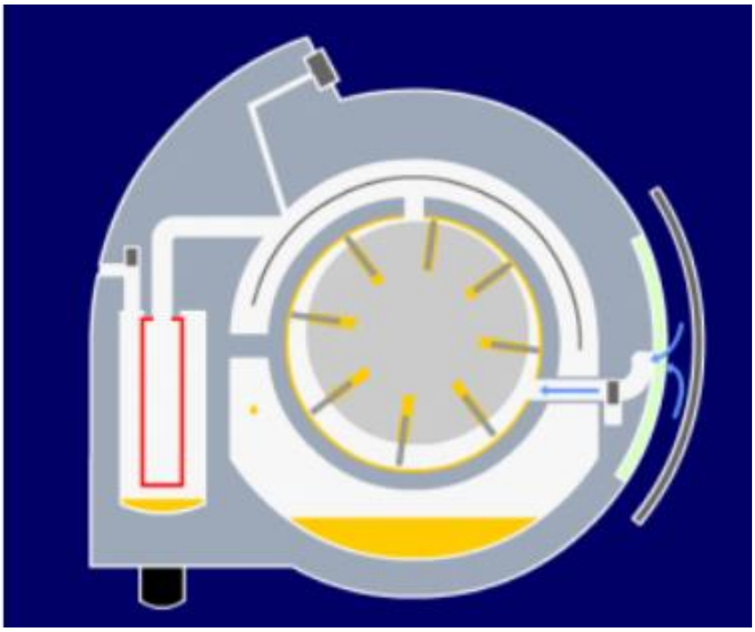


They can be employed in industrial and commercial purposes and their application can range between 3 horsepower (2.2 kW) to about 1,200 horsepower (890 kW).

Likewise, the discharge pressure can range between low to moderately high pressure (>1,200 psi or 8.3 MPa).

11.2.5 - 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.

11.2.6 - 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.

11.2.7 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.

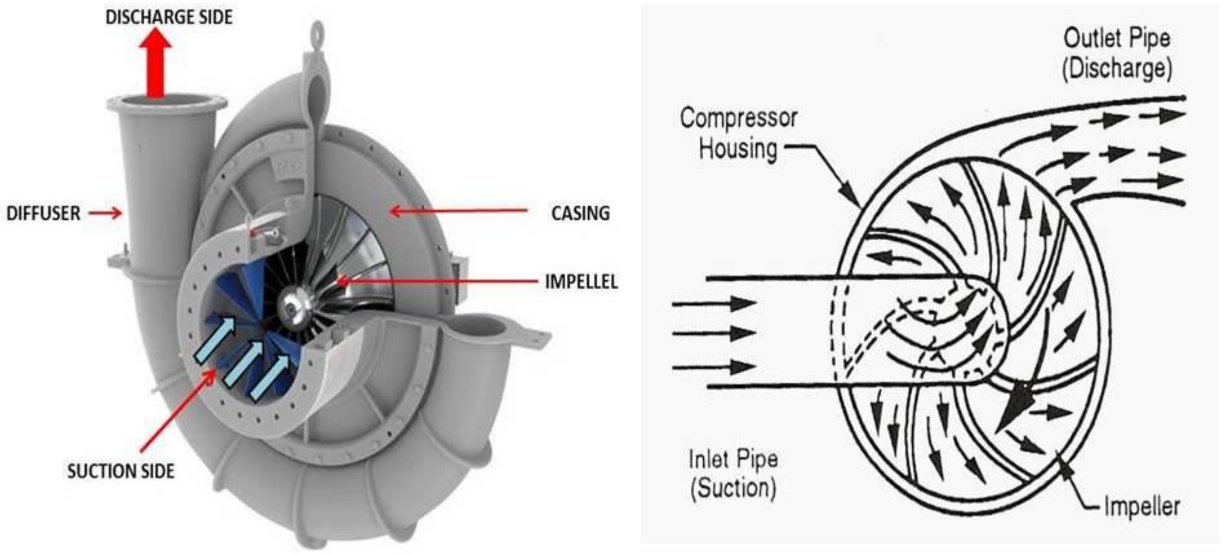
There are two basic types of dynamic compressors and these are:

A. Centrifugal compressors
B. Axial compressors

11.2.8 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

[21]

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).

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[21] https://www.mech4study.com/2017/11/centrifugal-compressor.html

Compressors

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.

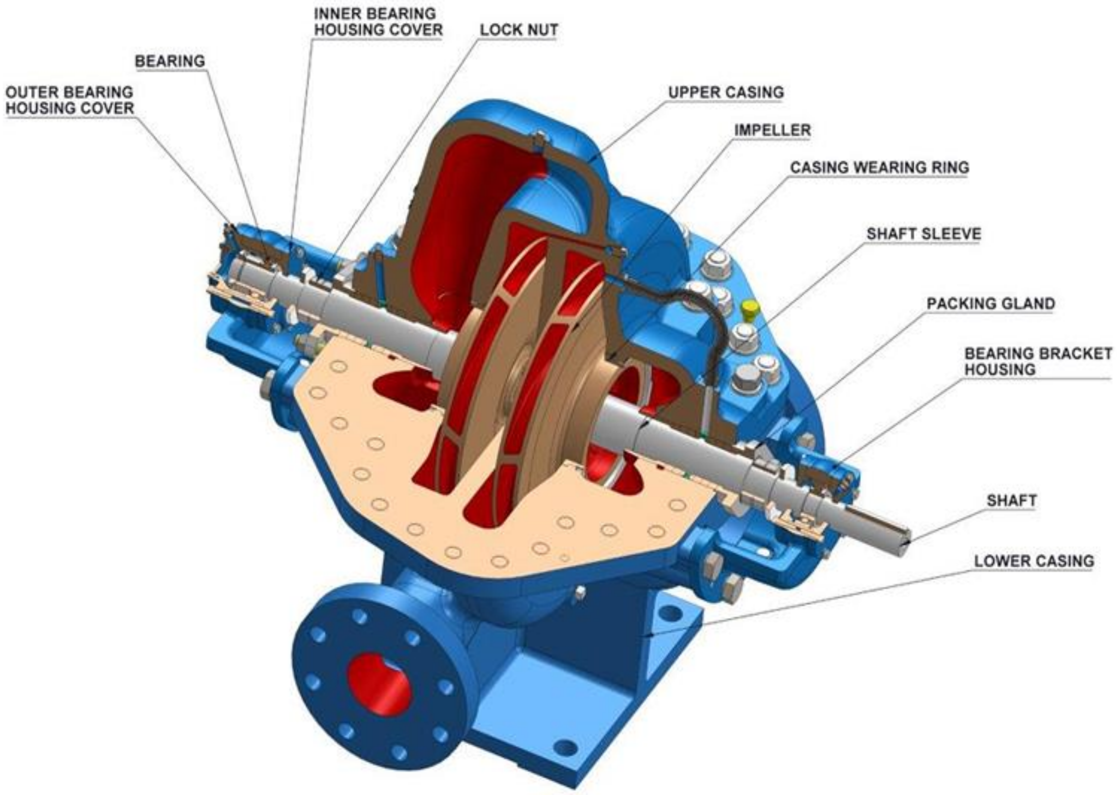
Centrifugal compressor also features two casing designs and these are:

11.2.9 - 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.



[22]

11.2.10 - 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.

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[22] https://www.flowmorepumps.com/product/horizontal-split-casing-pumps.html

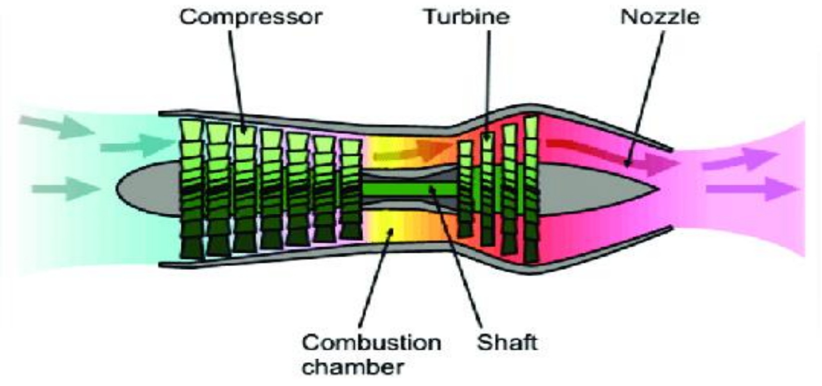
Here, the rotor bundle and the diaphragm seals are axially arranged in a steel barrel casing.

Generally, this design depends on the working pressure and the type of gas that is to be compressed.

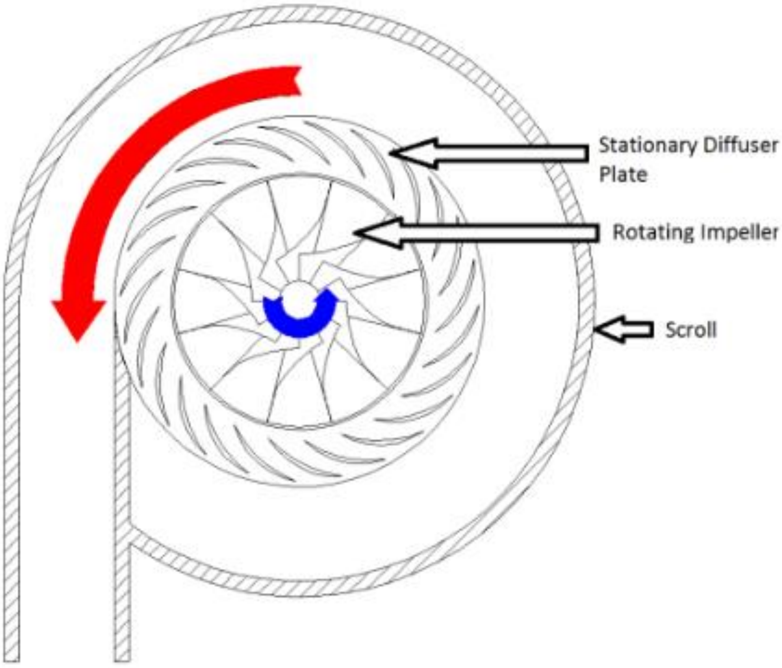
11.2.11 AXIAL-FLOW COMPRESSORS

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.



[23]



Axial Compressors-Centrifugal Compressors[24]

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[23] https://www.researchgate.net/figure/Axial-flow-compressor-engine_fig4_261477455

[24] https://cascousa.com/compressed-air-101/types-of-compressors/dynamic-displacement-compressors/

Compressors

When it comes to how this compressor works, gas is compressed with the use of an array of airfoils which are arranged in rows.

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.

11.2.12 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.

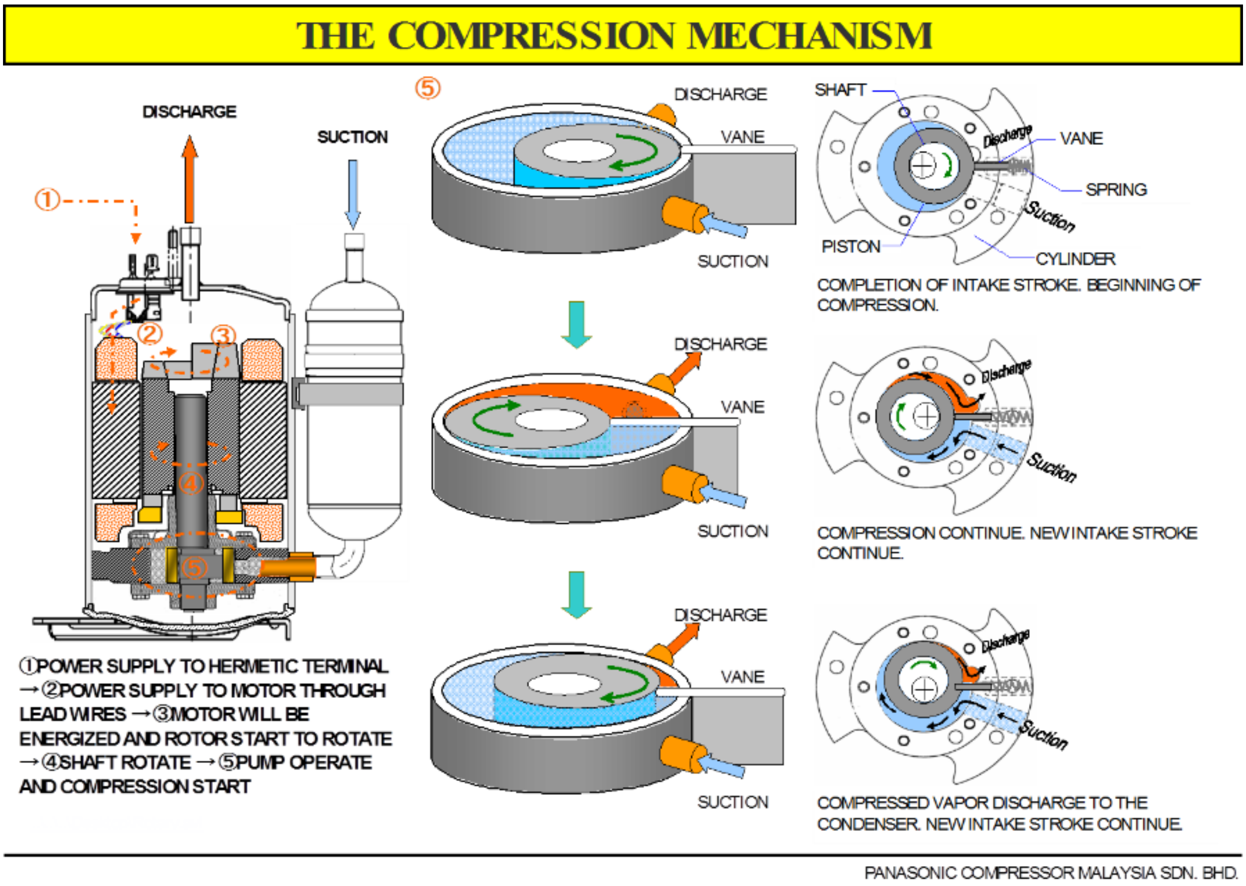
In comparison with other compressors, axial machines are relatively expensive since they require more parts and materials of high quality.

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.

11.2.13 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.

25

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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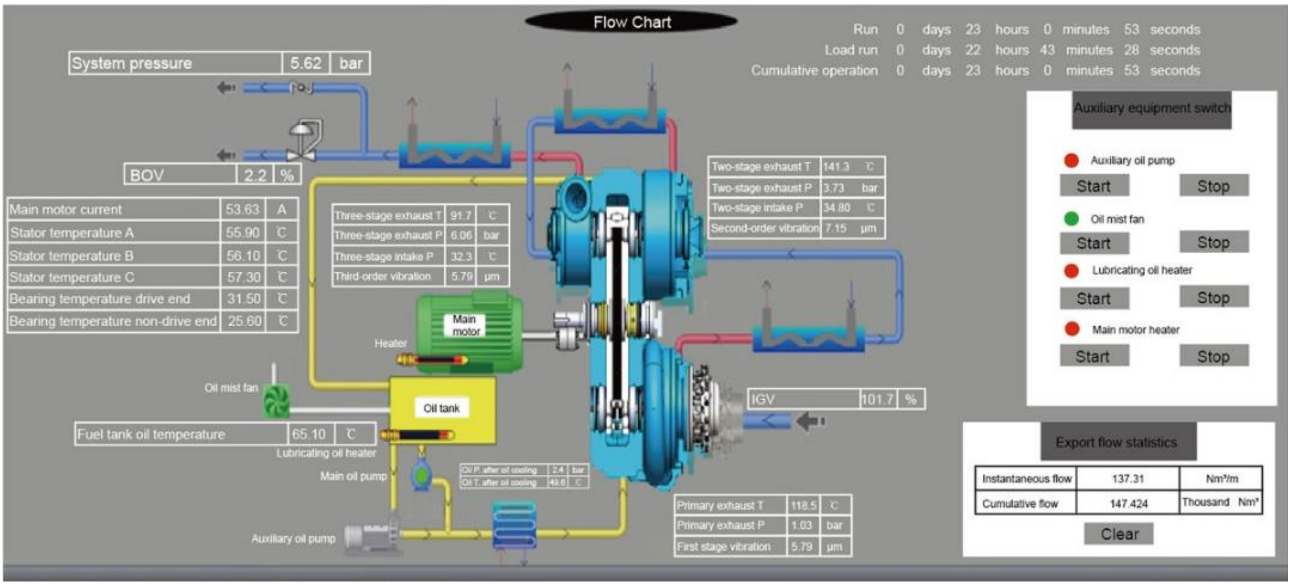
25 https://na.industrial.panasonic.com/complete-guide-rotary-compressors



Flow Chart

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	℃

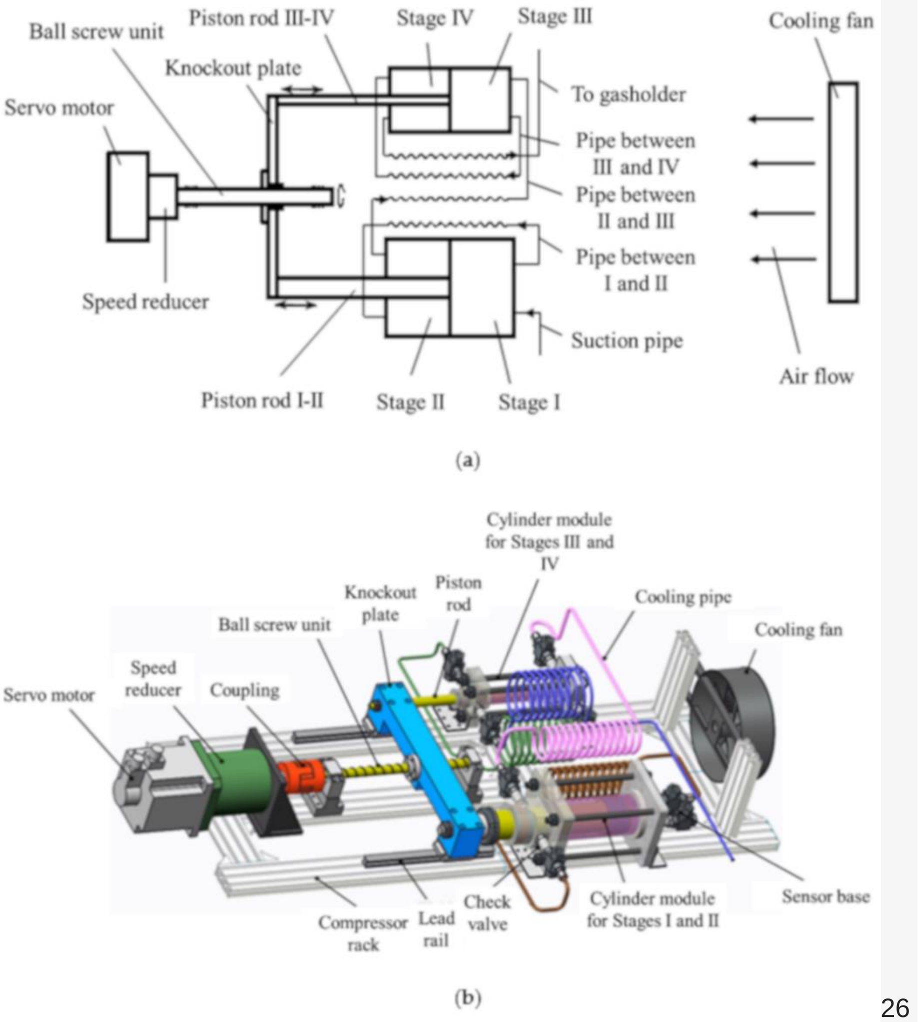
IGV 101.7 %

Primary exhaust T	118.5	℃
Primary exhaust P	1.03	bar
First stage vibration	5.79	μm

Auxiliary equipment switch
● Auxiliary oil pump
● Oil mist fan
● Lubricating oil heater
● Main motor heater

Export flow statistics

Instantaneous flow	137.31	Nm³/m
Cumulative flow	147.424	Thousand Nm³



*(**a**) Structural diagram and (**b**) 3D model of the multistage compressor unit.*[26]

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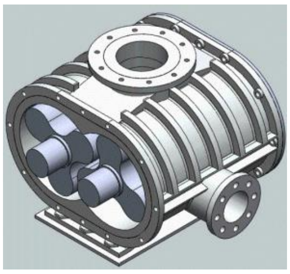
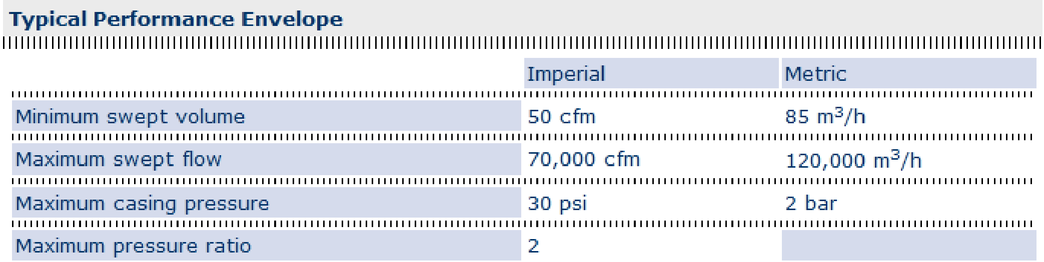
26 https://www.mdpi.com/1996-1073/13/1/112/htm

11.3 Gas compressors[27]

11.3.1 Positive displacement rotary blower



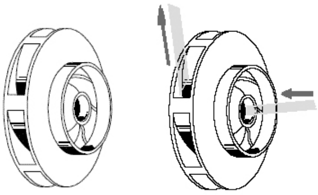
Two profiled rotors turn in a figure of eight shaped housing. They are geared together so that they run very close to each other, but cannot touch. There is no compression within the machine, it simply pushes gas into the system to which it is connected. Machines with semi-screw profile rotors are also available, which reduces noise and vibration.



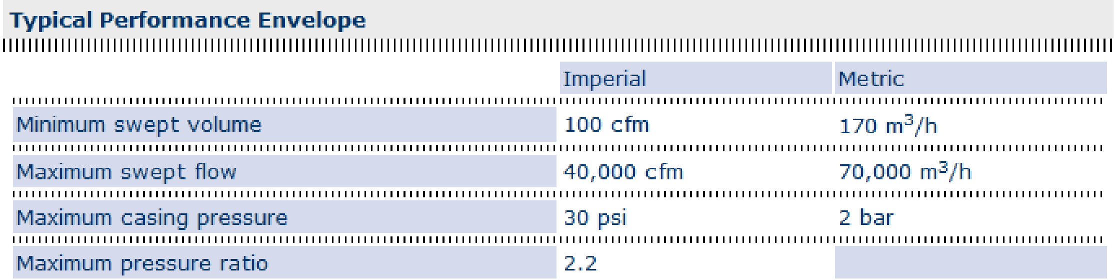
Typical Performance Envelope

	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	

11.3.2 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	

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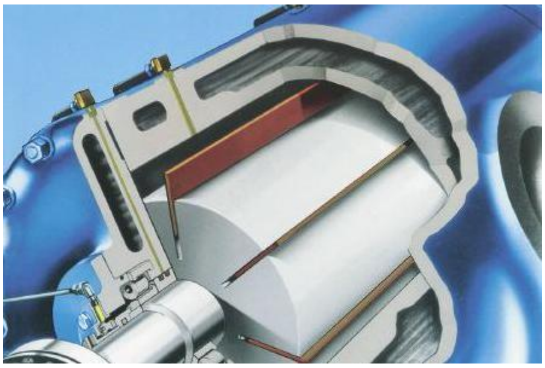
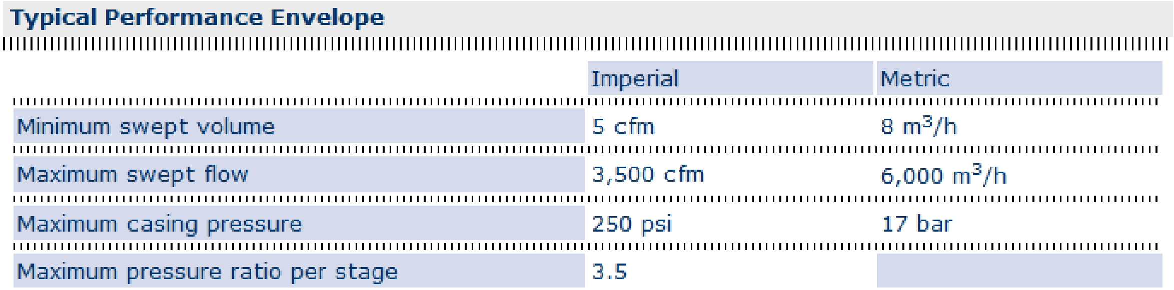
[27] http://www.gascompressors.co.uk/tech-osc.php

11.3.3 Rotary vane compressor



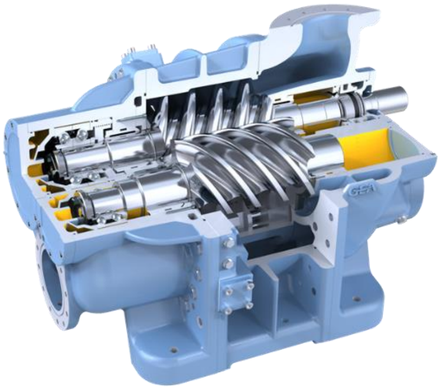
A single rotor is mounted offset in a cylindrical housing. Slots in the rotor contain vanes, which are thrown against the wall of the housing as it rotates. Oil is injected into the compression space to lubricate the bearings and vanes. As the rotor is offset, the segments that are created by the vanes 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.



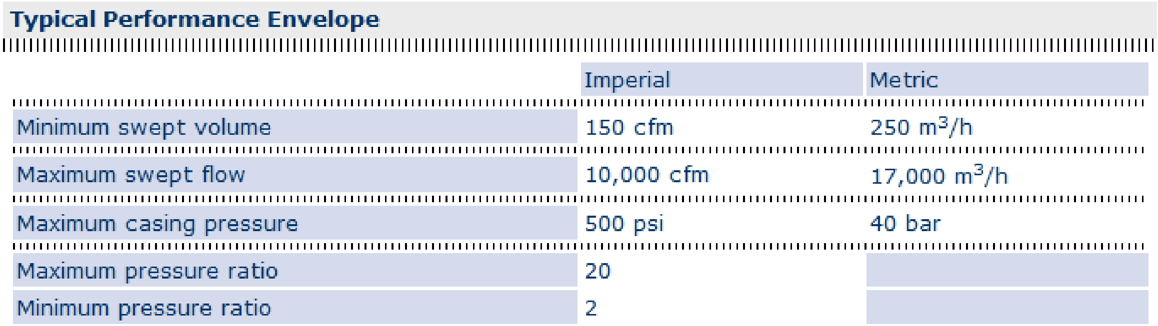
Typical Performance Envelope

	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	

11.3.4 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.

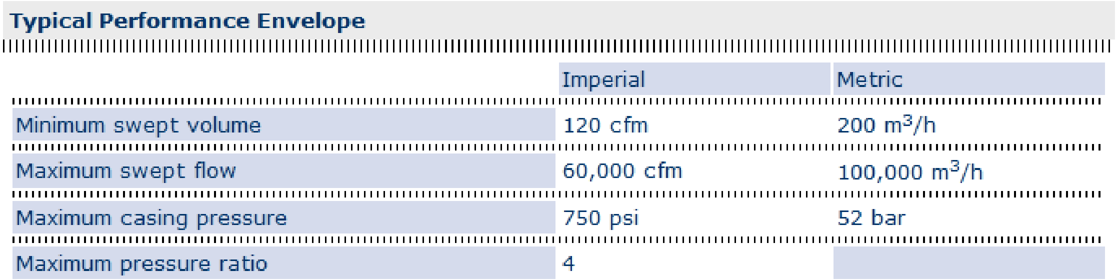


Typical Performance Envelope

	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	

11.3.5 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

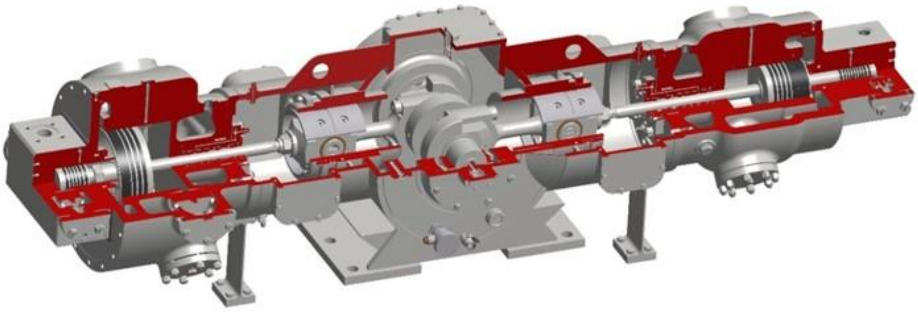
	Imperial	Metric
Minimum swept volume	120 cfm	200 m^3/h
Maximum swept flow	60,000 cfm	100,000 m^3/h
Maximum casing pressure	750 psi	52 bar
Maximum pressure ratio	4	

- 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.

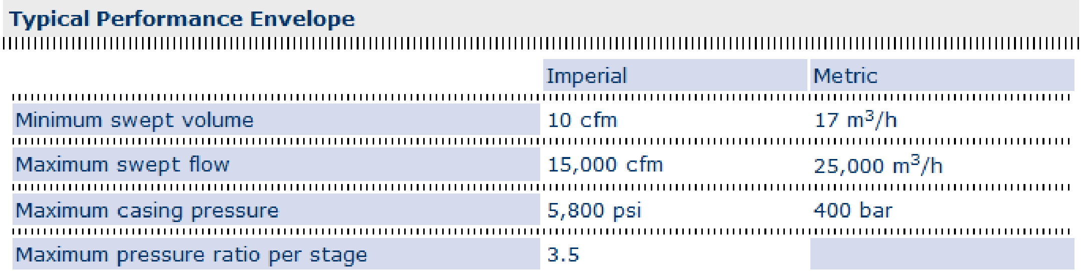
- Common applications
  - Refinery service.
  - Flare gas recovery.

11.3.6 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.

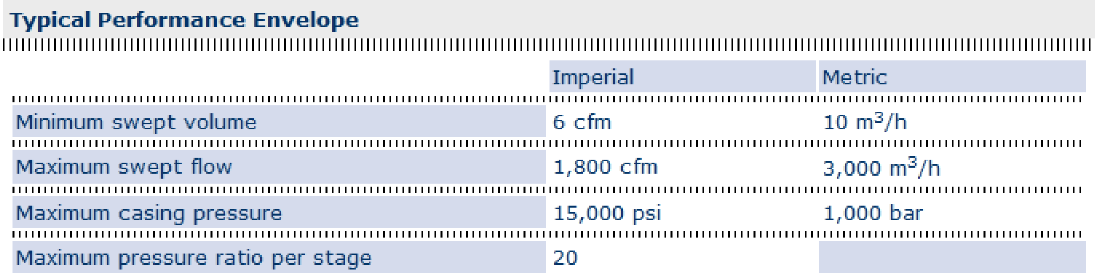


Typical Performance Envelope

	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.

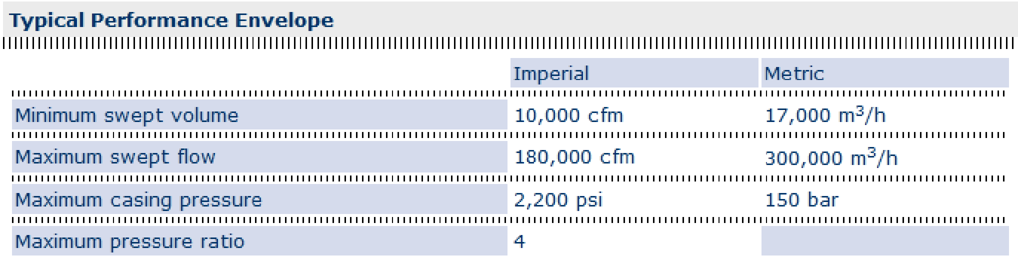


Typical Performance Envelope

	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	

11.3.7 Centrifugal compressor

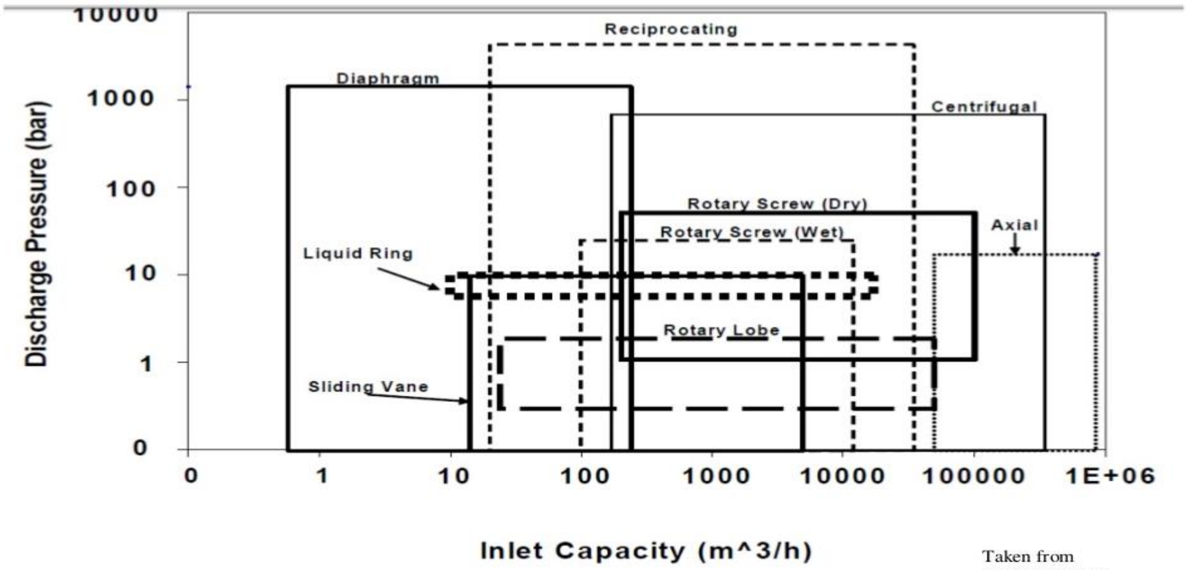
An impeller is attached to a rotating shaft within a cylindrical housing. Gas drawn into the housing near the centre, is then thrown towards the perimeter. The imparted velocity of the gas causes a pressure rise and flow. Multi-stage machines direct the gas back to the centre of the next stage. Differs 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	

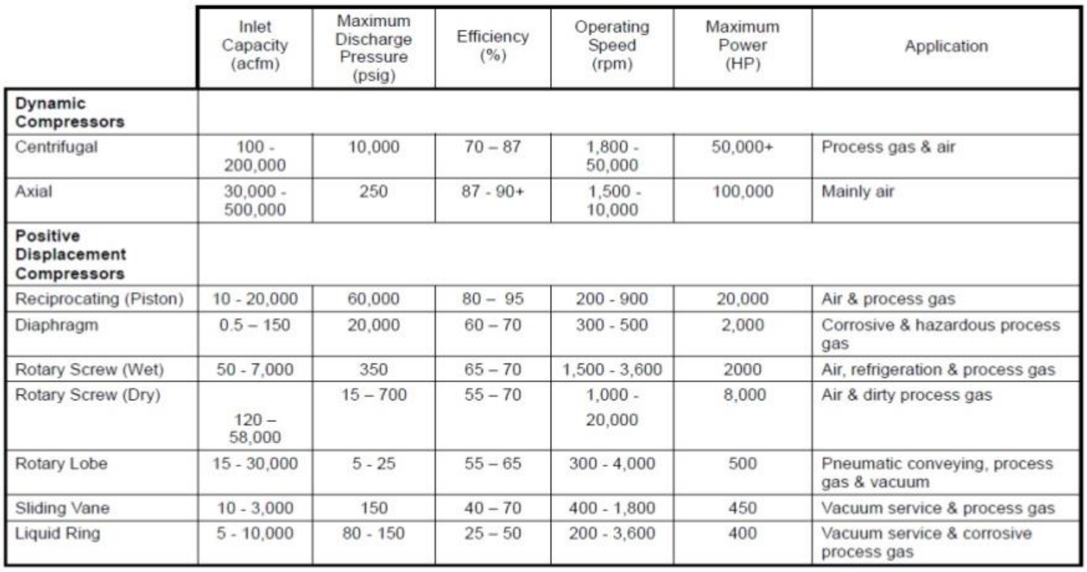
Graph showing operating regions of various compressors



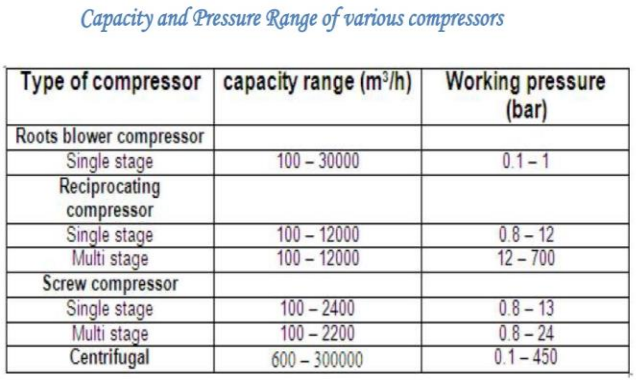
Taken from
PIP REEC001
Compressor Selection

Table showing operating conditions of various compressors

Table 1b. Summary of Typical Operating Characteristics of Compressors (US Units)

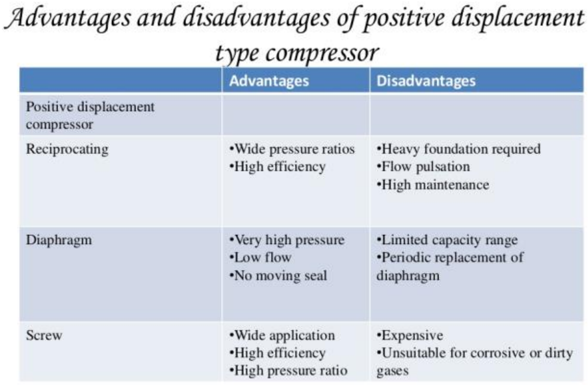


	Inlet Capacity (acfm)	Maximum Discharge Pressure (psig)	Efficiency (%)	Operating Speed (rpm)	Maximum Power (HP)	Application
Dynamic Compressors						
Centrifugal	100 - 200,000	10,000	70 – 87	1,800 - 50,000	50,000+	Process gas & air
Axial	30,000 - 500,000	250	87 - 90+	1,500 - 10,000	100,000	Mainly air
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



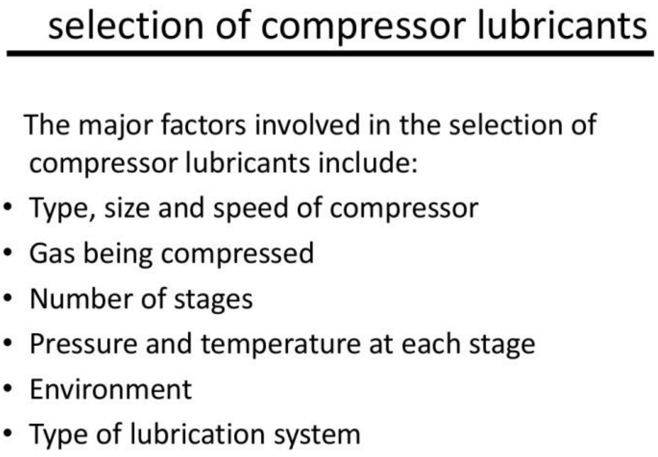
Capacity and Pressure Range of various compressors

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

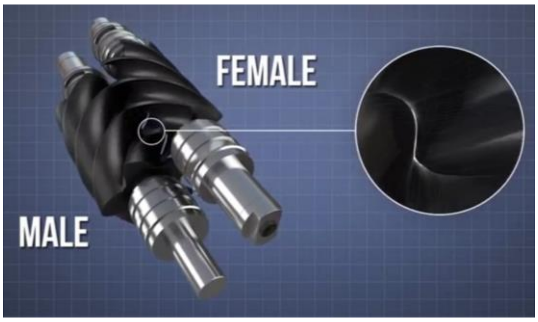


selection of compressor lubricants

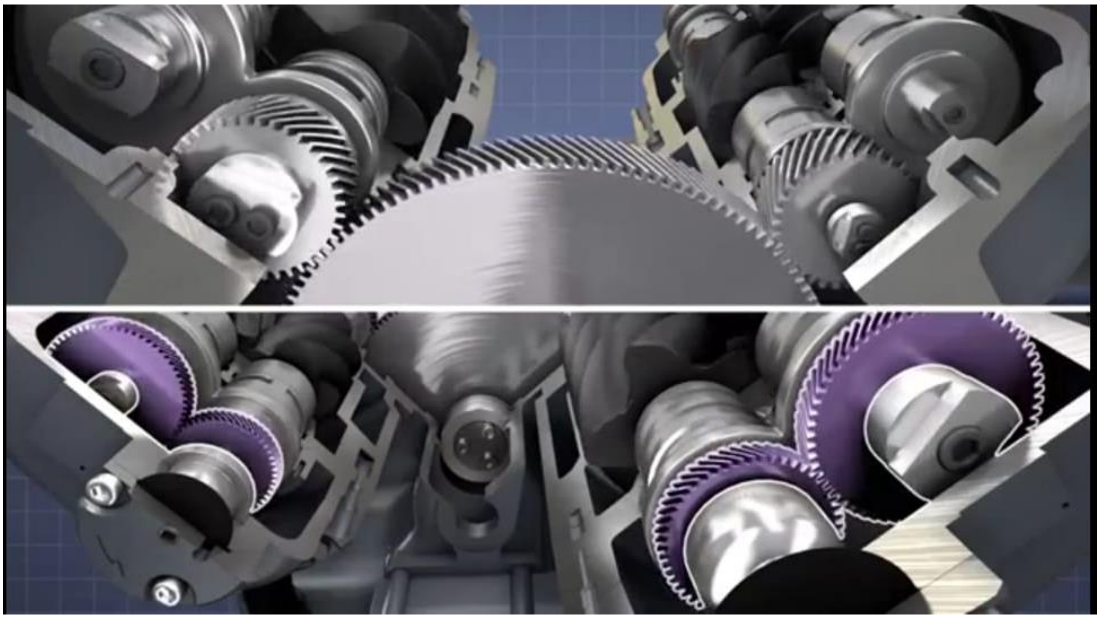
The major factors involved in the selection of compressor lubricants include:

- Type, size and speed of compressor
- Gas being compressed
- Number of stages
- Pressure and temperature at each stage
- Environment
- Type of lubrication system

11.4 Oil-free screw air compressor process

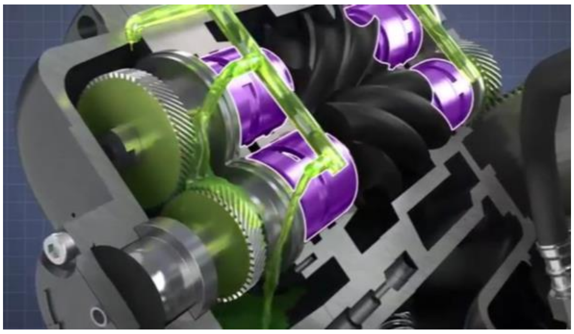


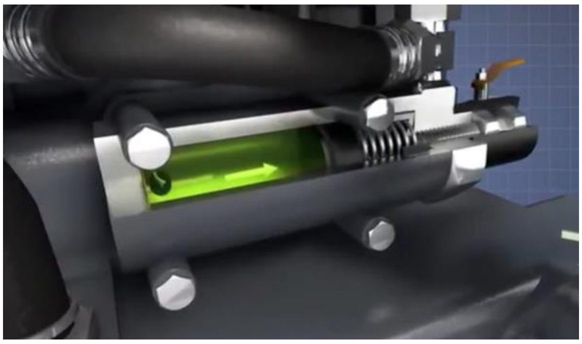
The oil-free industrial air compressor is a two-stage oil-free compressor unit. both compression stages comprise male and female rotors, with special protective coating. there's no physical contact either between the matched rotor pairs or the rotors and the air and casing. everything is separated by 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.

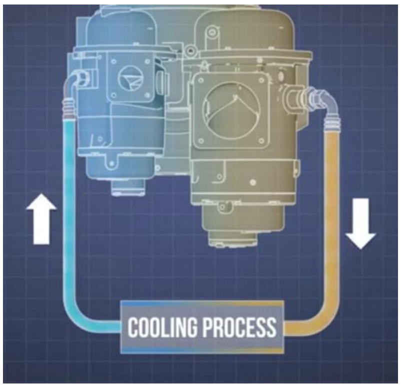
Hot oil drains to an oil reservoir located below the air and via to oil returned pipes. The hot oil is then pumped to a cooler and returns to the air environ oil filter. A pressure relief valve fitted to the front of the air and ensures that oil pressure doesn't exceed 2.5 bar or 36 psi.





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.



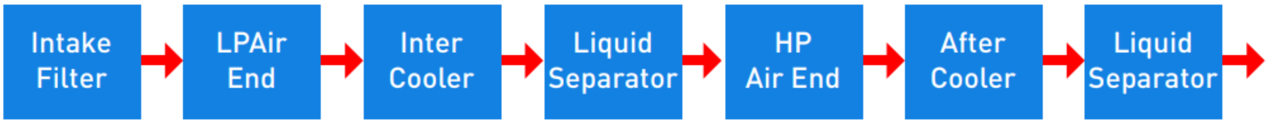
When cooled, the air contract providing a greater number of air molecules in the same volume, this results in more efficient second stage compression. The cooled compressed air passes through a moisture separator, then on to the inlet port of the second stage. The volume of the air is greatly reduced 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.

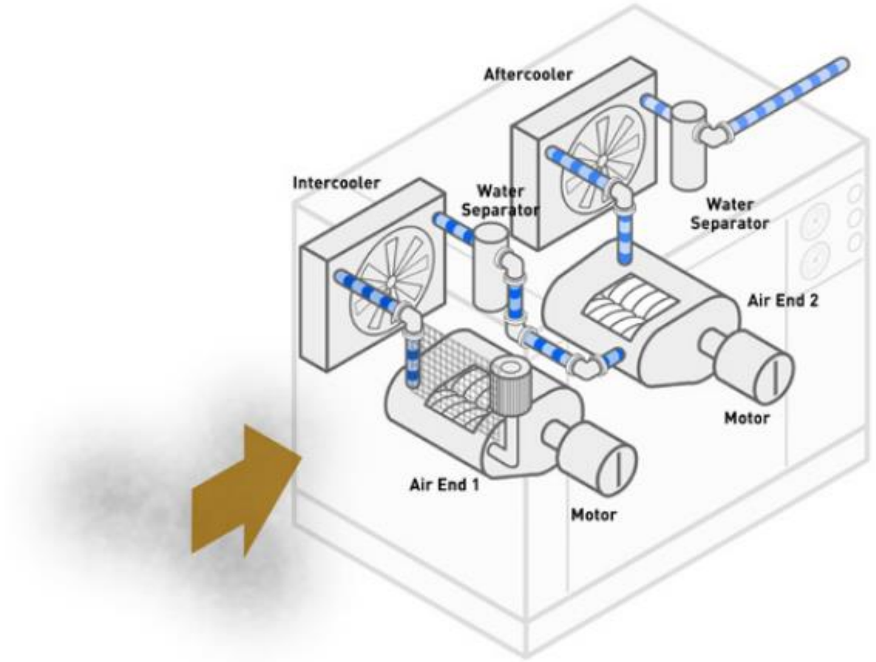
The air then passes through a final second stage air or water cooling process to ensure the delivery air is at the right temperature. Then after a final journey through a moisture separator, the air is ready to exit the compressor at the delivery port.

11.5 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





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

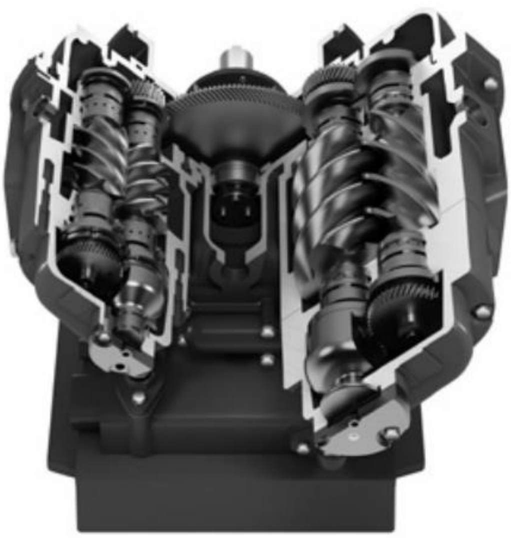
Compression

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.

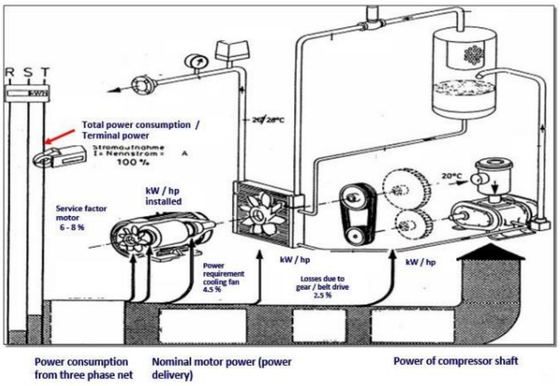
For example, on a typical oil free rotary screw compressor with 2 compression stages, an intercooler and aftercooler. Stage 1 will typically compress the air up to a pressure around 3.5 bar g, stage 2 will then compress the air to the discharge pressure of 7 bar g.

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.

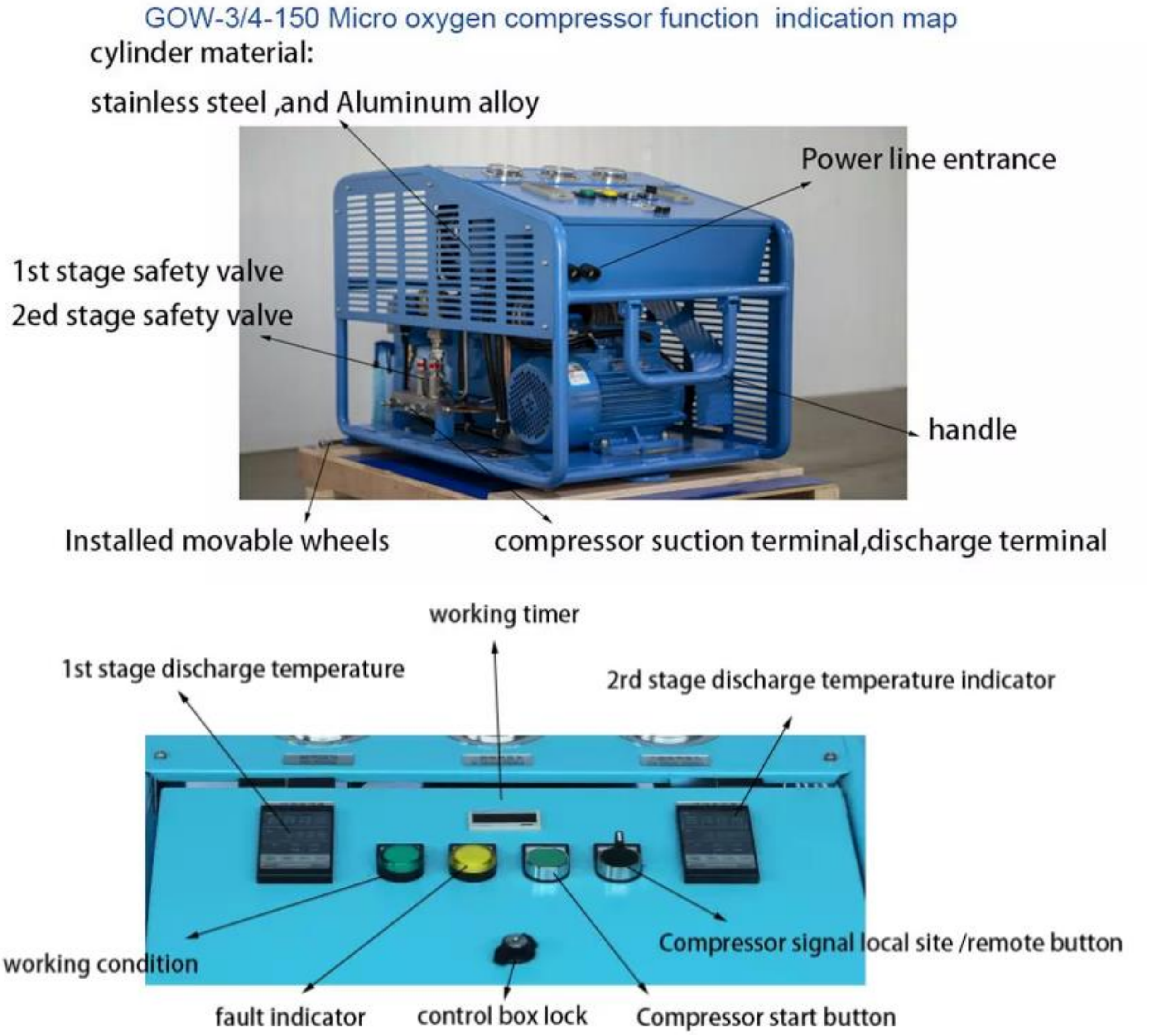
Oil Reclamation (Air / Oil Separator)

As there is no oil used in the compression stage, there is no requirement for an air / oil separator on an oil free compressor.



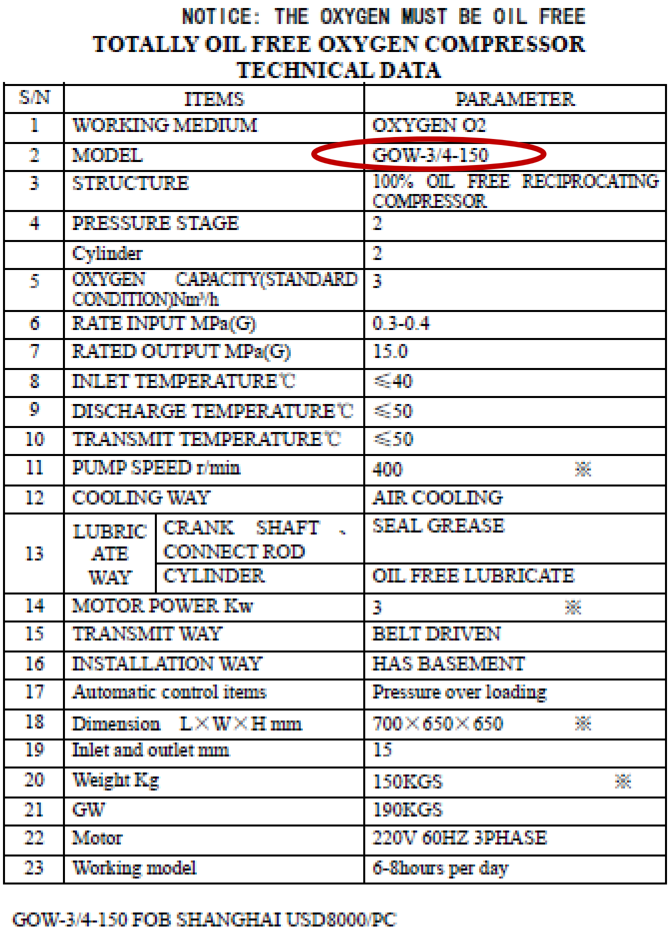
Compressor #1: (info completed)

https://www.oxygen-compressors.com/2m3-High-Pressure-Industrial-Booster-Oxygen-Compressor-pd46014866.html



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



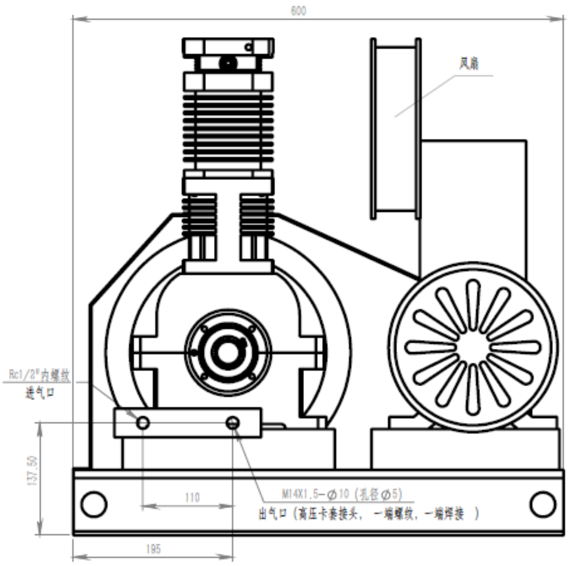
NOTICE: THE OXYGEN MUST BE OIL FREE

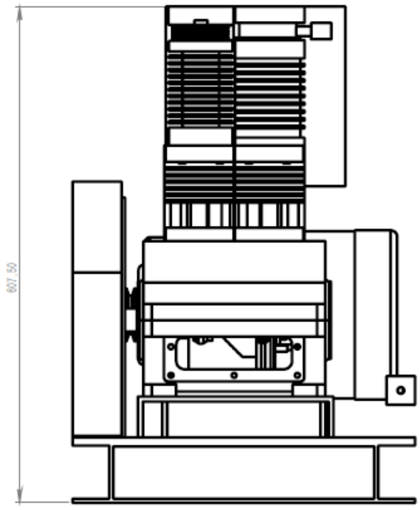
TOTALLY OIL FREE OXYGEN COMPRESSOR

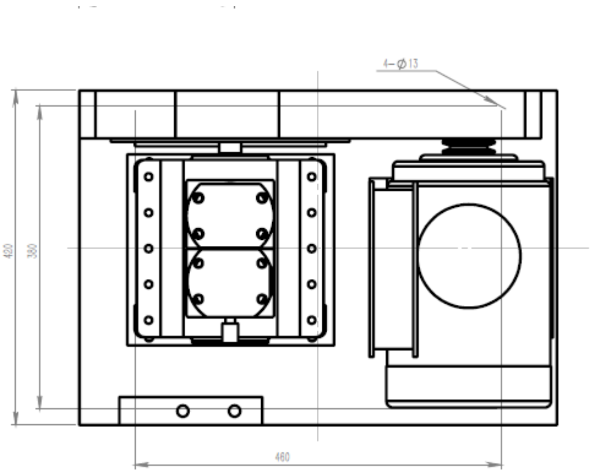
TECHNICAL DATA

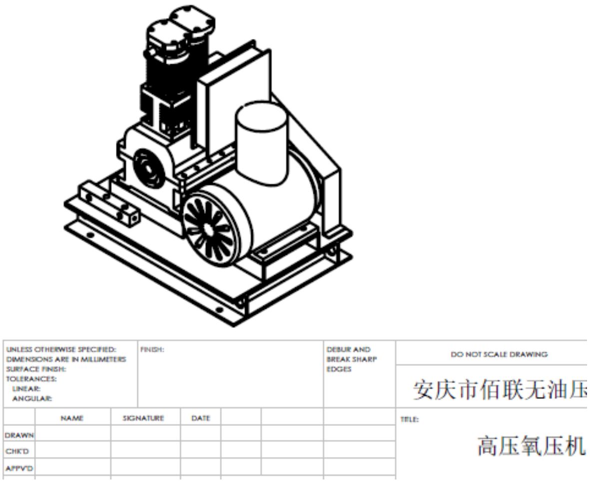
S/N	ITEMS		PARAMETER
1	WORKING MEDIUM		OXYGEN O2
2	MODEL		GOW-3/4-150
3	STRUCTURE		100% OIL FREE RECIPROCATING COMPRESSOR
4	PRESSURE STAGE		2
	Cylinder		2
5	OXYGEN CAPACITY(STANDARD CONDITION)Nm³/h		3
6	RATE INPUT MPa(G)		0.3-0.4
7	RATED OUTPUT MPa(G)		15.0
8	INLET TEMPERATURE℃		≤40
9	DISCHARGE TEMPERATURE℃		≤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



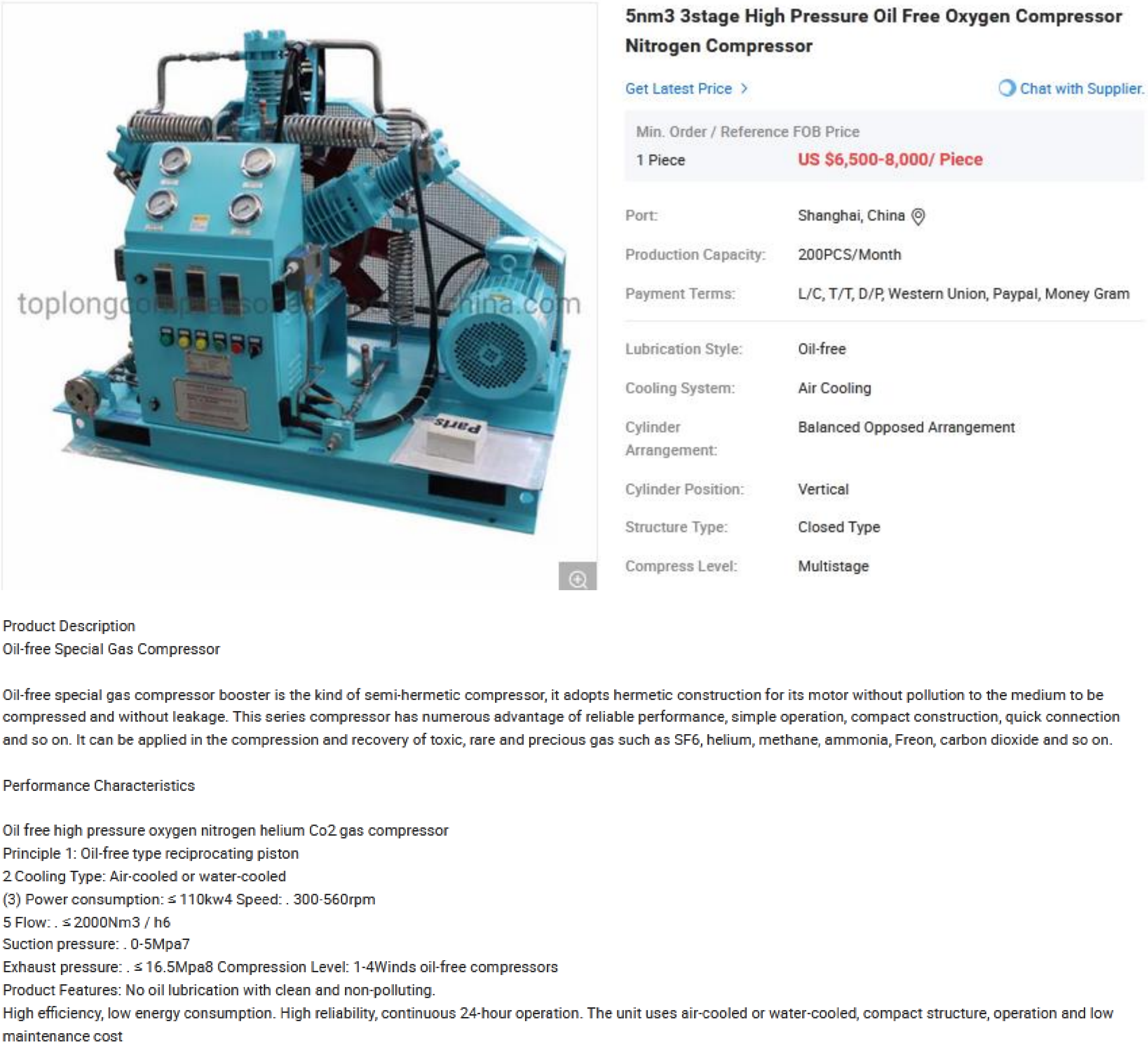






Compressor #2: (info uncompleted)

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

Min. Order / Reference FOB Price	
1 Piece	US $6,500-8,000/ Piece

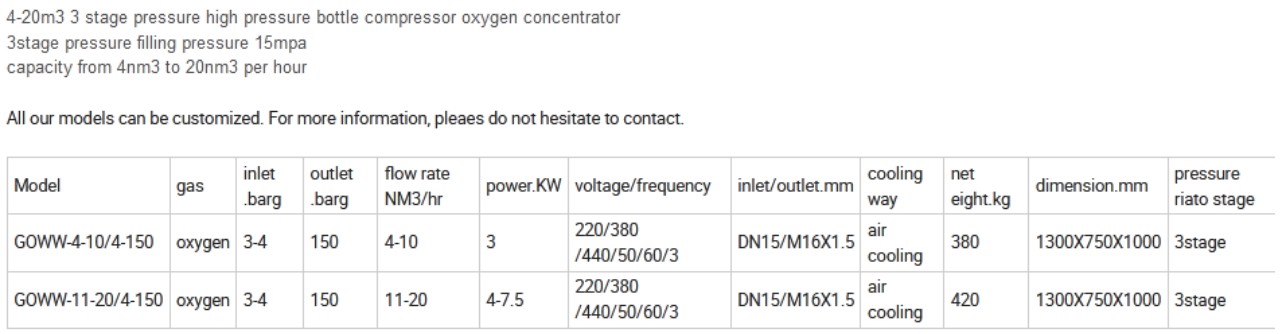
Port:	Shanghai, China
Production Capacity:	200PCS/Month
Payment Terms:	L/C, T/T, D/P, Western Union, Paypal, Money Gram
Lubrication Style:	Oil-free
Cooling System:	Air Cooling
Cylinder Arrangement:	Balanced Opposed Arrangement
Cylinder Position:	Vertical
Structure Type:	Closed Type
Compress Level:	Multistage

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



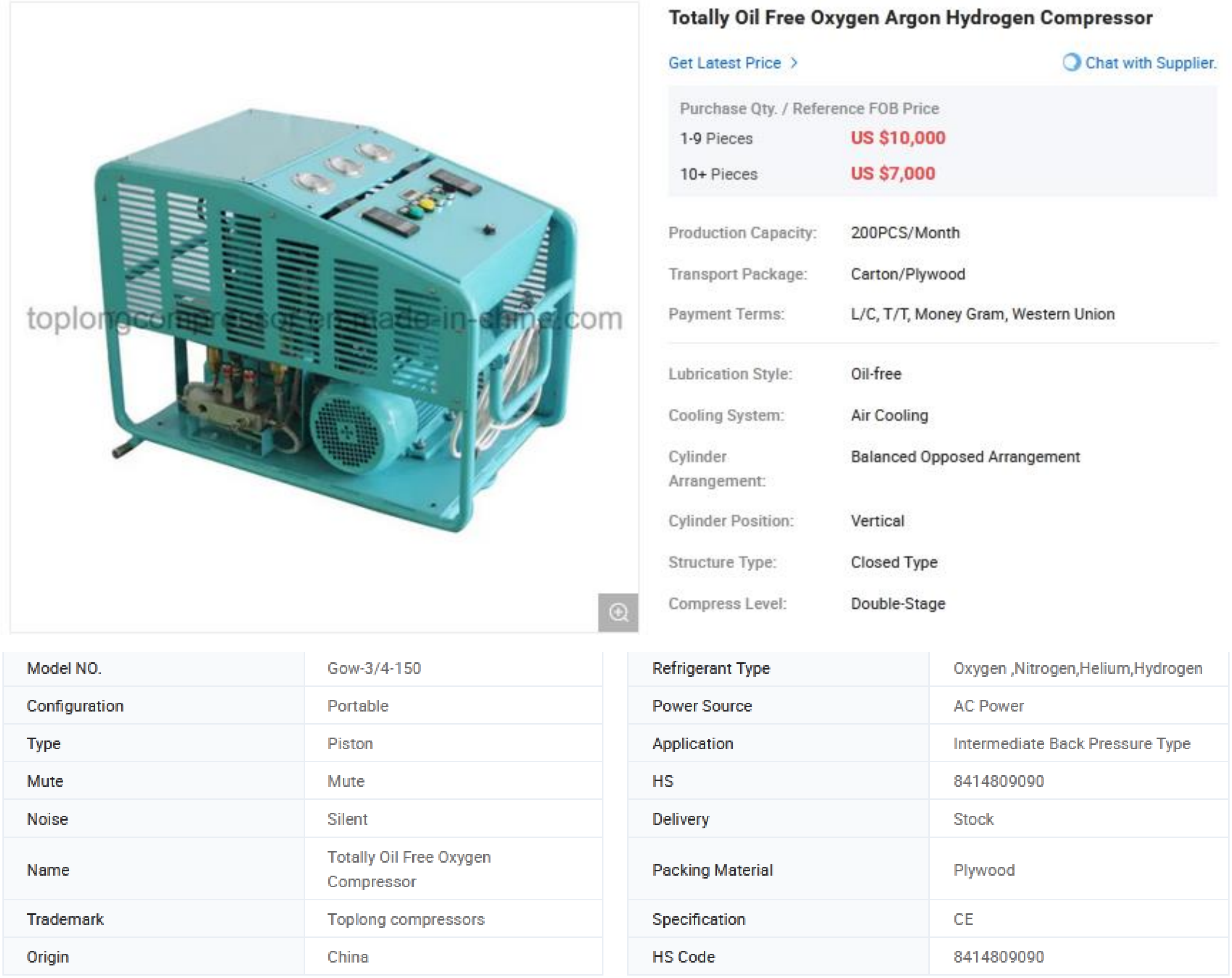
4-20m3 3 stage pressure high pressure bottle compressor oxygen concentrator
3stage pressure filling pressure 15mpa
capacity from 4nm3 to 20nm3 per hour

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



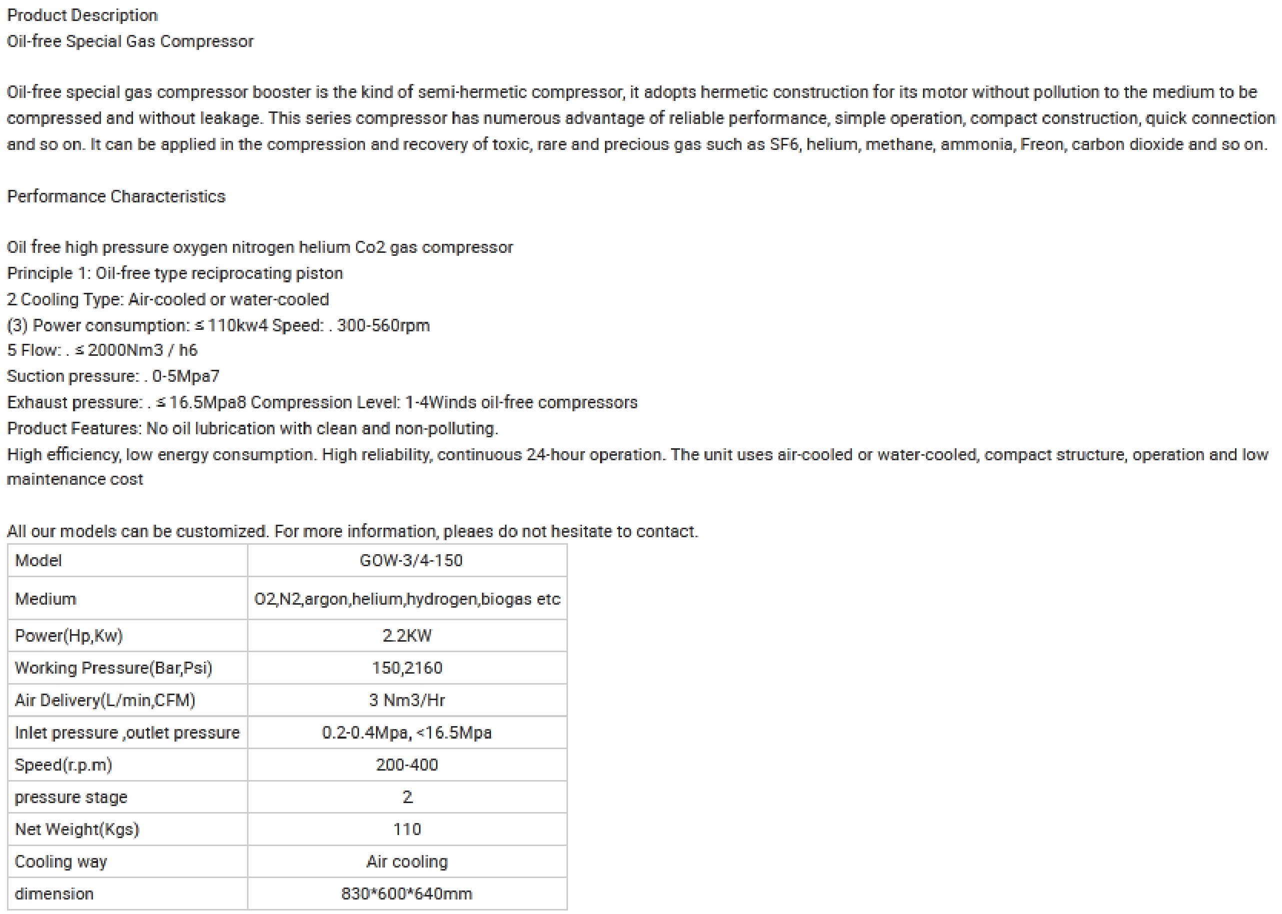
Totally Oil Free Oxygen Argon Hydrogen Compressor

Get Latest Price >
Chat with Supplier.

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

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Principle 1: Oil-free type reciprocating piston
2 Cooling Type: Air-cooled or water-cooled
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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

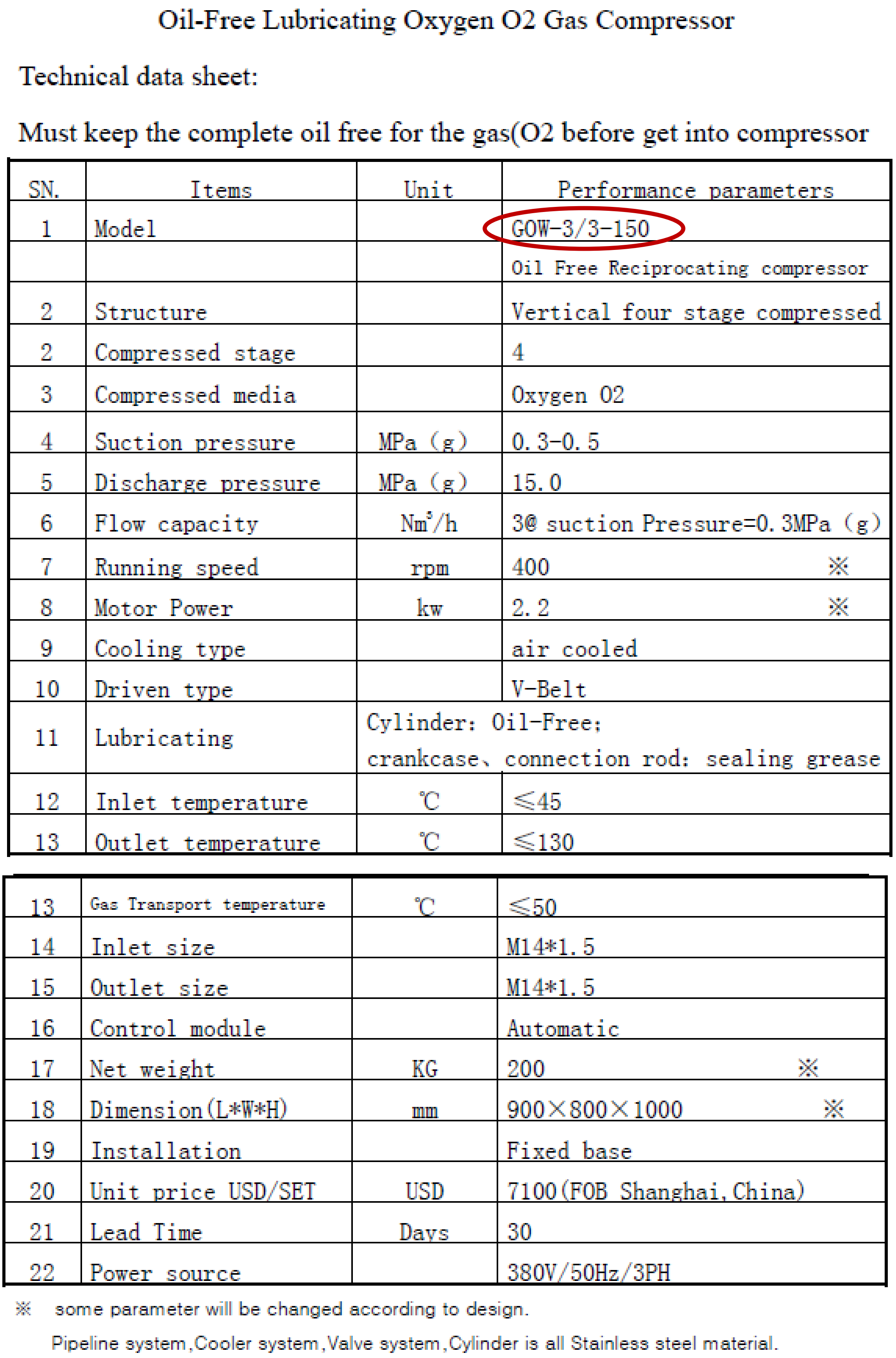
Compressor #4: (same family of compressor #1)

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:

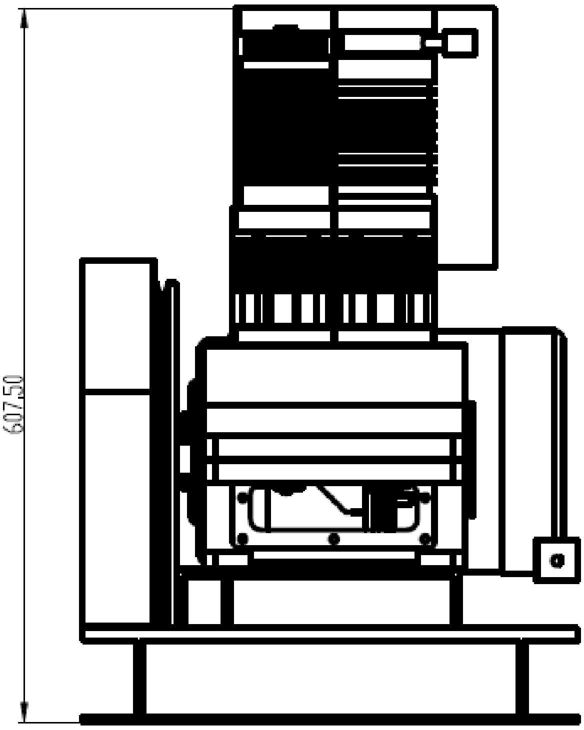
Must keep the complete oil free for the gas(O2 before get into compressor

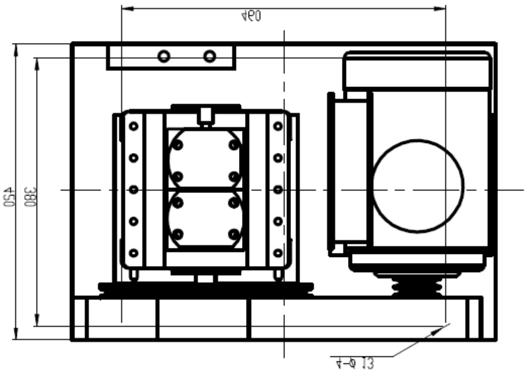
SN.	Items	Unit	Performance parameters
1	Model		GOW-3/3-150
			Oil Free Reciprocating compressor
2	Structure		Vertical four stage compressed
2	Compressed stage		4
3	Compressed media		Oxygen O2
4	Suction pressure	MPa（g）	0.3-0.5
5	Discharge pressure	MPa（g）	15.0
6	Flow capacity	Nm^3/h	3@ suction Pressure=0.3MPa（g）
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

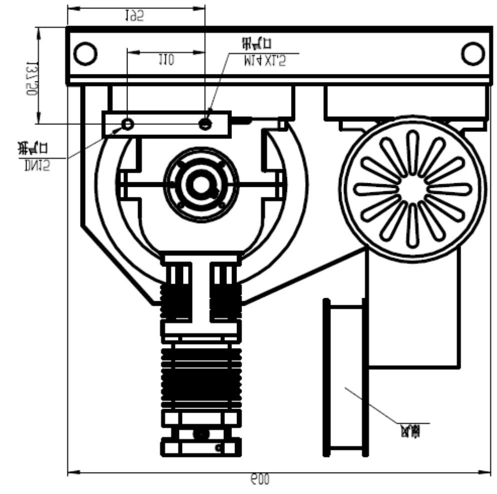
※ some parameter will be changed according to design.

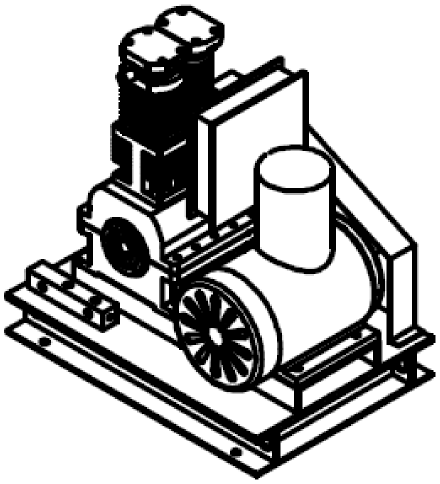
Pipeline system,Cooler system,Valve system,Cylinder is all Stainless steel material.

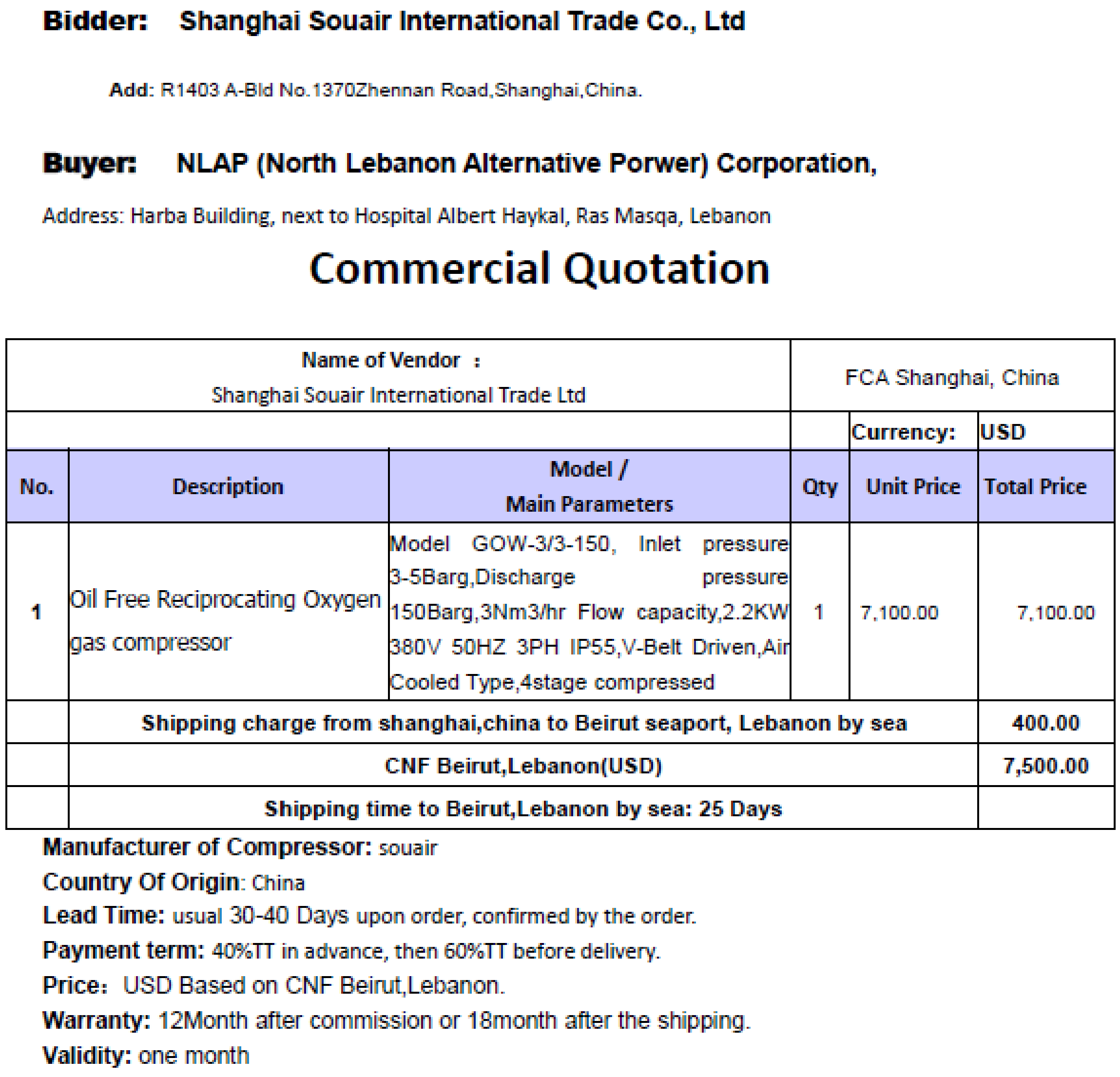
GOW-3/4-150











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

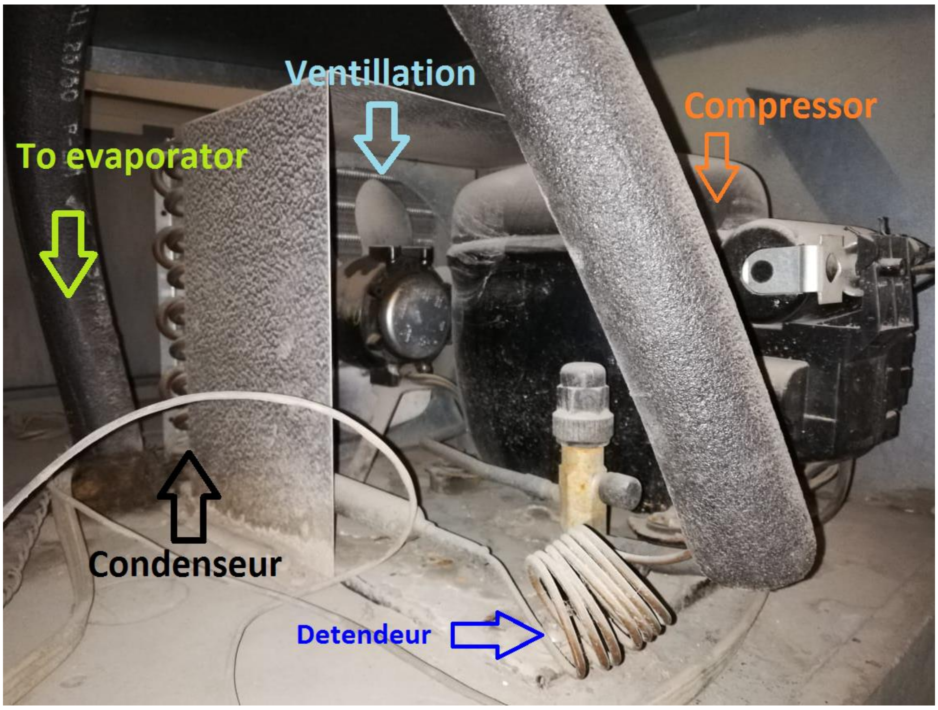
Oxywise Answer: (Monday 15.3.2021)
I'm sorry we don't have a RIX unit that small.
I can offer an unbranded CE marked Oxygen compressor?
Price is circa €8k. Leadtime 5 weeks.

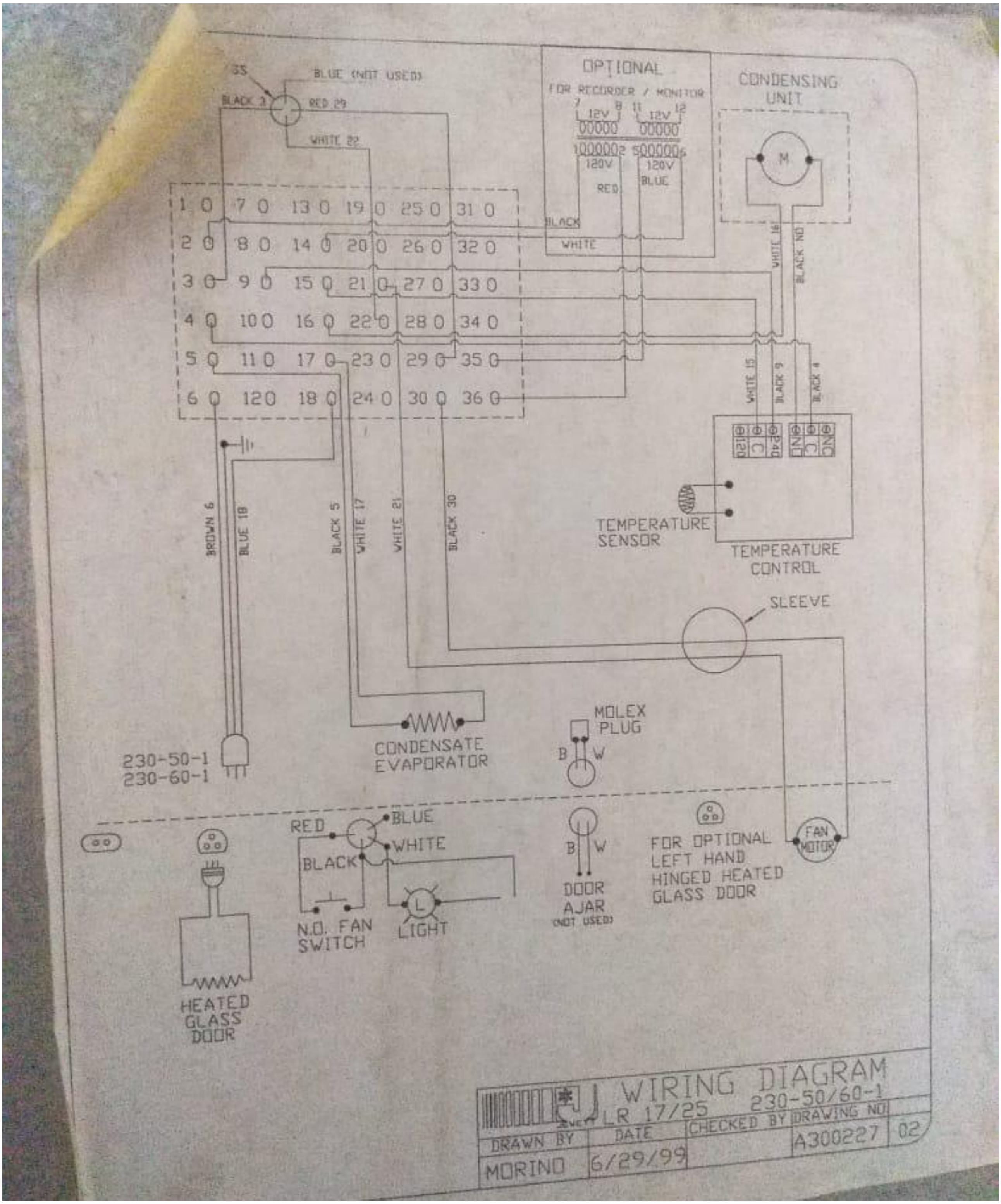
12 Calculation of Oxygen flow rate outlet by electrolysis:

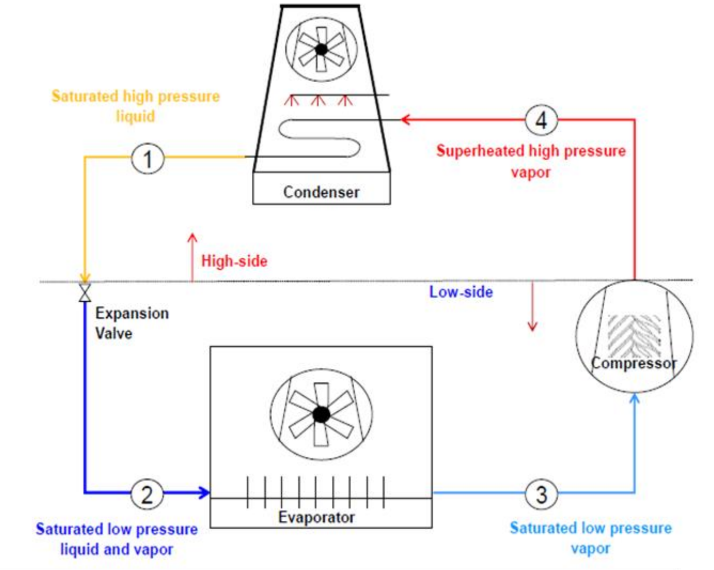
- Power :2.4 kW (voltage =4V; current = 150 A)
    - Gas flow rate Hydrogen all stacks = 2.27 L/min =136.2 L/hr
    - **Gas flow rate Oxygen all stacks = 1.13 L/min = 67.8 L/hr**
- Power : 25 kW
    - Gas flow rate Hydrogen all stacks = 23.65 L/min = 1418.75 L/hr
    - **Gas flow rate Oxygen all stacks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

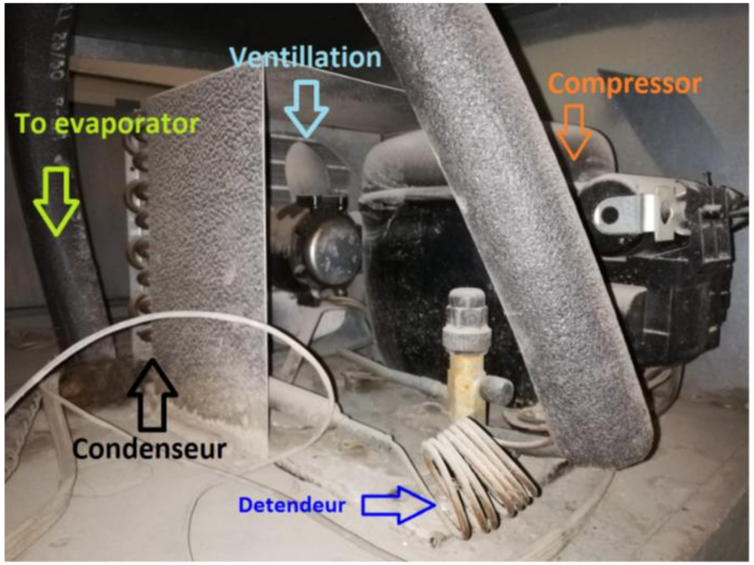
13 Analysis of refrigerator devices in AECENAR Center

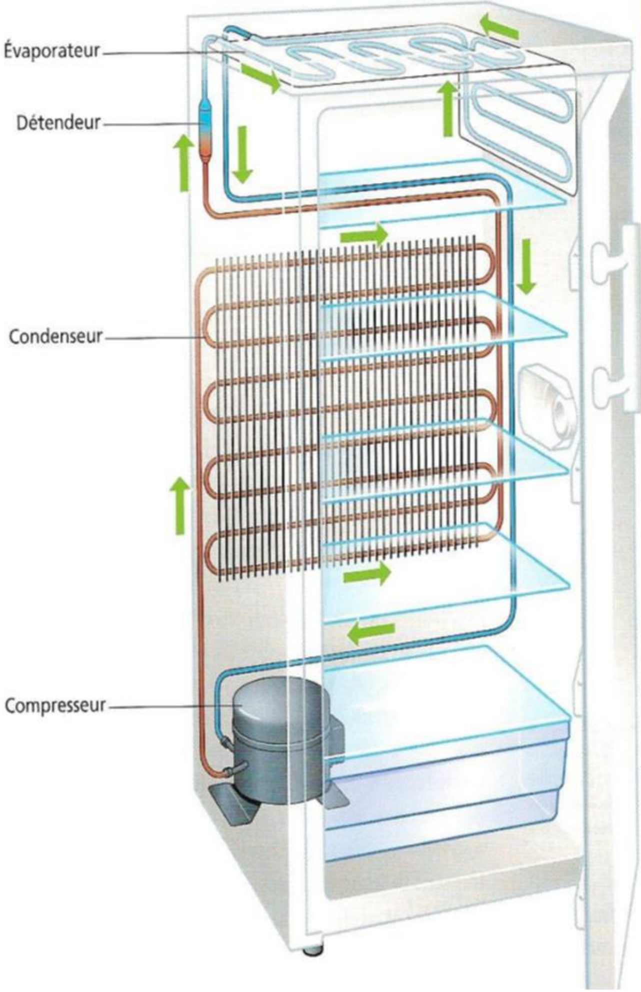
13.1 Device1 : Laboratory fridge

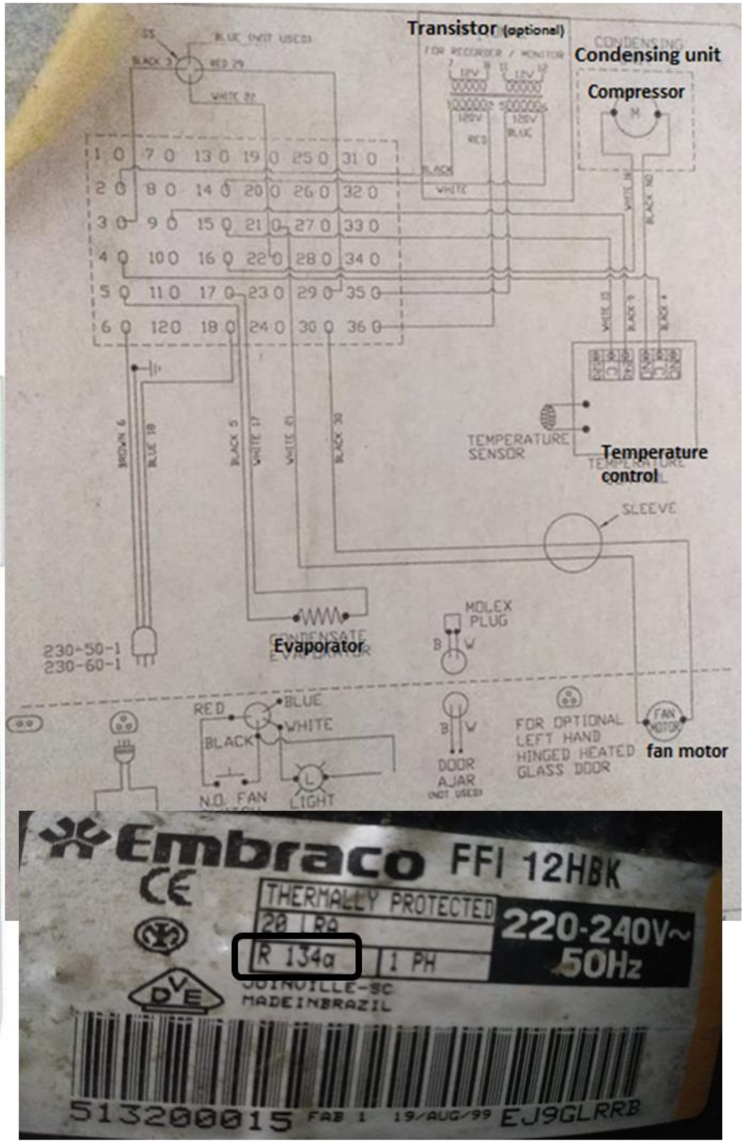


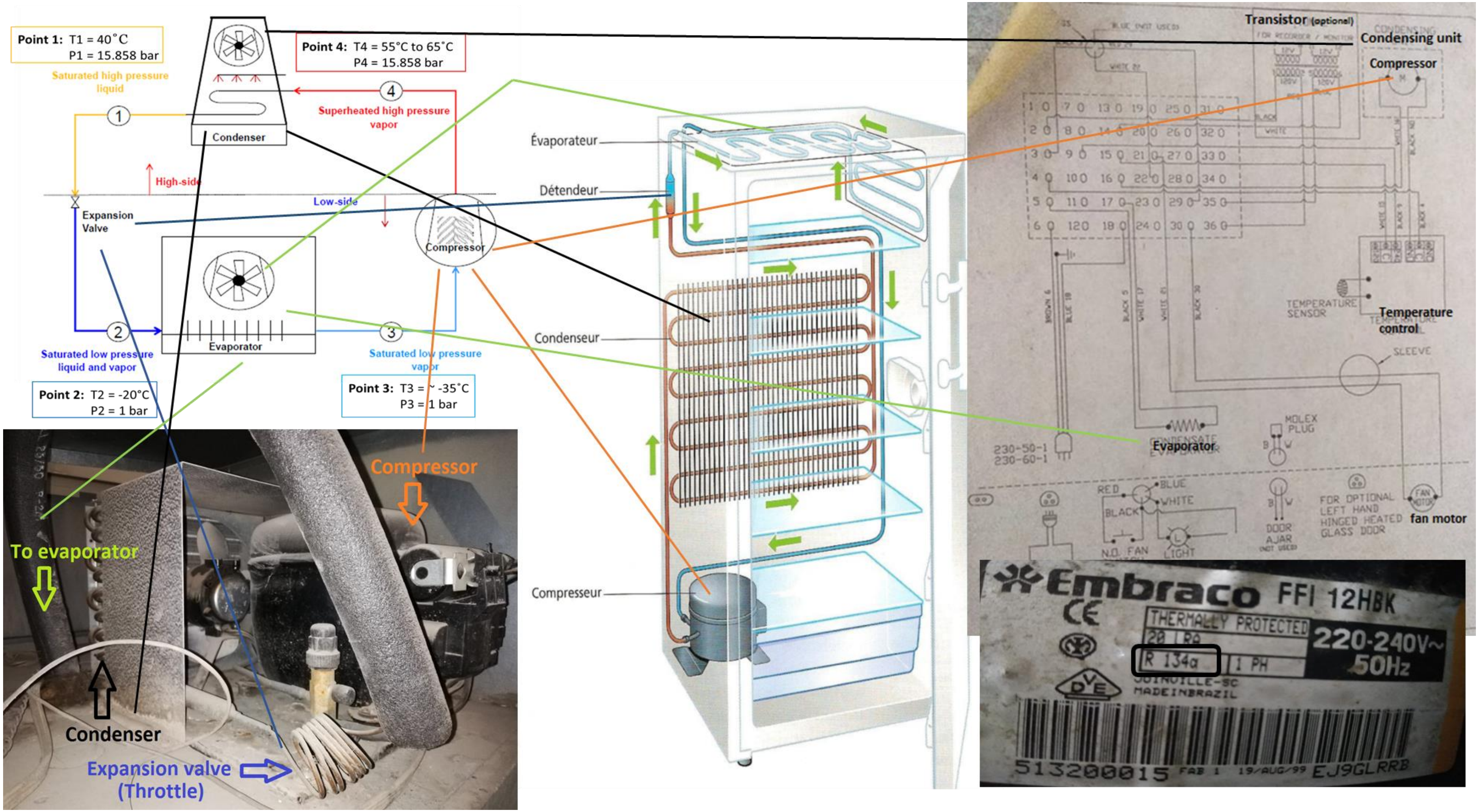

SS
BLUE (NOT USED)
BLACK 3
RED 29
WHITE 22
OPTIONAL
FOR RECORDER / MONITOR
7
8
11
12
12V
12V
1
2
5
6
120V
120V
RED
BLUE
BLACK
WHITE
CONDENSING UNIT
M
WHITE 16
BLACK NO
1 0
7 0
13 0
19 0
25 0
31 0
2 0
8 0
14 0
20 0
26 0
32 0
3 0
9 0
15 0
21 0
27 0
33 0
4 0
10 0
16 0
22 0
28 0
34 0
5 0
11 0
17 0
23 0
29 0
35 0
6 0
12 0
18 0
24 0
30 0
36 0
WHITE 15
BLACK 9
BLACK 4
120
C
240
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

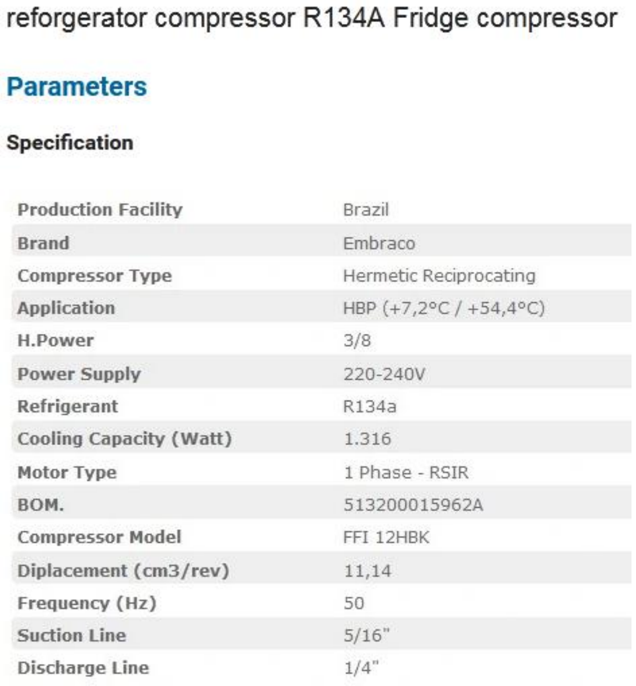

Saturated high pressure liquid
1
Condenser
4
Superheated high pressure vapor
High-side
Low-side
Expansion Valve
Compressor
Evaporator
2
3
Saturated low pressure liquid and vapor
Saturated low pressure vapor


Ventillation
Compressor
To evaporator
Condenseur
Detendeur


Évaporateur
Détendeur
Condenseur
Compresseur


Transistor (optional)
Condensing unit
Compressor
Temperature control
TEMPERATURE SENSOR
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
FAB 1
19/AUG/99
EJ9GLRRB


Point 1: T1 = 40°C
P1 = 15.858 bar
Saturated high pressure liquid
Point 4: T4 = 55°C to 65°C
P4 = 15.858 bar
Superheated high pressure vapor
Condenser
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
Compressor
To evaporator
Condenser
Expansion valve (Throttle)
Évaporateur
Détendeur
Condenseur
Compresseur
Transistor (optional)
FOR RECORDER / MONITOR
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 (NOT USED)
FOR OPTIONAL LEFT HAND HINGED HEATED GLASS DOOR
FAN MOTOR
fan motor
Embraco FFI 12HBK
THERMALLY PROTECTED
R 134a
1 PH
220-240V~ 50Hz
JOINVILLE-SC
MADE IN BRAZIL
513200015 FAB 1 19/AUG/99 EJ9GLRRB

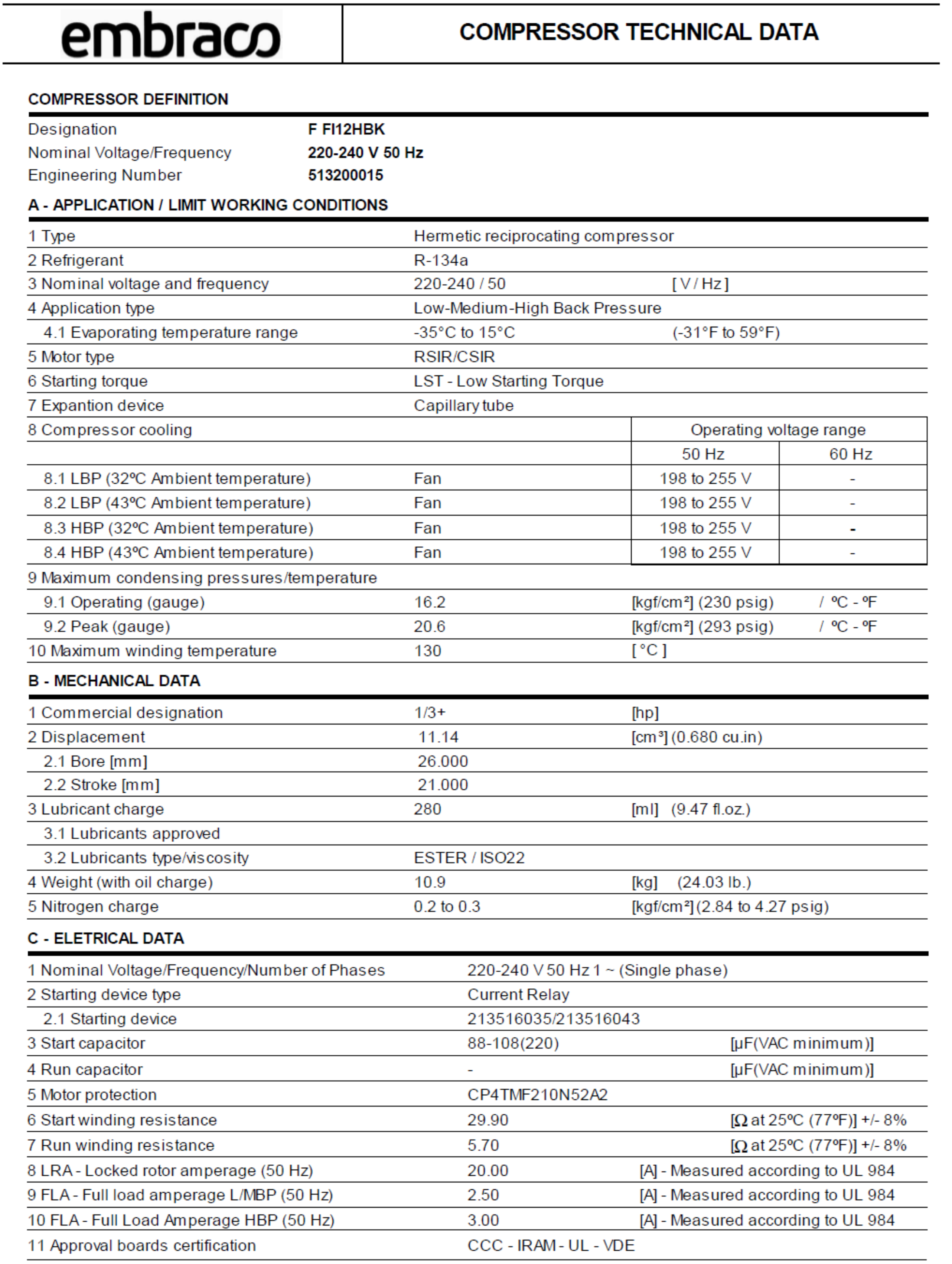


reforgerator compressor R134A Fridge compressor

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

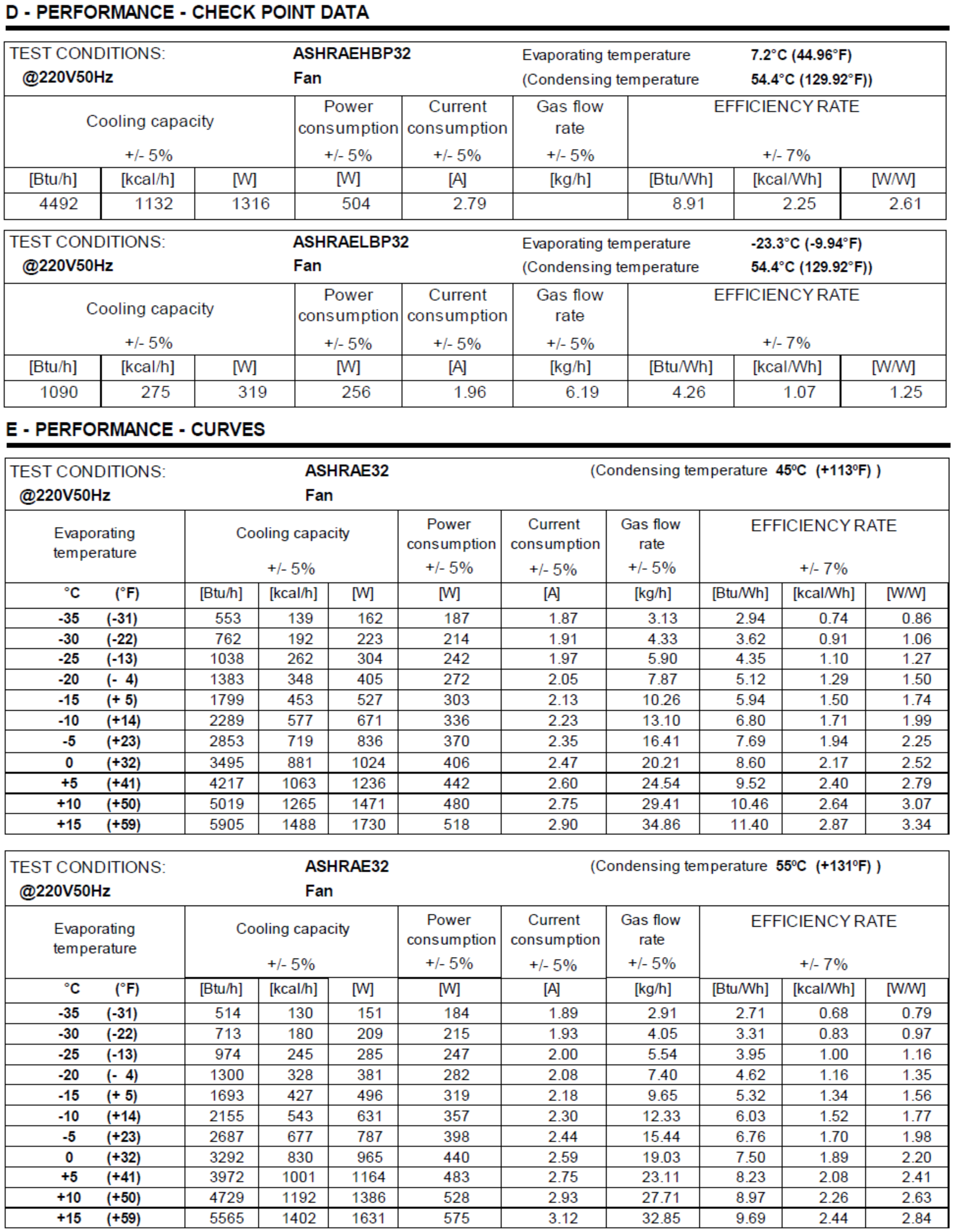
1 Type	Hermetic reciprocating compressor		
2 Refrigerant	R-134a		
3 Nominal voltage and frequency	220-240 / 50	[V / Hz]	
4 Application type	Low-Medium-High Back Pressure		
4.1 Evaporating temperature range	-35°C to 15°C	(-31°F to 59°F)	
5 Motor type	RSIR/CSIR		
6 Starting torque	LST - Low Starting Torque		
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

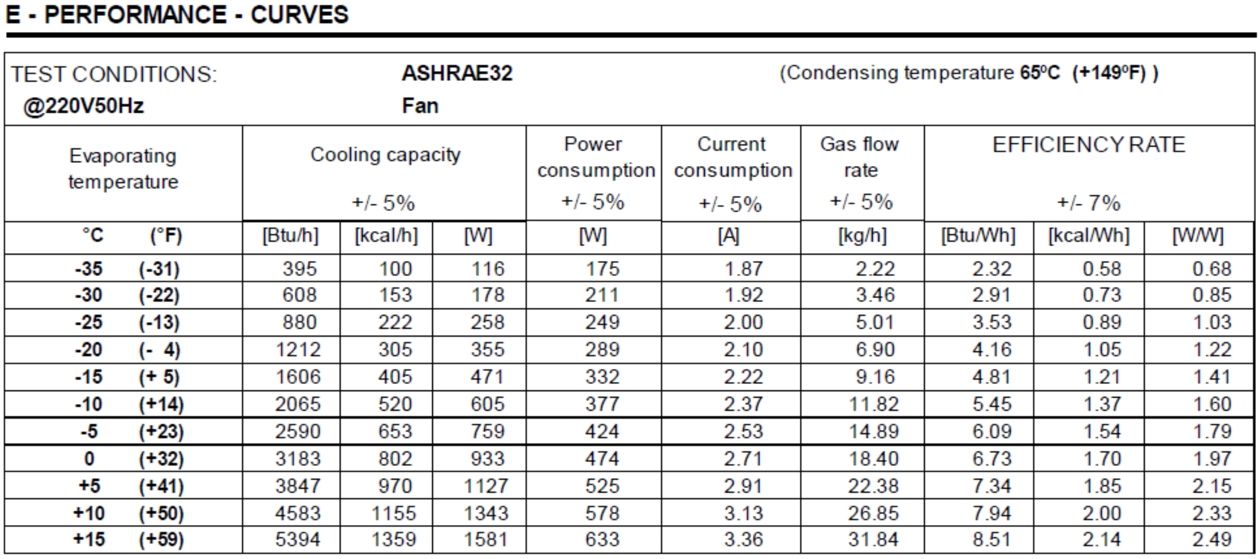
E - PERFORMANCE - CURVES

TEST CONDITIONS: **ASHRAE32** (Condensing temperature **45°C (+113°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)**	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

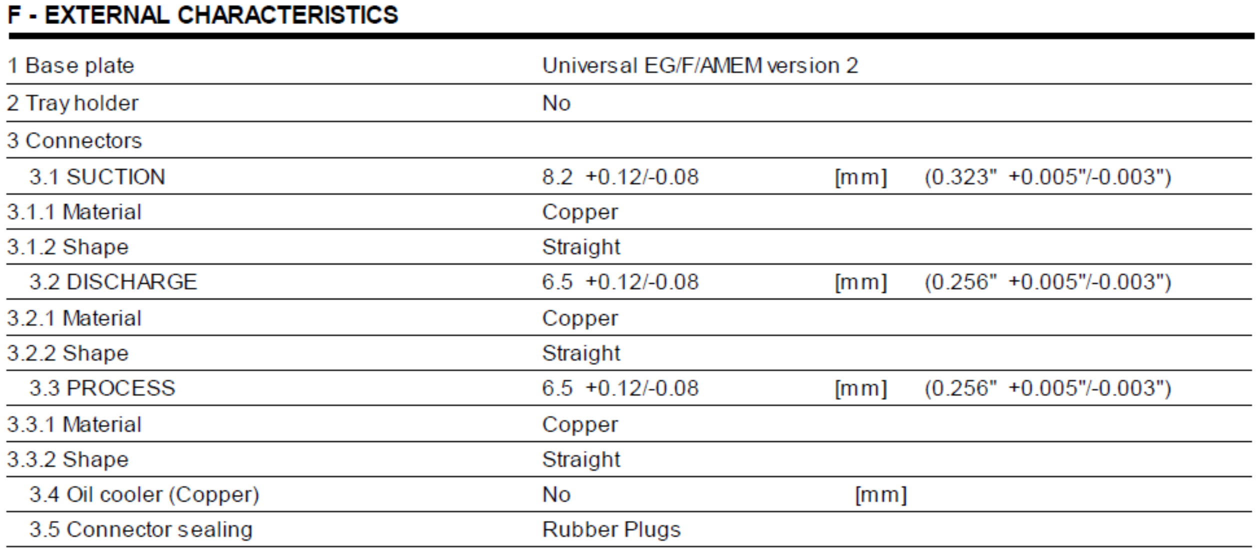
TEST CONDITIONS: **ASHRAE32** (Condensing temperature **55°C (+131°F)**)
@220V50Hz **Fan**

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)**	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: **@220V50Hz**		**ASHRAE32** **Fan**			(Condensing temperature **65°C (+149°F)**)					
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.

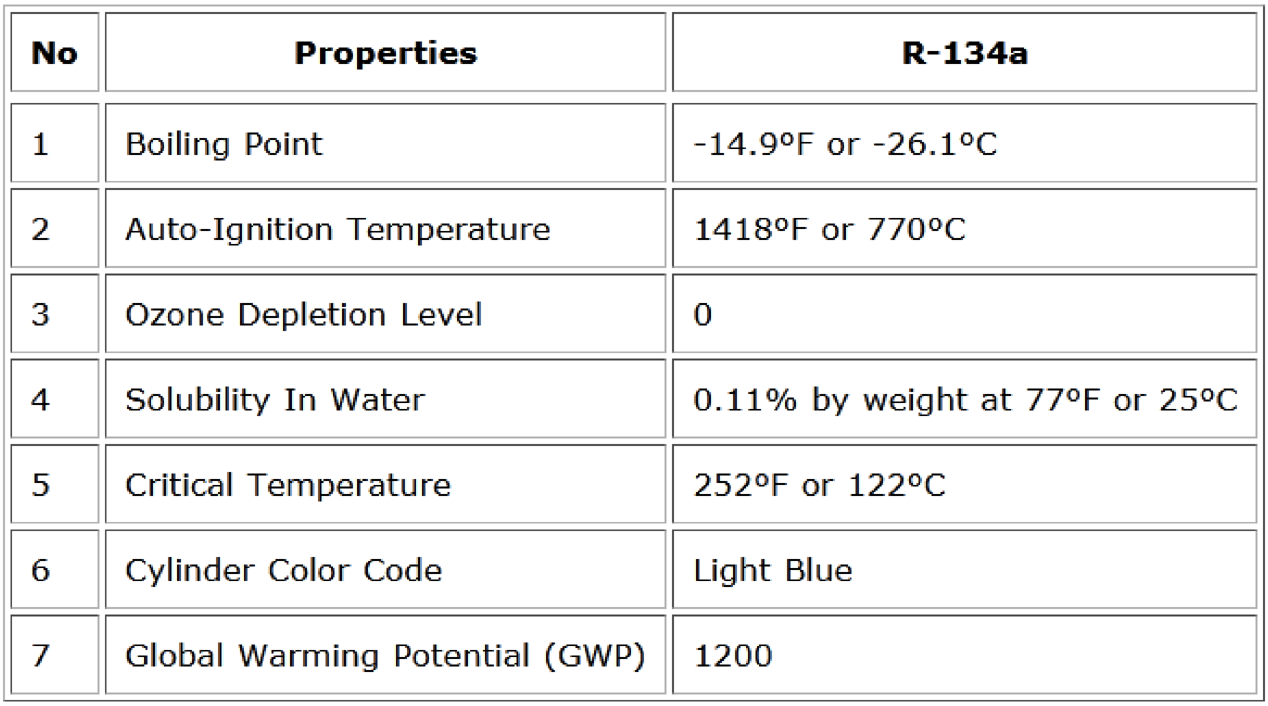
Currently it is also being widely used in the air conditioning system in newer automotive vehicles. The manufacturing industry use it in plastic foam blowing. Pharmaceuticals industry use it as a propellant.

It exists in gas form when expose to the environment as the boiling temperature is -14.9°F or -26.1°C.

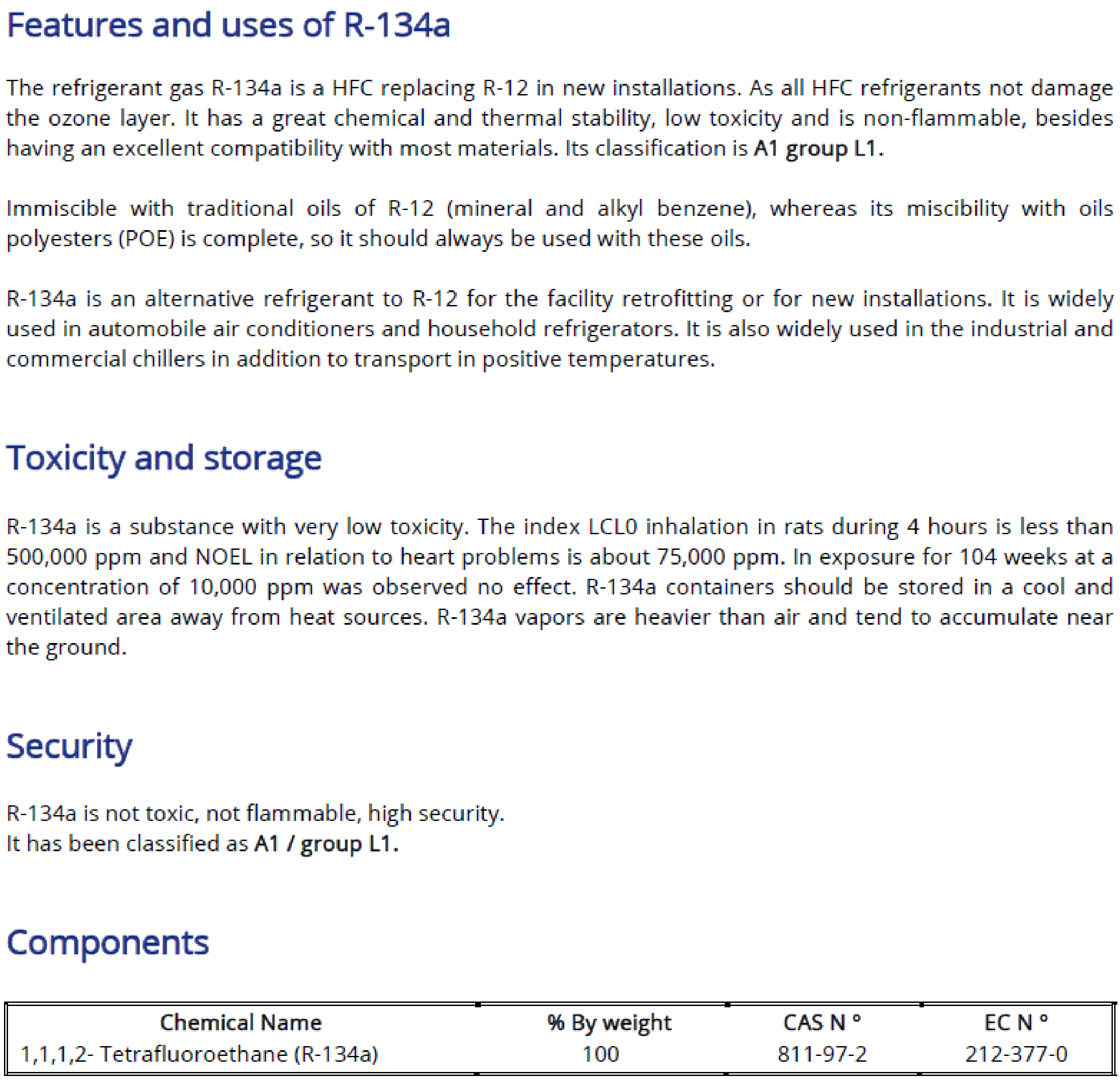
This refrigerant is not 100% compatible with the lubricants and mineral-based refrigerant currently used in R-12. Design changes to the condenser and evaporator need to be done to use this refrigerant.

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

[28]

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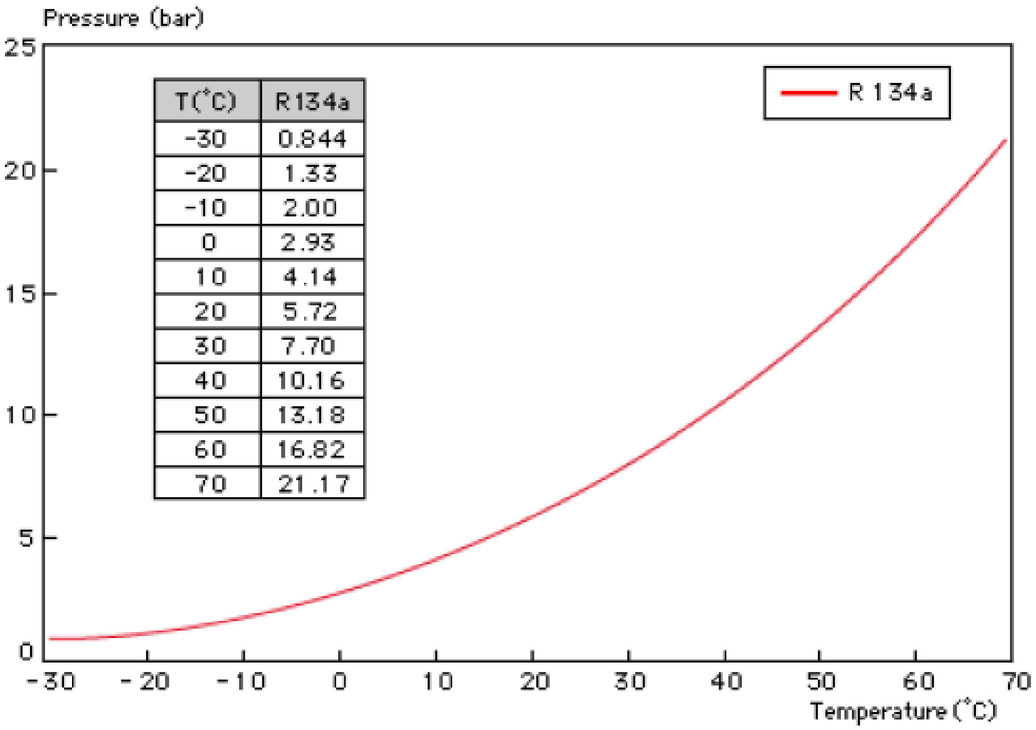
[28] https://gas-servei.com/shop/docs/technical-data-sheet-r-134a-gas-servei.pdf

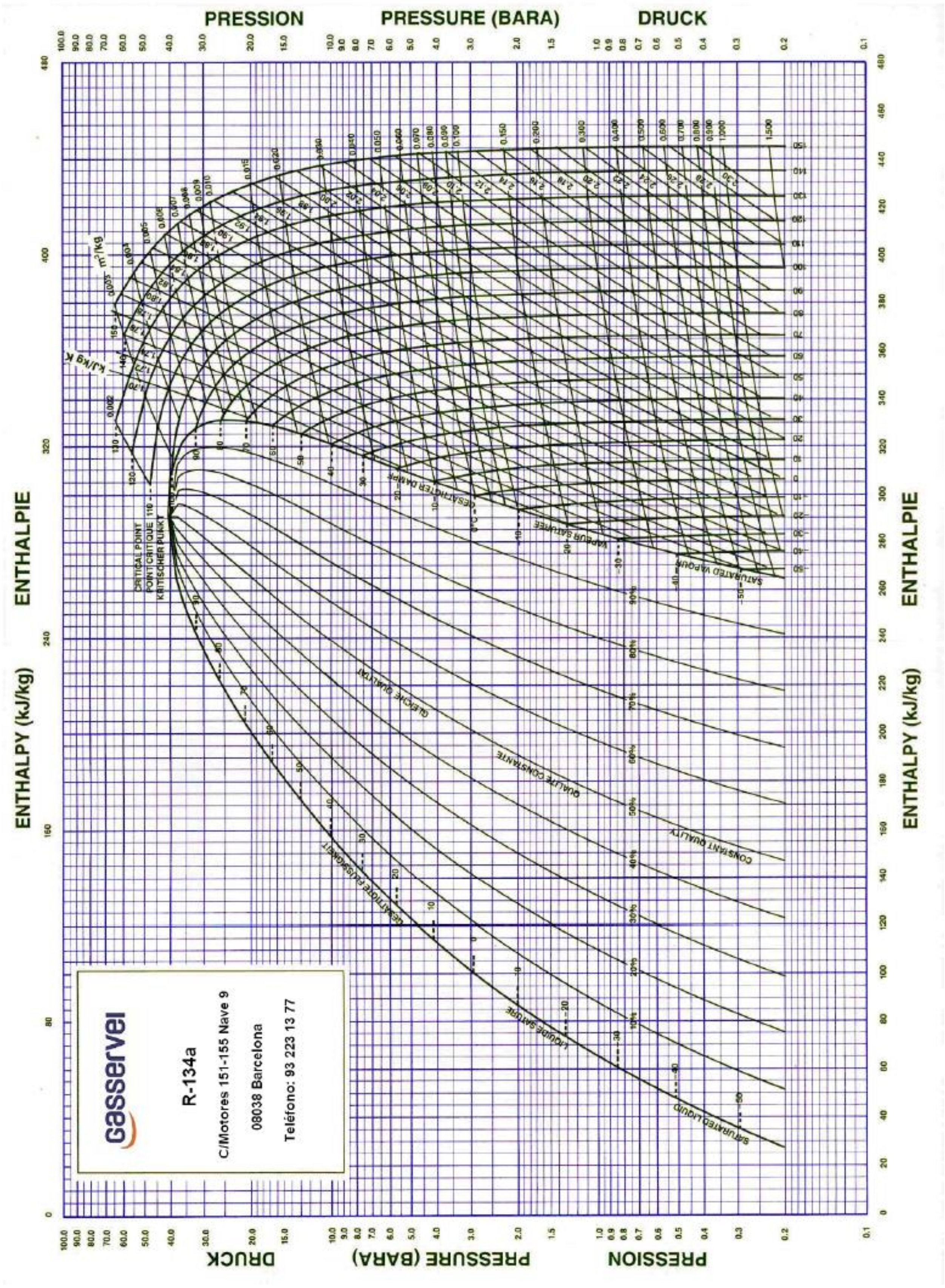
Chart Pressure / Temperature



Thermodynamic properties

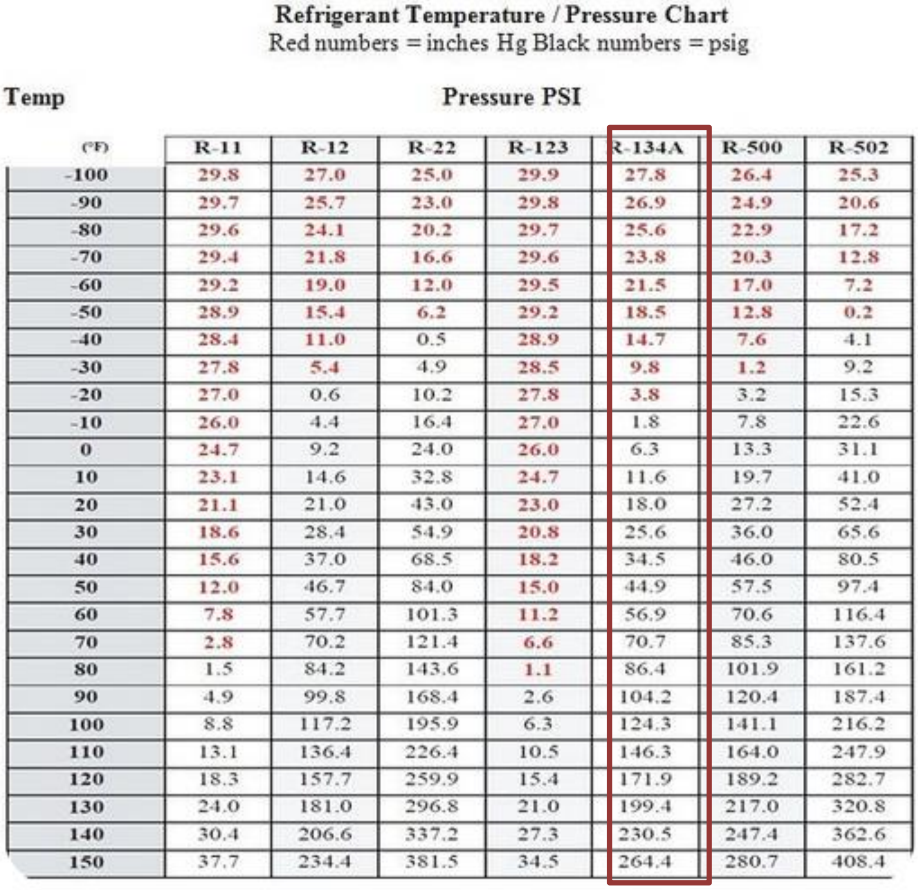
TEMP. (°C)	ABSOLUTE PRESSURE (bar)		DENSITY (Kg/m³)		ENTHALPY (kJ/Kg)		ENTROPY (kJ/Kg.K)	
	BUBBLE	DEW	BUBBLE	DEW	BUBBLE	DEW	BUBBLE	BUBBLE
-40	0.51	0.51	1413.94	2.76	149.45	375.65	0.8008	1.7710
-35	0.66	0.66	1399.95	3.50	155.53	378.93	0.8266	1.7646
-30	0.84	0.84	1385.72	4.39	161.67	382.20	0.8521	1.7590
-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 (°F)	Pressure PSI 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

[29]

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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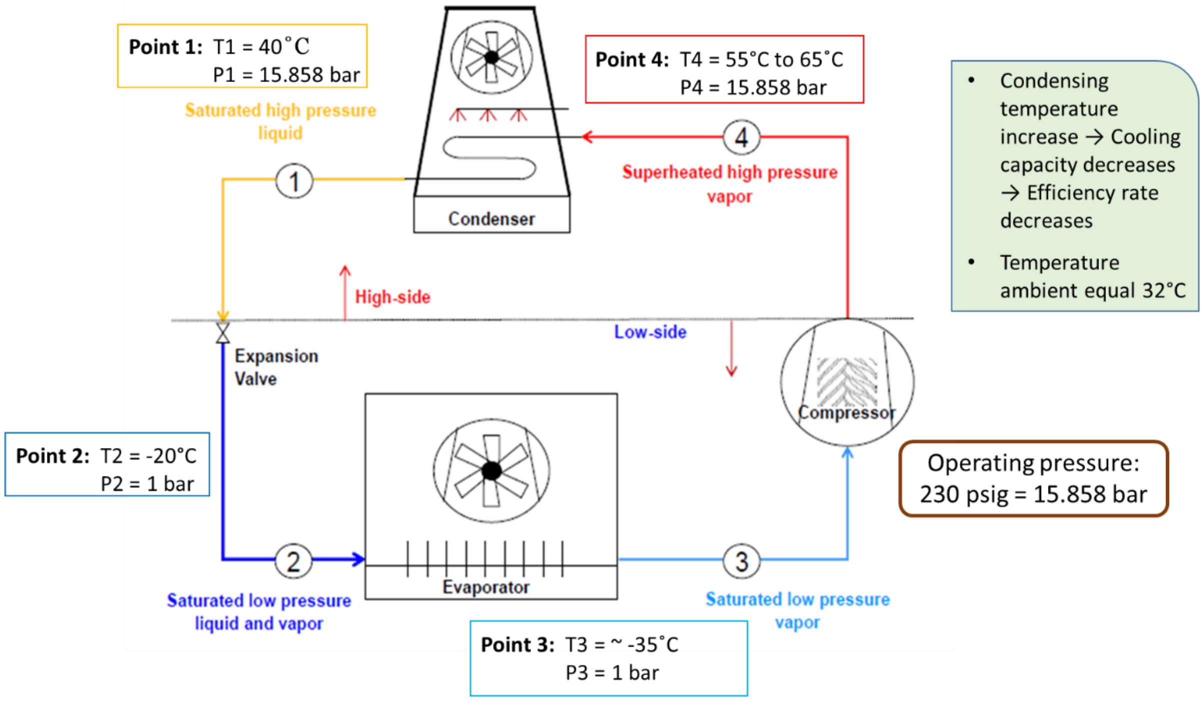
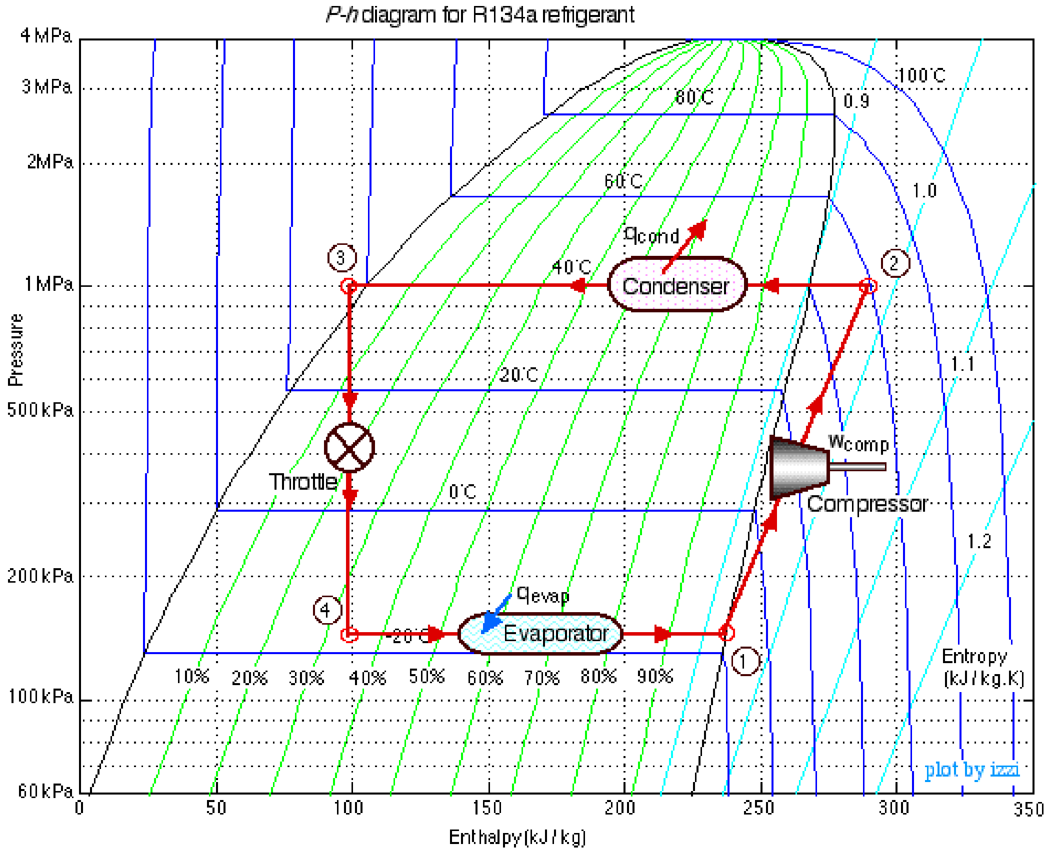
[29] https://www.pinterest.com/pin/333829391133607747/





[30]

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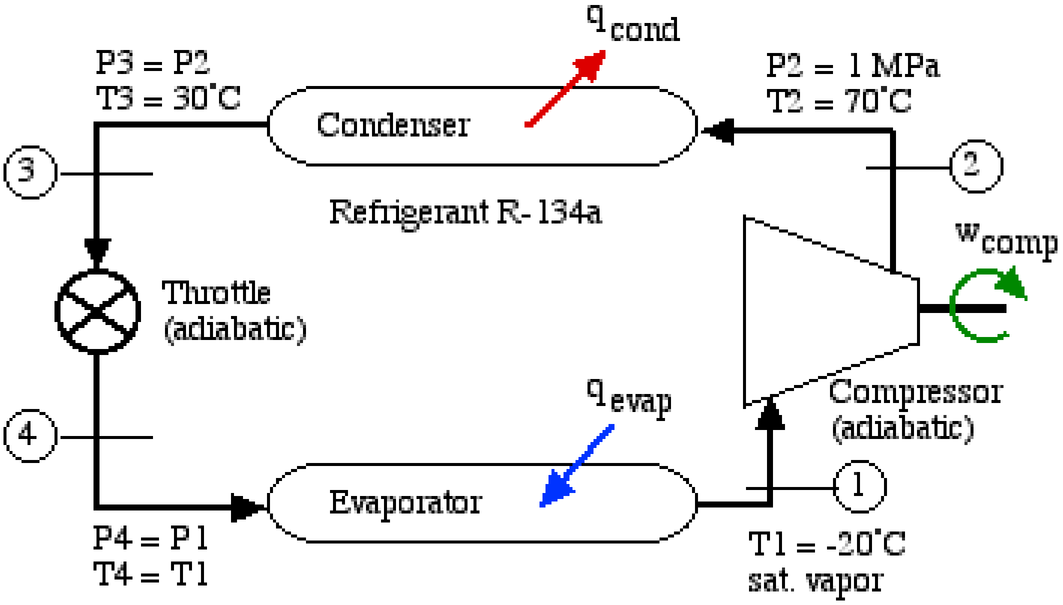
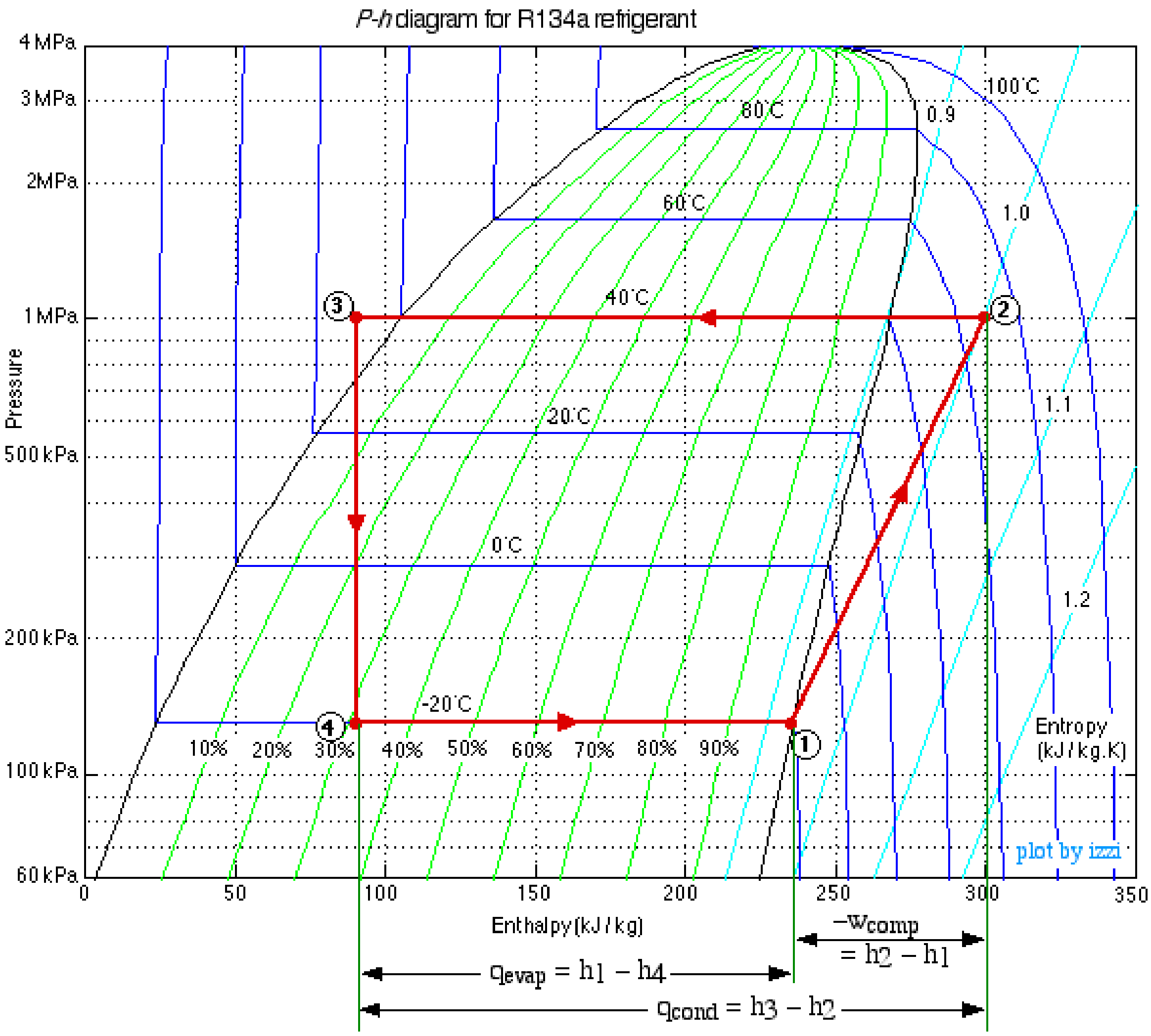
[30] https://www.ohio.edu/mechanical/thermo/Intro/Chapt.1_6/refrigerator/refrig_problems.html





31

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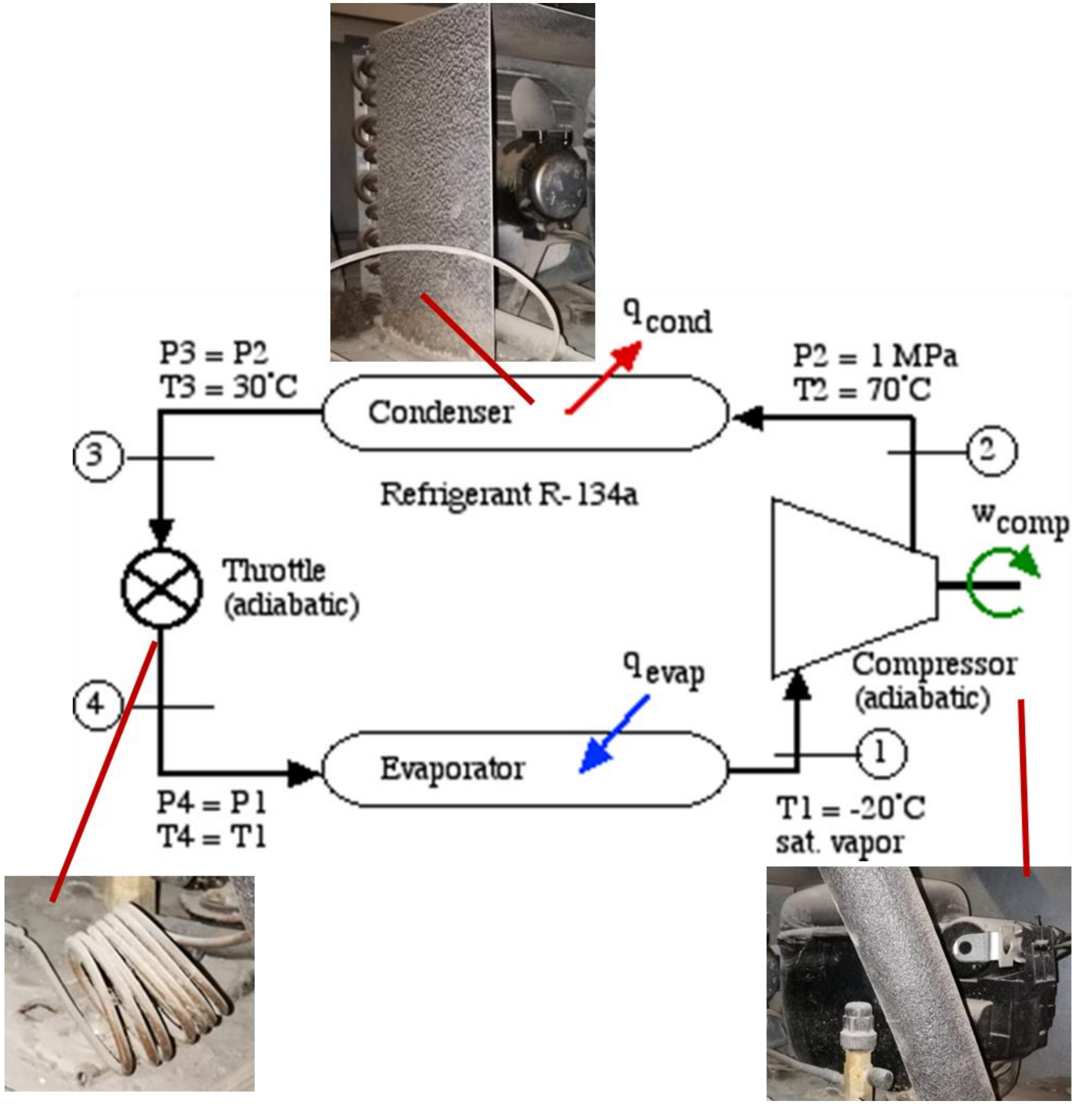
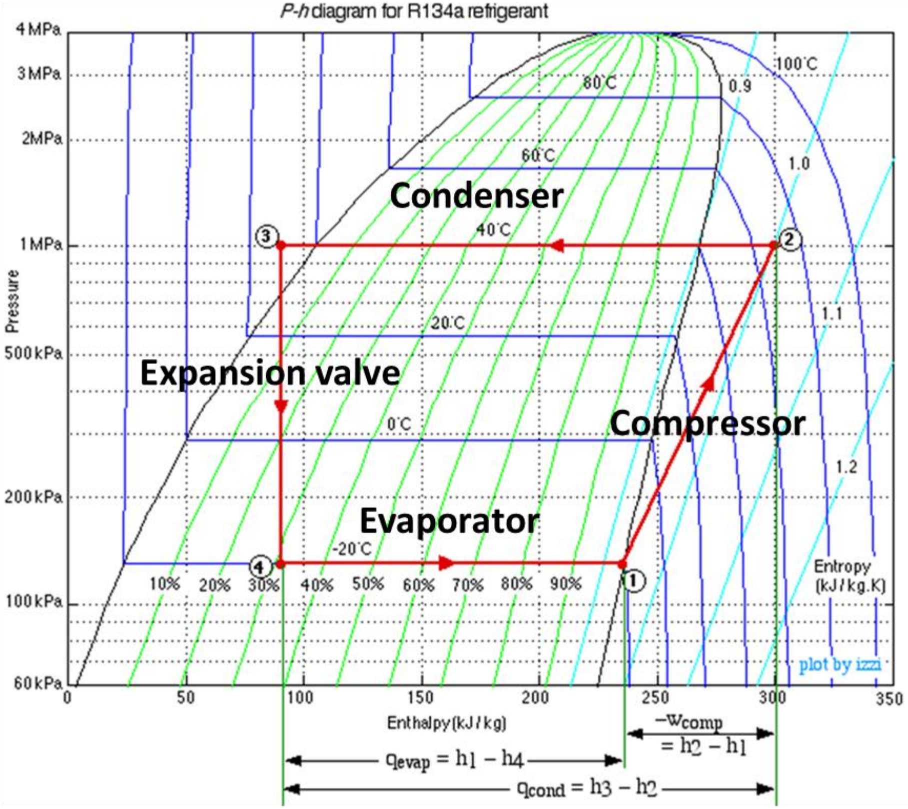
31 https://www.ohio.edu/mechanical/thermo/Intro/Chapt.1_6/Chapter4c.html


q_cond
P3 = P2
T3 = 30°C
P2 = 1 MPa
T2 = 70°C
Condenser
Refrigerant R-134a
3
2
Throttle
(adiabatic)
w_comp
Compressor
(adiabatic)
q_evap
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
Condenser
Expansion valve
Compressor
Evaporator
3
2
4
1
10%
20%
30%
40%
50%
60%
70%
80%
90%
Entropy
(kJ / kg.K)
plot by izzi
0
50
100
150
200
250
300
350
Enthalpy (kJ / kg)
−w_comp
= h2 − h1
q_evap = h1 − h4
q_cond = h3 − h2

13.2 Device 2: Carrier Air conditioner

CARRIER
Model: CRVD243M-0B

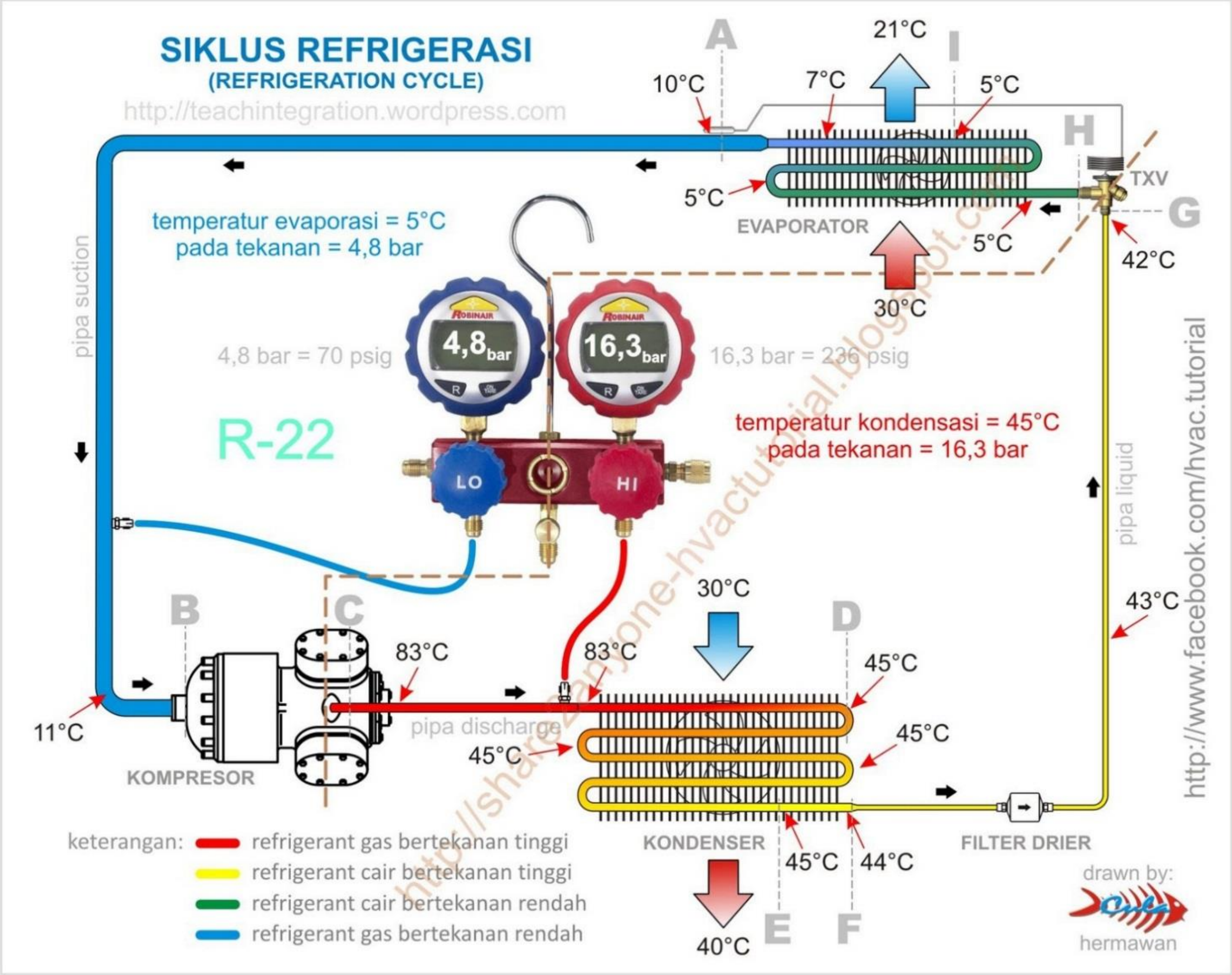
Cooling Capacity:
24000 BTU/hr
Cooling Capacity (SASO):
5420 W
Heating Capacity: 5.0 KW

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:
DB72201390

Made in Saudi Arabia


SIKLUS REFRIGERASI
(REFRIGERATION CYCLE)
http://teachintegration.wordpress.com
A
I
H
G
B
C
D
E
F
10°C
7°C
21°C
5°C
5°C
5°C
42°C
30°C
EVAPORATOR
TXV
temperatur evaporasi = 5°C
pada tekanan = 4,8 bar
pipa suction
4,8 bar
16,3 bar
4,8 bar = 70 psig
16,3 bar = 236 psig
LO
HI
R-22
temperatur kondensasi = 45°C
pada tekanan = 16,3 bar
pipa liquid
http://www.facebook.com/hvac.tutorial
http://sharingappone-hvactutorial.blogspot.com
30°C
83°C
83°C
45°C
45°C
45°C
43°C
11°C
pipa discharge
KOMPRESOR
KONDENSER
FILTER DRIER
45°C
44°C
40°C
keterangan:
refrigerant gas bertekanan tinggi
refrigerant cair bertekanan tinggi
refrigerant cair bertekanan rendah
refrigerant gas bertekanan rendah
drawn by:
hermawan

13.2.1 Filter dryer: 32

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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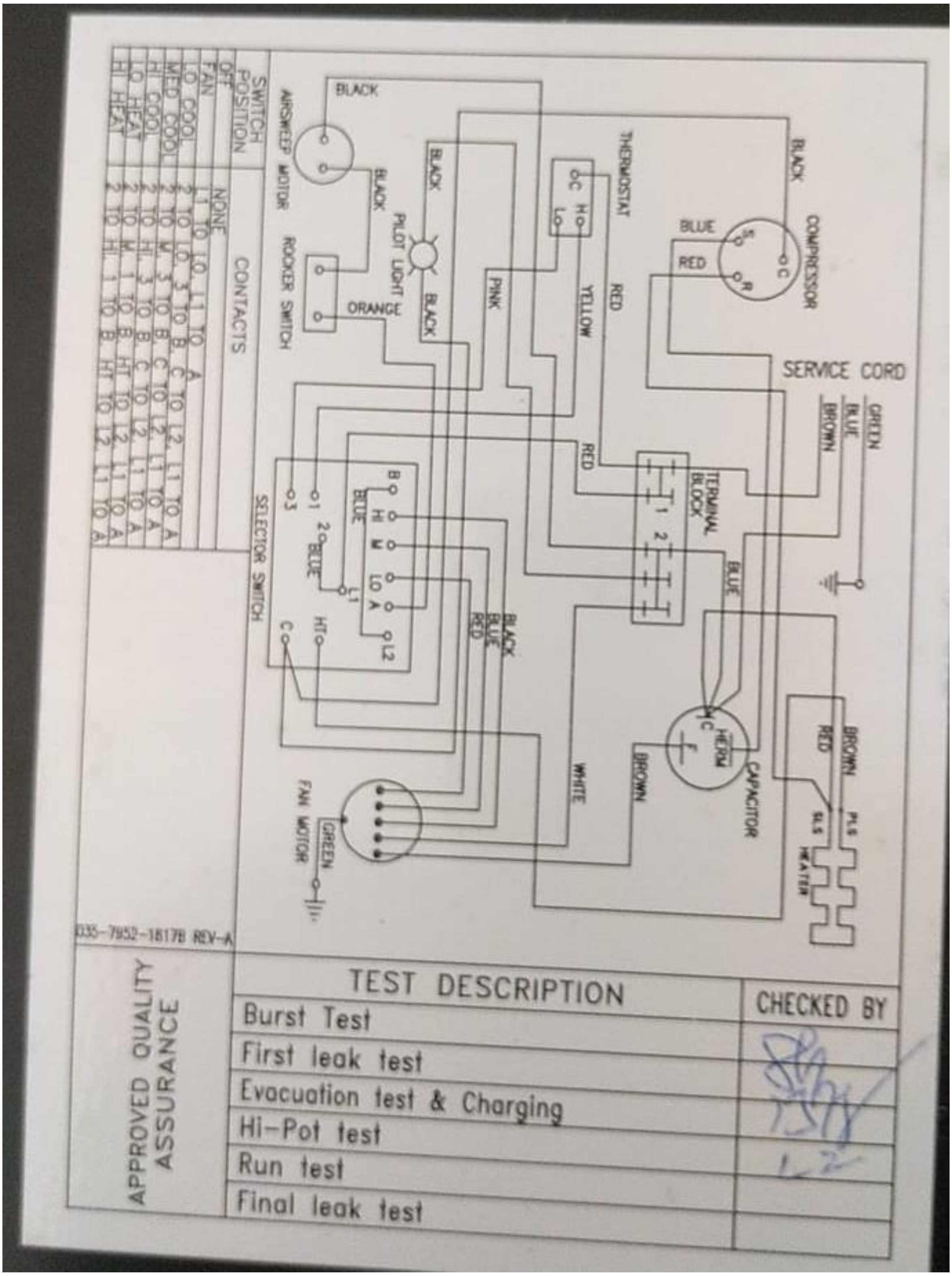
32 https://theengineeringmindset.com/filter-driers-how-do-they-work/



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

TEST DESCRIPTION	CHECKED BY
Burst Test	
First leak test	
Evacuation test & Charging	
Hi-Pot test	
Run test	
Final leak test	

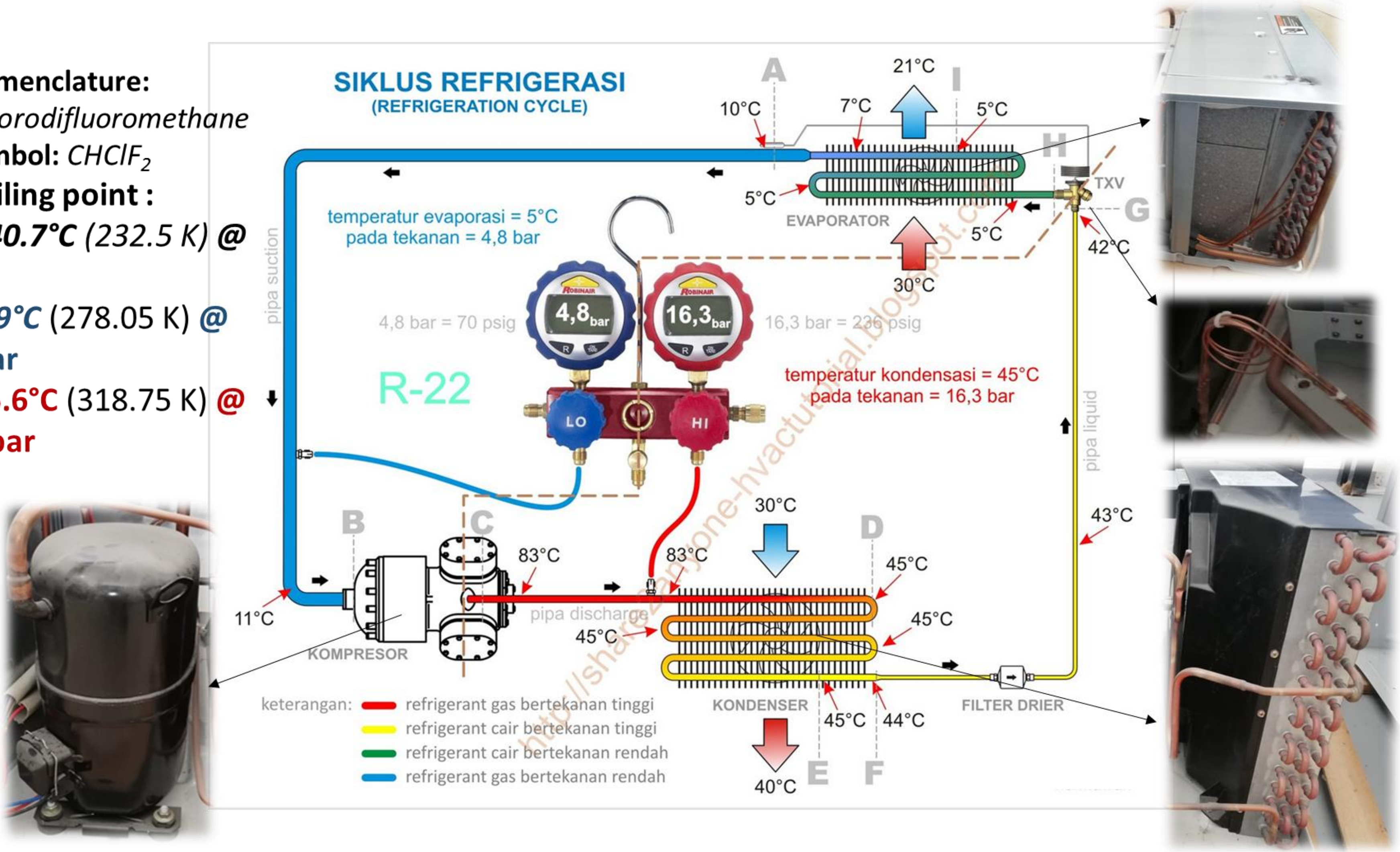
R-22

- **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**



[33]

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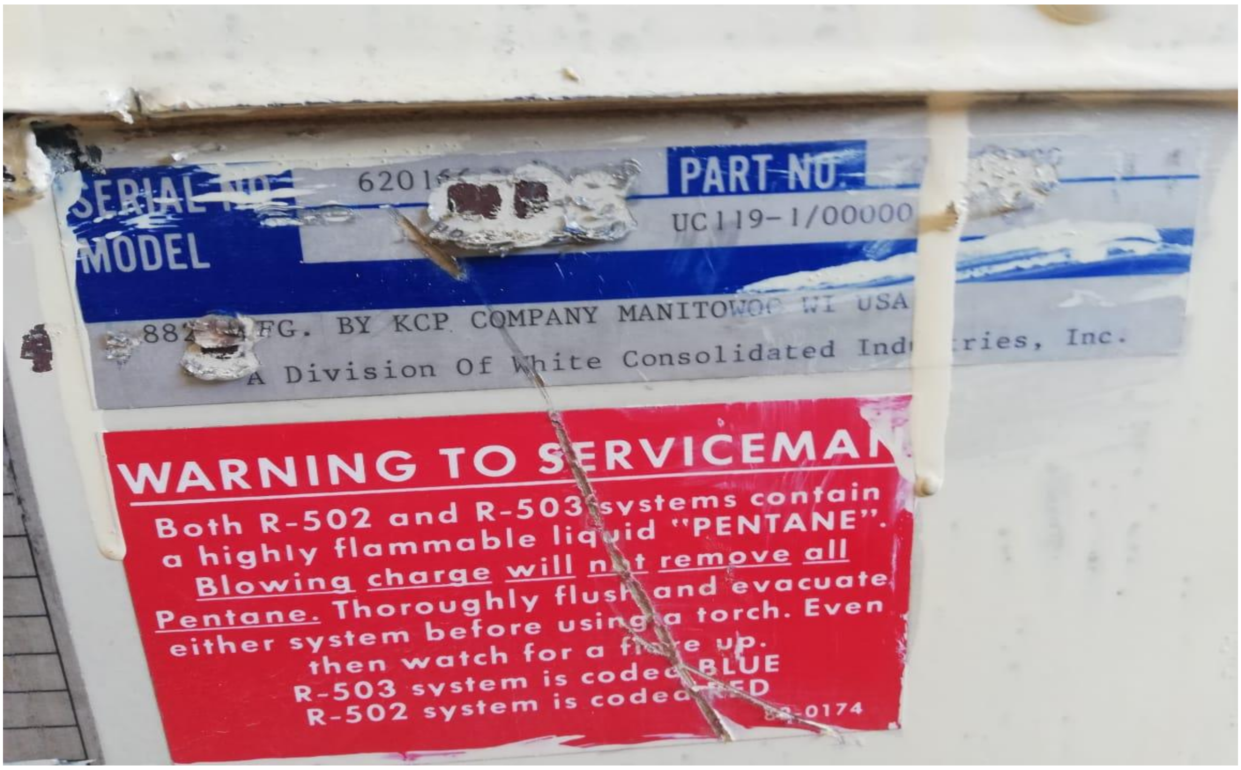
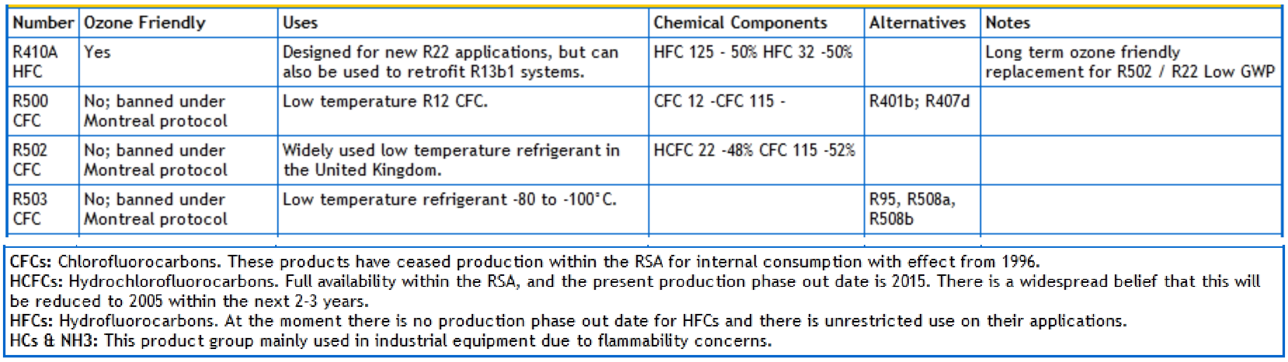
33 https://refrigerants.com/product/r22/

13.3 Device 3 : Kelvinator fridge

		HIGH STAGE			[illegible] STAGE		
SURE	L.S.	162			1[illegible]		
	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					

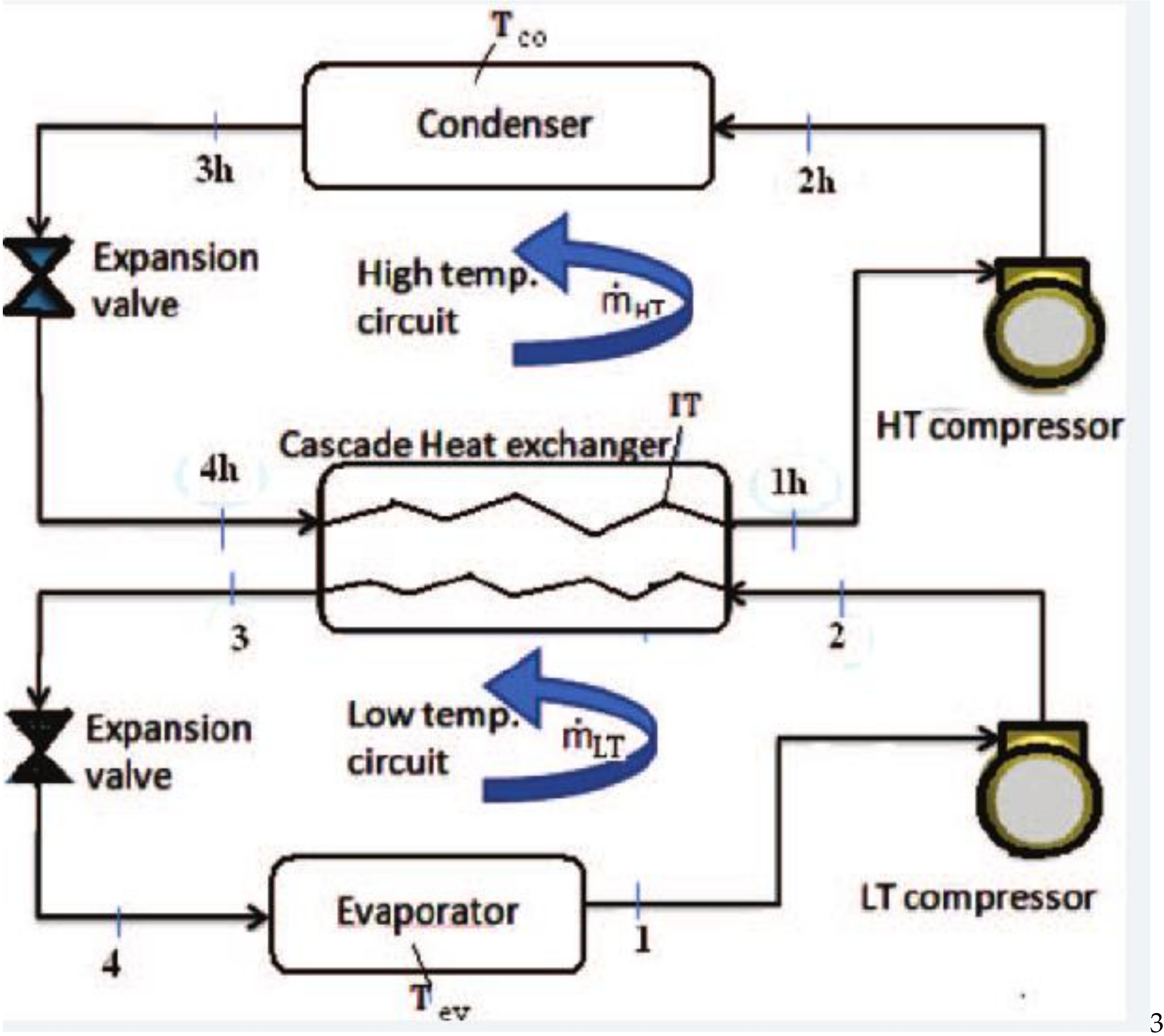

SERIAL NO
620166
MODEL
PART NO.
UC119-1/00000
MFG. BY KCP COMPANY MANITOWOC WI USA
A Division Of White Consolidated Industries, Inc.
WARNING TO SERVICEMAN
Both R-502 and R-503 systems contain a highly flammable liquid "PENTANE". Blowing charge will not remove all Pentane. Thoroughly flush and evacuate 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



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.

[34]



[35]

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[34] http://www.proairlda.com/gases.htm

[35] 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**

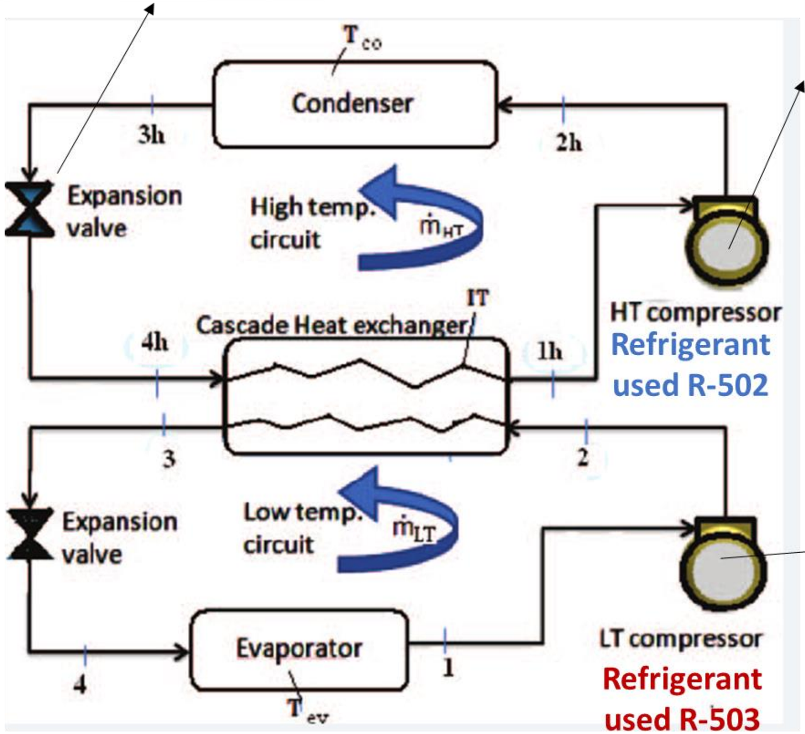
T= 61.5°C (334.7 K) **@ 25.85 bar**

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**



[36] [37] [38]

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[36] https://secureservercdn.net/198.71.233.179/m9v.7b6.myftpupload.com/wp-content/uploads/2019/12/SDS-R22.pdf?time=1618519493

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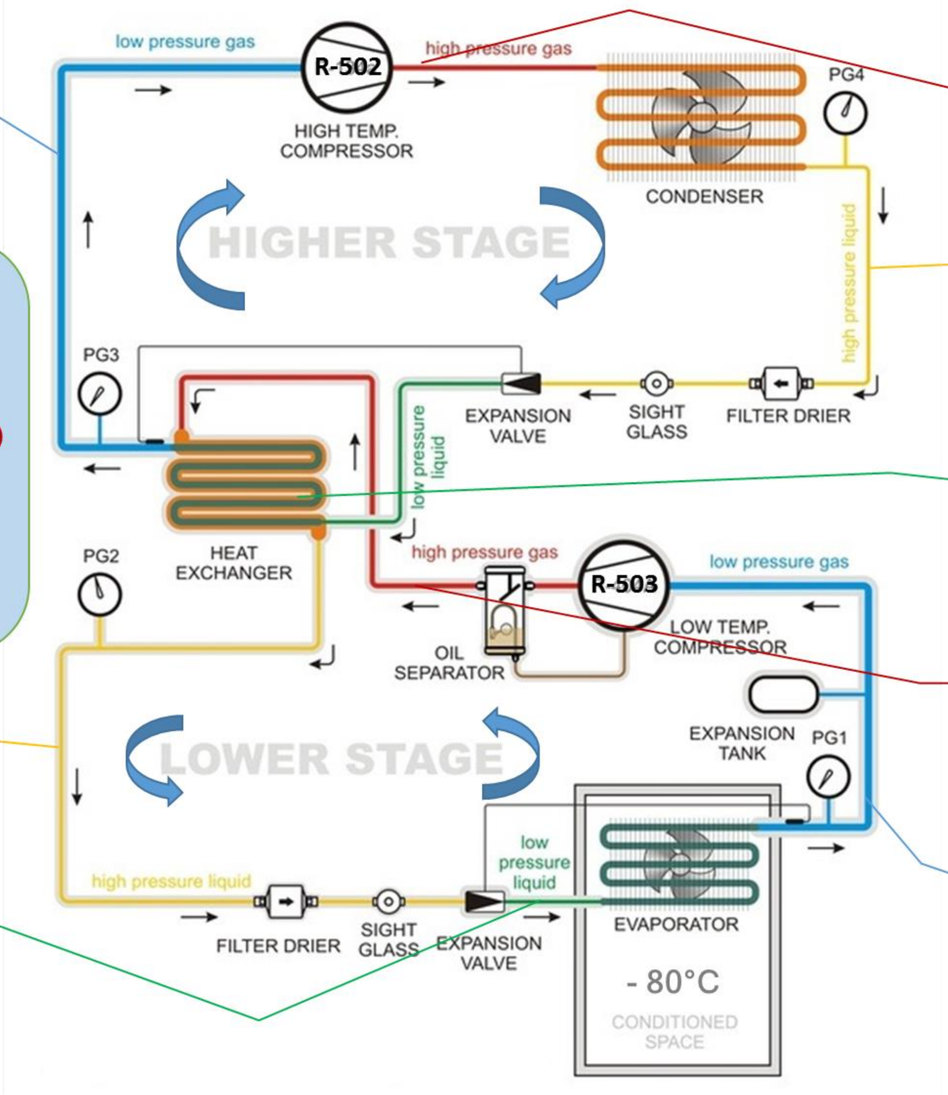
37 https://www.cc.kyushu-u.ac.jp/scp/system/library/PROPATH/manuals/p-propath/r503.pdf

38 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
P_B= 25.85 bar
T_B= -30 (< -20 °C)

Point C: Liq or Gas
P_C= 1 bar
T_C= - 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
P_A= 25.85 bar
T_A= 10°C (> -20 °C)

Point D: Gas
P_D= 1 bar
T_D= - 83°C (> -87.50 °C)

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39 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

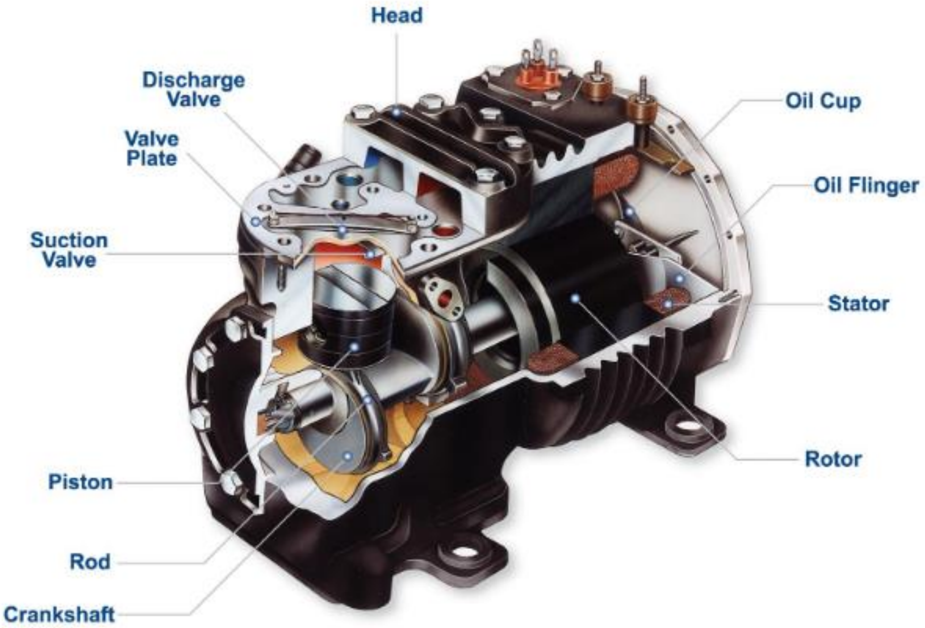
The high stage condenser is cooled by air cooled, while the low stage condenser is cooled by the high stage evaporator.

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.

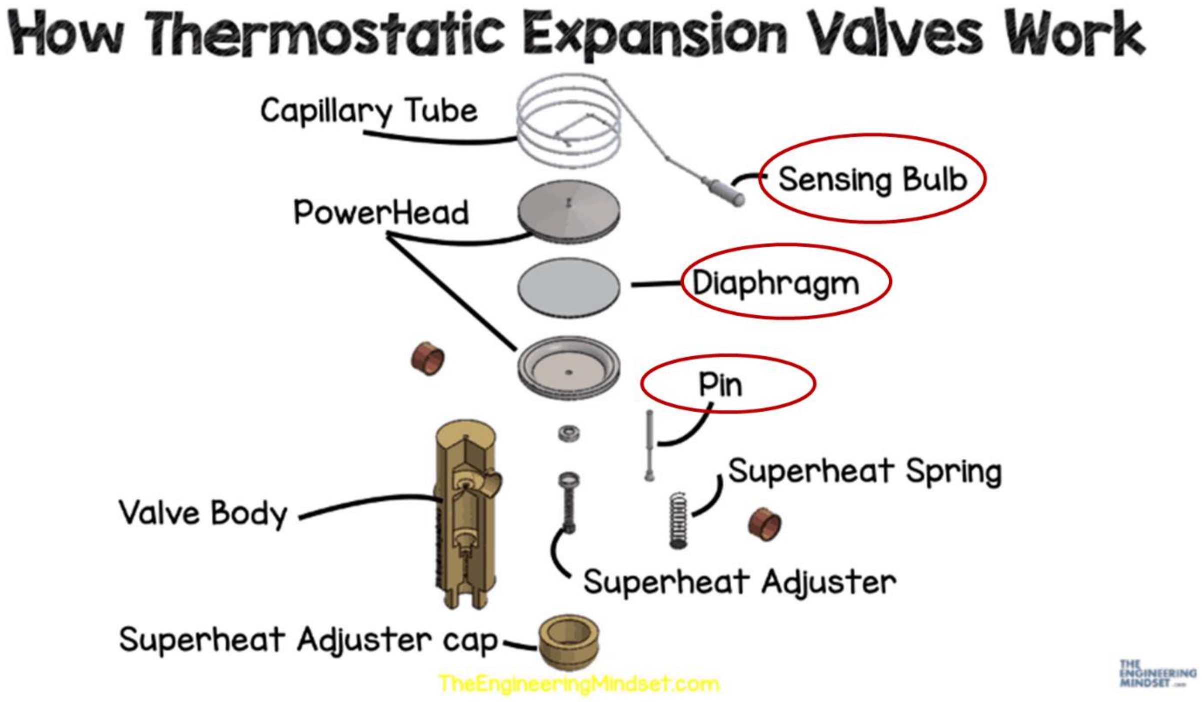
Answer to #2 – no. If each compressor puts out 100 PSI, your downstream air line will not see 200 PSI. What you will do is increase the available compressed air flow at the pressure the system needs.

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



[40]

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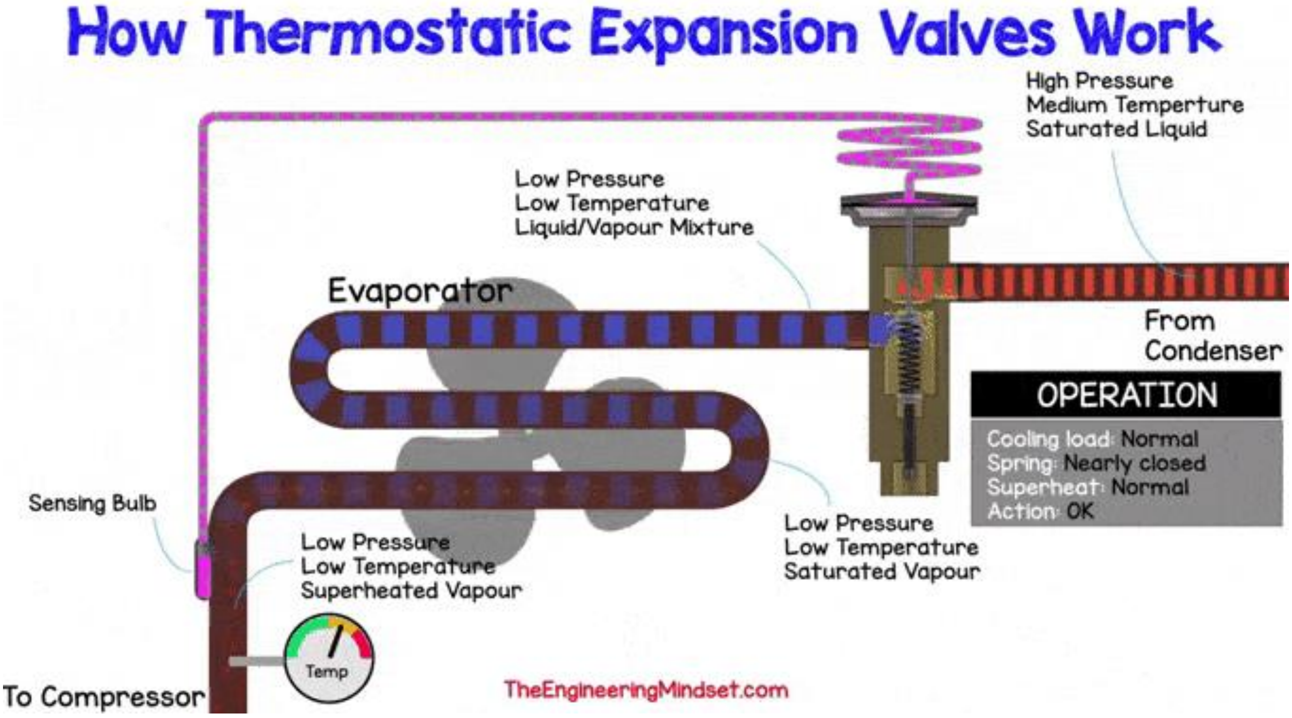
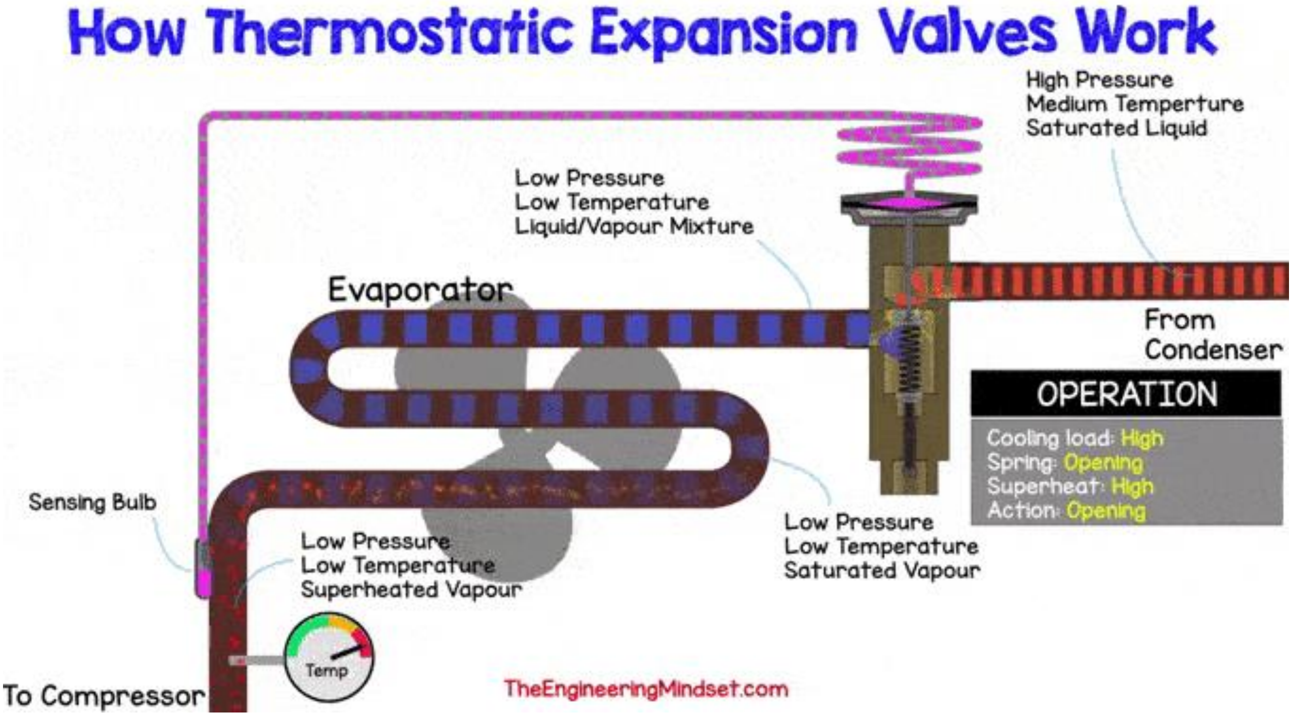
[40] https://theengineeringmindset.com/thermostatic-expansion-valves-work/





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:

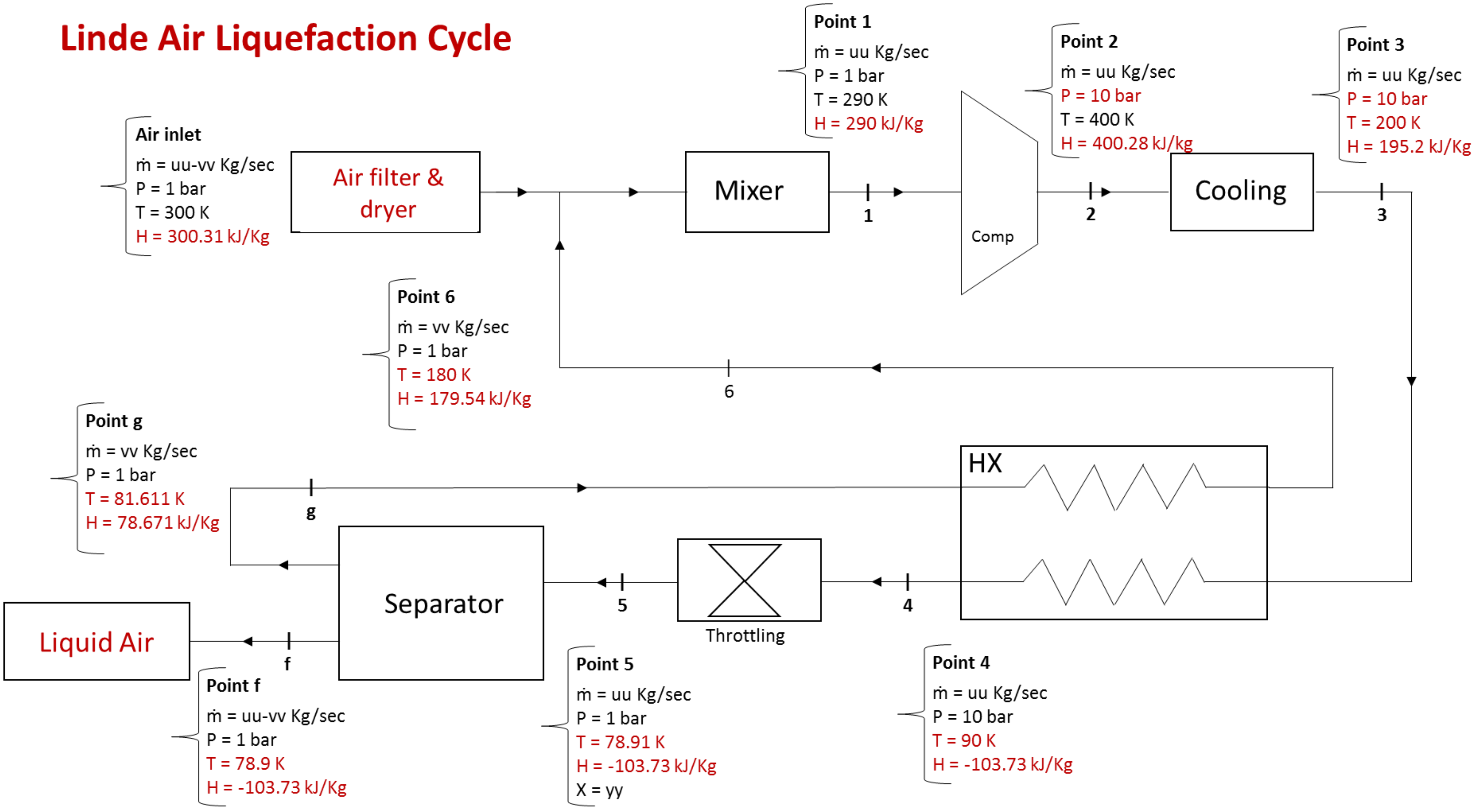
- **Liquid-charged bulbs**
- MOP (Maximum Operating Pressure) bulbs – also called gas-charged bulbs
- Adsorption-filled bulbs

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



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 cycle	Point 3	Point 4 (10 bar, 1 MPa)		Point 5 (1 bar, 0.1 MPa)	Point g	Point 6
	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.

LOX Prototype System Concept & Mechanical Design

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Association for Economical and Technological Cooperation in the Euro-Asian and North-African Region
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Institute for Chemical Process Technology (ICPT)
http://aecenar.com/institutes/icpt

Air Liquefaction and Cryogenics – Report 1 (2021),

Part II: **LOX Prototype System Concept & Mechanical Design**

Author: Mariam El Rez
Editor: Samir Mourad

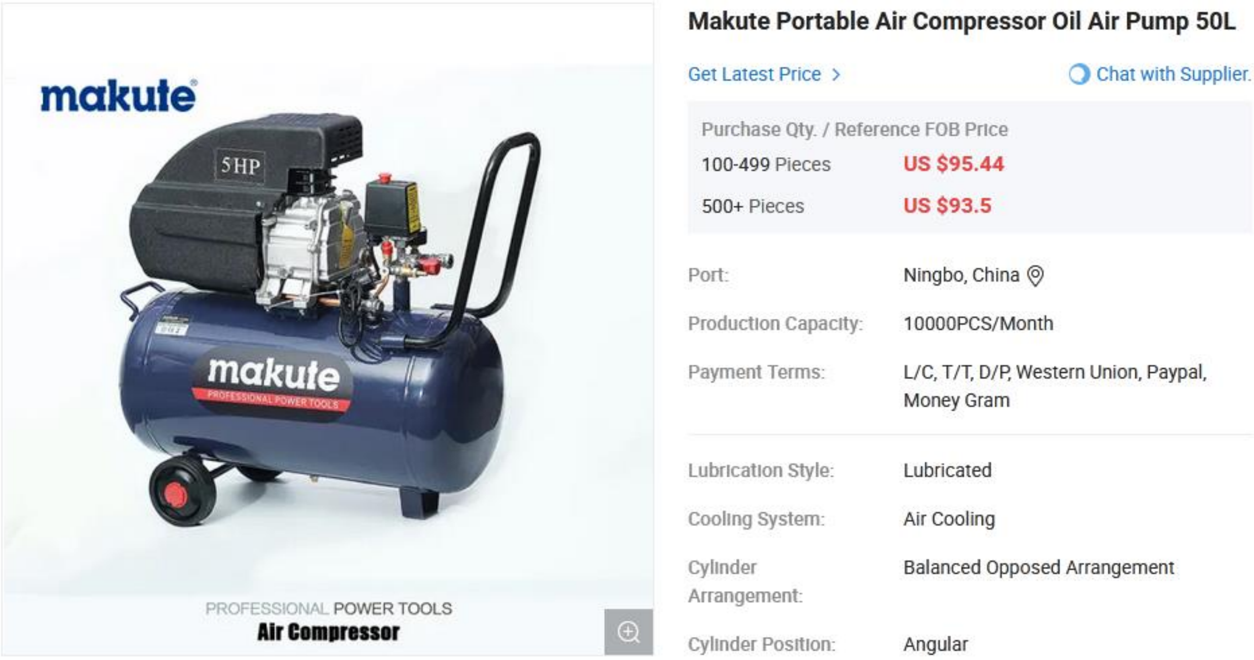
Last update: Aug 2021

Contents

14 System Design of LOX Production Prototype

14.1 Air Compressor

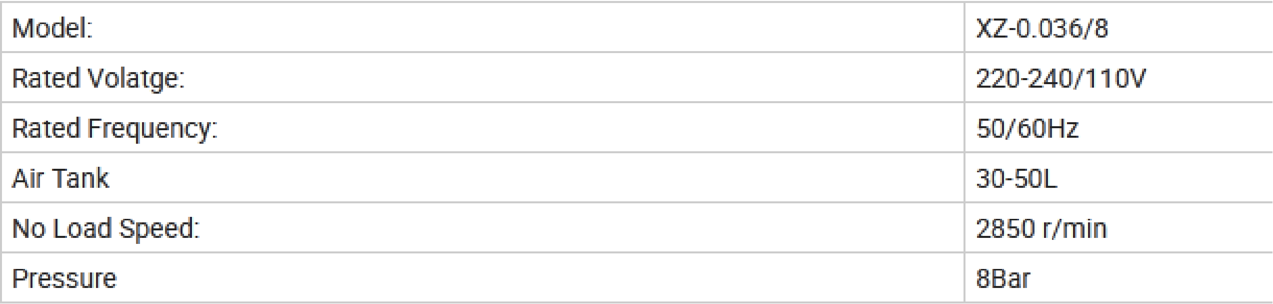
#1 (with oil)



Makute Portable Air Compressor Oil Air Pump 50L

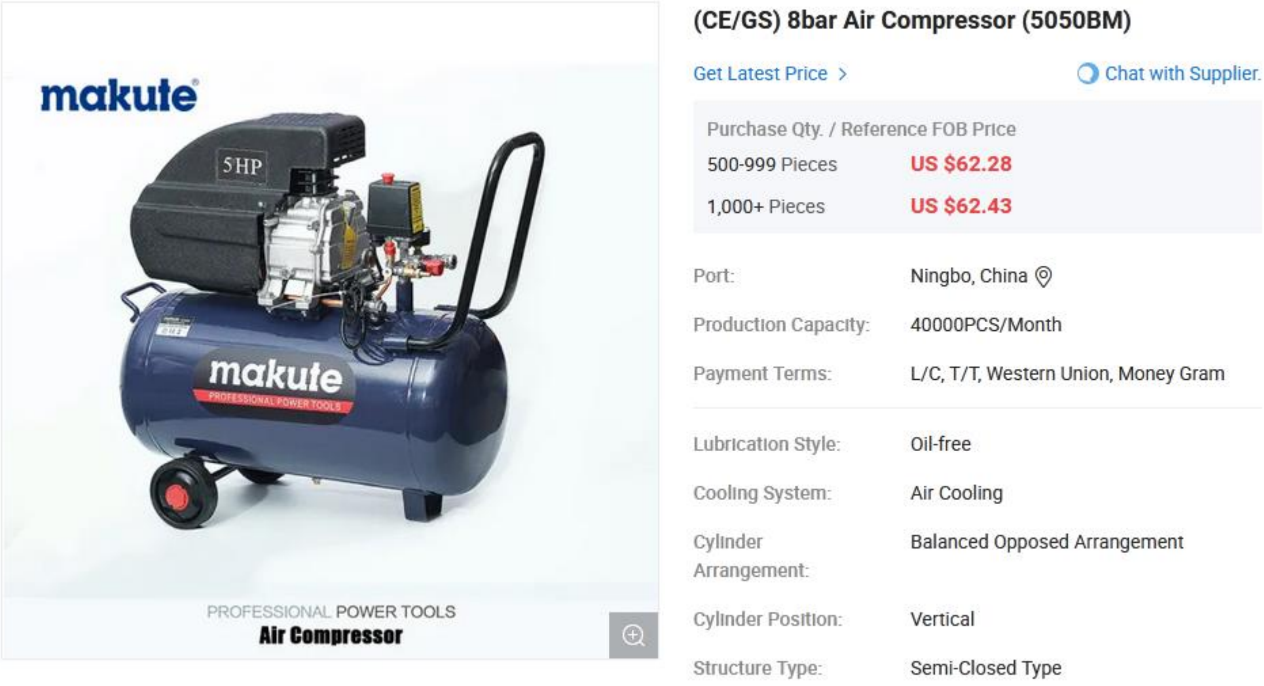
Purchase Qty. / Reference FOB Price	
100-499 Pieces	US $95.44
500+ Pieces	US $93.5

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

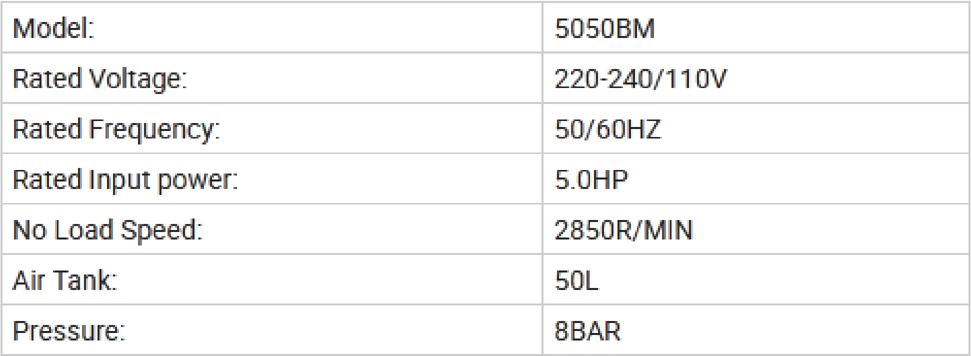
#2 (oil free)



(CE/GS) 8bar Air Compressor (5050BM)

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

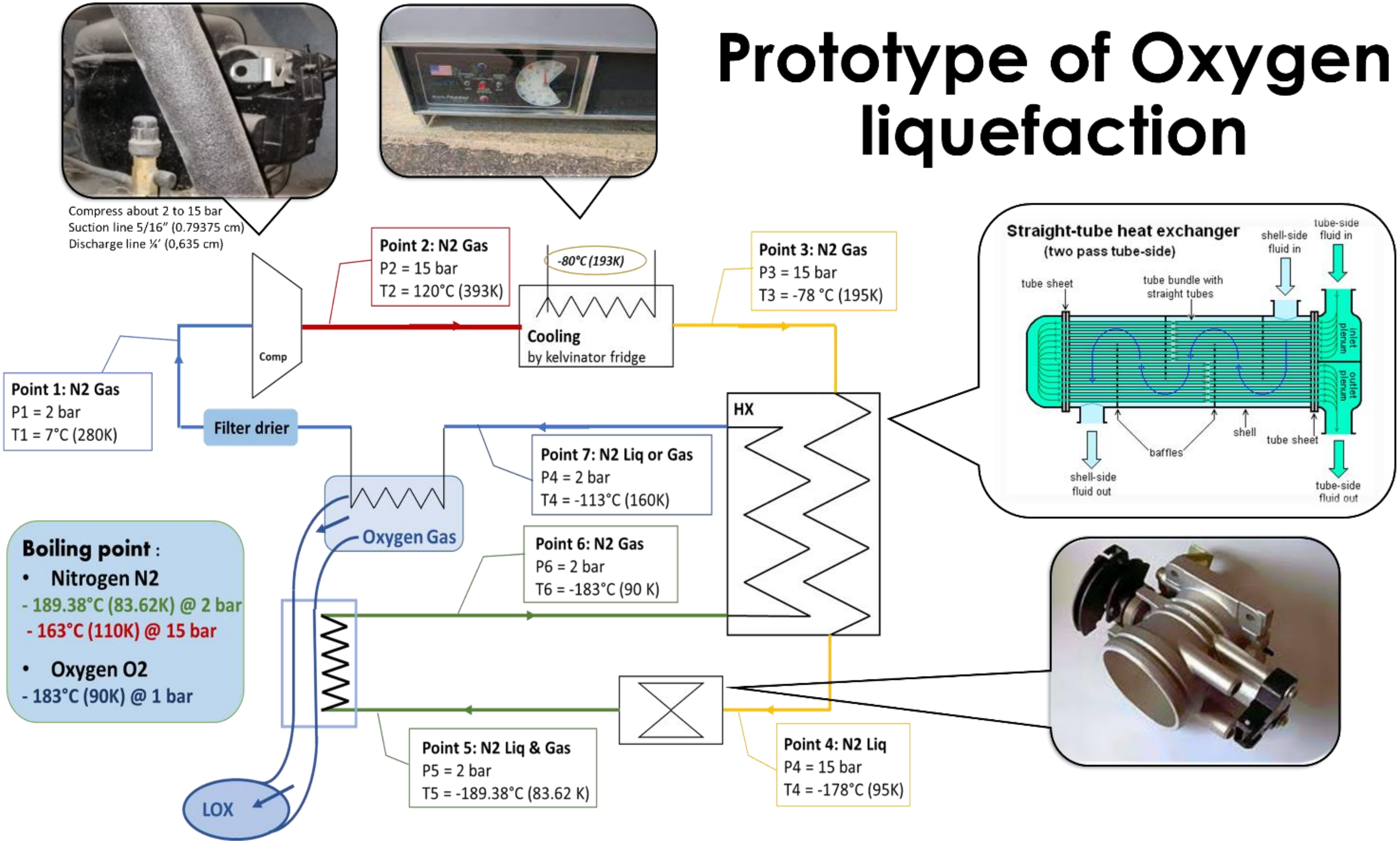


Model:	5050BM
Rated Voltage:	220-240/110V
Rated Frequency:	50/60HZ
Rated Input power:	5.0HP
No Load Speed:	2850R/MIN
Air Tank:	50L
Pressure:	8BAR

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

14.2 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)

Boiling point :
- **Nitrogen N2**

- 189.38°C (83.62K) @ 2 bar
- 163°C (110K) @ 15 bar

- **Oxygen O2**

- 183°C (90K) @ 1 bar

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.

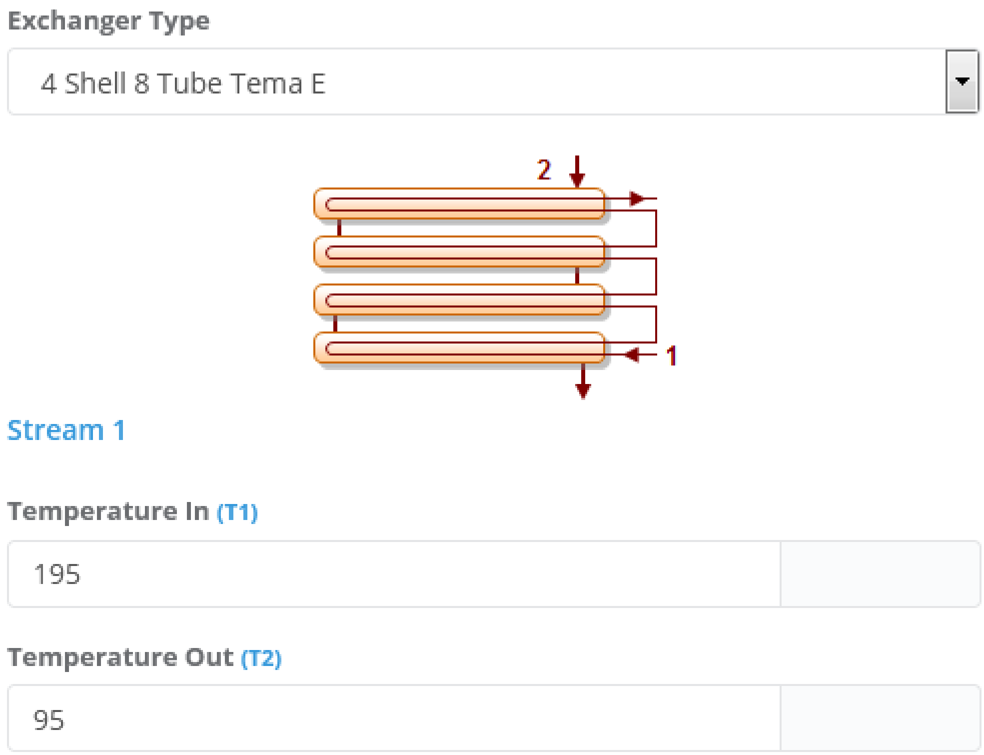
Oxygen gas can also be prepared and cooled to about 170 K in nitrogen before returning directly to the compressor (160 K).

14.3 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.

14.3.1 Data:



Exchanger Type

4 Shell 8 Tube Tema E

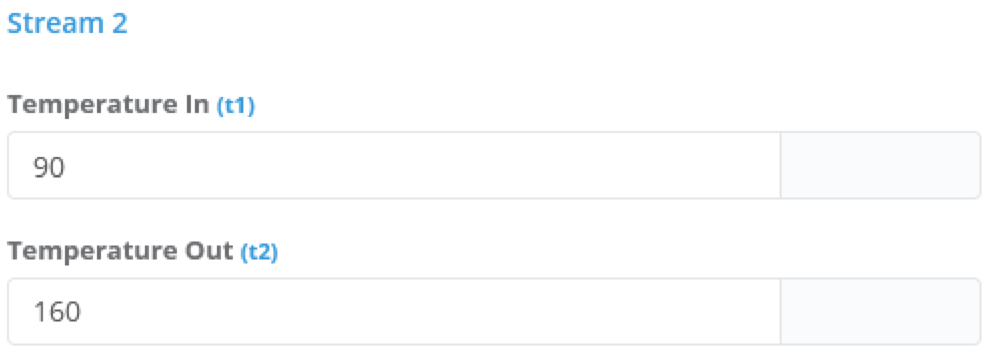
Stream 1

Temperature In (T1)

195

Temperature Out (T2)

95



Stream 2

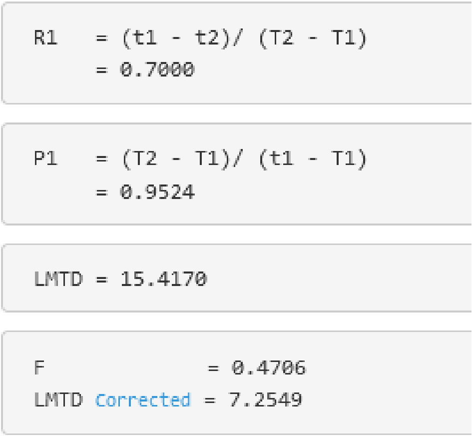
Temperature In (t1)

90

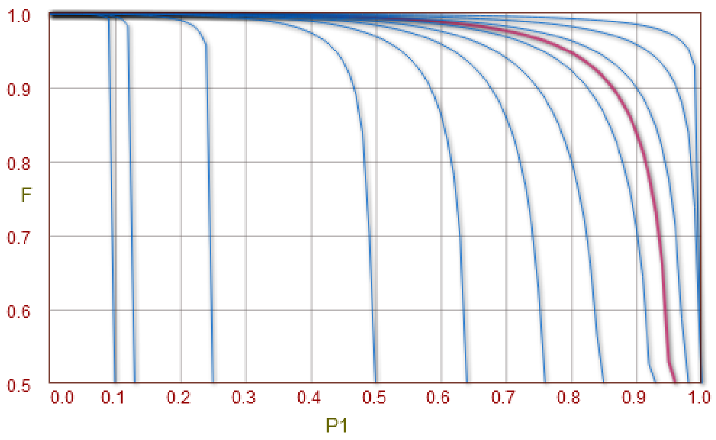
Temperature Out (t2)

160

14.3.2 Result:



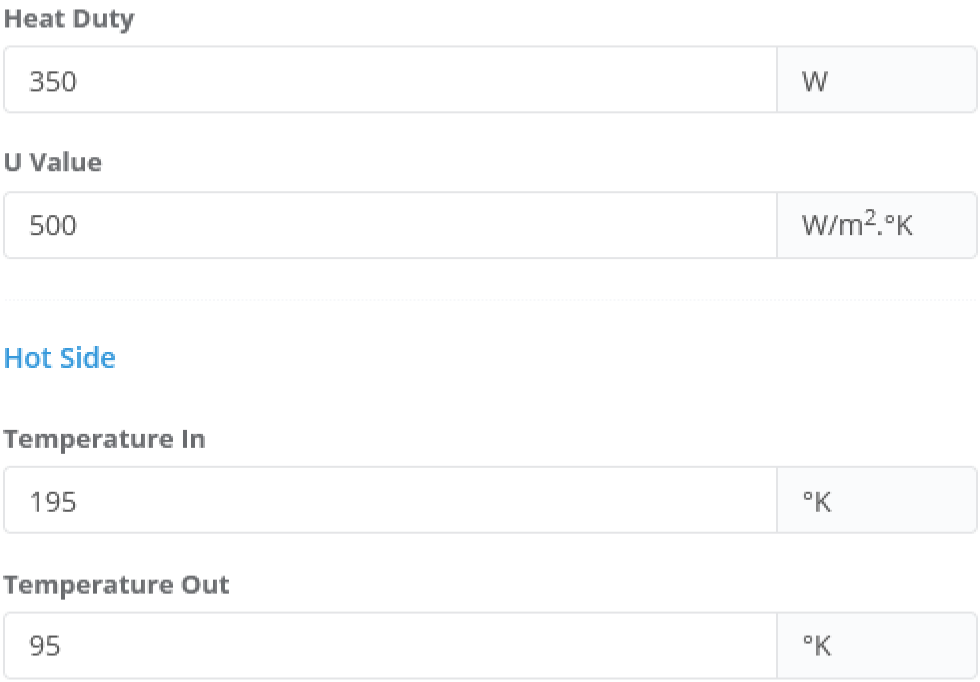
```
R1   = (t1 - t2)/ (T2 - T1)
     = 0.7000

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.

14.3.3 Data



Heat Duty

350 W

U Value

500 W/m^2.°K

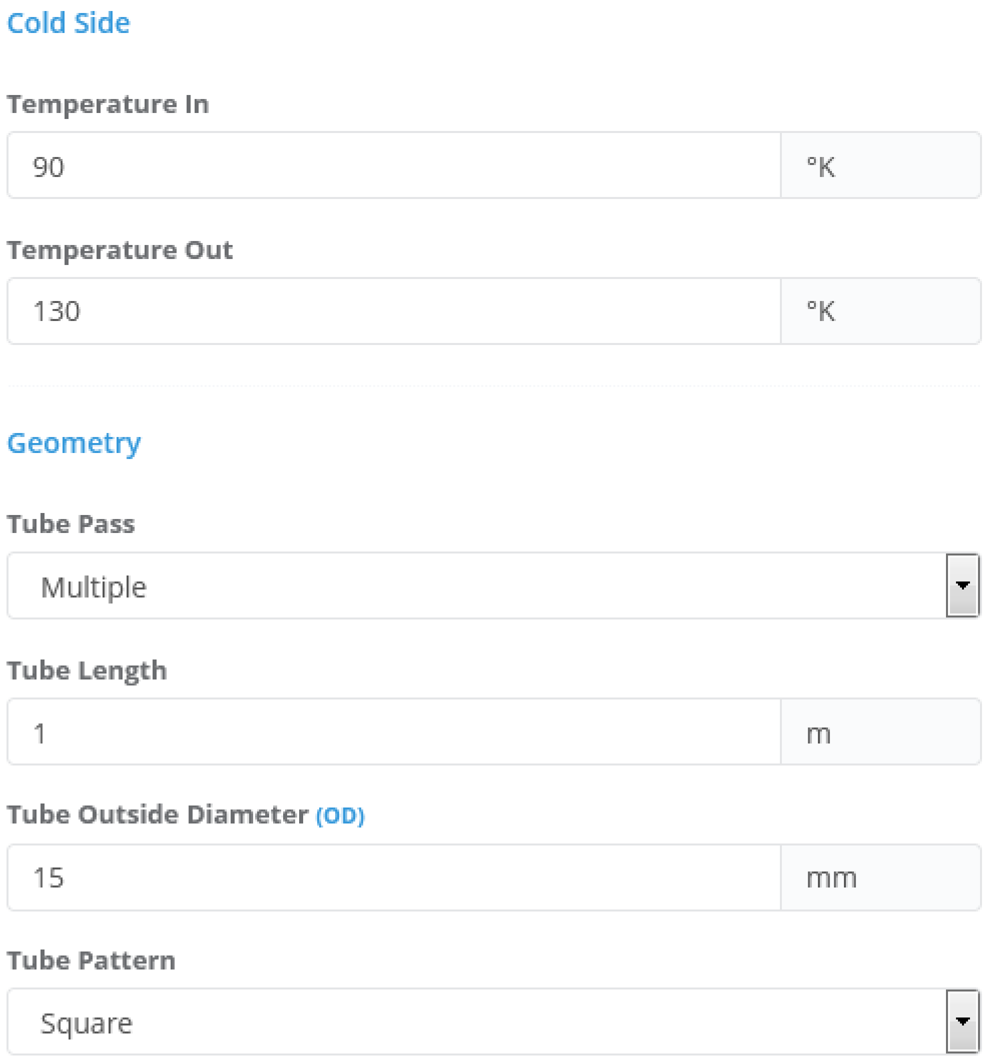
Hot Side

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

14.3.4 Result

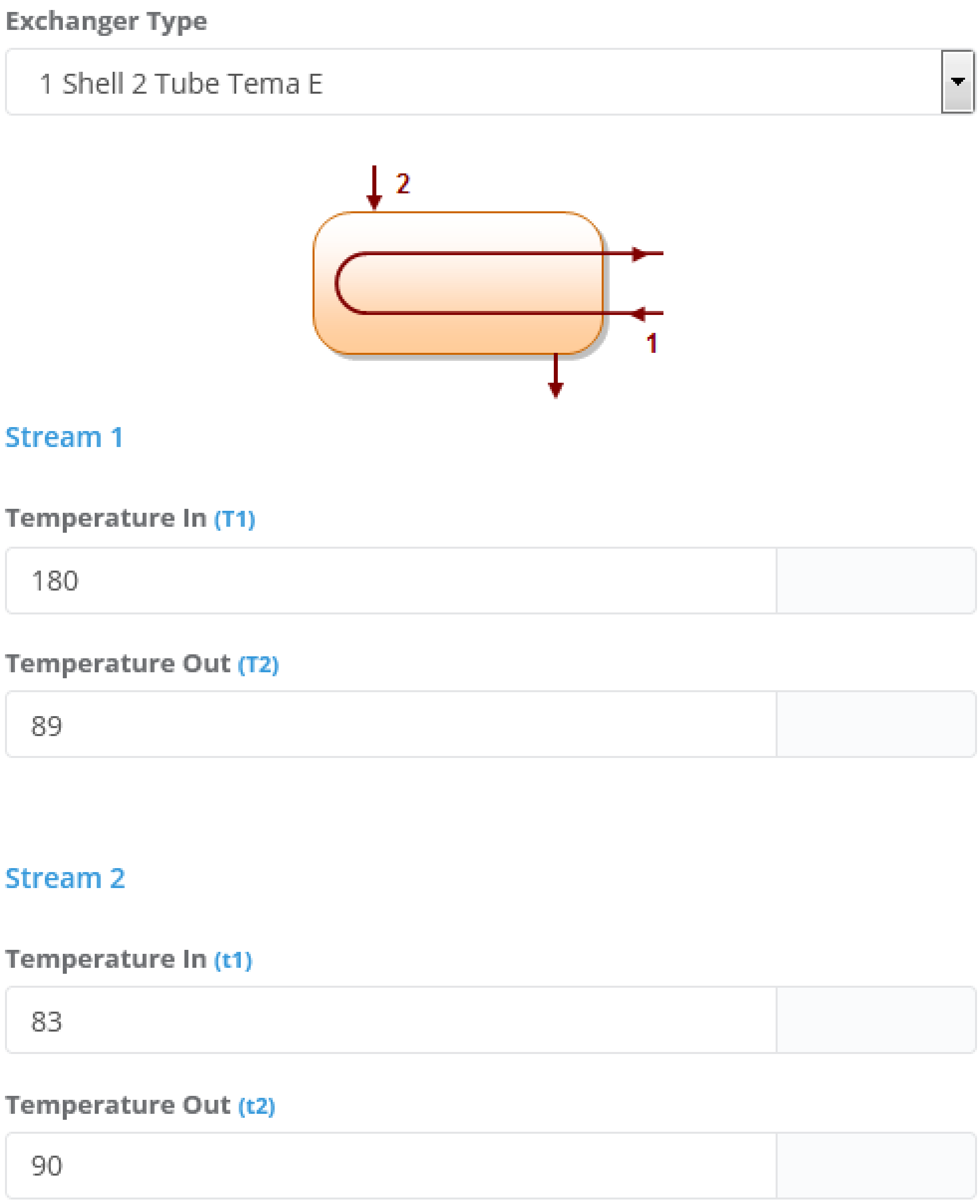
Tube Pitch	21.3500	mm
LMTD	23.39	°K
Correction Factor (F)	0.8381	
LMTD (Corrected)	19.61	°K
Shell in Series	3	
Total Area	0.04	m^2
Area per Shell	0.01	m^2
Tubes per Shell	0	
Shell ID (Estimate)	88.31	mm

14.4 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.

14.4.1 Data:



Exchanger Type

1 Shell 2 Tube Tema E

Stream 1

Temperature In (T1)

180

Temperature Out (T2)

89

Stream 2

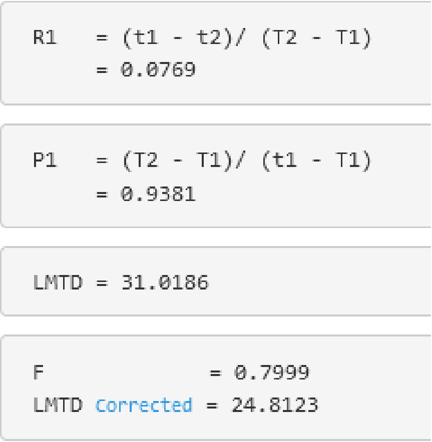
Temperature In (t1)

83

Temperature Out (t2)

90

14.4.2 Result:

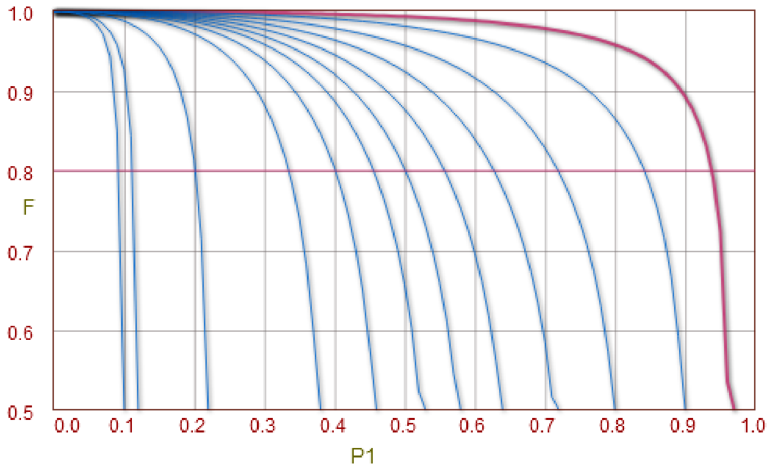


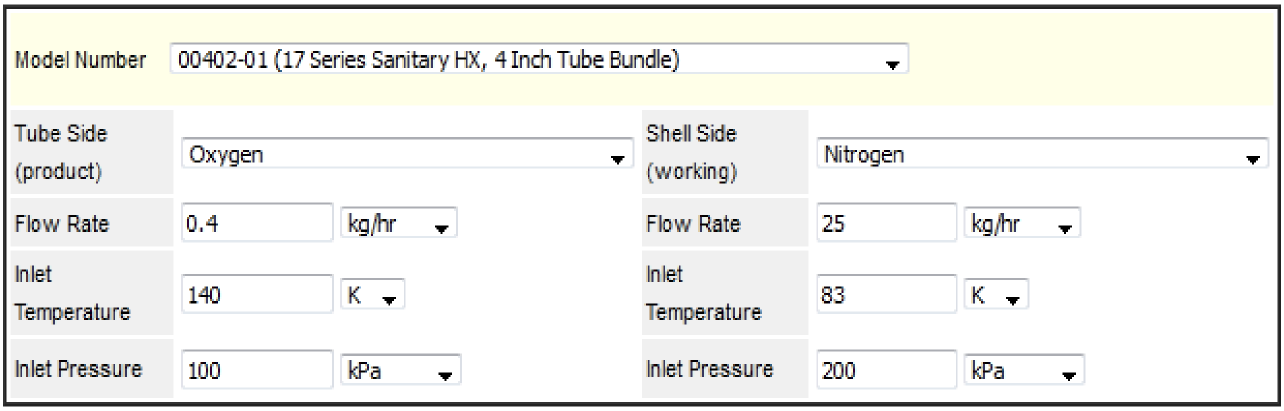
```
R1   = (t1 - t2)/ (T2 - T1)
     = 0.0769
```

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

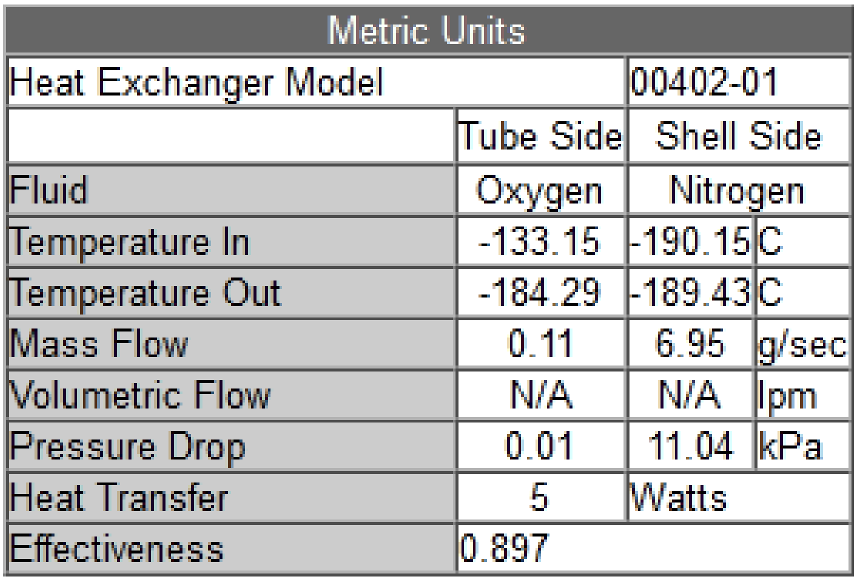
```
LMTD = 31.0186
```

```
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



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		

[41]

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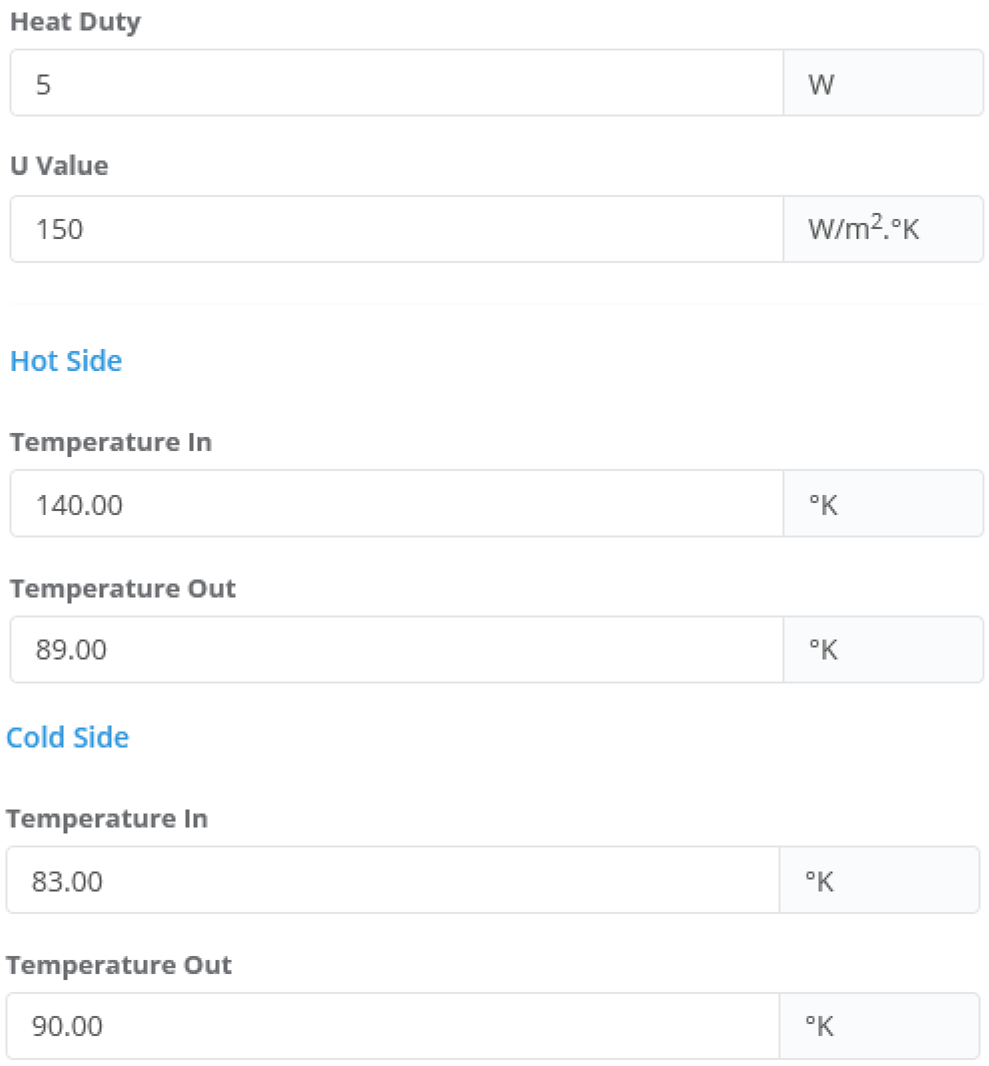
[41] http://calc.exergyllc.com/

Shortcut Heat Exchanger Sizing

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

14.4.3 Data:



Heat Duty
5 W

U Value
150 W/m²·°K

Hot Side

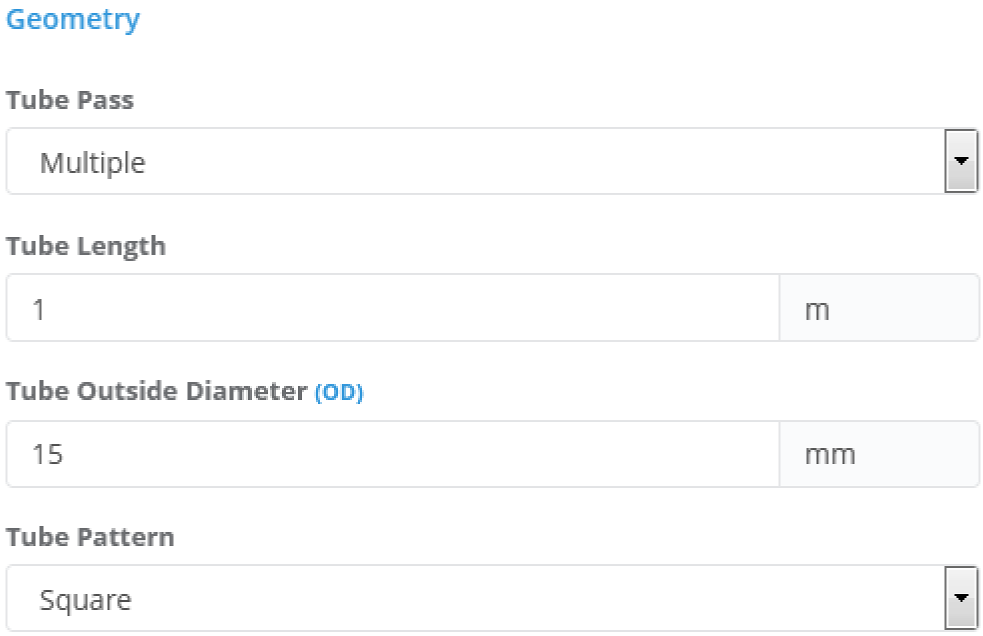
Temperature In
140.00 °K

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

14.4.4 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	m^2
Area per Shell	0.00	m^2
Tubes per Shell	0	
Shell ID (Estimate)	79.41	mm

[42]

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[42] https://checalc.com/calc/ShortExch.html

15 Components of Oxygen liquefaction prototype

15.1 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

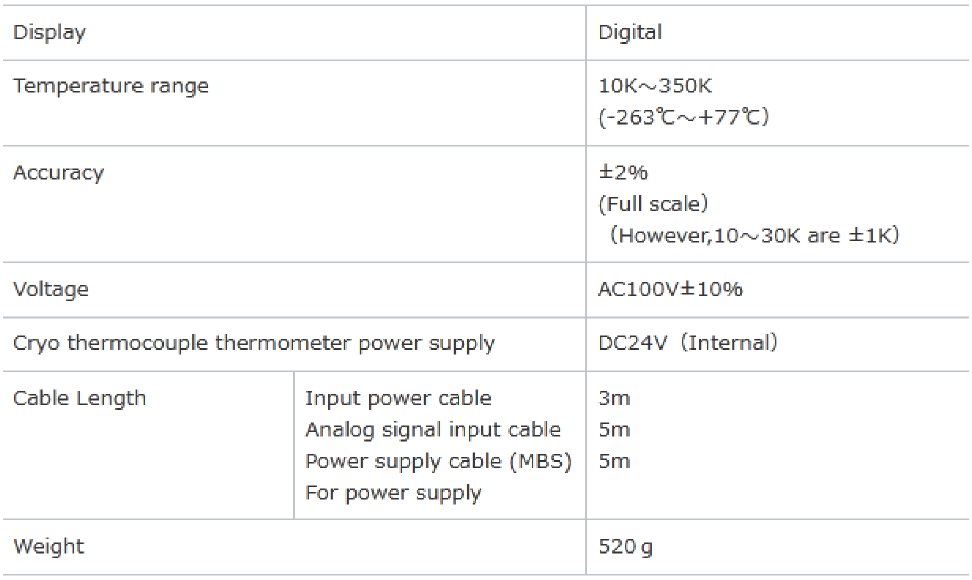
15.2 Cryometer

15.2.1 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.

15.2.2 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

16 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 C& (=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

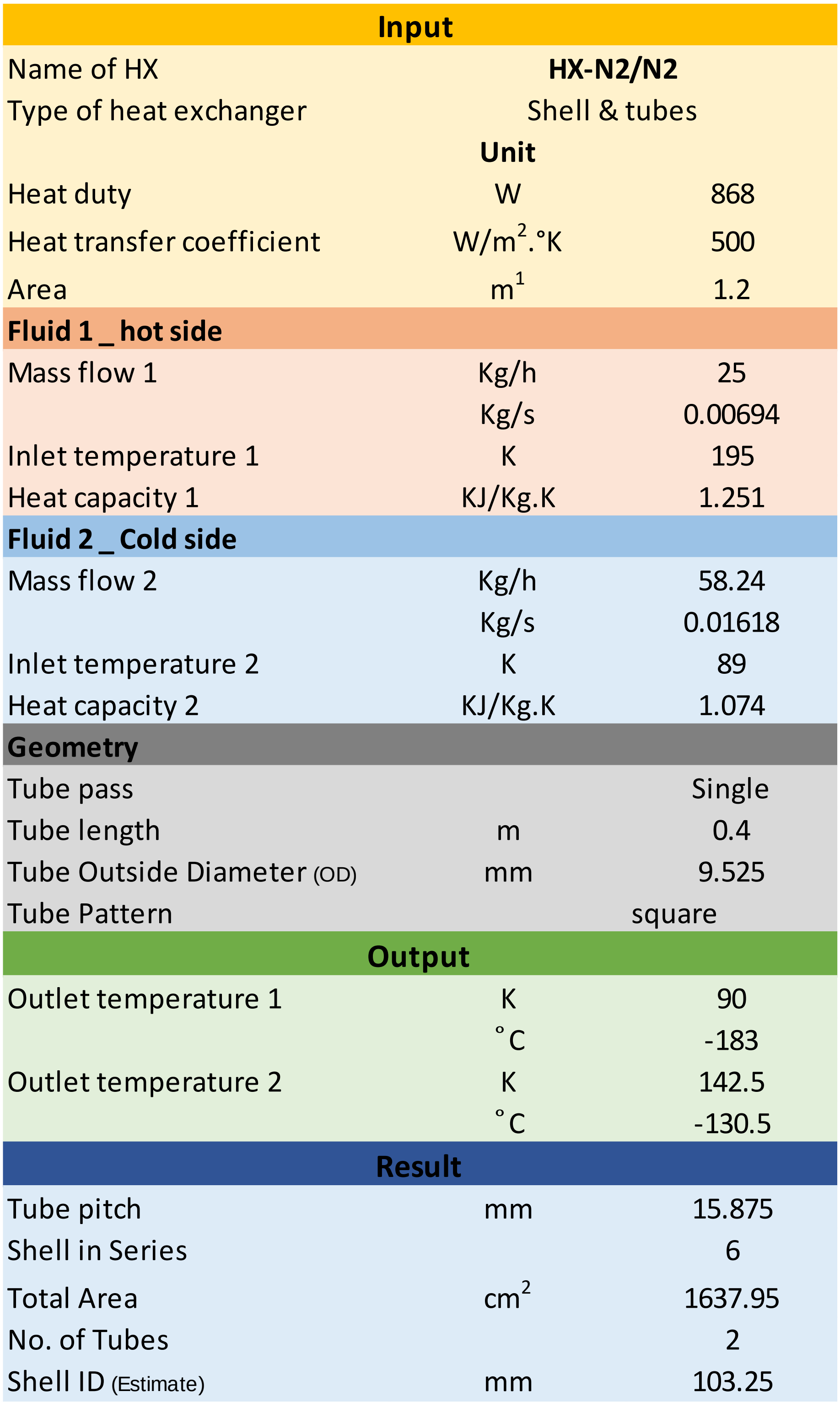
$$q = U\,A\,\Delta T_{\mathrm{m}}$$

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.

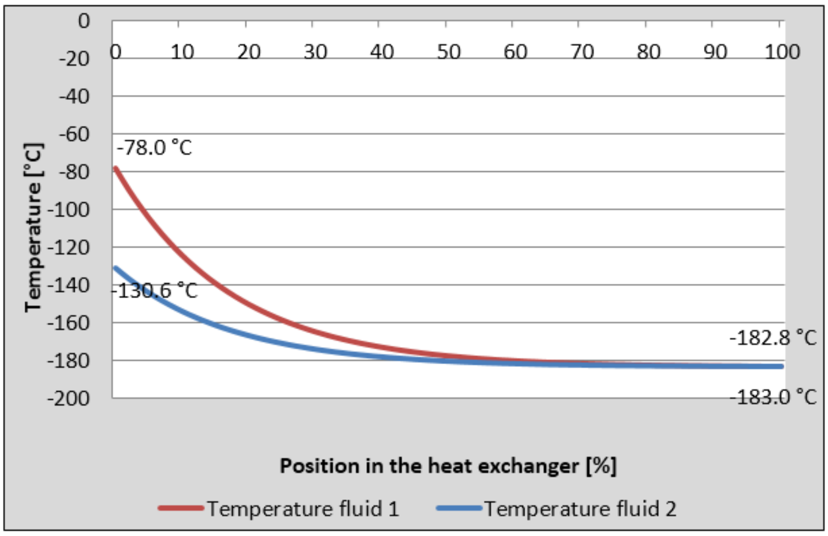
Second, on the basis of 1st law of thermodynamics, the heat transfer rate q must also equal the rate of heat lost by the hot fluid stream and gained by the cold fluid stream:

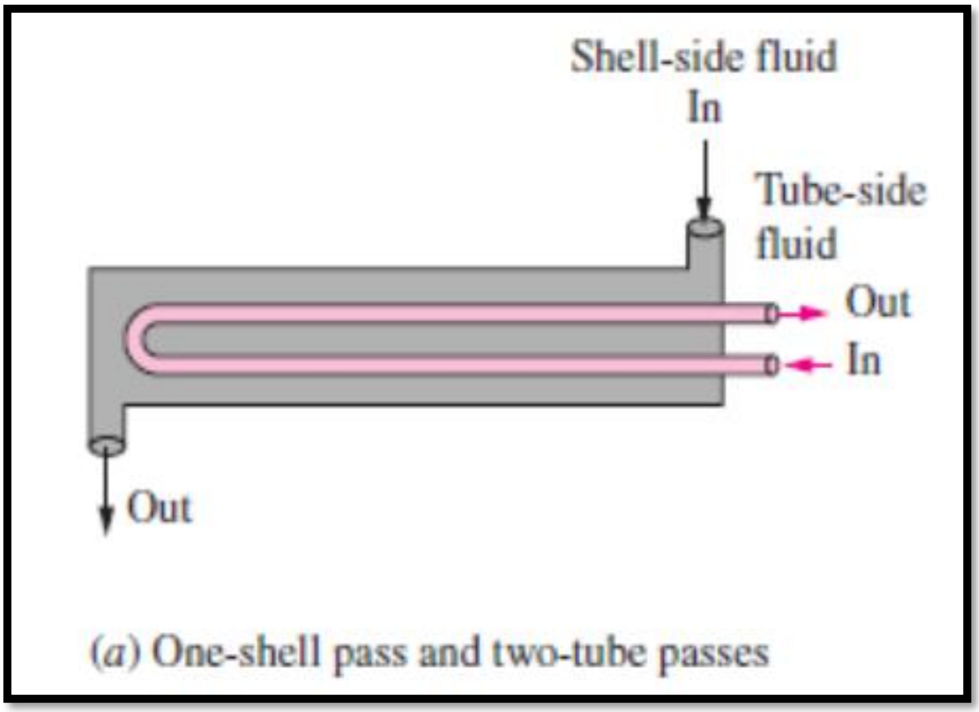
$$q = \dot{C}_{hot}\left(T_{hot,in} - T_{hot,out}\right) = \dot{C}_{cold}\left(T_{cold,out} - T_{cold,in}\right)$$

16.1 HX- N_2/N_2

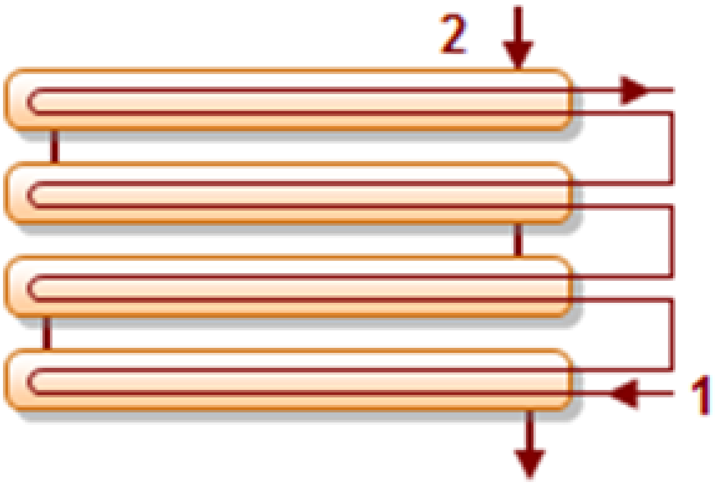


Input		
Name of HX	**HX-N2/N2**	
Type of heat exchanger	Shell & tubes	
	Unit	
Heat duty	W	868
Heat transfer coefficient	W/m^2.°K	500
Area	m^1	1.2
Fluid 1 _ hot side		
Mass flow 1	Kg/h	25
	Kg/s	0.00694
Inlet temperature 1	K	195
Heat capacity 1	KJ/Kg.K	1.251
Fluid 2 _ Cold side		
Mass flow 2	Kg/h	58.24
	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



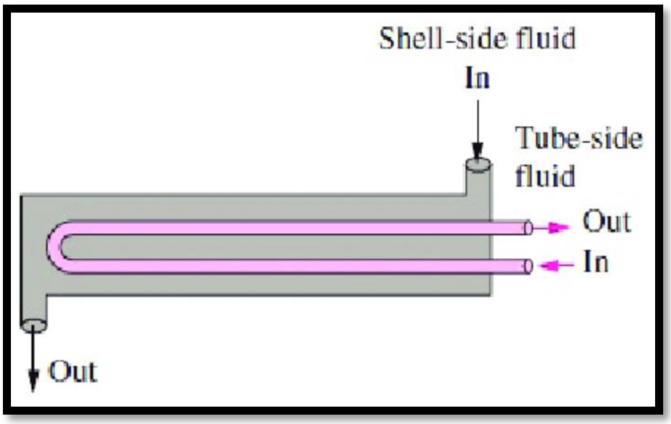


(*a*) One-shell pass and two-tube passes

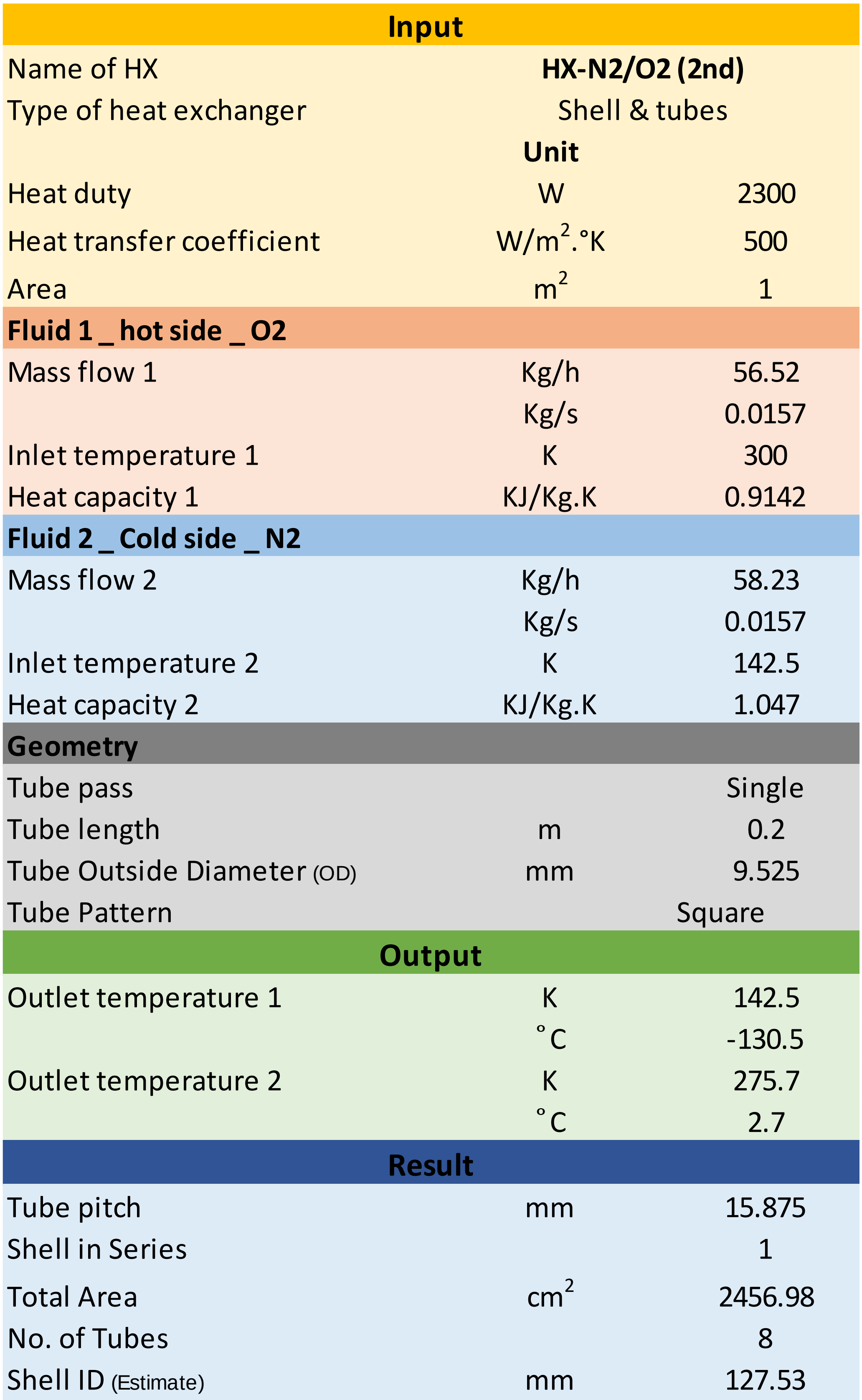


16.2 HX-N2/O2 main

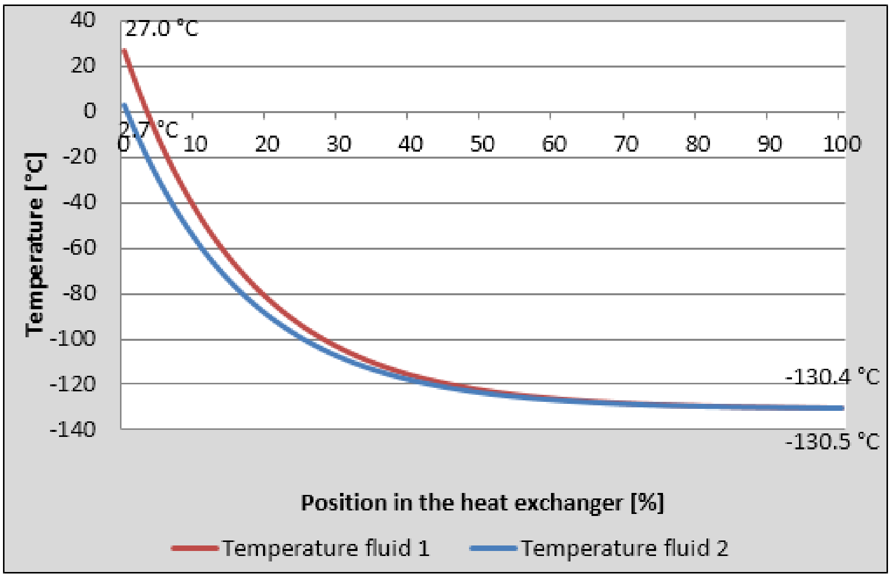
Input		
Name of HX	**HX-N2/O2 Main**	
Type of heat exchanger	shell & tubes	
	Unit	
Heat duty	W	92.42
Heat transfer coefficient	$W/m^2.^\circ K$	500
Area	m^2	0.018
Fluid 1 _ hot side _ O2		
Mass flow 1	Kg/h	4.739
	Kg/s	0.001316
Inlet temperature 1	K	142.5
Heat capacity 1	KJ/Kg.K	0.9298
Fluid 2 _ Cold 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

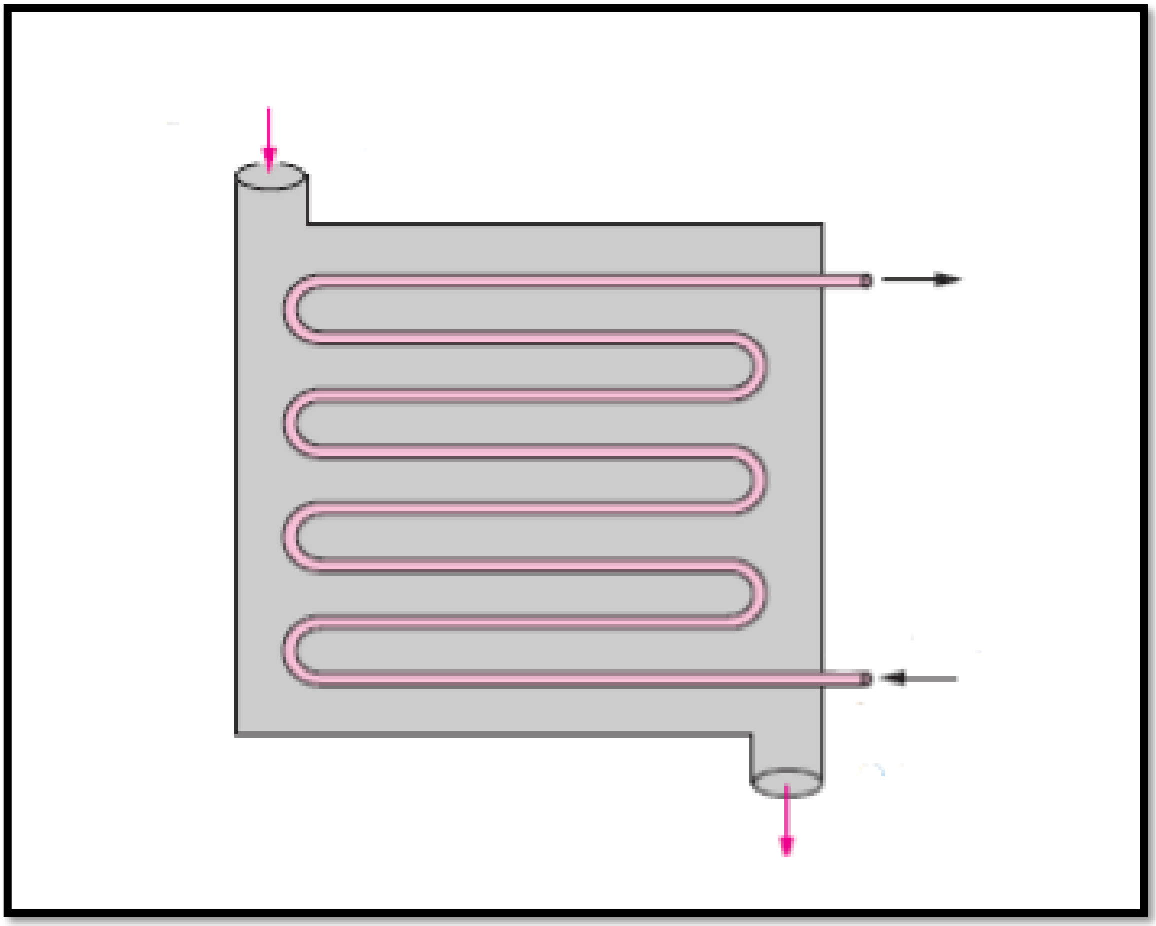


3.2. HX-N2/O2 (2nd)



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
0
10
20
30
40
50
60
70
80
90
100
27.0 °C
2.7 °C
-130.4 °C
-130.5 °C
Position in the heat exchanger [%]
Temperature fluid 1
Temperature fluid 2



16.3 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**

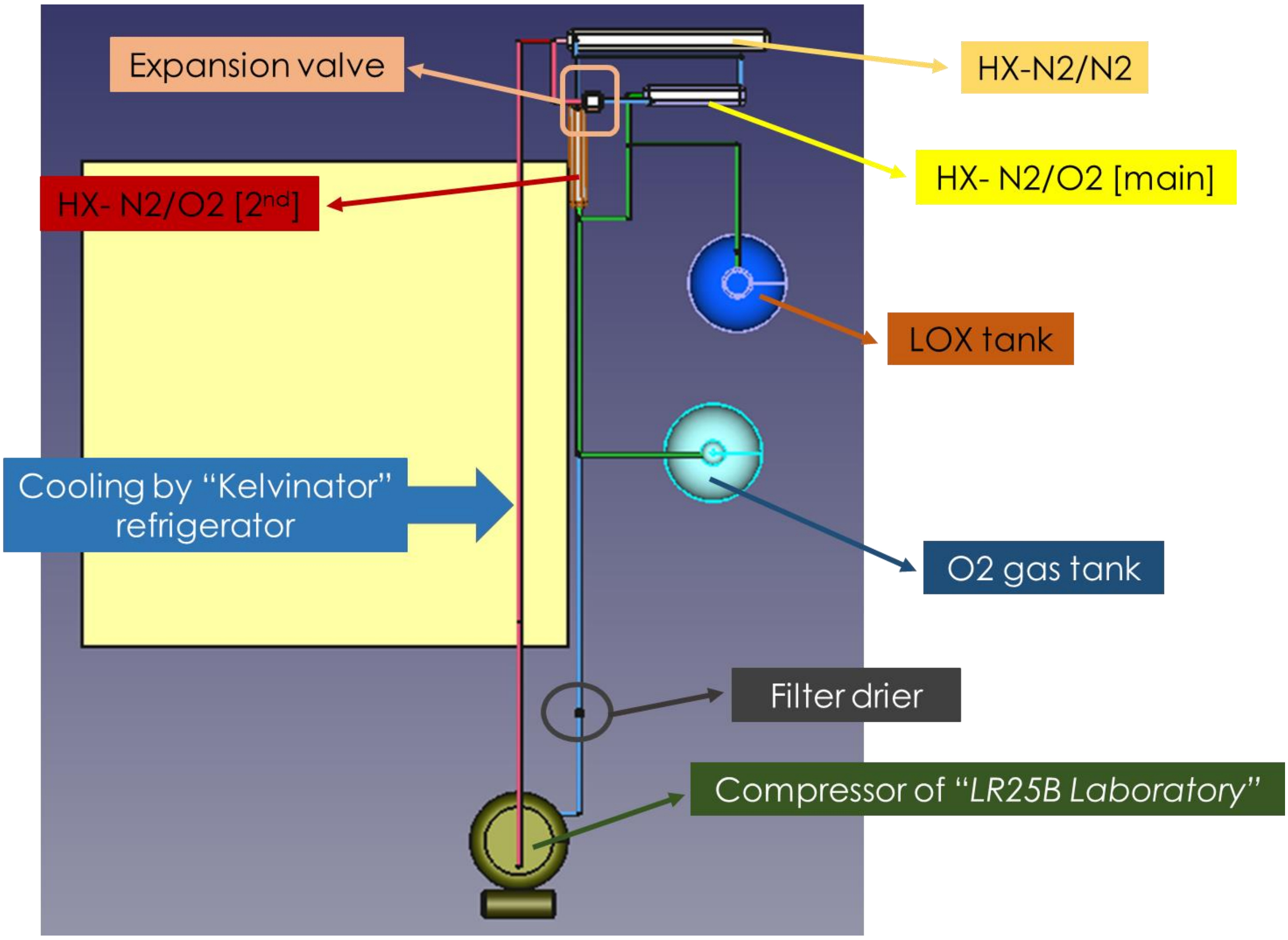
For HX-N2/O2 [2nd]											
Stream data				Results			Units	Final results			Units
	Units	Hot	Cold	Heat capacity ratio	Cr	0.8363		LMDT	LMDT	60.5	
Flow rate	Kg/hr	**56.52**	**58.23**	Number of transfer units	NTU	3.5192		Surface Area	S	0.507249982	m2
Inlet temp.	K	**300**	**129**	Effectivenes	ξ	0.6316		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				

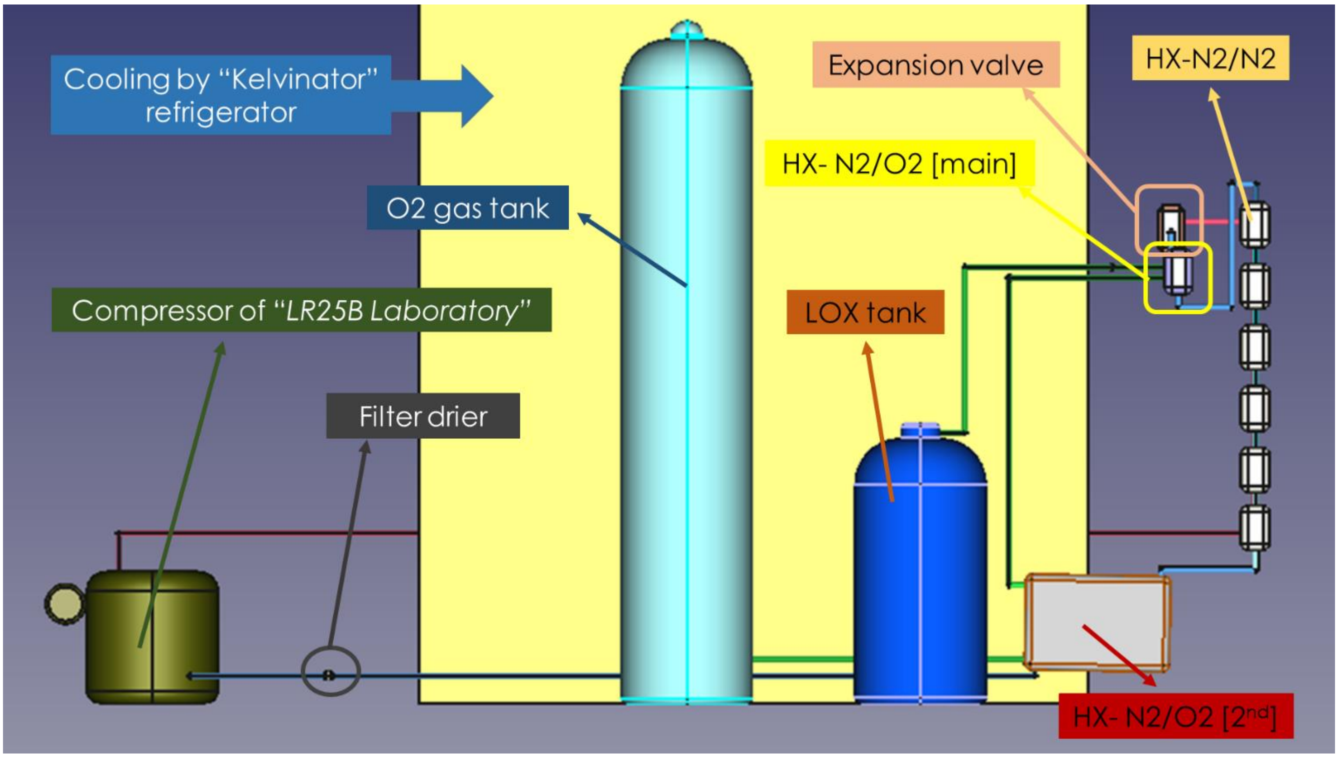
For HX-N2/O2 [Main]											
Stream data				Results			Units	Final results			Units
	Units	Hot	Cold	Heat capacity ratio	Cr	0.0834		LMDT	LMDT	31.787	
Flow rate	Kg/hr	**4.739**	**25**	Number of transfer units	NTU	3.4197		Surface Area	S	0.027718617	m2
Inlet temp.	K	**192**	**83**	Effectivenes	ξ	0.9541		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				

17 FreeCad Design

17.1 Prototype design on FreeCad

prototype cycle of oxygen liquefaction.FCStd





17.2 Heat exchanger design HX-N_2/N_2

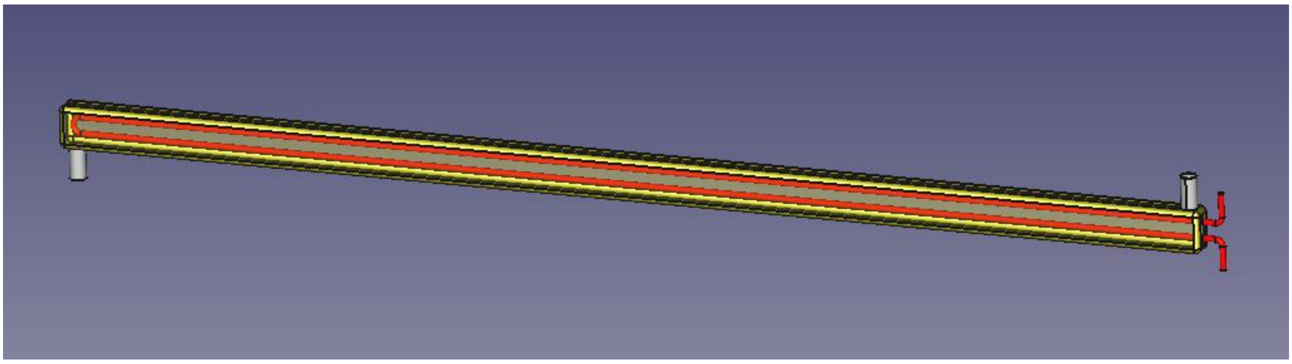
6 shell , 12 tubes

Shell – Cold side – N_2

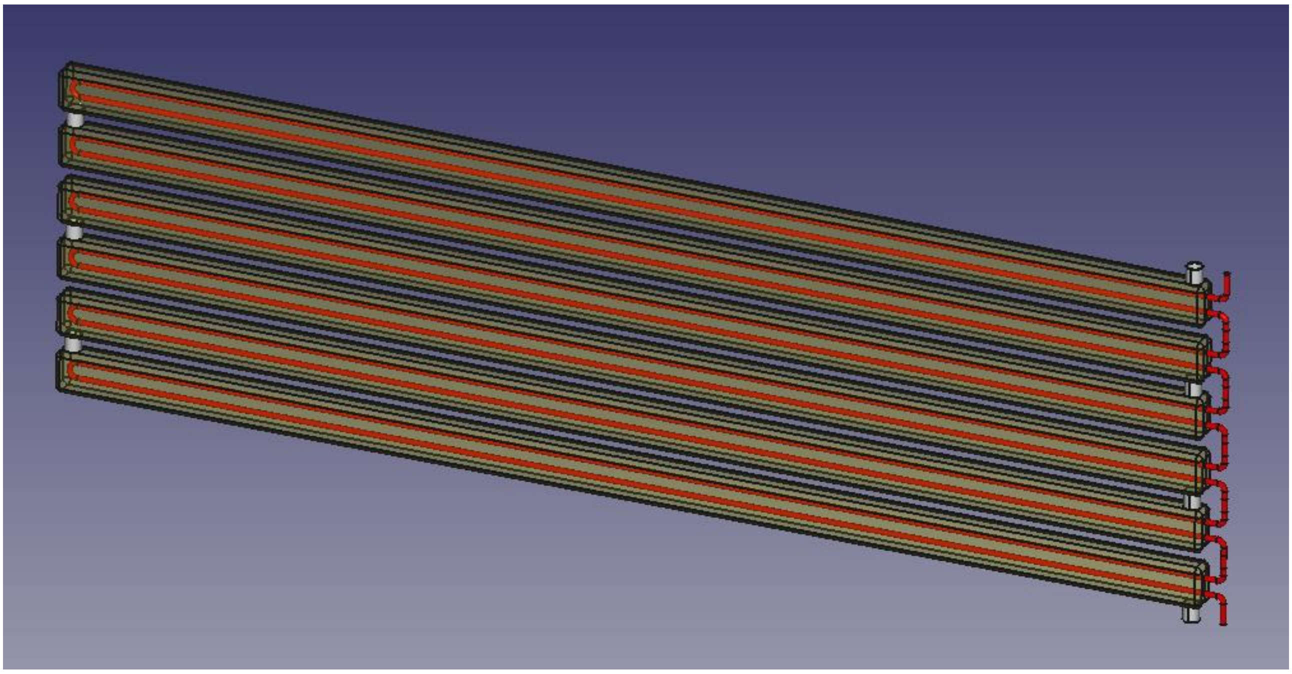
Tubes – Hot side – N_2

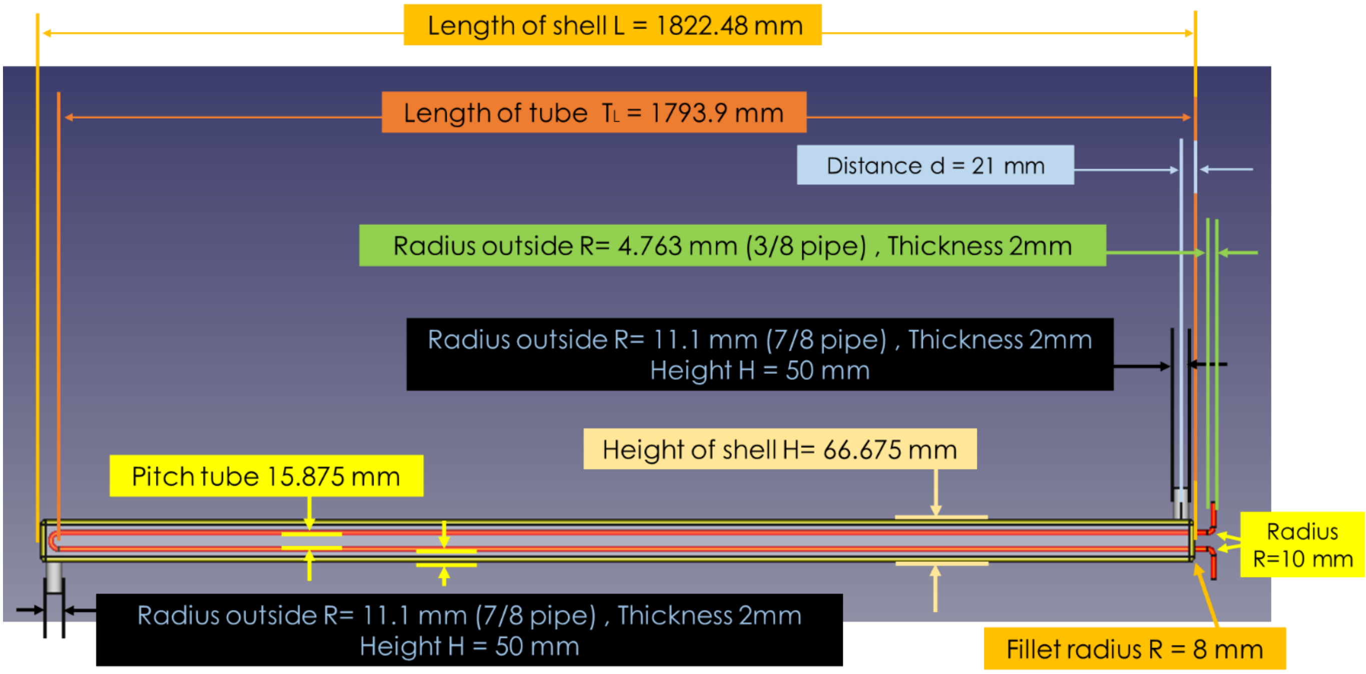
HX_N2-N2 _ ONE SHELL.FCStd

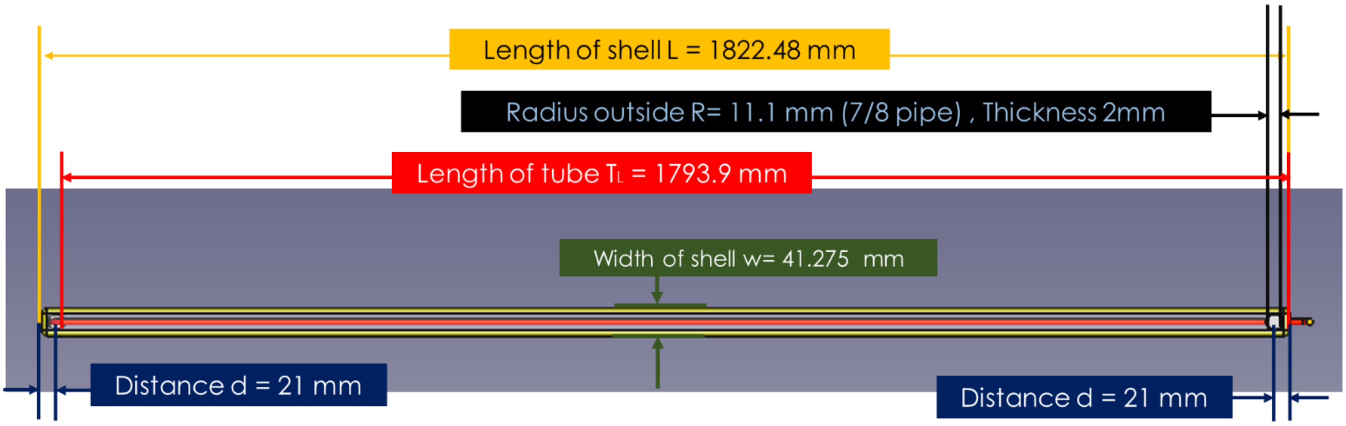
HX_N2-N2.FCStd

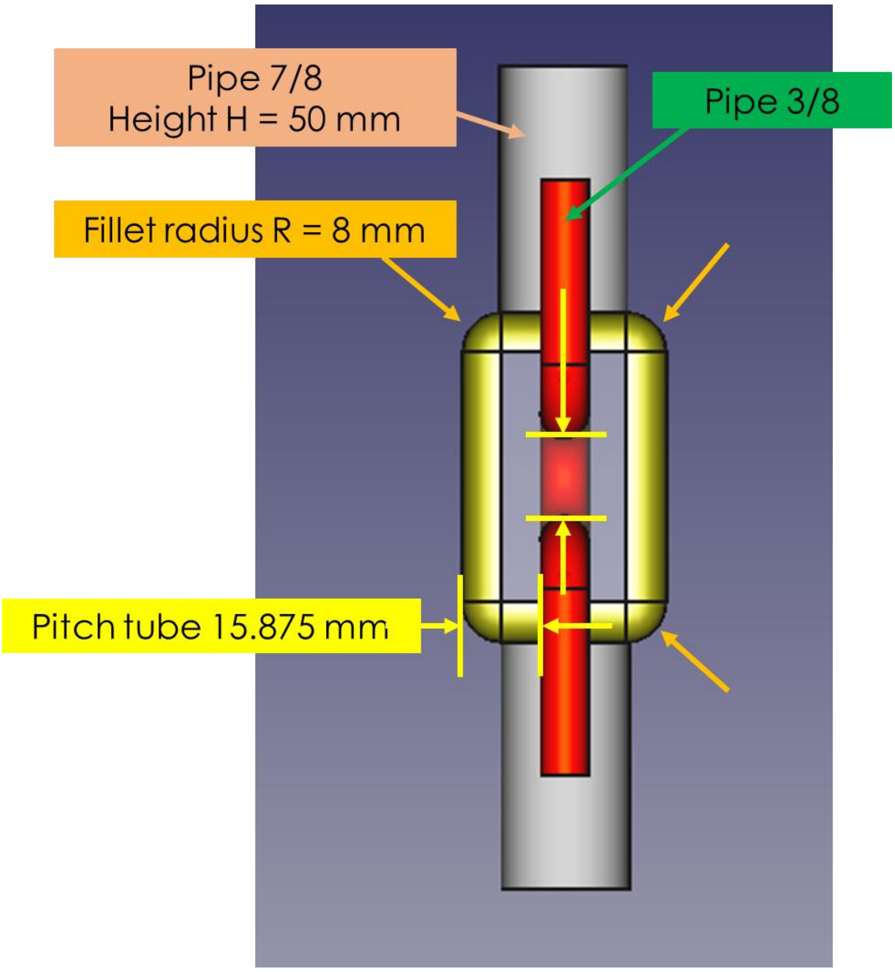


FreeCad Design

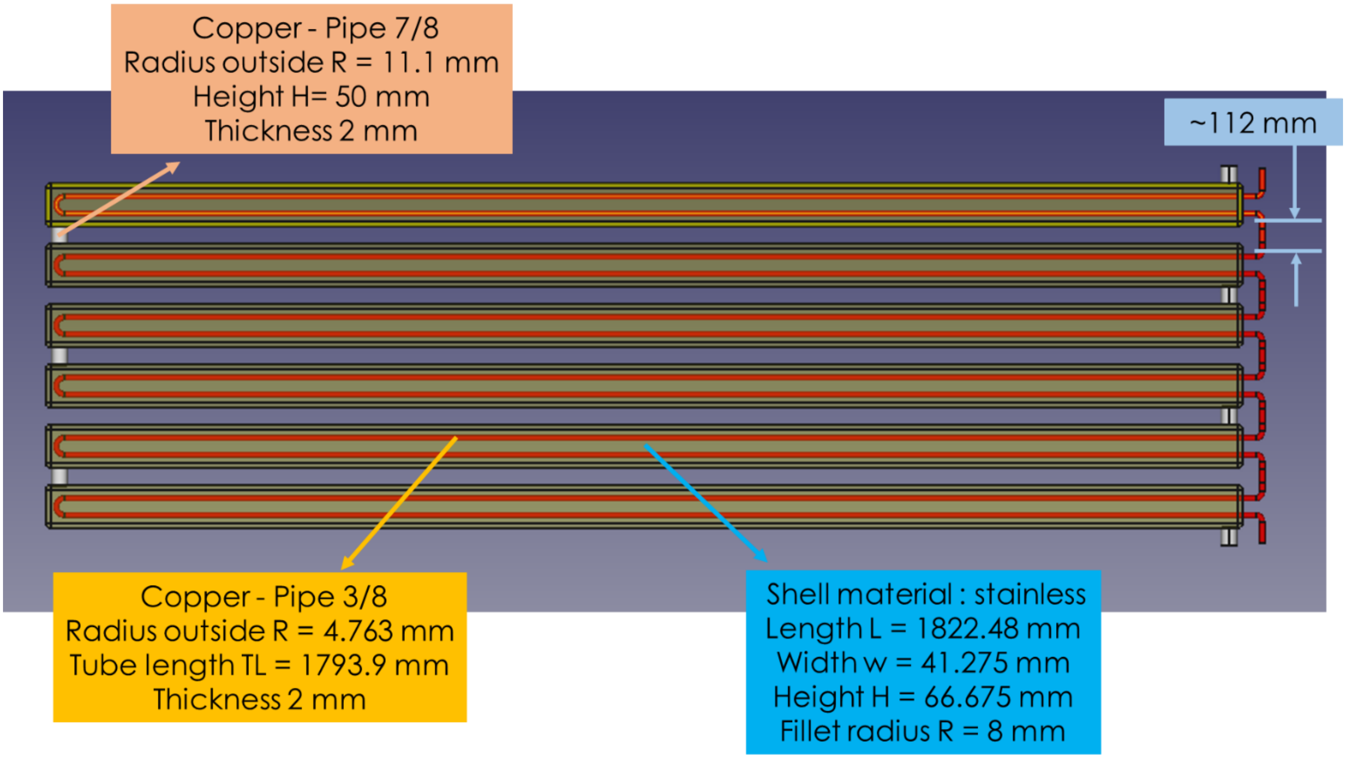





Length of shell L = 1822.48 mm
Radius outside R= 11.1 mm (7/8 pipe) , Thickness 2mm
Length of tube T$_L$ = 1793.9 mm
Width of shell w= 41.275 mm
Distance d = 21 mm
Distance d = 21 mm


Pipe 7/8
Height H = 50 mm
Pipe 3/8
Fillet radius R = 8 mm
Pitch tube 15.875 mm

FreeCad Design



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

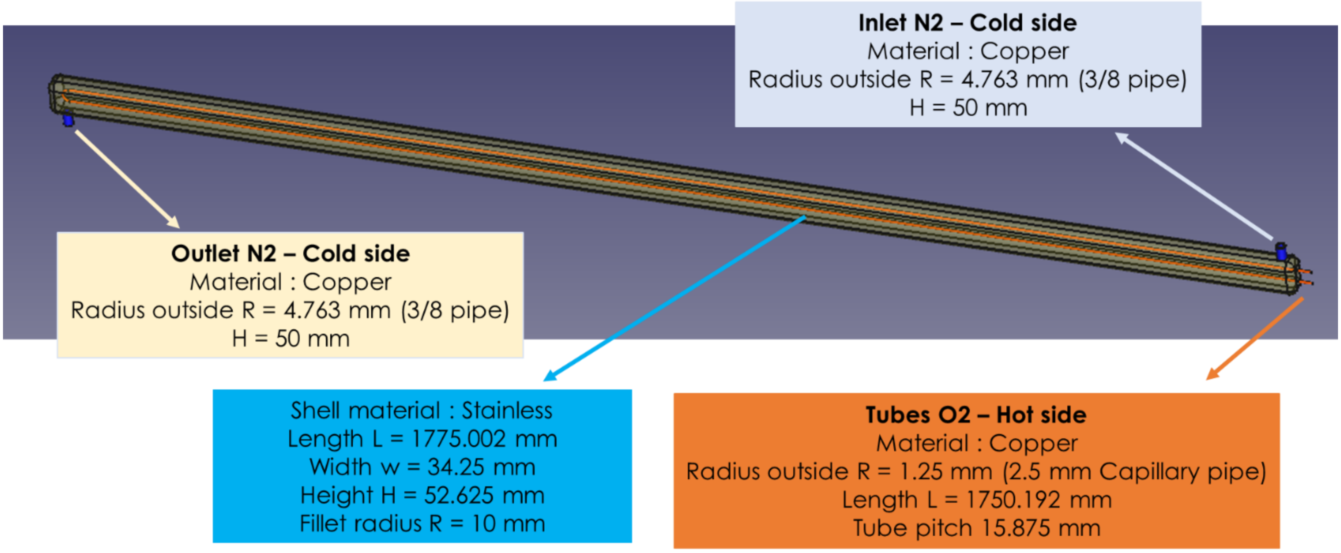
17.3 Heat exchanger design HX-N_2/O_2 [Main]

1 shell , 2 tubes

Shell – Cold side – N_2

Tubes – Hot side – O_2

HX_N2-O2 Main.FCStd

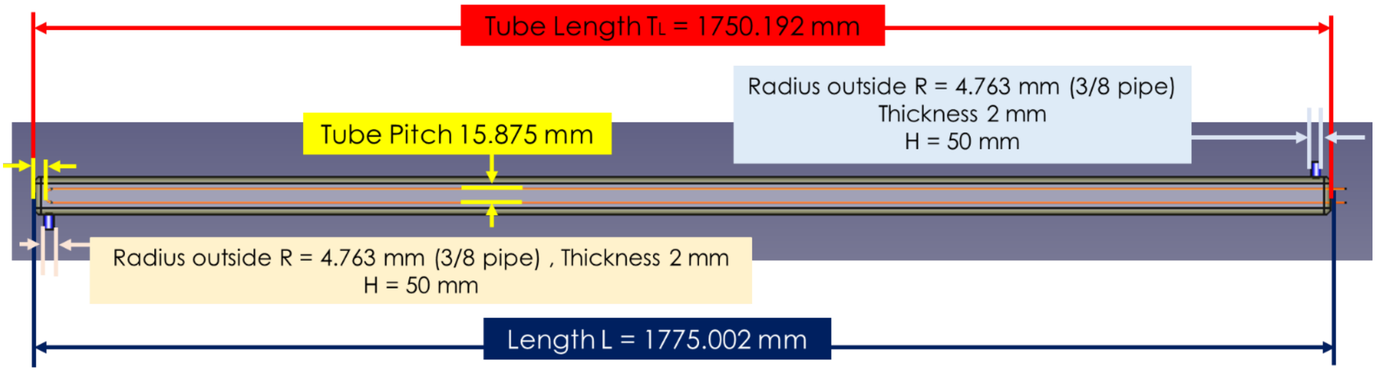


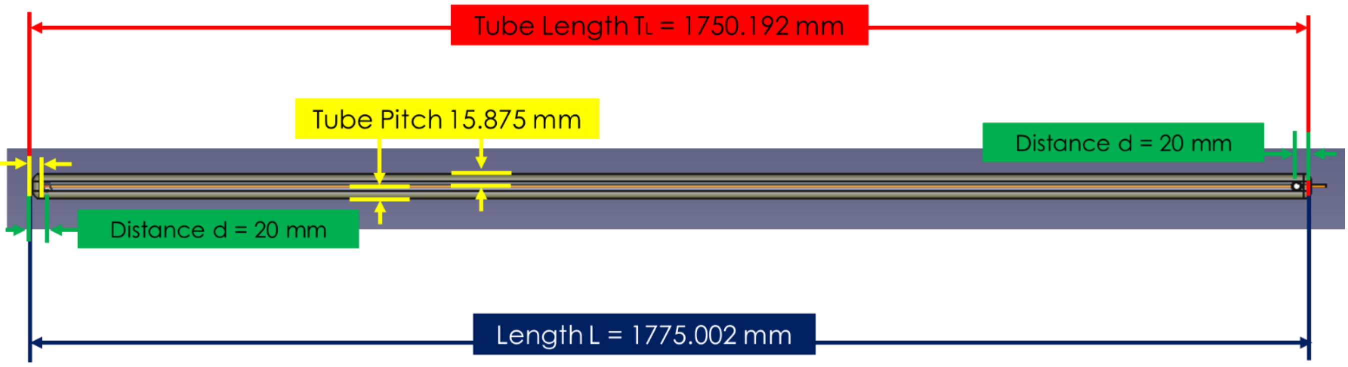
Inlet N2 – Cold side
Material : Copper
Radius outside R = 4.763 mm (3/8 pipe)
H = 50 mm

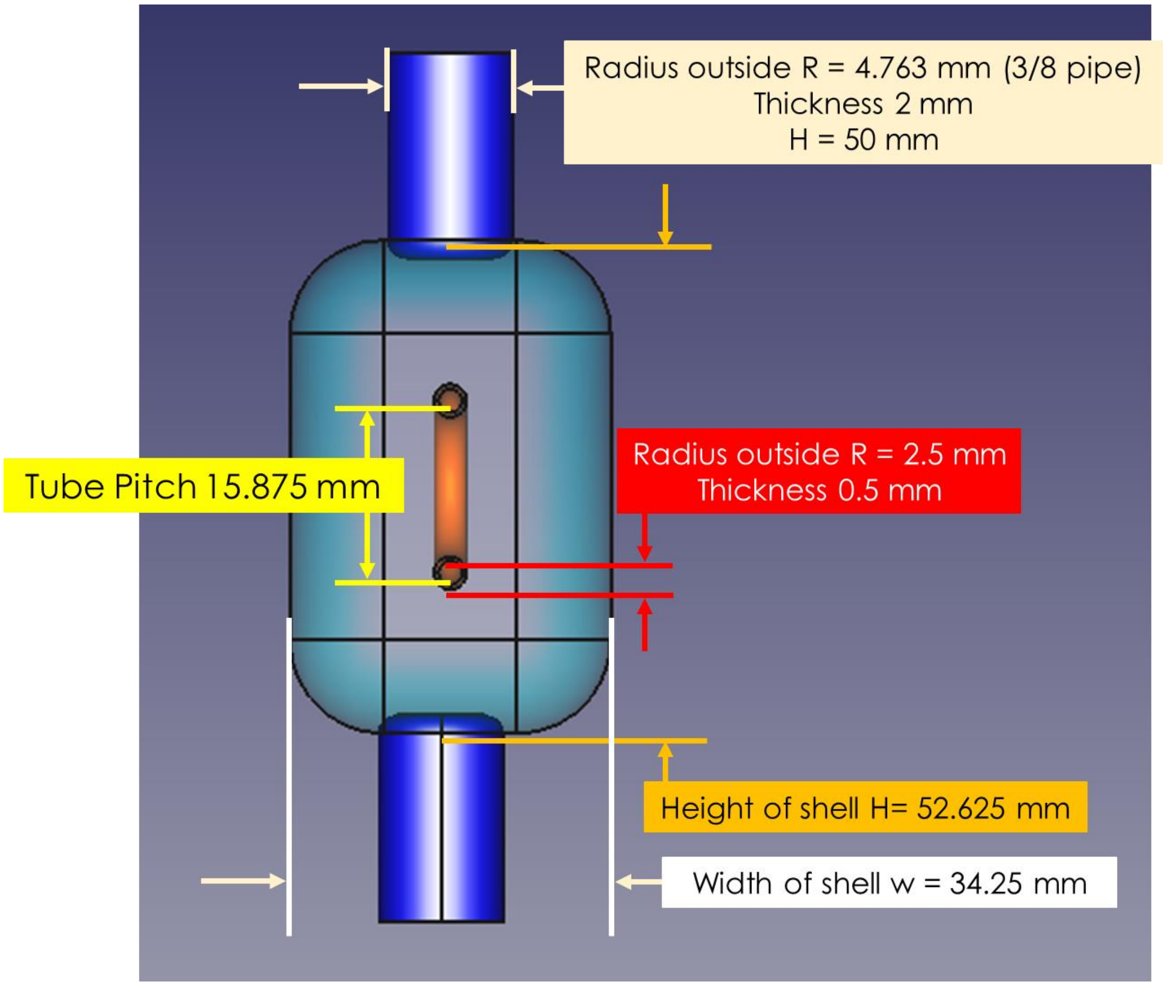
Outlet N2 – Cold side
Material : Copper
Radius outside R = 4.763 mm (3/8 pipe)
H = 50 mm

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 TL = 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 TL = 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

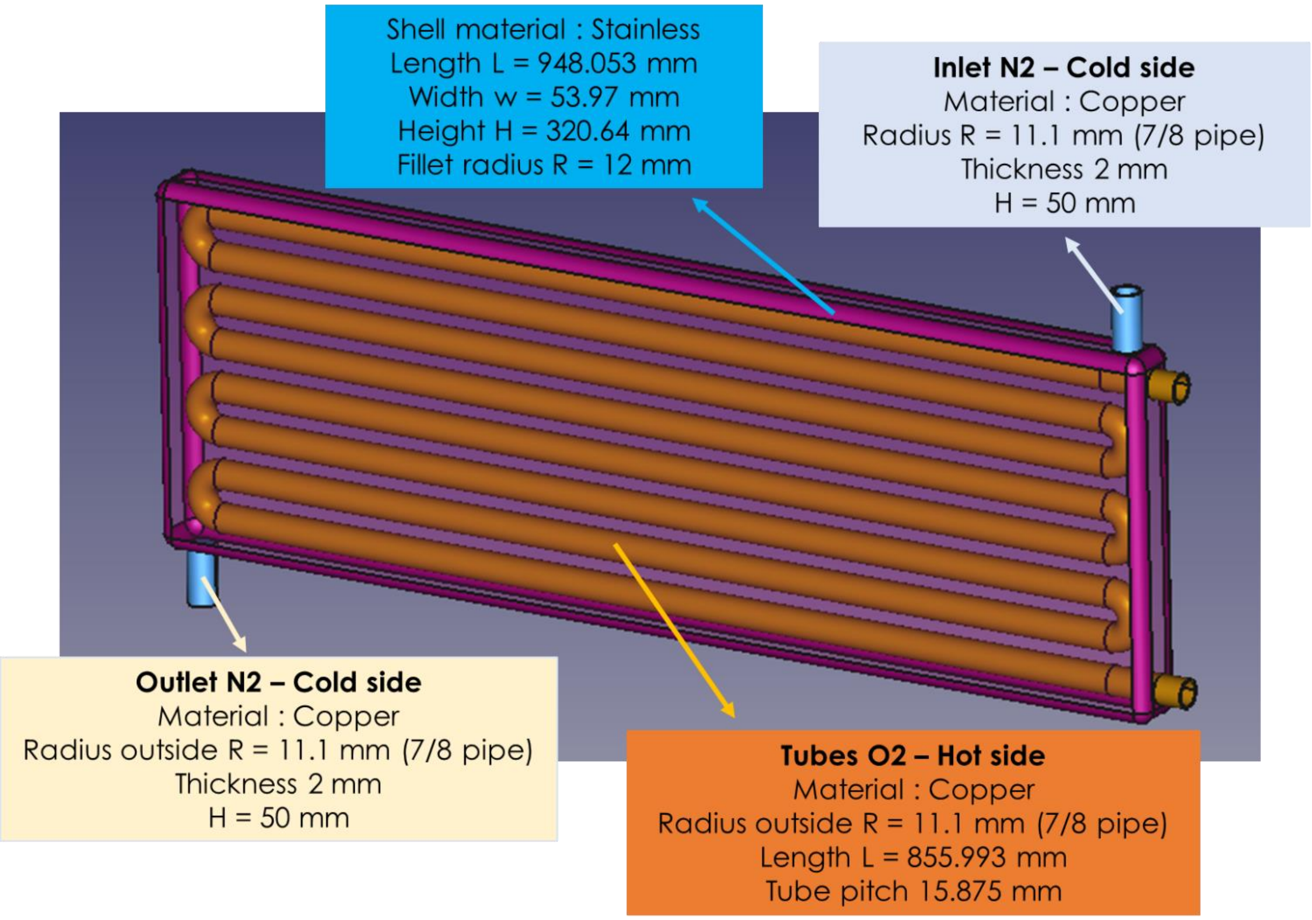
17.4 Heat exchanger design HX-N_2/O_2 [2nd]

1 shell , 8 tubes

Shell – Cold side – N2

Tubes – Hot side – O2

HX_N2-O2 (2nd).FCStd

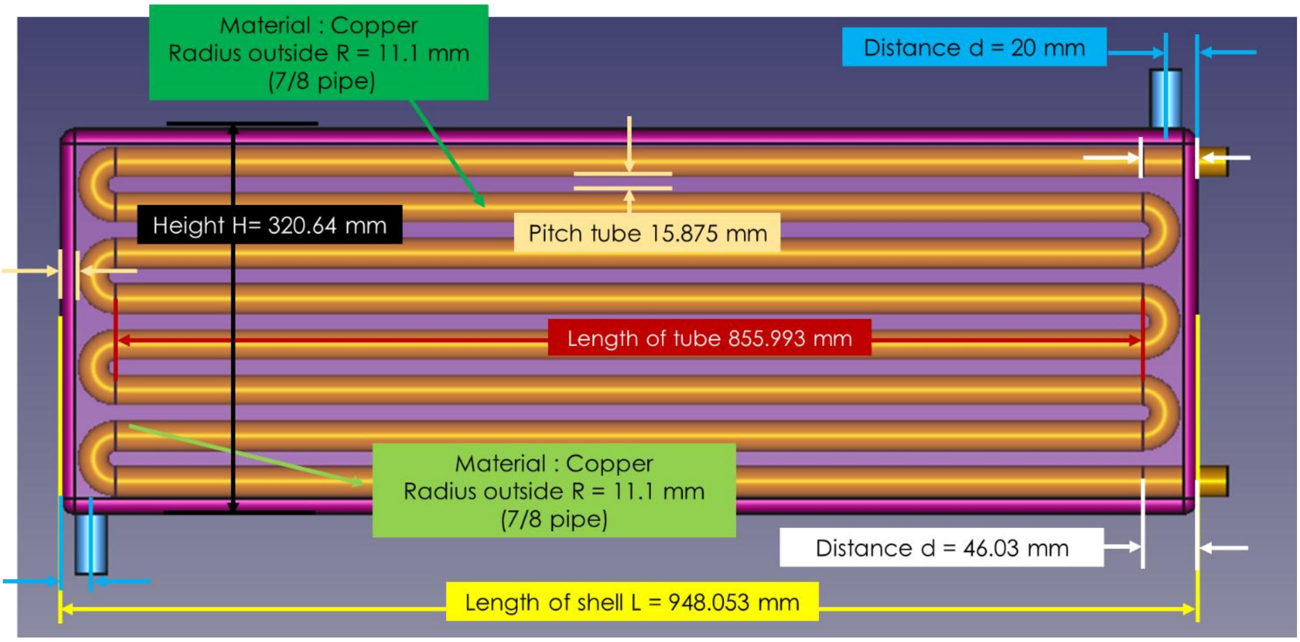


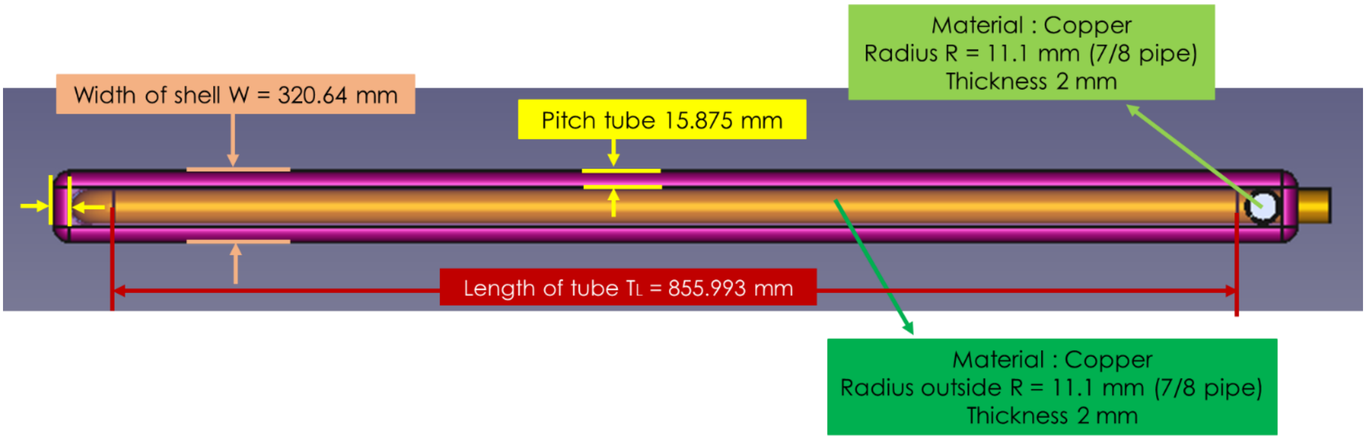
Shell material : Stainless
Length L = 948.053 mm
Width w = 53.97 mm
Height H = 320.64 mm
Fillet radius R = 12 mm

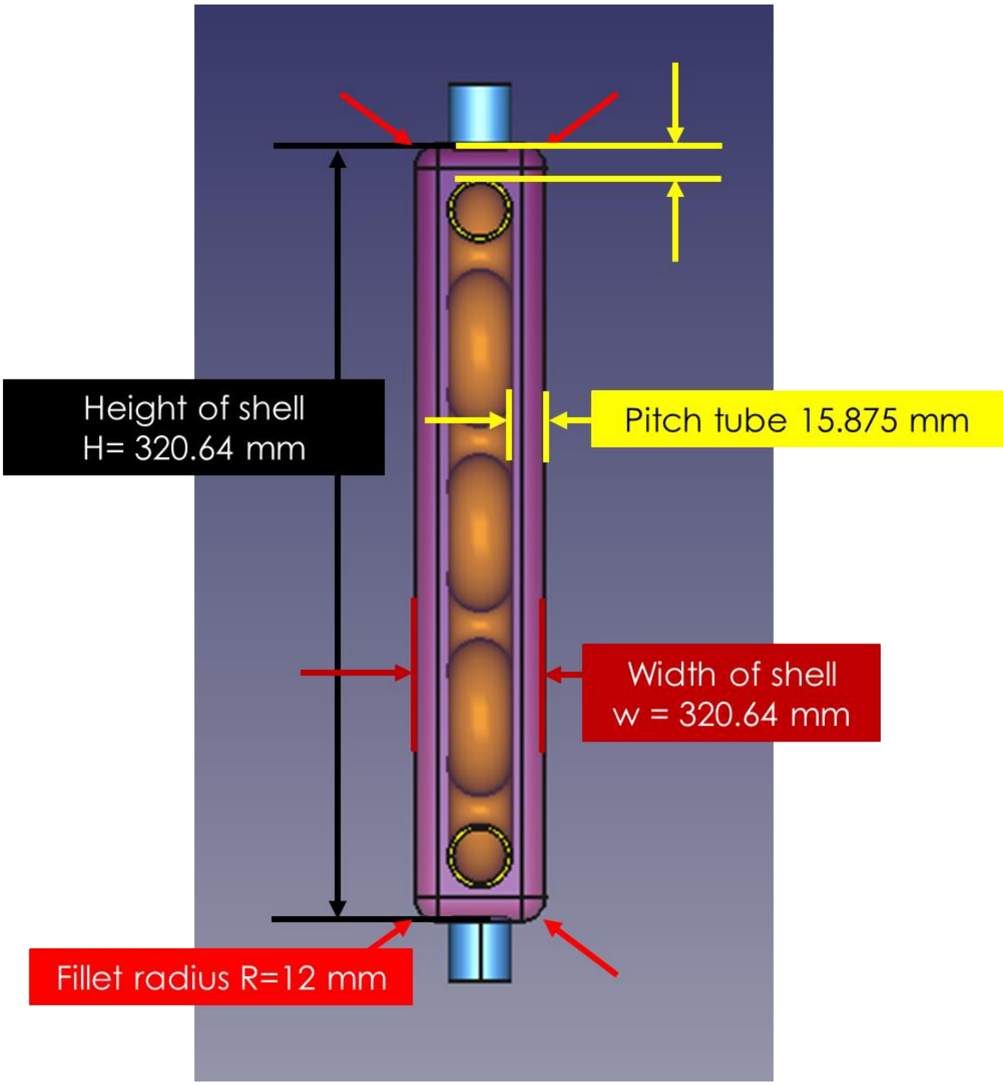
Inlet N2 – Cold side
Material : Copper
Radius R = 11.1 mm (7/8 pipe)
Thickness 2 mm
H = 50 mm

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



17.5 Cooling design [Inside kelvinator]

$Q_{conv} = m_{dot} * C_p * (T_i - T_o)$

$= 25\ kg/h * 1.088375\ KJ/Kg.K * (335 - 195)$

$= 25/3600 * 1.088375 * 140 = 1.0575\ KW = 1057.5\ W$

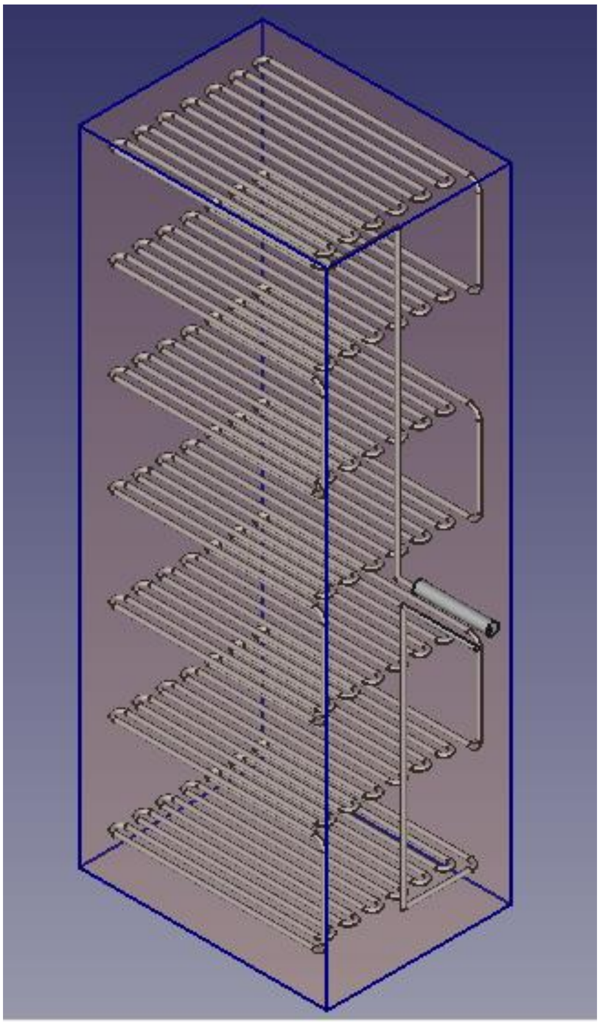
$Q_{conv} = h * A_s * LMTD$ or $LMTD = \dfrac{\Delta To - \Delta Ti}{\ln\left(\frac{\Delta To}{\Delta Ti}\right)} = 33.2$

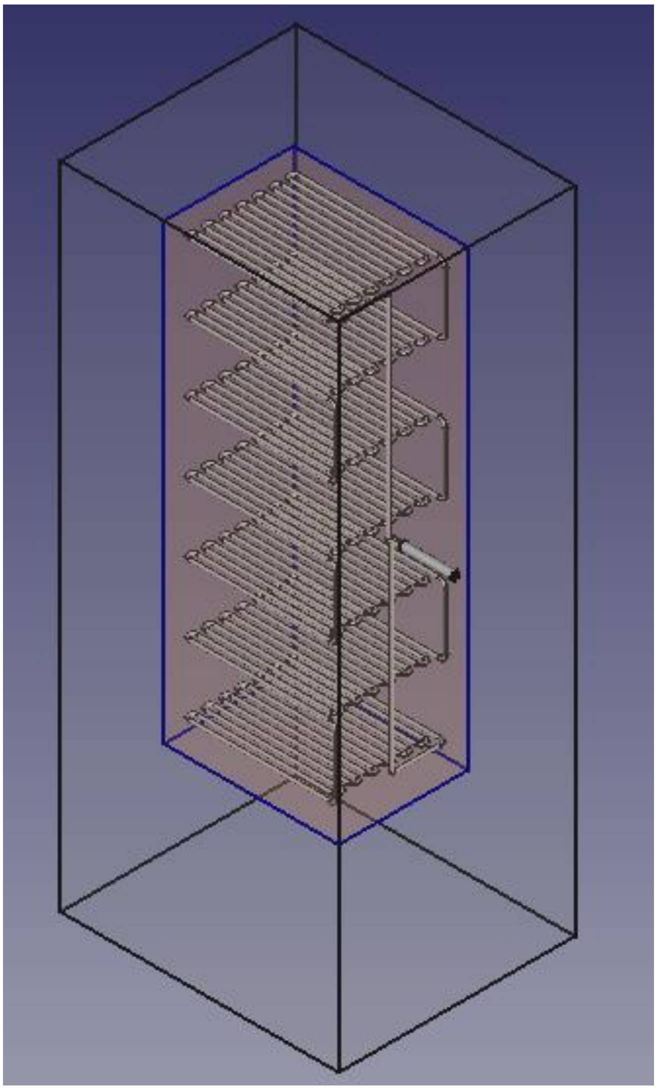
$A_s = \dfrac{1057.5}{h * 33.2} = \dfrac{1057.5}{25 * 33.2} = 1.274\ m^2$

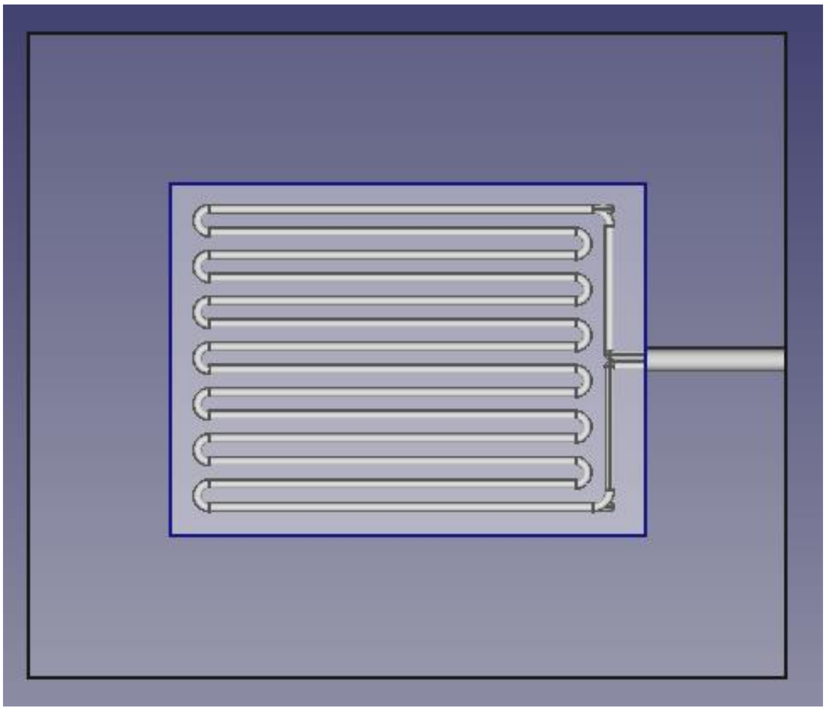
Or $A_s = 2 * \pi * R * h \rightarrow h = \dfrac{As}{2 * \pi * R} = \dfrac{1.274}{\pi * 9.525 * 10\text{^}{-3}} = 42.58\ m$

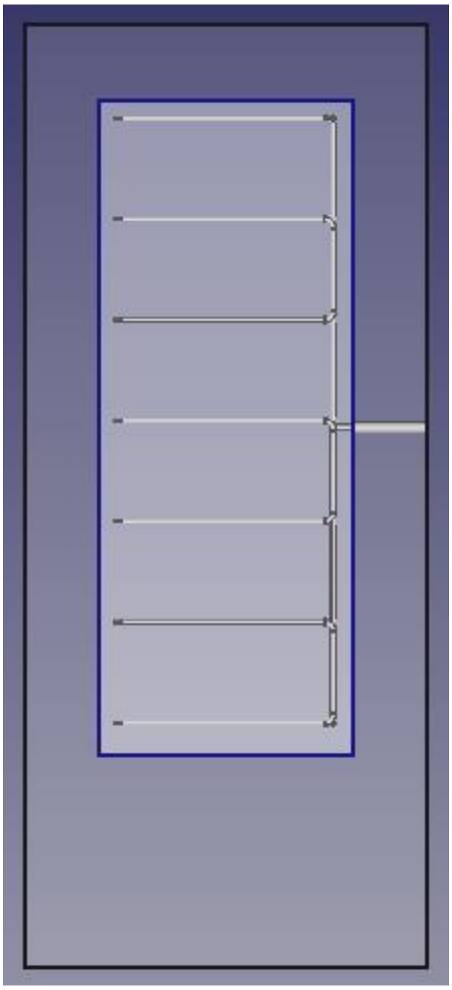
17.6 Cooling FreeCad design

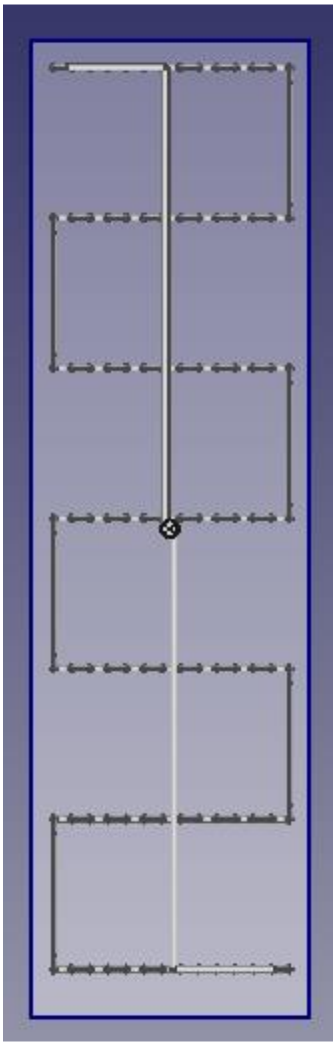
COOLING.FCStd

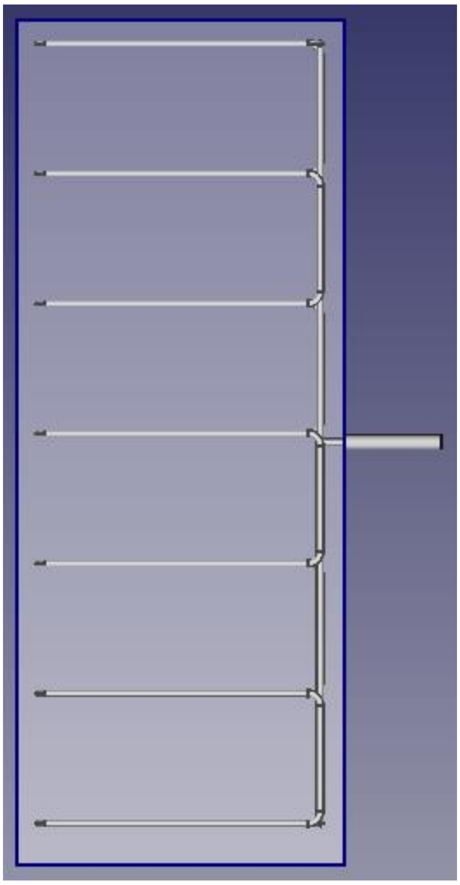


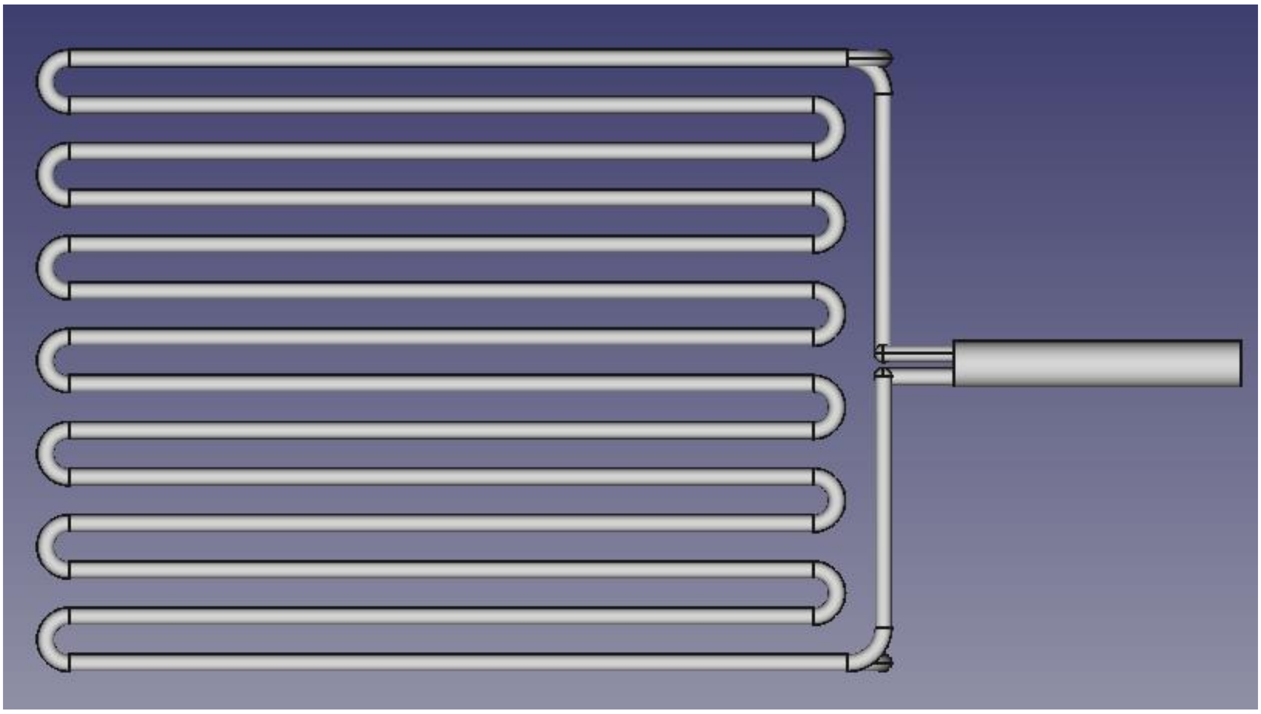


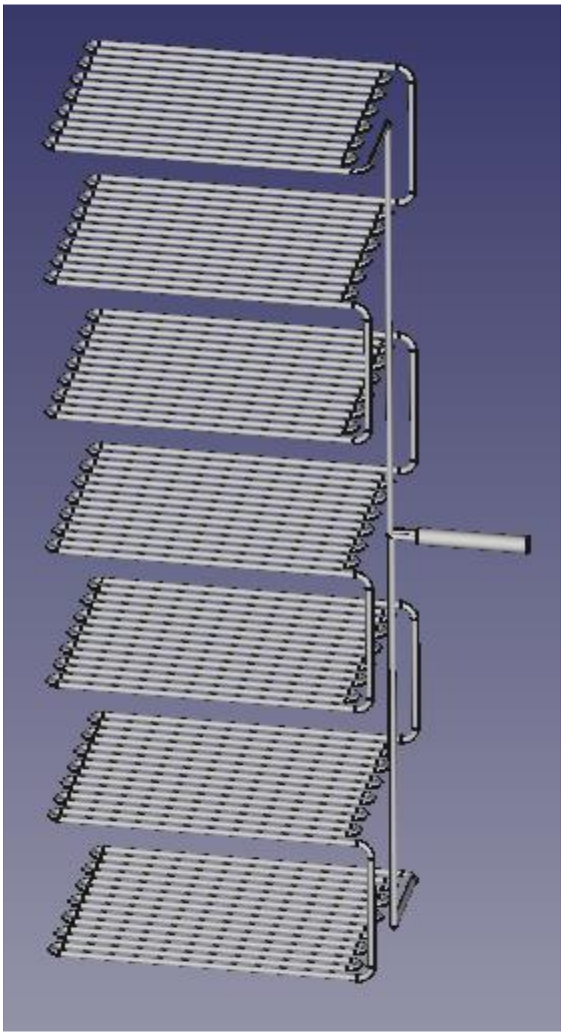


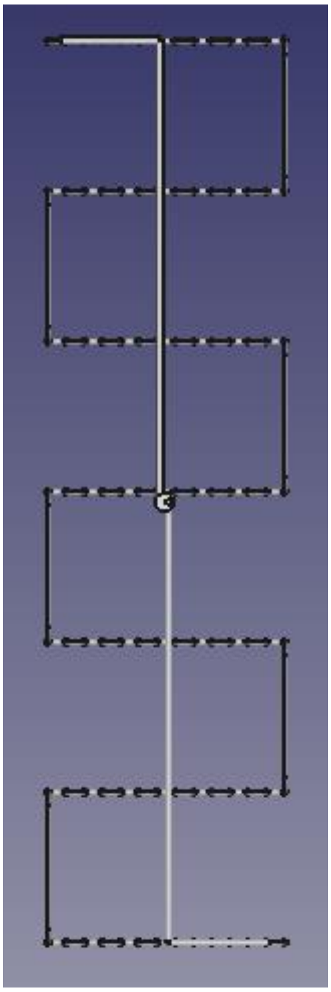




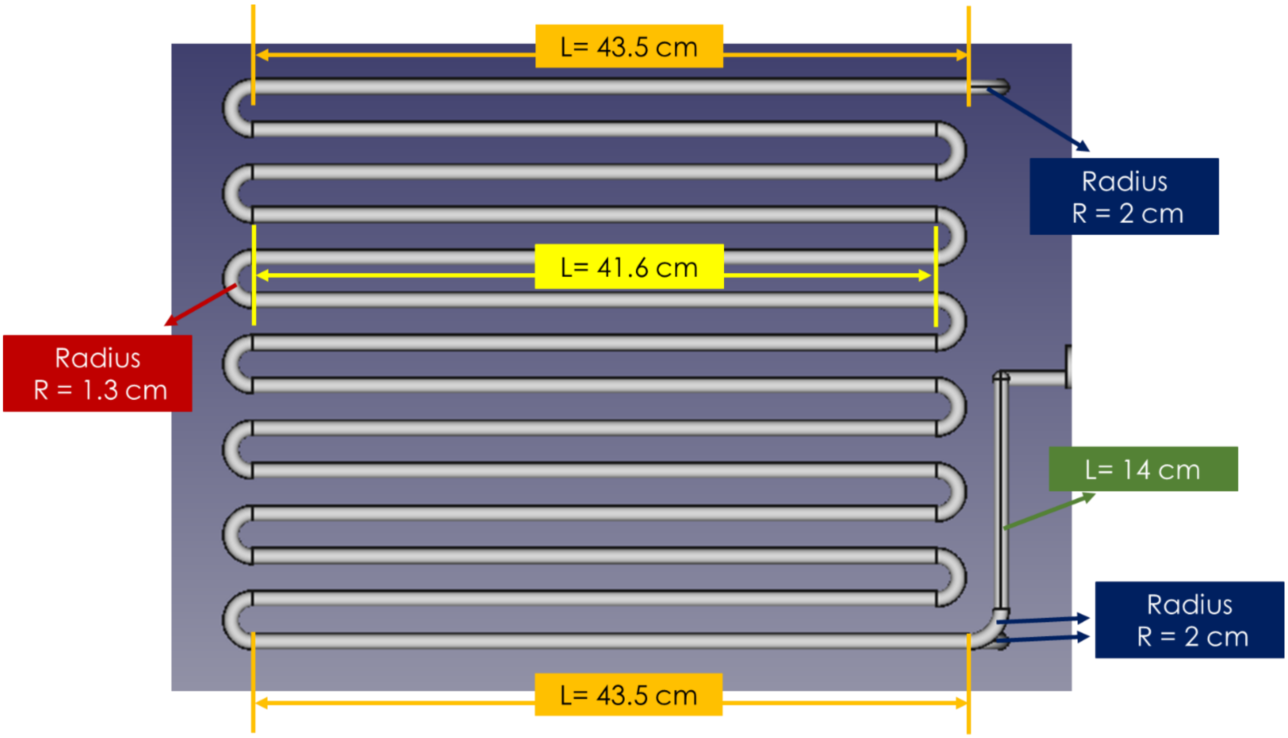


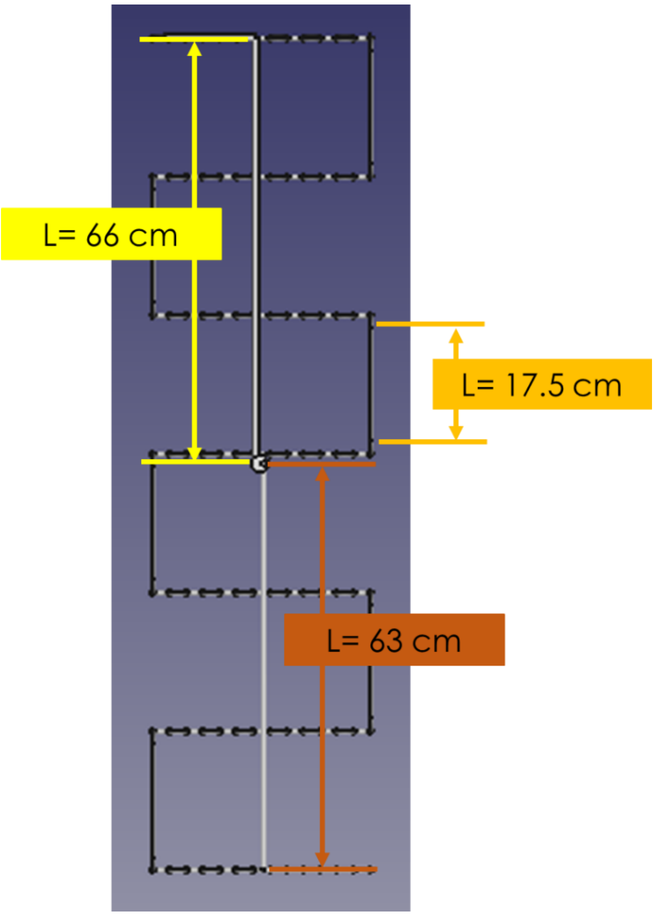






FreeCad Design





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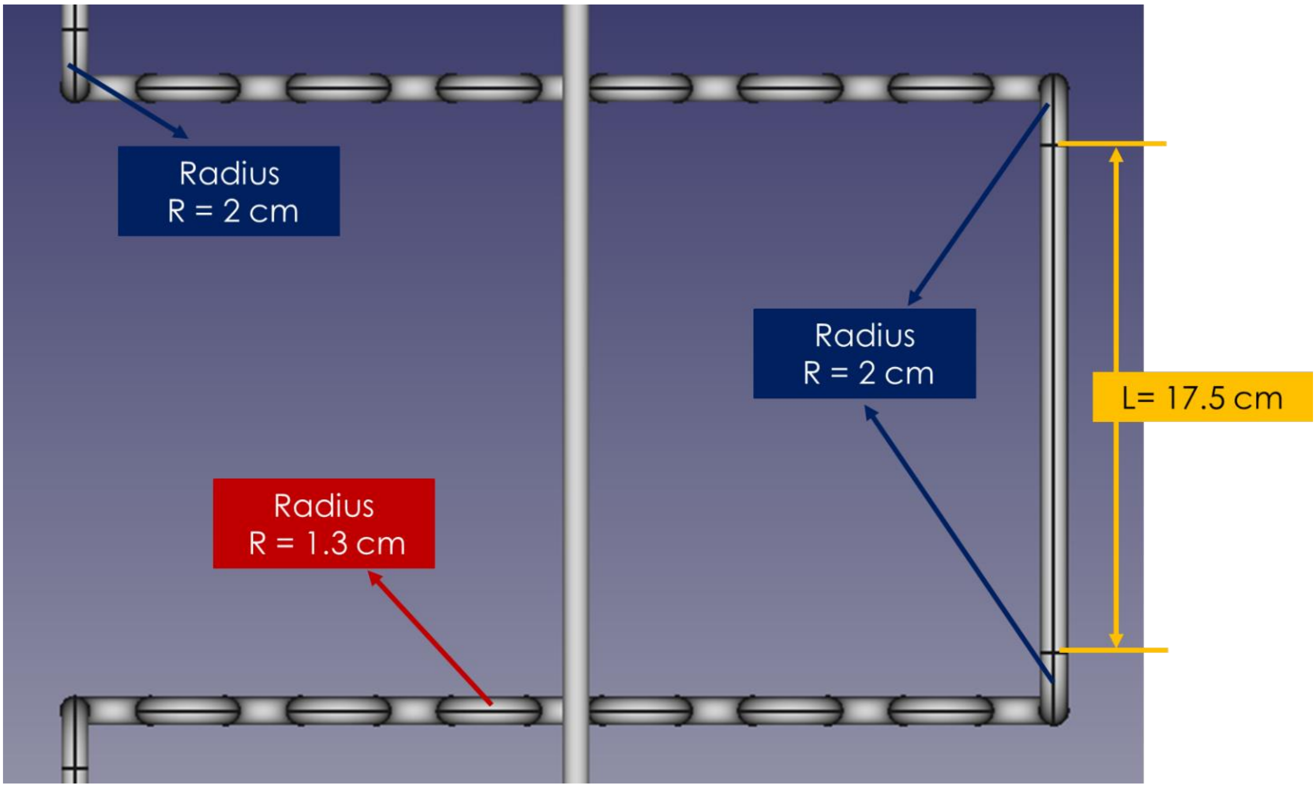


18 Price of prototype components

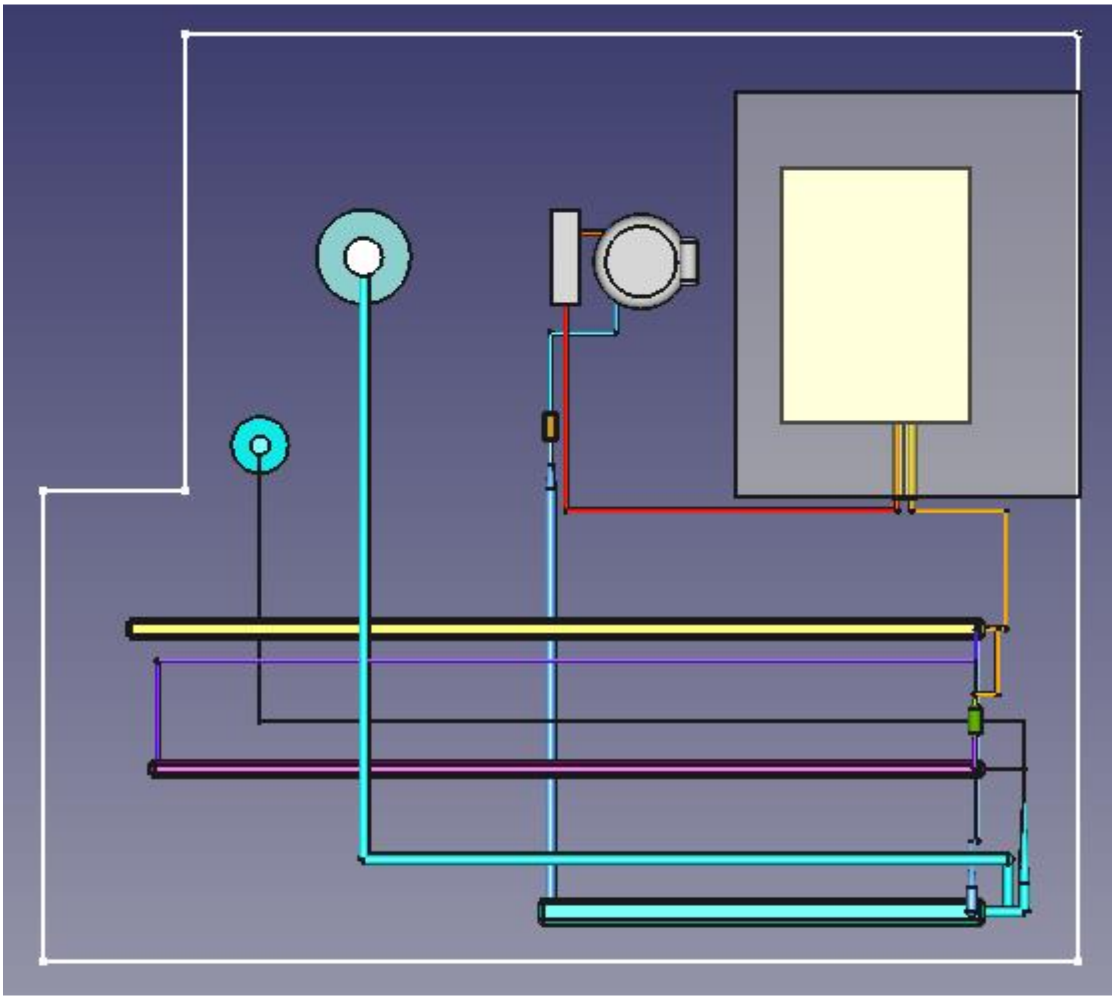
Components of prototype	Source	Characteristics	General price	# of piece	Total cost excluding hand cost	Notes
Compressor	*LR25B laboratory* refrigerator	Press 2 bar to 15 bar	___	1	___	
Condenser	*LR25B laboratory* refrigerator	Air cooling	___	1	___	
Cooling	*Kelvinator* refrigerator	Copper pipes (3/8)	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		

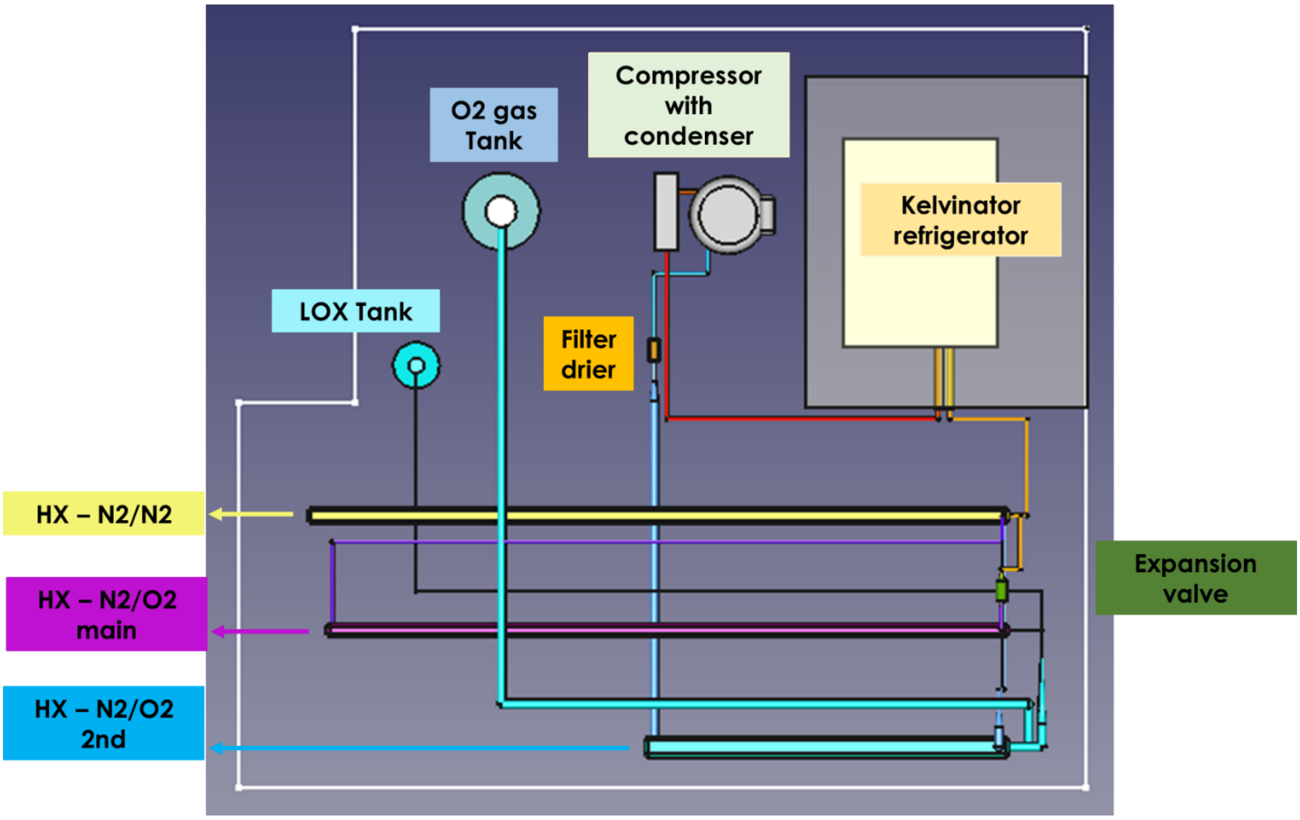
- General space of prototype is : L * W * H = 1.93 m * 2 m * 1.2 m (except height of kelvinator refrigerator = ~ 1.7 m)

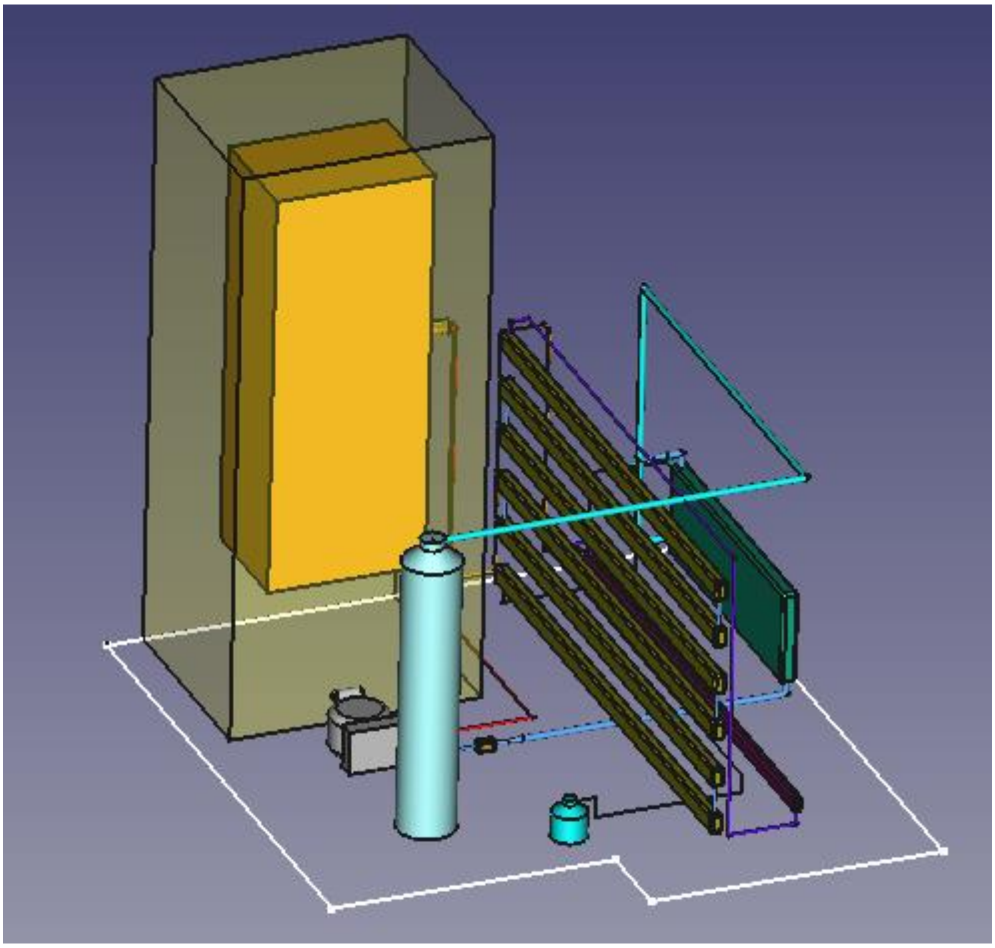
		Stainless steel	Steel	Copper
Price		1 - 1.5 $/Kg	100 - 300 $/Ton	9.35 $/Kg
Density		7500 Kg/m3	8050 Kg/m3	8.96 g/cm3
HX-N2/N2	Volume needed	0.002348004 m3	0.002348004 m3	2348.004 cm3
	Mass	17.61 Kg	18.90 Kg	21.038 Kg
	Cost	17.61 - 26.415 $	1.89 - 5.67 $	196.71 $
HX-N2/O2 main	Volume needed	0.000305524 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 $

19 Real layout design of prototype in AECENAR Facility

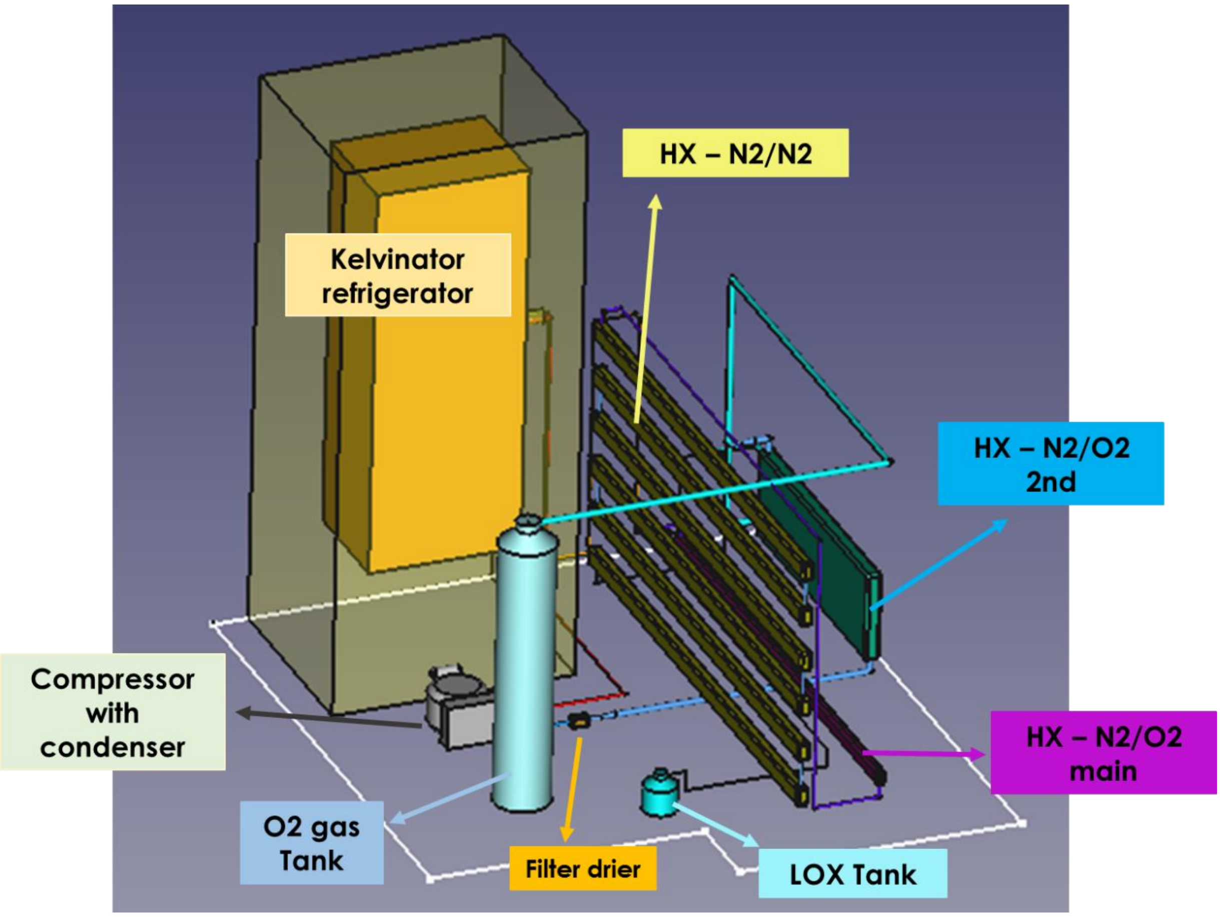
real prototype.FCStd

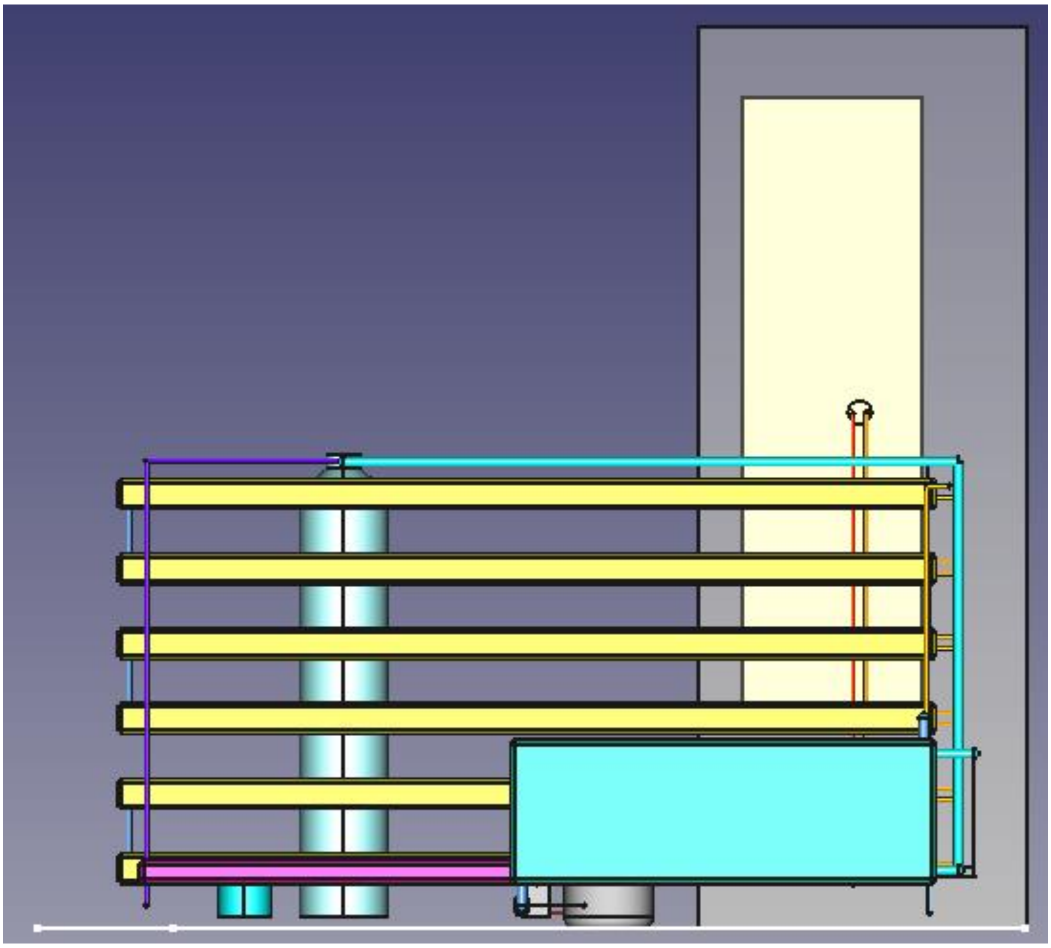


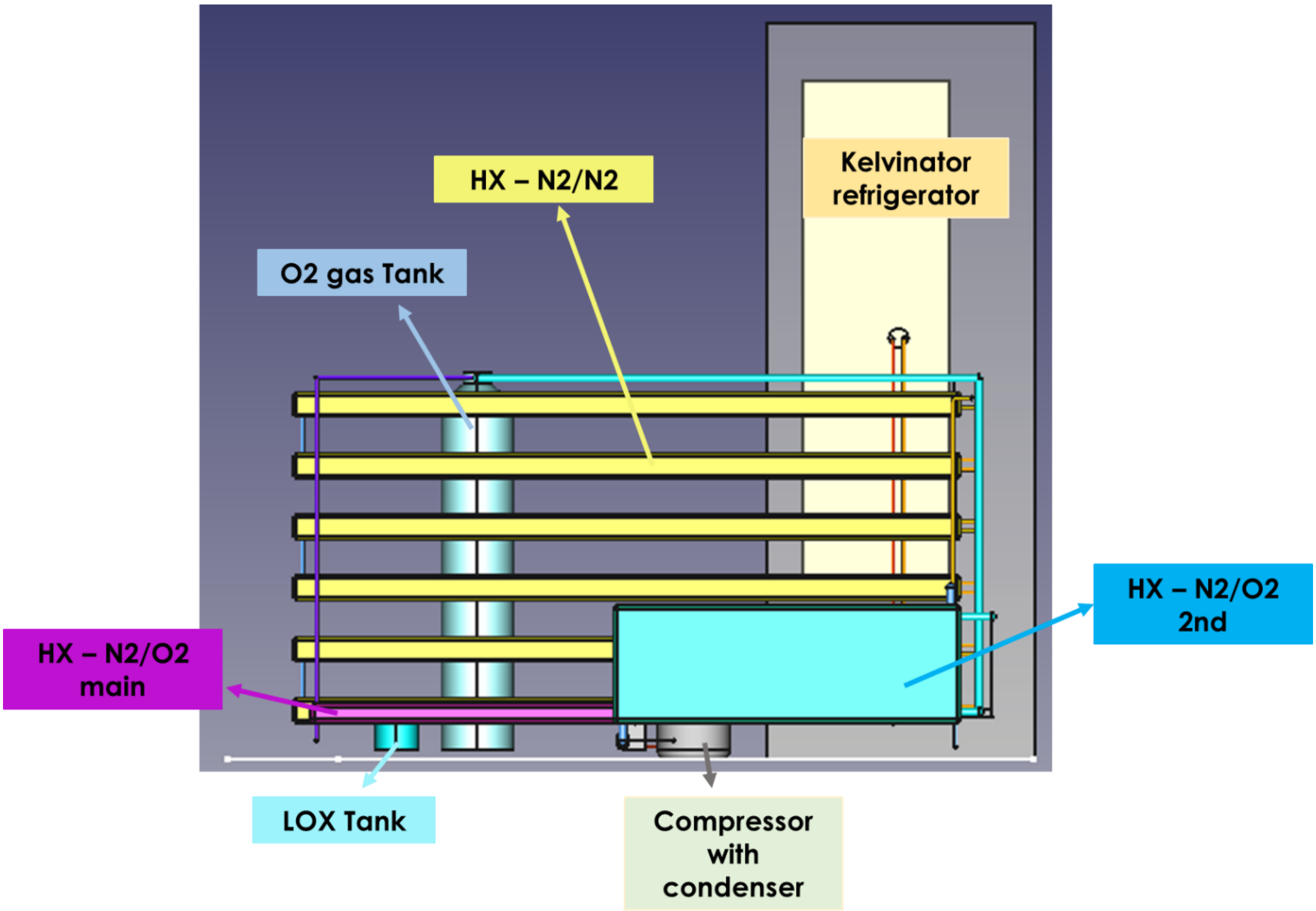

O2 gas Tank
Compressor with condenser
Kelvinator refrigerator
LOX Tank
Filter drier
HX – N2/N2
HX – N2/O2 main
Expansion valve
HX – N2/O2 2nd



Real layout design of prototype in AECENAR Facility






HX – N2/N2
Kelvinator refrigerator
O2 gas Tank
HX – N2/O2 2nd
HX – N2/O2 main
LOX Tank
Compressor with condenser

Real layout design of prototype in AECENAR Facility


IP Camera

Real layout design of prototype in AECENAR Facility

20 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

Real design of cooling (inside kelvinator refrigerator)

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.

21 First experiment (Expr #1)

The first experiment (Expr #1) aims to:

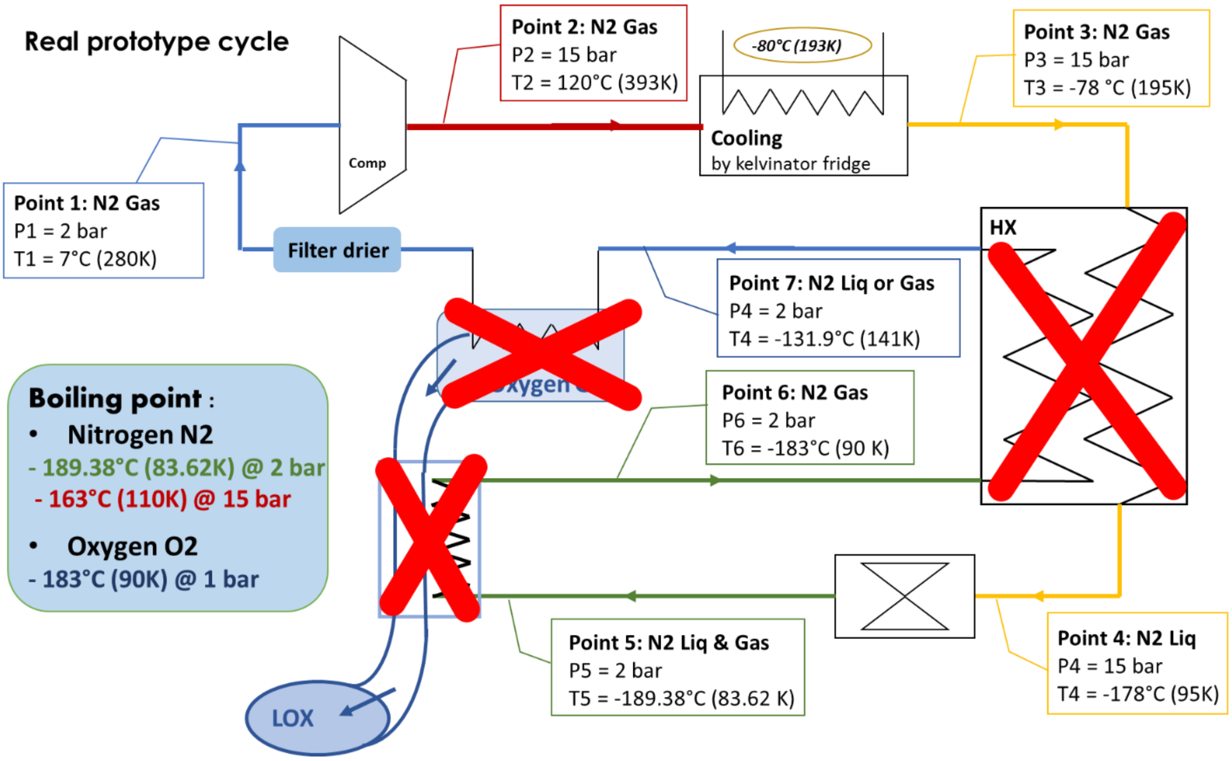
1- Compressor operation test with nitrogen gas instead of R-134a,

2- Make sure that the Kelvinator refrigerator is running correctly

3- Ensure that the expansion valve is compatible with the design.

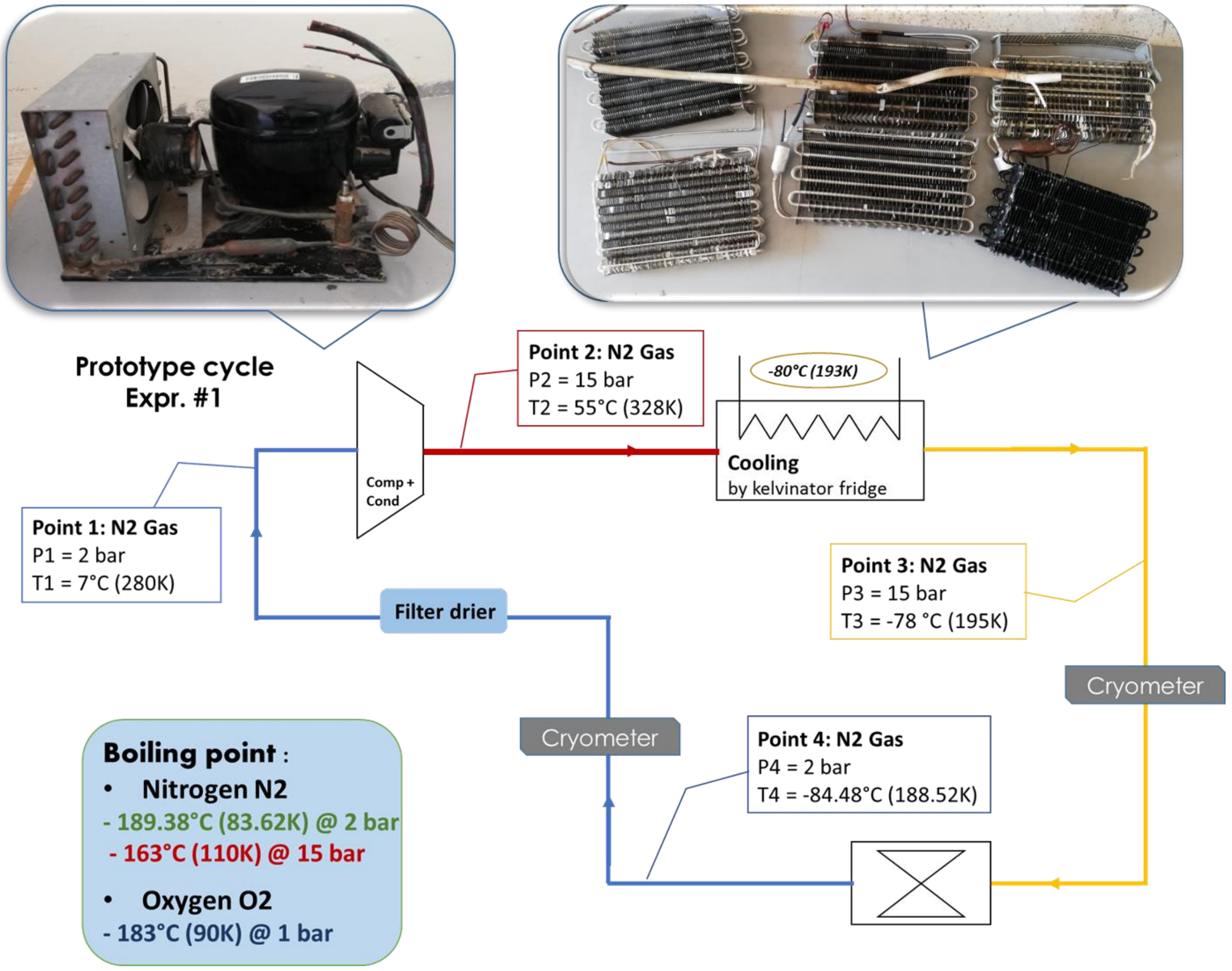
Therefore, the three heat exchangers (HX-N2/N2, HX-N2/O2 main, HX-N2/O2 2nd) will be excluded from this experiment.

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).

First experiment (Expr #1)



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
…

First experiment (Expr #1)

Fuel Cell

Last update: 22 January 2022

CONTENTS

List of figures

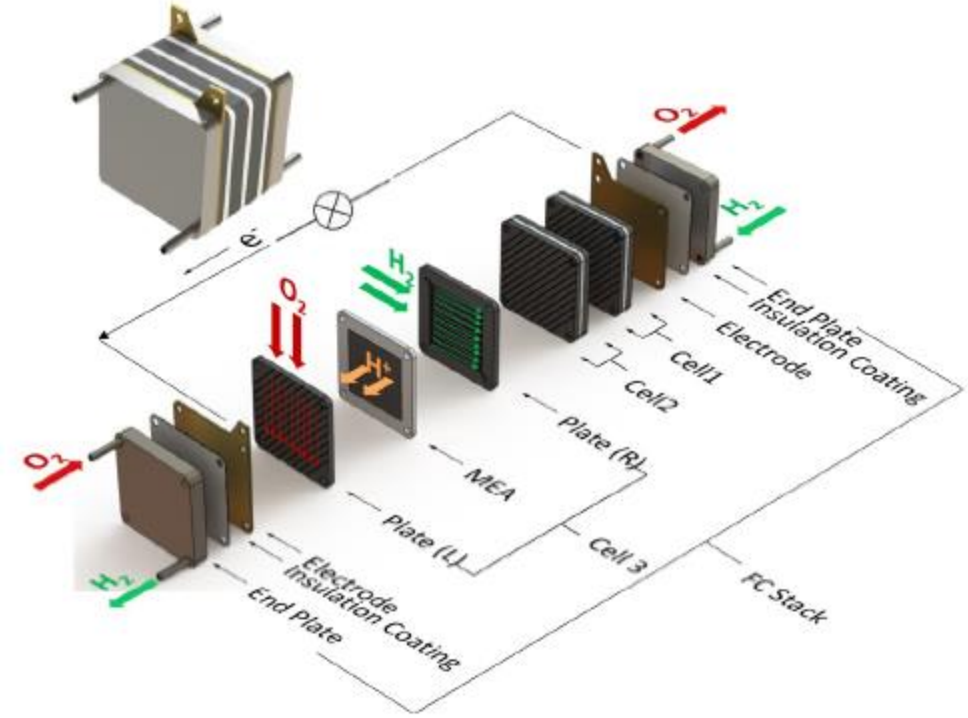


Fig. 1 :Schematics of a fuel cell stack operation and components[43]

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.

---

[43] https://www.researchgate.net/publication/309898224_A_review_on_prognostics_and_health_monitoring_of_proton_exchange_membrane_fuel_cell/download

First experiment (Expr #1)

$$2H_2 + O_2 \rightarrow 2H_2O + Energy \qquad \textbf{\textit{(1)}}$$

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.

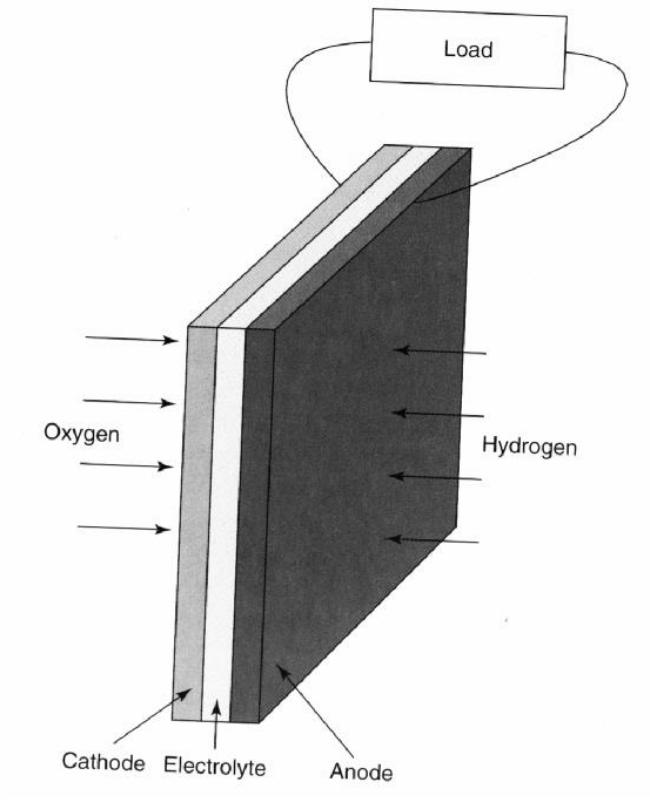


fig. 2 :Basic structure of a fuel cell.

22 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.

22.1 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.

$$2H_2 \rightarrow 4H^+ + 4e^- \quad \textbf{(2)}$$

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)

$$O_2 + 4e^- + 4H^+ \rightarrow 2H_2O \quad \textbf{(3)}$$

The electrons are not allowed to pass through the electrolyte because then no current would flow in the external circuit.

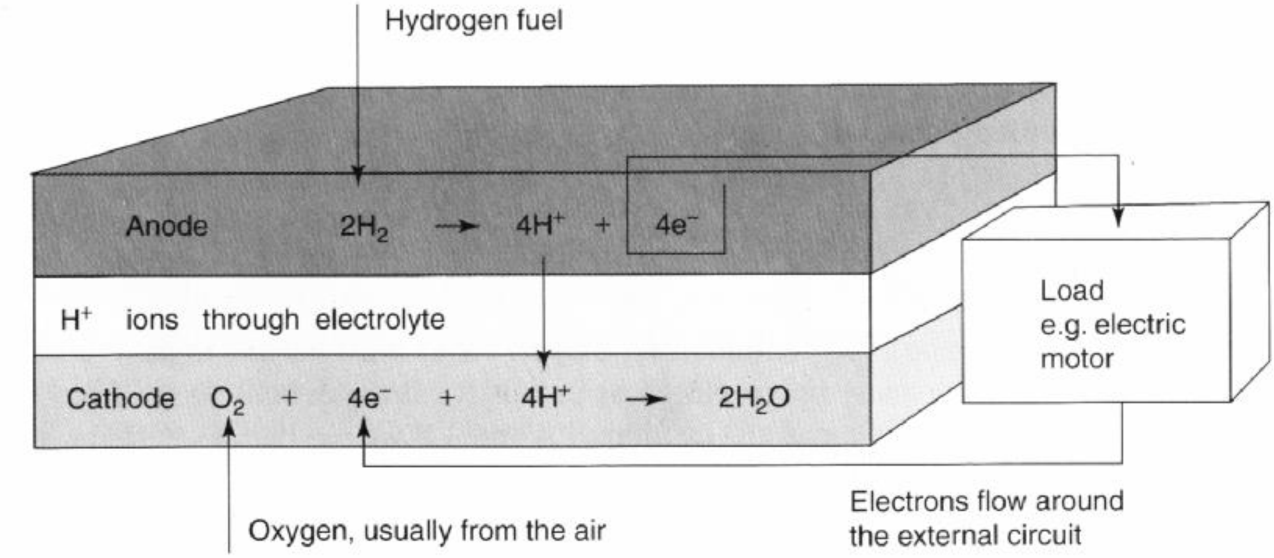


Fig. 3:Electrode reactions and electrical flow for an acid electrolyte fuel cell. The electrons flow from the anode to the cathode via an external circuit.

22.2 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).

$$2H_2 + 4OH^- \rightarrow 4H_2O + 4e^- \quad \textbf{(4)}$$

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.

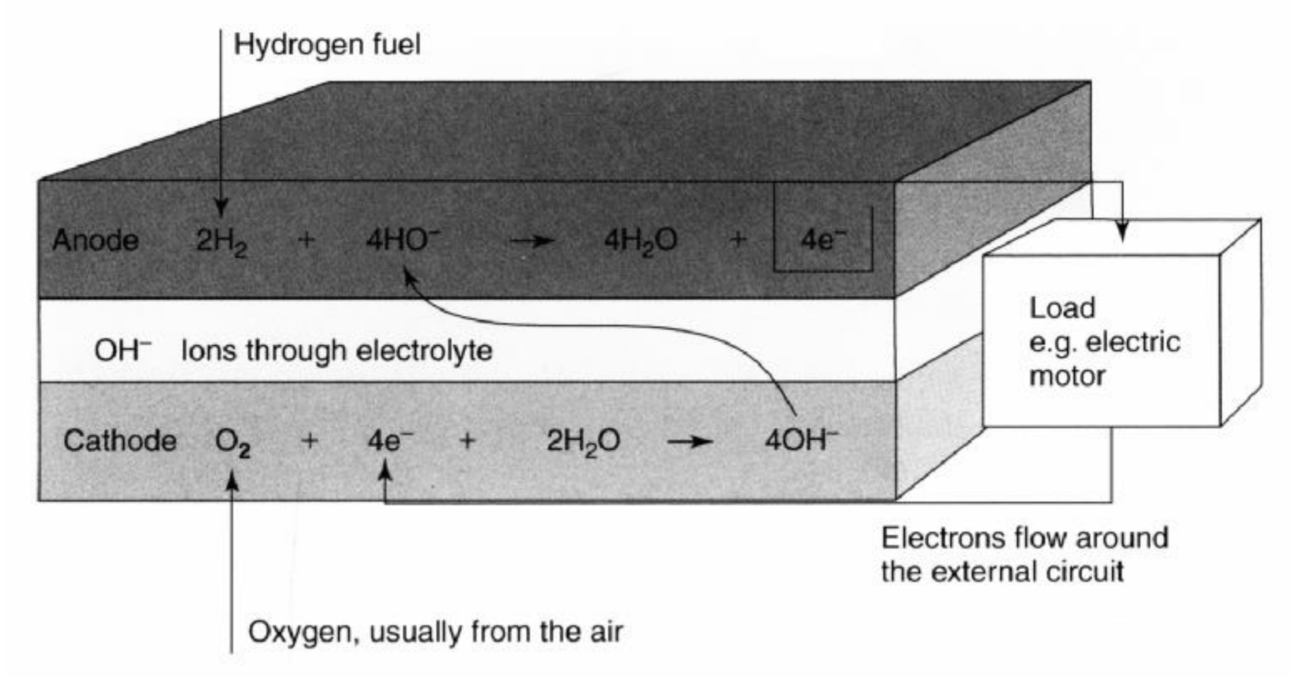


Fig. 4:Electrode reactions and electrical flow for an alkaline electrolyte fuel cell.

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.

22.3 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.

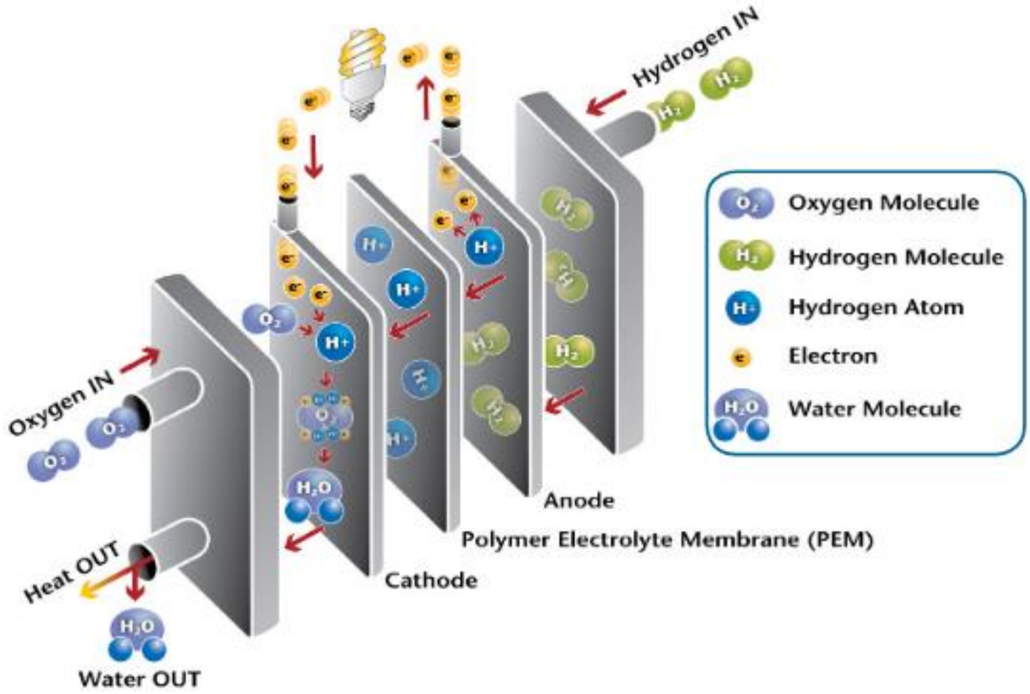
- There are currently 6 types of fuel cell:
  - AFC (Alkaline fuel Cell),
  - PEMFC (Proton Exchange Membran Fuel Cell),

  - 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



[44]

Fig. 5: PEMFC

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[44] https://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/fct_h2_fuelcell_factsheet.pdf

23 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.

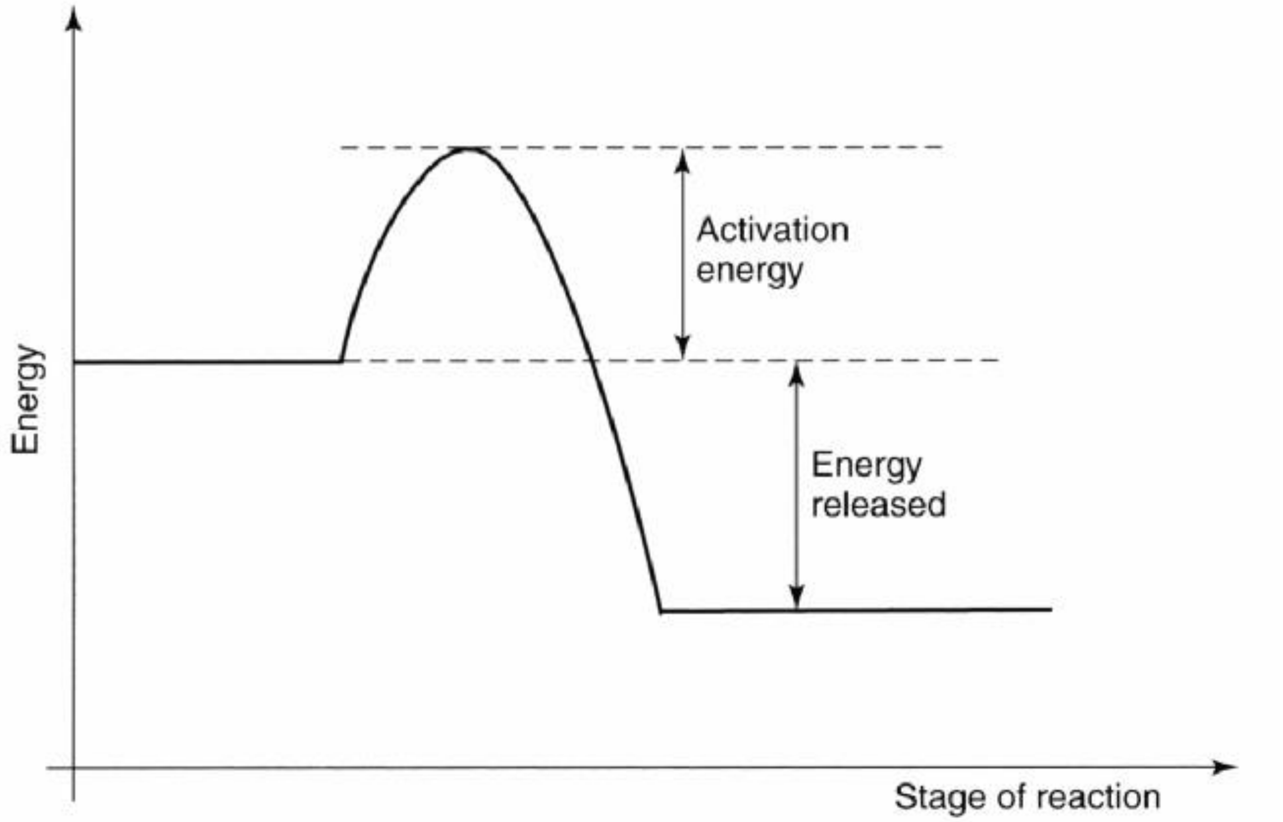


Fig. 6: Activation energy diagram for a simple exothermic chemical reaction.

24 Fuel cell stack

24.1 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.

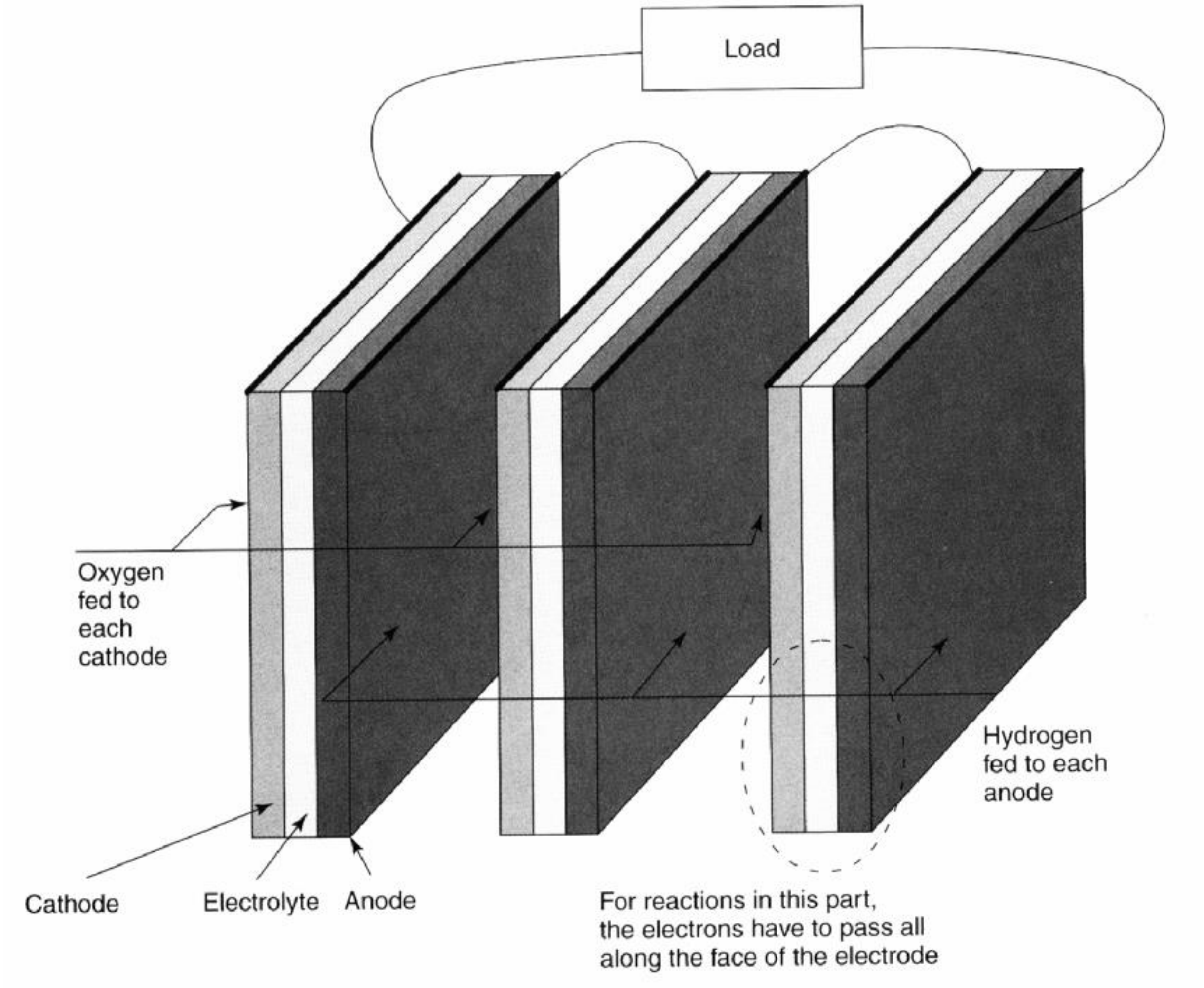


Fig. 7:Simple series connection from the anode of one cell to the cathode of the next one.

24.2 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.

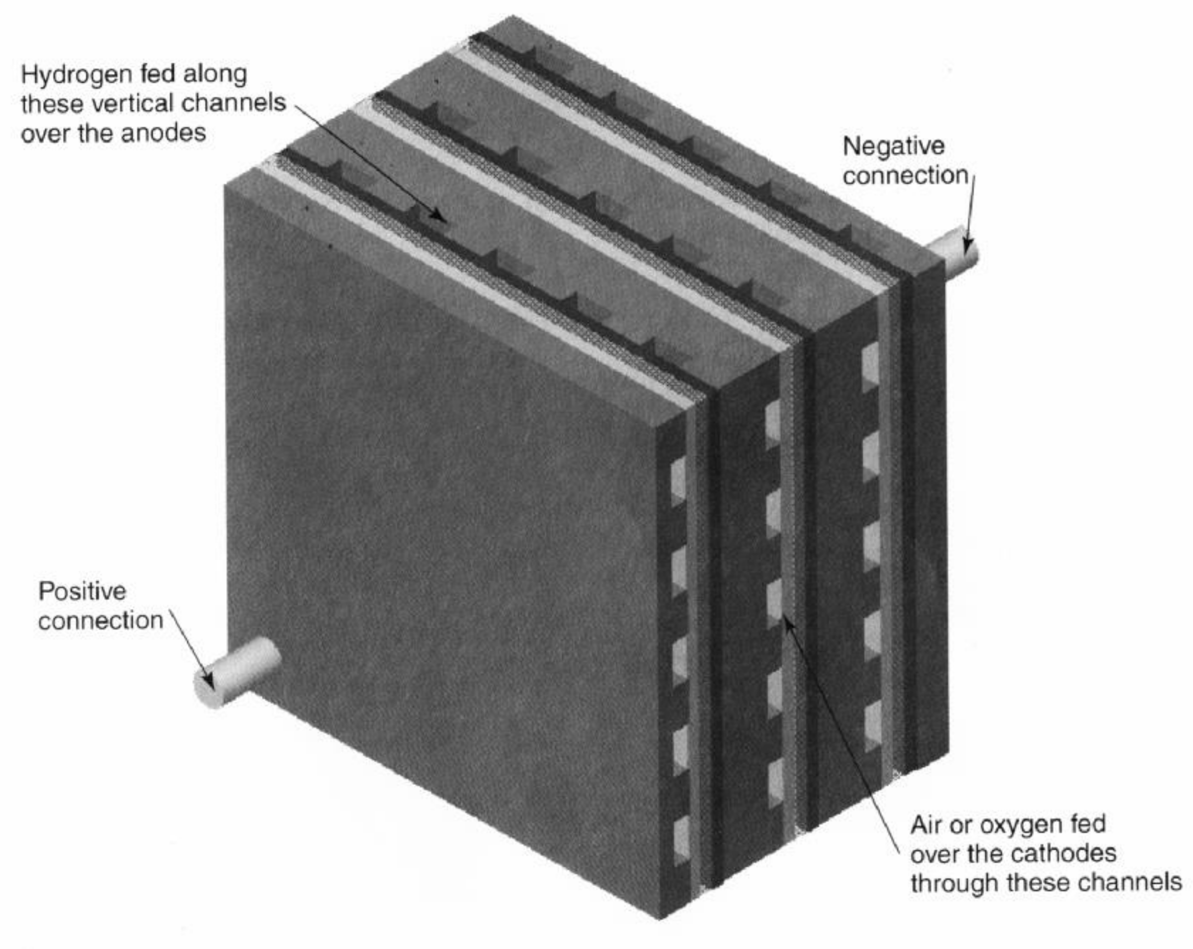


Fig. 8: A fuel cell stack, consisting of three cells connected with bipolar plates.

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.

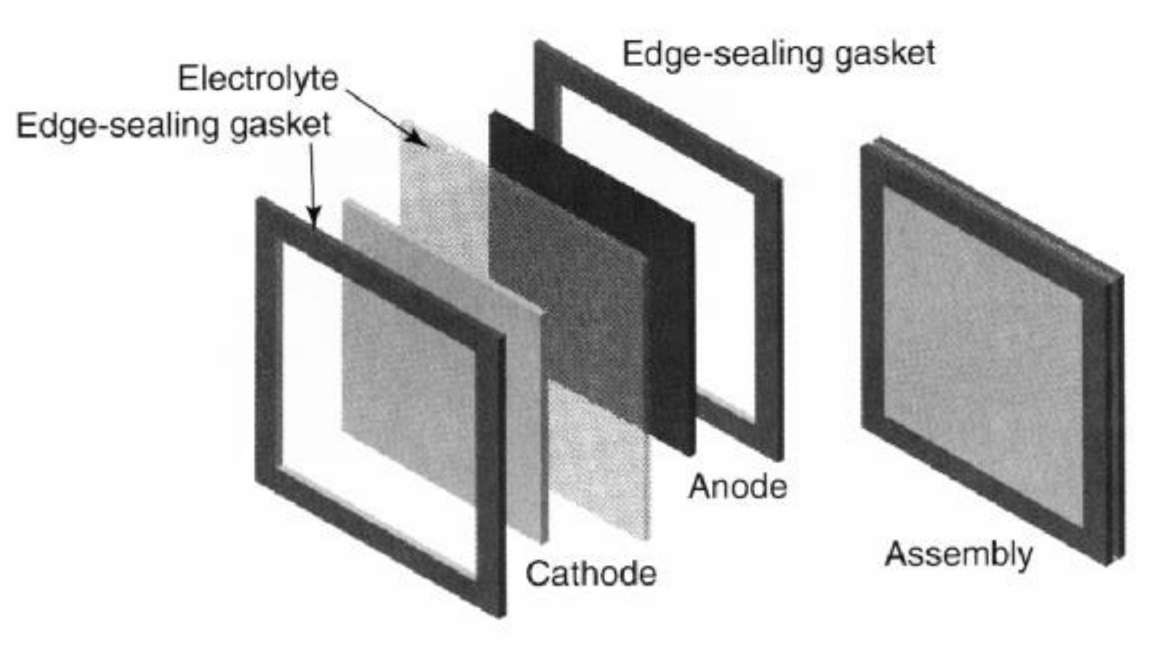


Fig. 9:Structure of a fuel cell with edge seals to prevent leakage of the gas at the edges of the electrodes.

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.

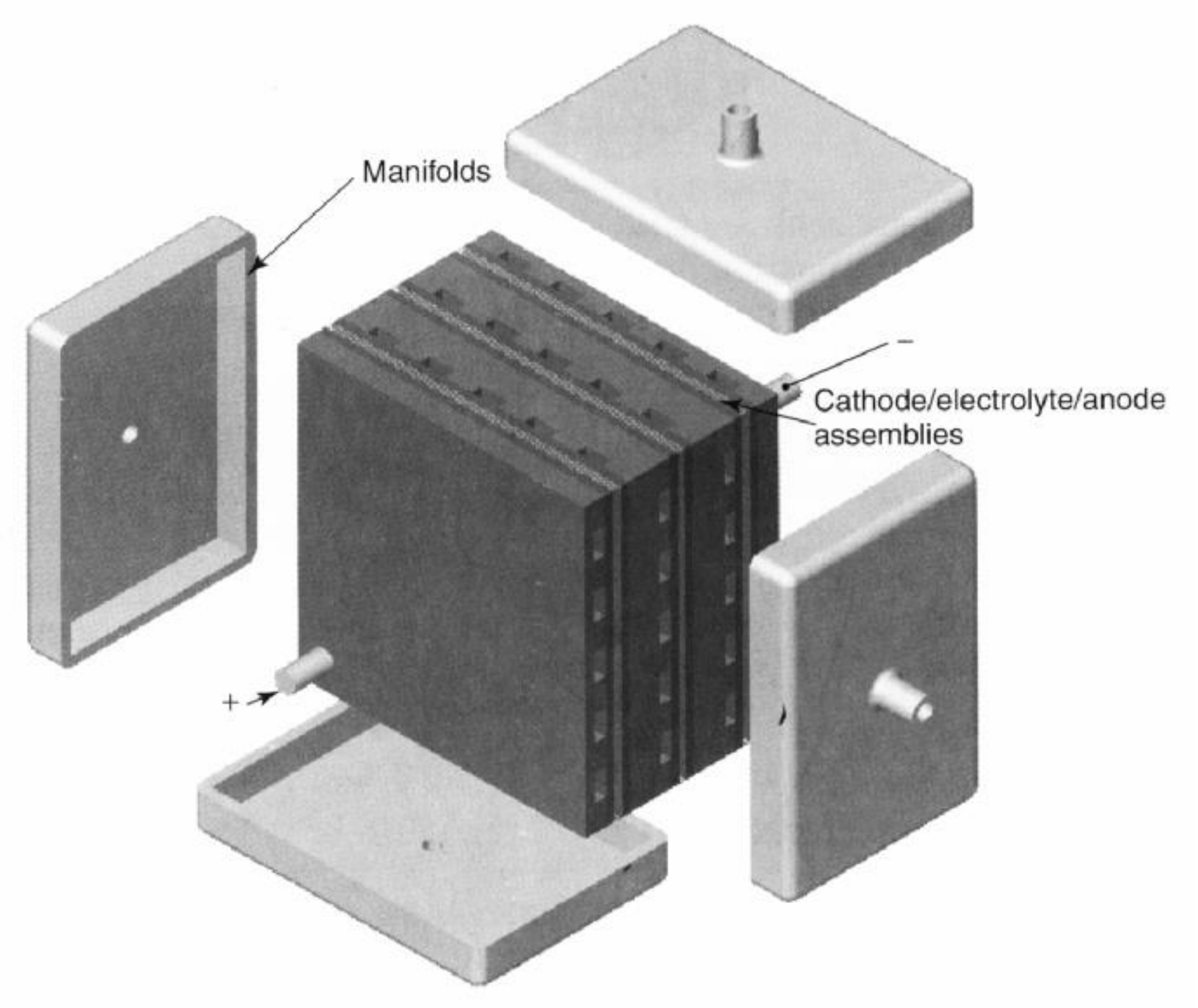


Fig. 10:Fuel cell stack with external manifolding

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.

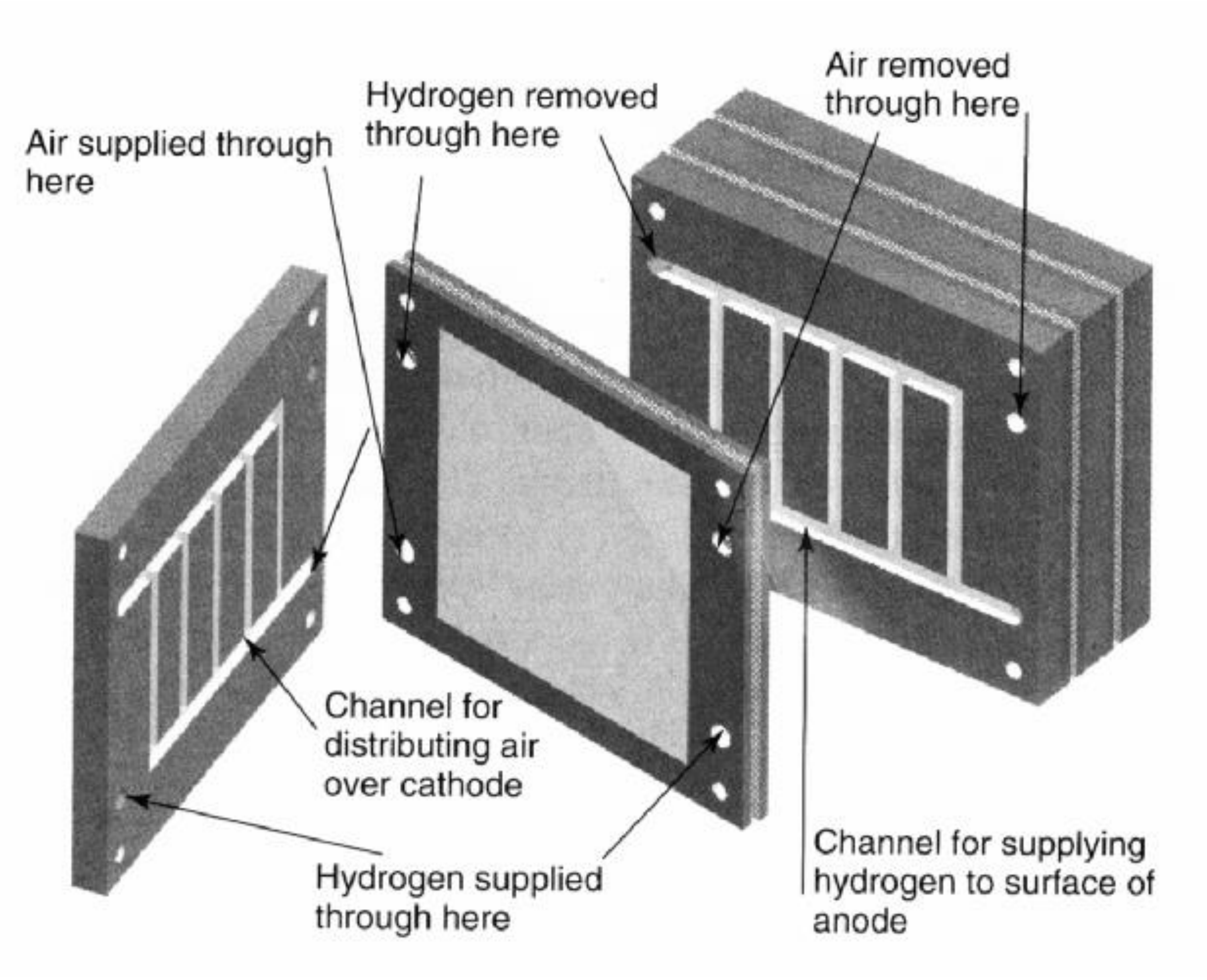


Fig. 11: Fuel cell stack with internal manifolding. A more complex bipolar plate is used to allow the reactant gases to be fed to the electrodes through internal channels.

25 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.

26 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.

27 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.

28 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

29 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)

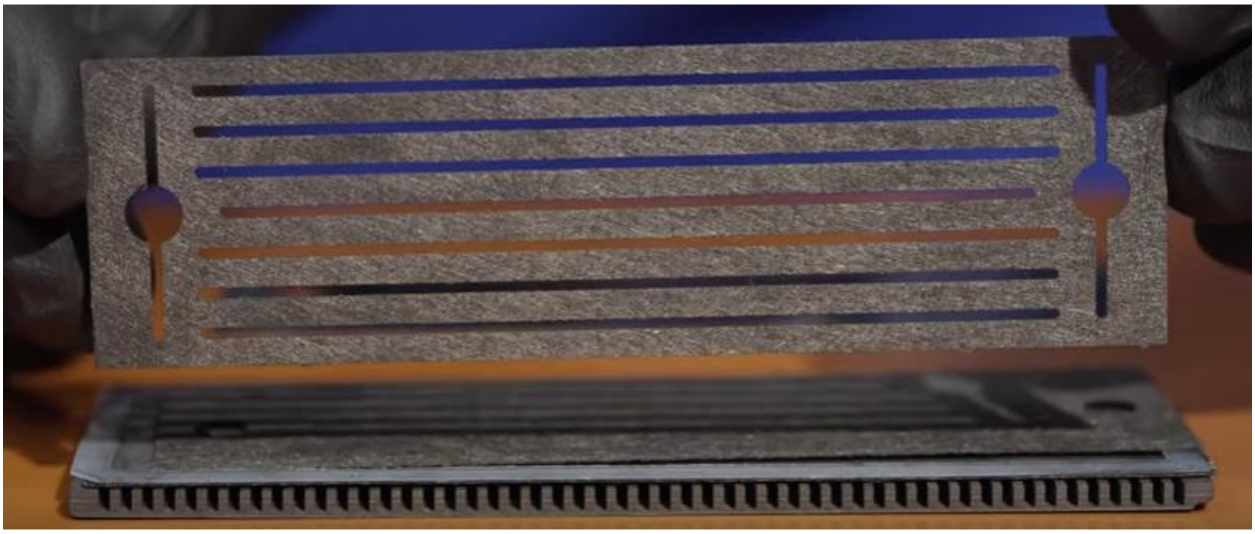


Fig. 13: Gas diffusion layer for anode

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).

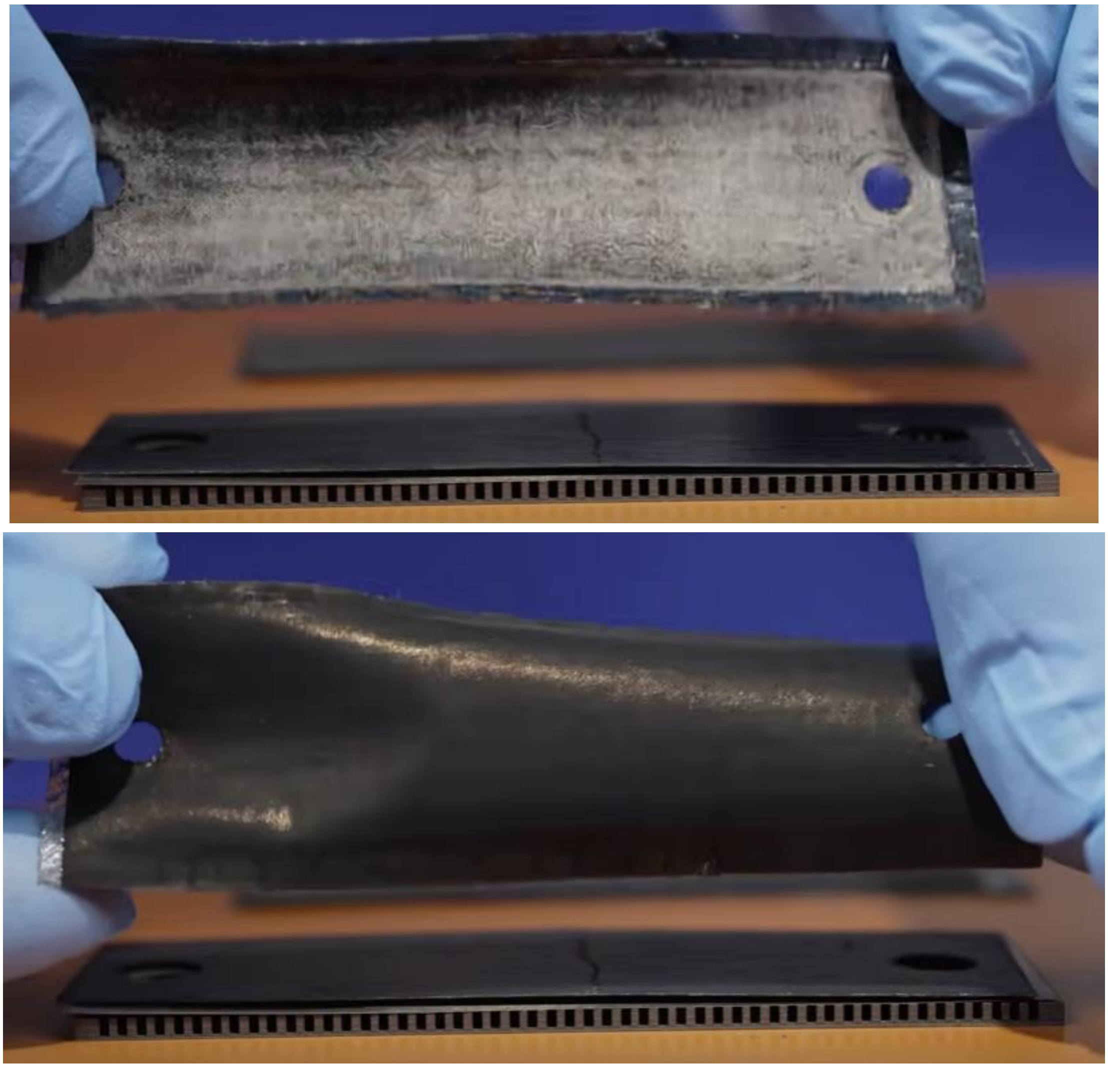


Fig. 14 : Membrane electrode assembly

Next , the cathode gas diffusion layer

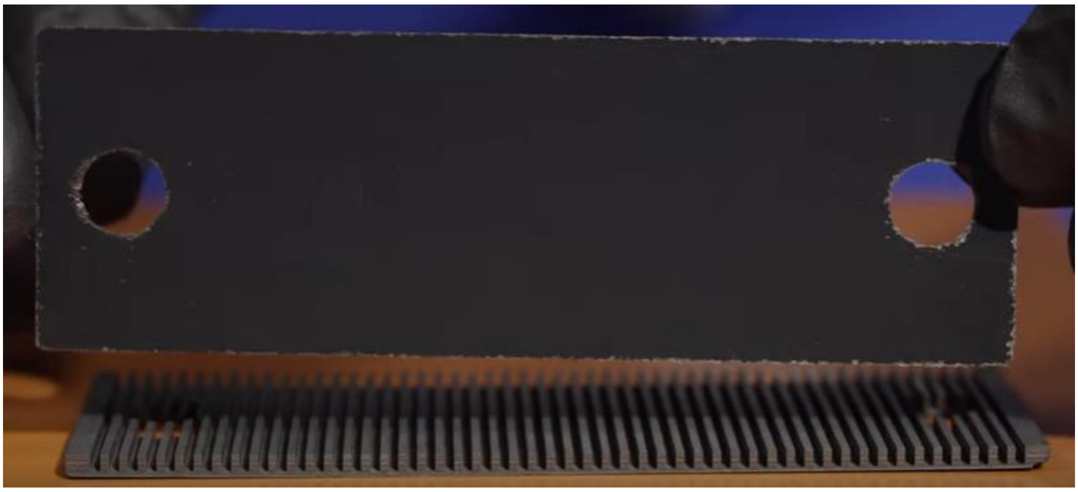


Fig. 15: Cathode gas diffusion layer

A perforated metal plate

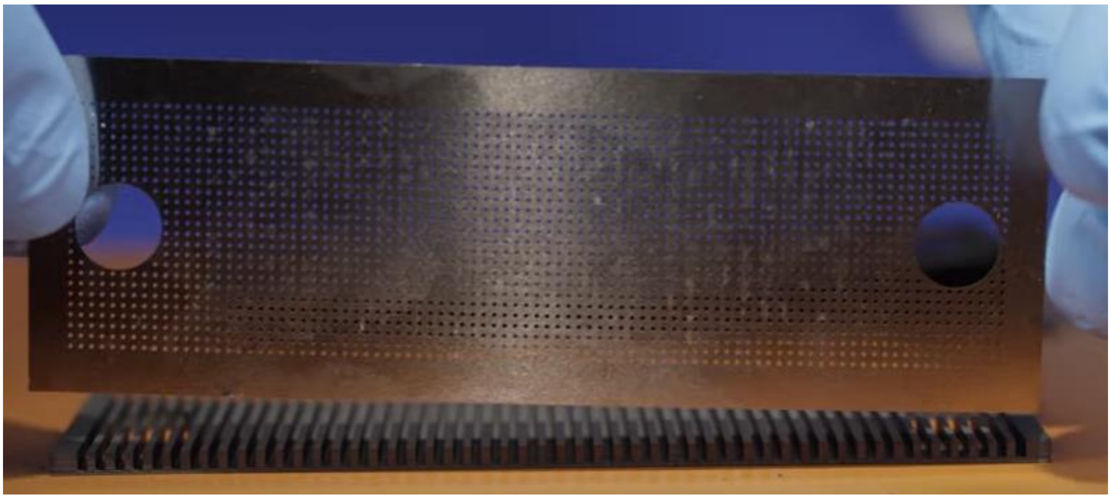


Fig. 16: Perforated metal plate

And finally the bipolar plate, which acts as a current collector and distributes air in the element.

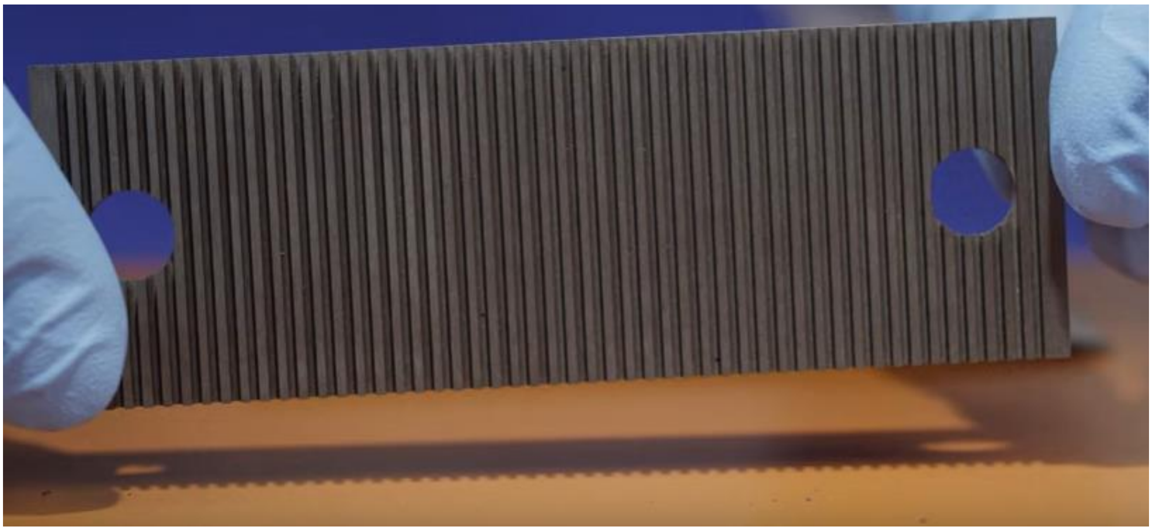


Fig. 17: Bipolar plate

To create a working fuel cell stack, several single cells are connected in series.

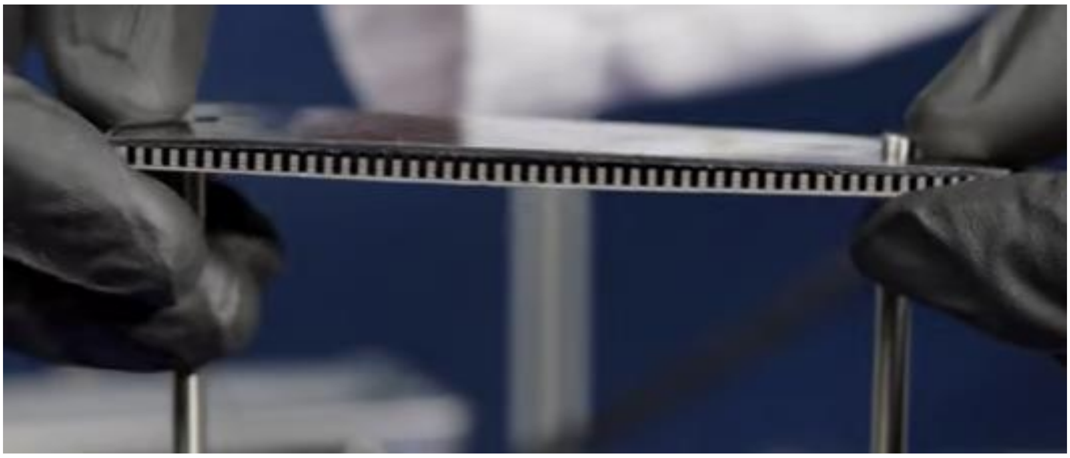
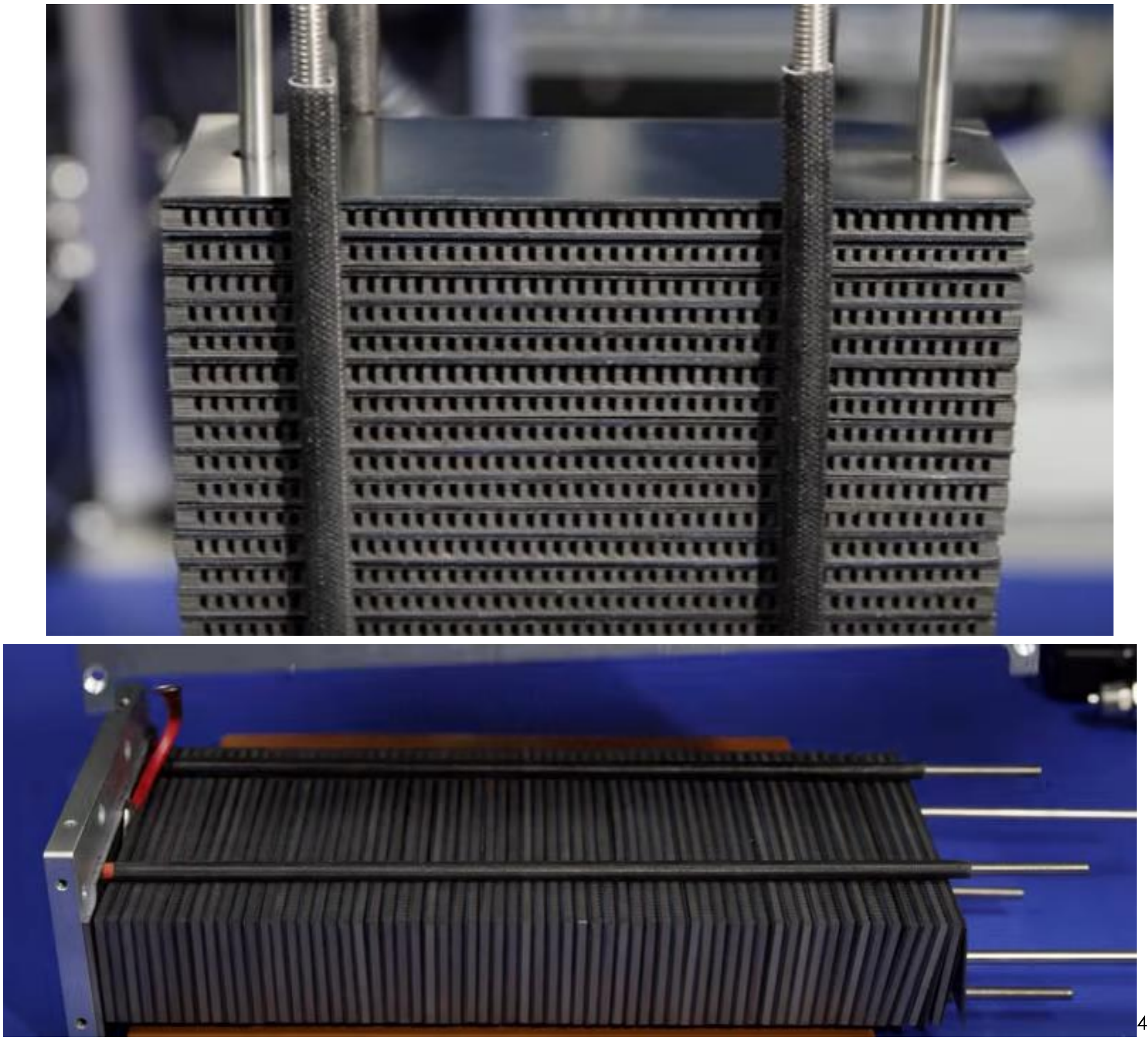


Fig. 18: Single cell



[45]

Fig. 19: Stack of PEMFC

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[45] https://www.youtube.com/watch?v=yrAAVOgBmcE

Fig. 20: Air inlet and cooling

30 How Fuel Cells Work [46]

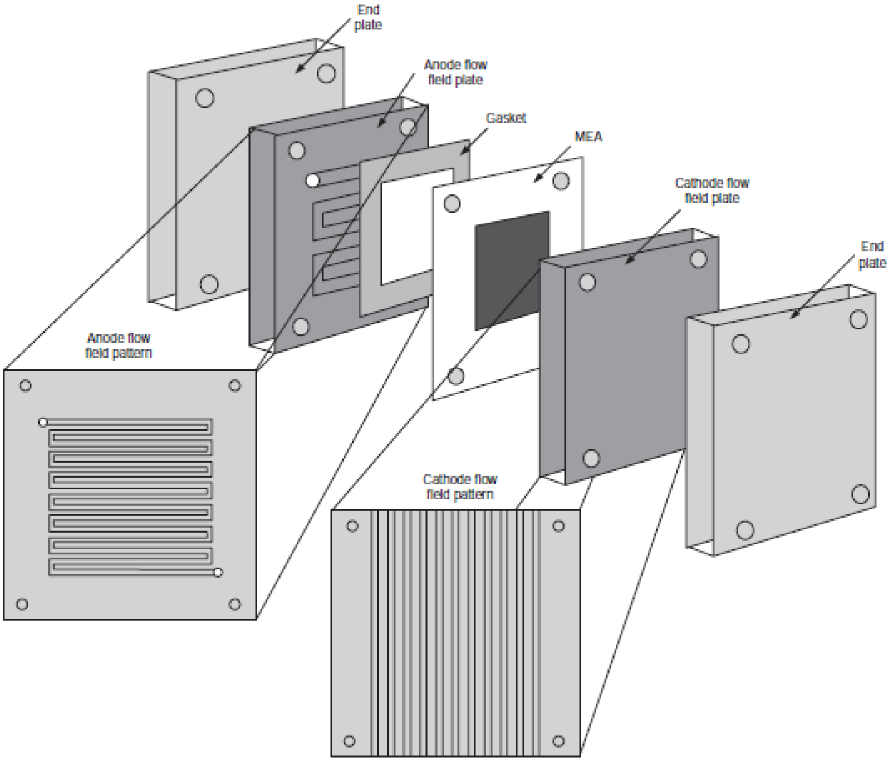

Fig. 21: An exploded view of a fuel cell stack [47]

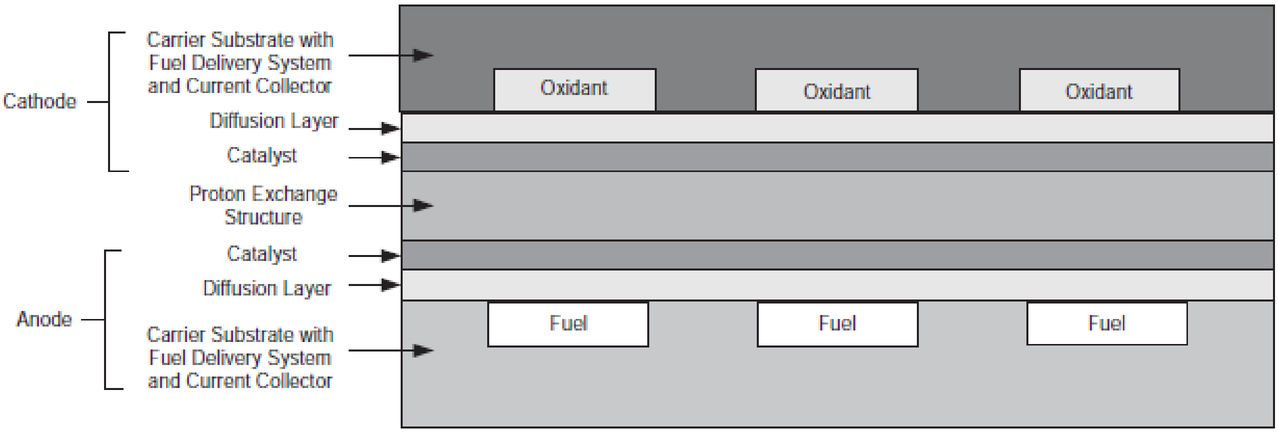

Fig. 22: Basic micro fuel cell based upon traditional fuel cell design [5]

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[46] https://www.energy.gov/eere/fuelcells/fuel-cells

[47] https://www.sciencedirect.com/book/9780123742599/pem-fuel-cell-modeling-and-simulation-using-matlab

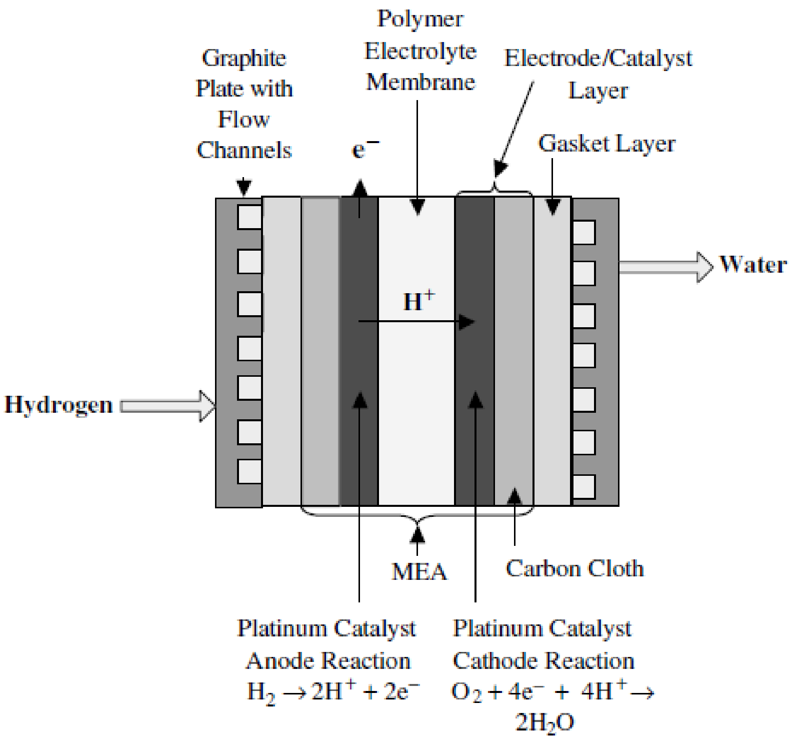
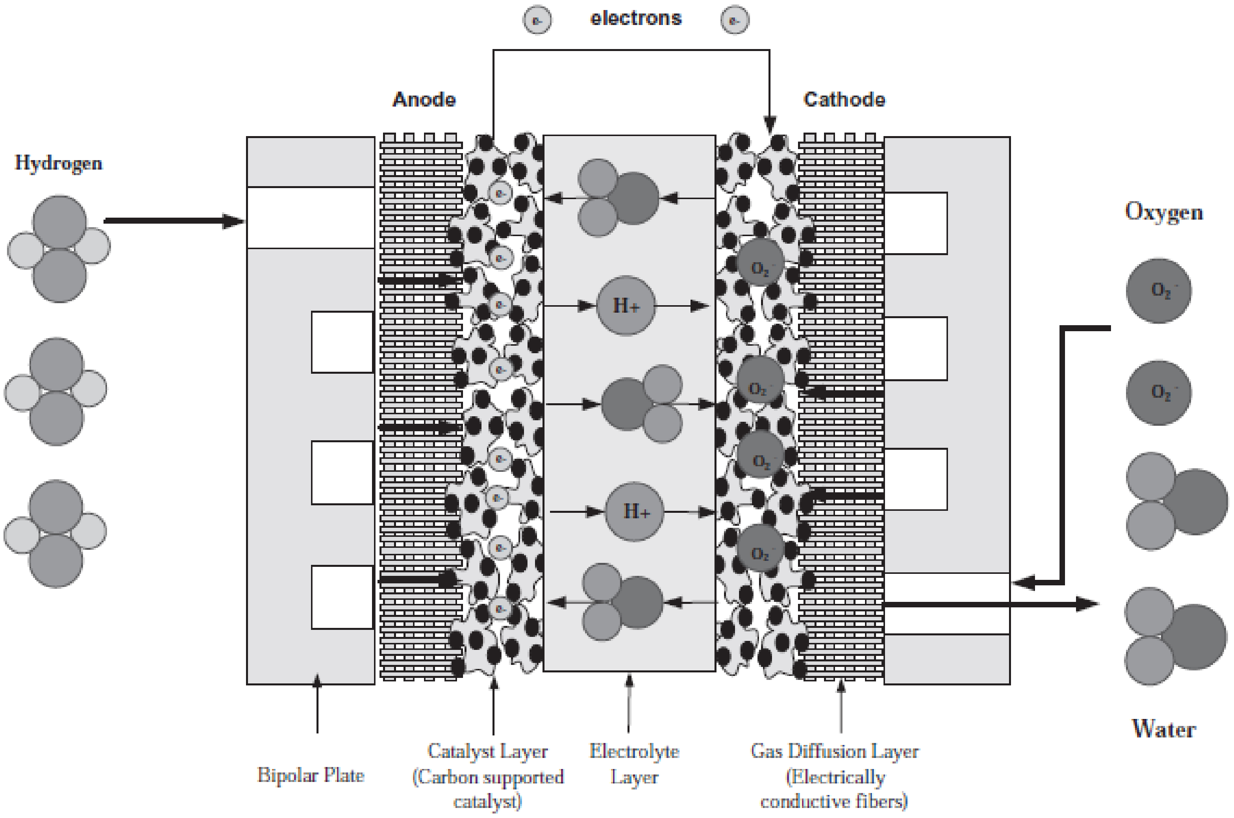


Fig. 23: Generalized schematic of a single fuel cell [48]



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[48] 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]

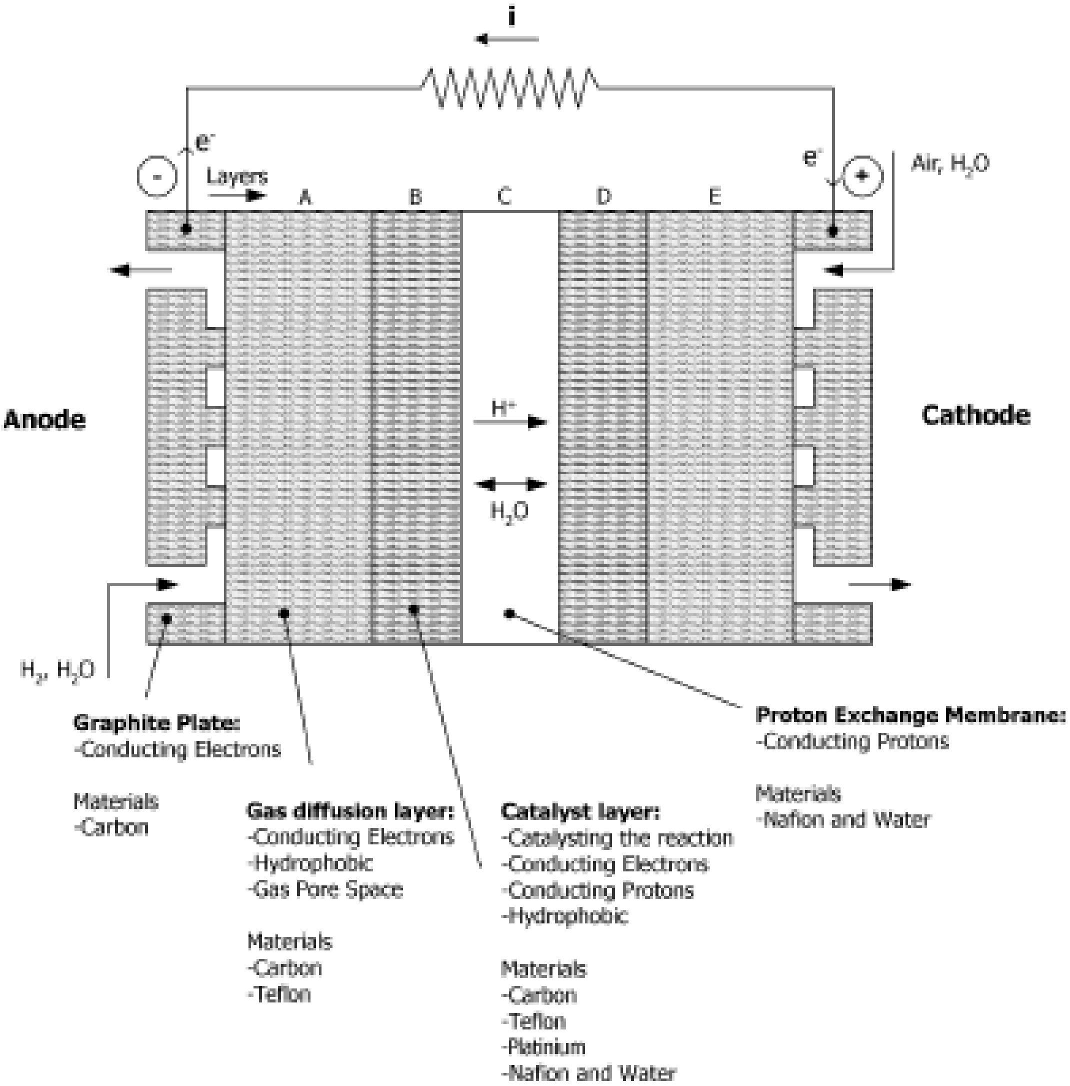

Fig. 25:A cross section of the PEM fuel cell. The unit cell is made of 7 layers which are made of different compositions of material providing the layers with different properties [49]

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

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[49] https://www.scribd.com/document/447288677/Design-and-Control-of-Fuel-Cell-System-for-Tran-z-lib-org-pdf

- Fuel cell systems
- Types of fuel cells.

30.1 Parts of a fuel cell

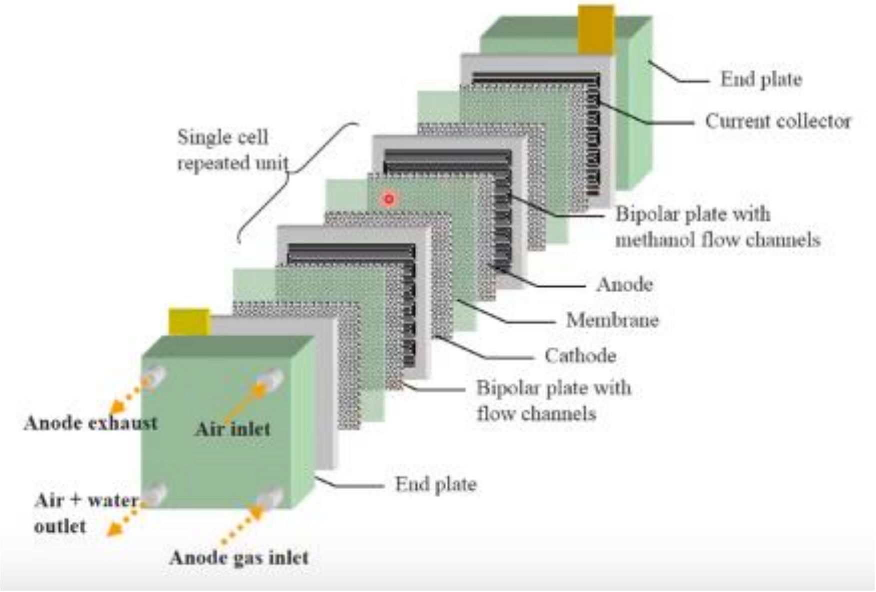


Fig. 26: PEMFC – flowing path of fuel and air

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.

30.1.1 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 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).

30.1.2 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.

30.2 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.

30.2.1 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.

30.2.2 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.

30.2.3 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%.

30.2.4 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%.

30.2.5 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.

31 Cell structure

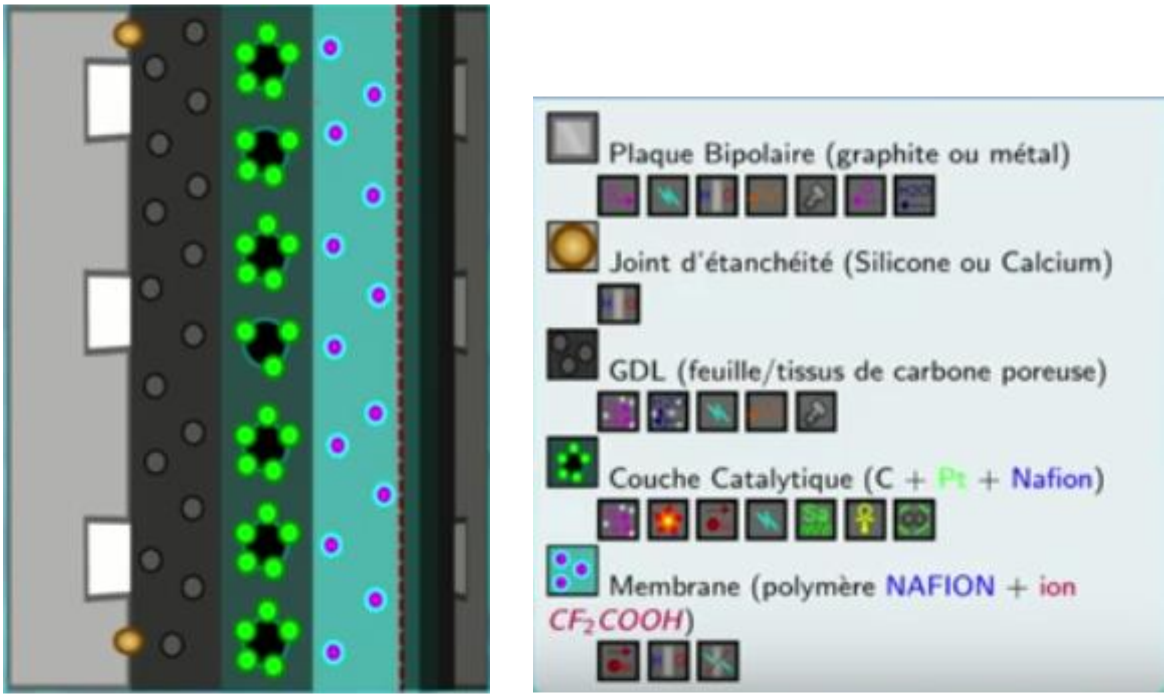


Fig. 27: Cell structure

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.

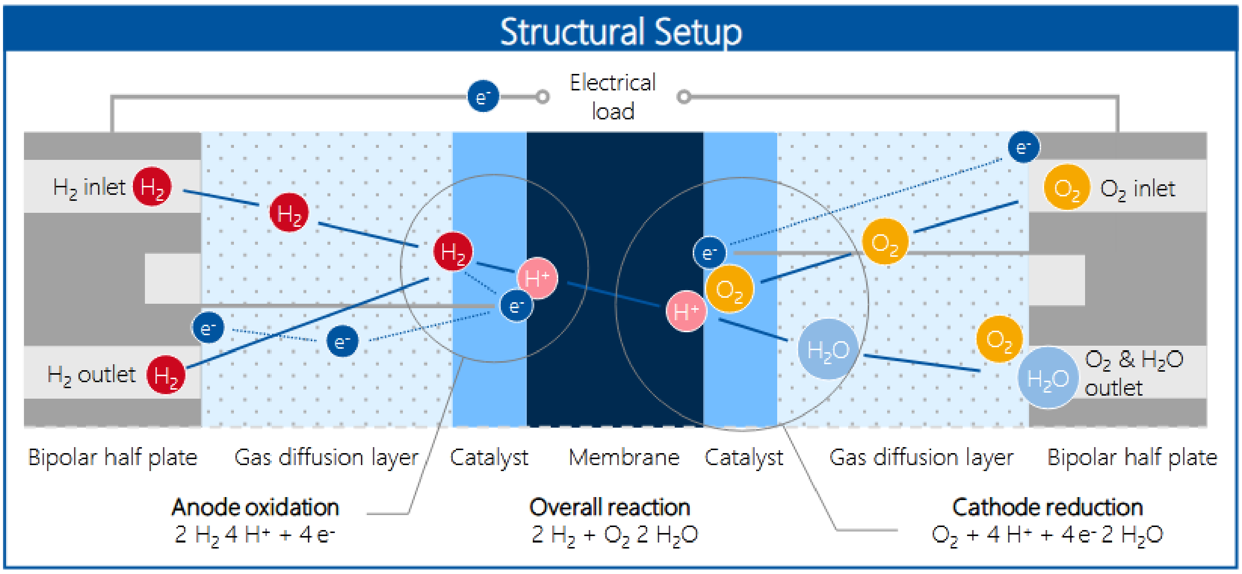
Then we have gaskets, gaskets are usually calcium or silicone, they are there only to avoid queues and hydrogen leakage is therefore a fuel cell explosion.

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.



[50]

Fig. 28: Structural setup

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[50] https://bz.vdma.org/documents/266669/49673320/FuelCellProductionBrochures_FuelCellComponents_Edition1_online_en_PEM_v07_scn_1606398023504.pdf/35fca3ae-b8e5-37e6-a685-d2dcae8a3d15

32 Analysis of quantities

32.1 Fluidic quantities

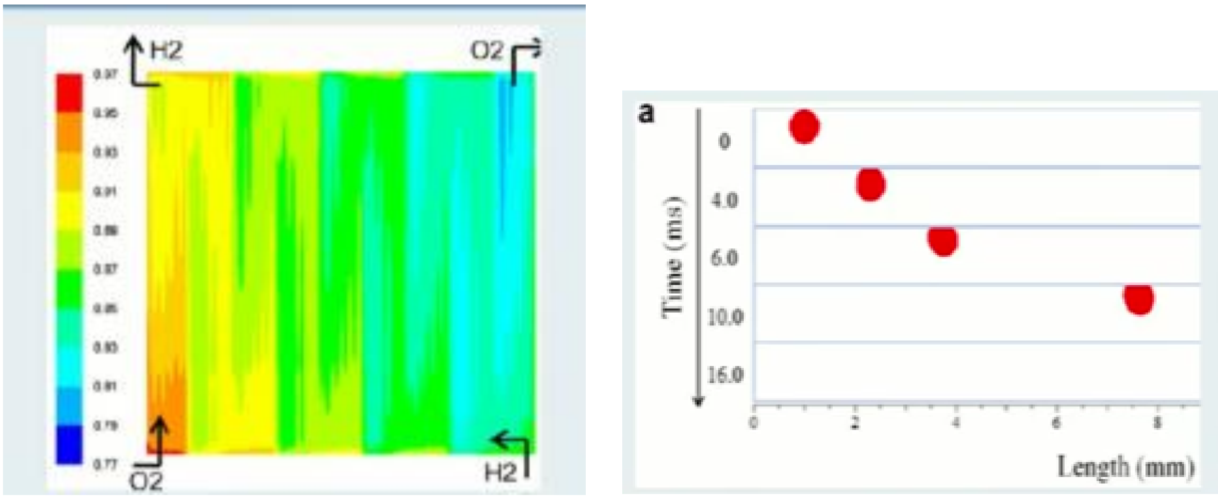
32.1.1 In the canals

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



Pressure distributions (O_2) **_Dynamic_**

Fig. 29: Fluidic quantities (Pressure distributions & dynamics) variations in the canals

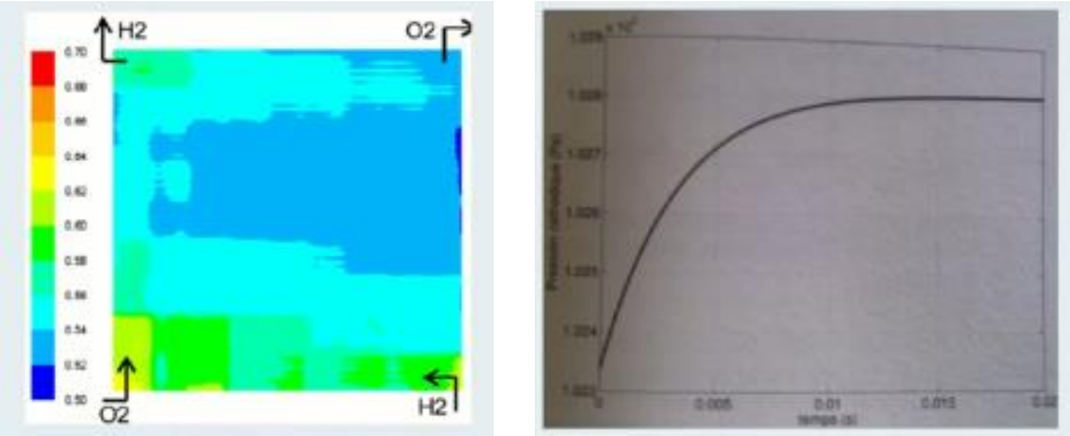
32.1.2In the GDL

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

32.1.3 In the membrane

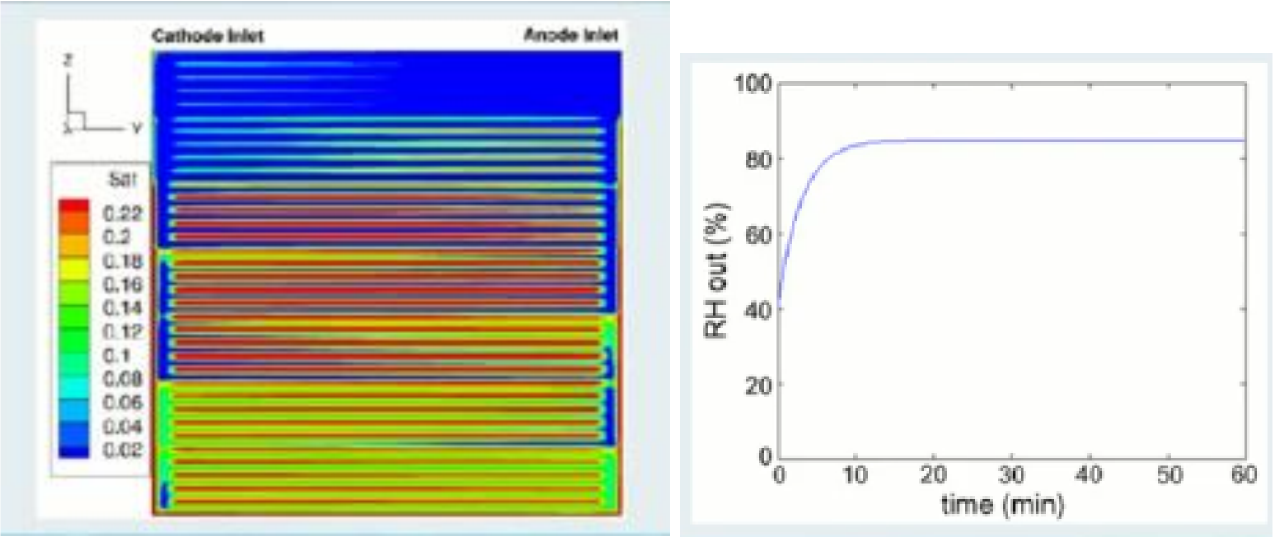
Sizes

- 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

32.2 Thermal quantities

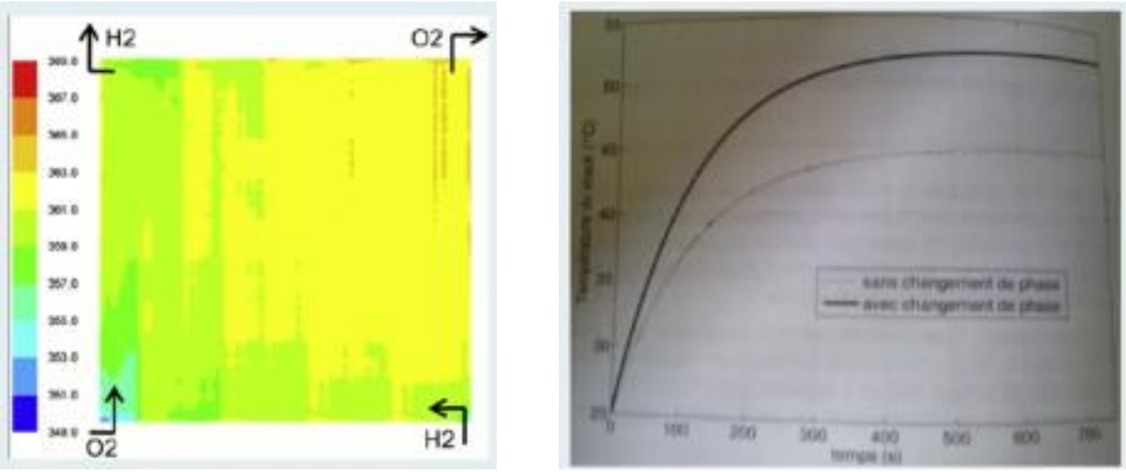
32.2.1 In the electrode

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

32.2.2 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

32.3 Electric dynamic

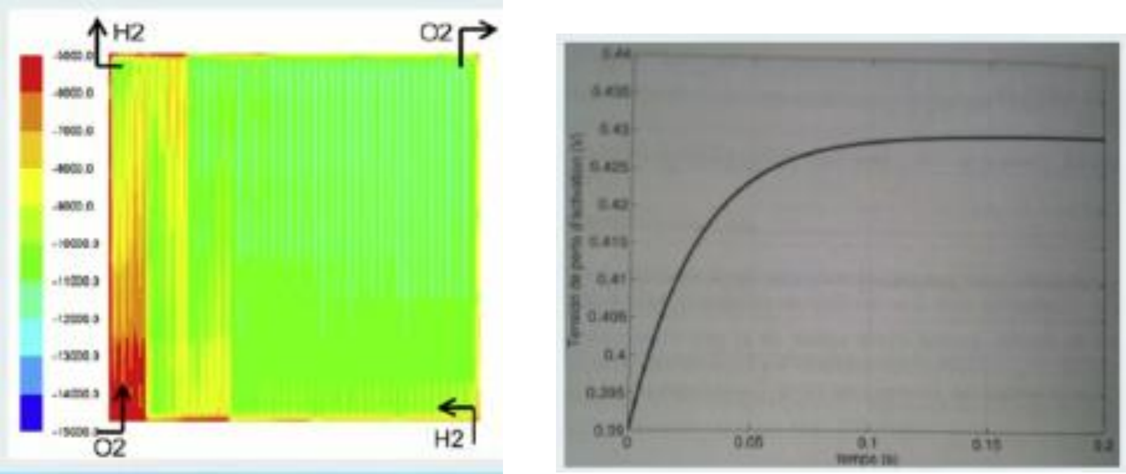
32.3.1 In the channels and the diffusion layer

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

32.3.2 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

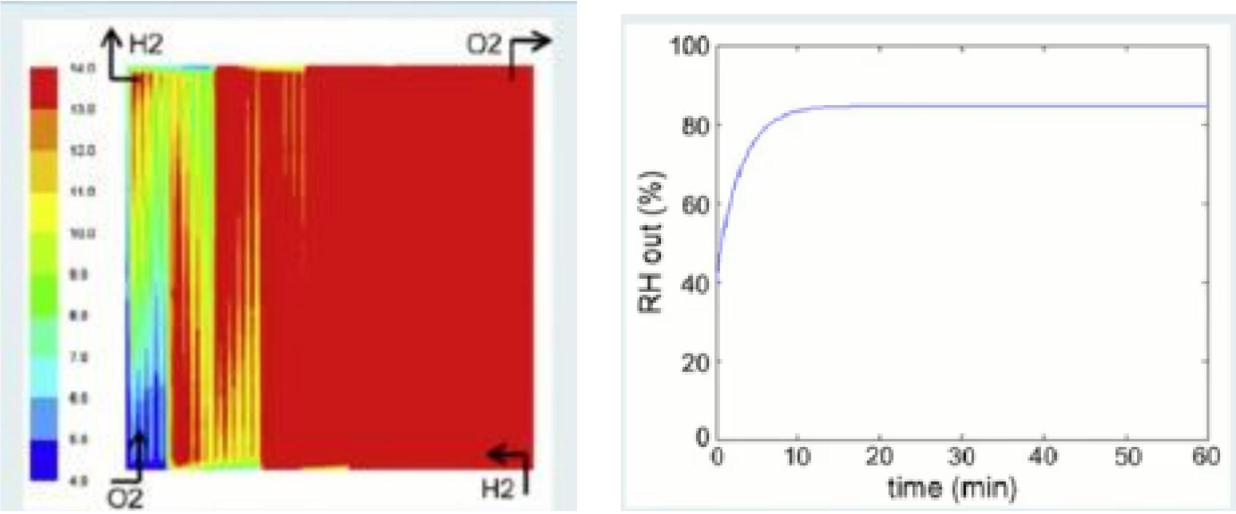
32.3.3 In the membrane

Sizes

- Voltage 0.5 - 1.3 v
- Current 0 - 50 A

Setting

- Resistance 0.25 – 3 Ω



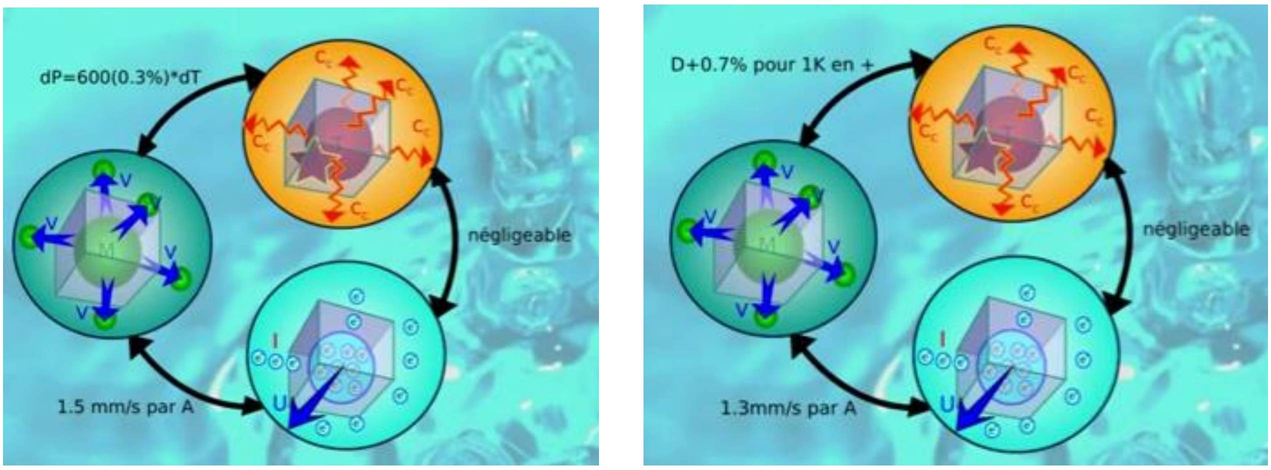
Distributions* (water content)** ***Dynamic

Fig. 34: Electric dynamic (Distributions & dynamics) variations in the membrane

33 Parametric influence

33.1 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

33.1.1 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.

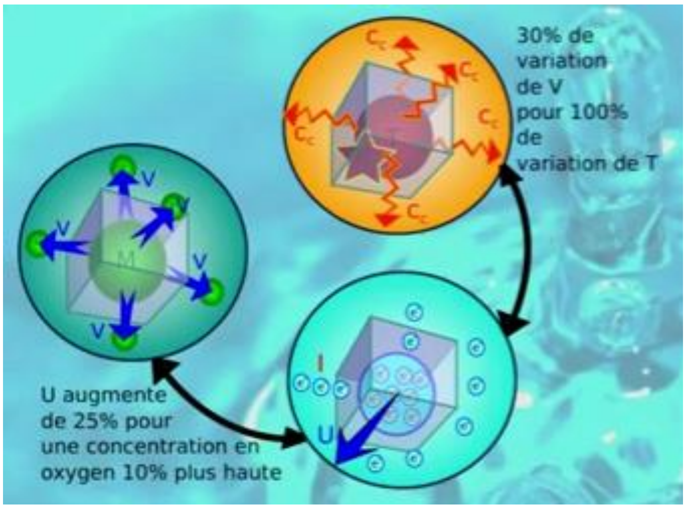


Fig. 36: Parametric influence in the catalytic layer

33.2 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.

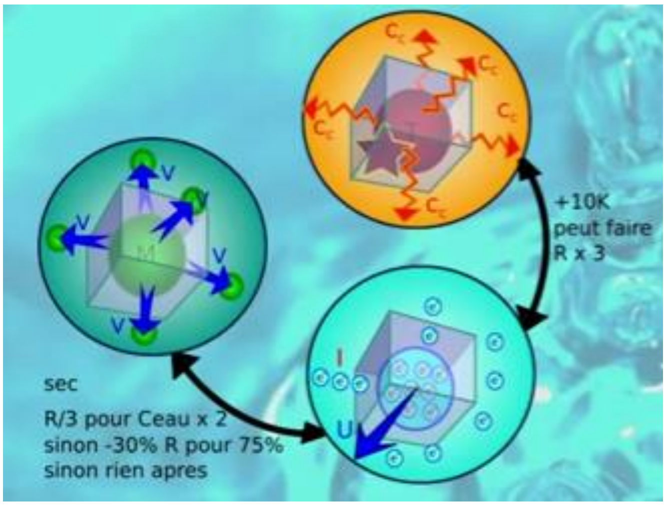
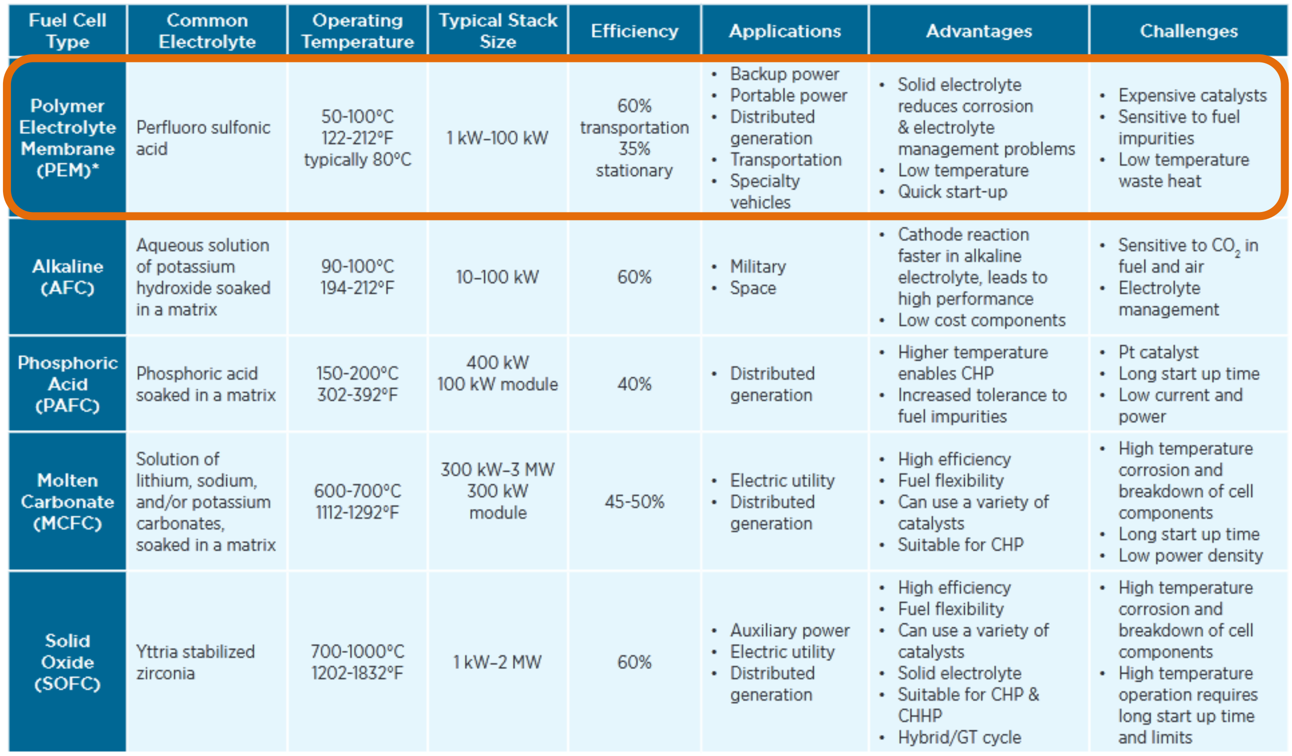


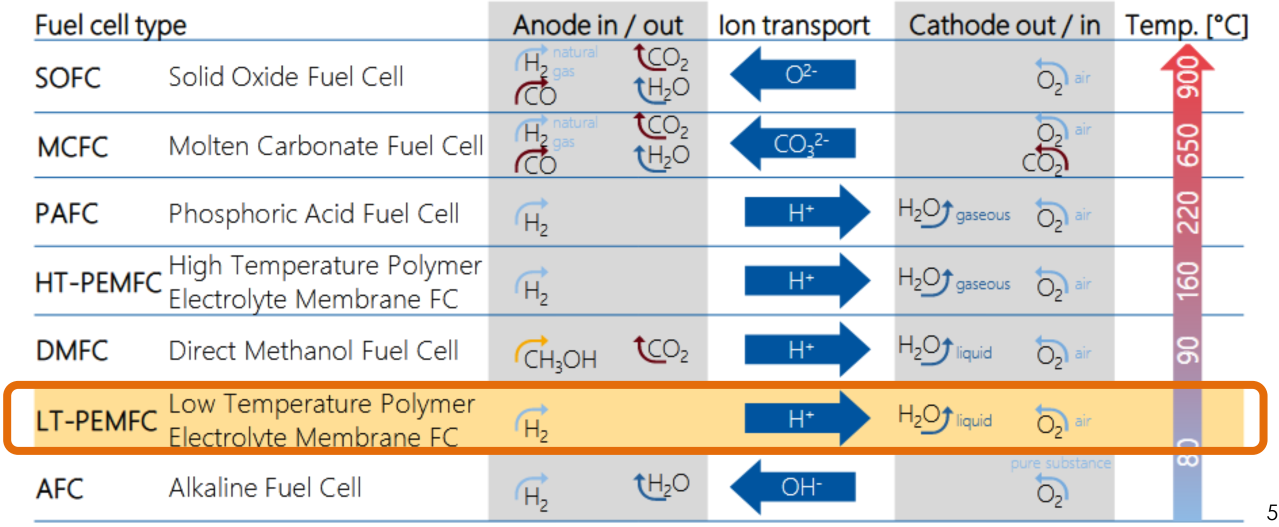
Fig. 37: Parametric influence in the membrane

34 Comparison of Fuel Cell technologies [51]



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



[52]

Fig. 39: Comparison of Fuel Cell type

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[51] https://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/fct_h2_fuelcell_factsheet.pdf

[52] https://bz.vdma.org/documents/266669/49673320/FuelCellProductionBrochures_FuelCellComponents_Edition1_online_en_PEM_v07_scn_1606398023504.pdf/35fca3ae-b8e5-37e6-a685-d2dcae8a3d15

35 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 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 of the 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:

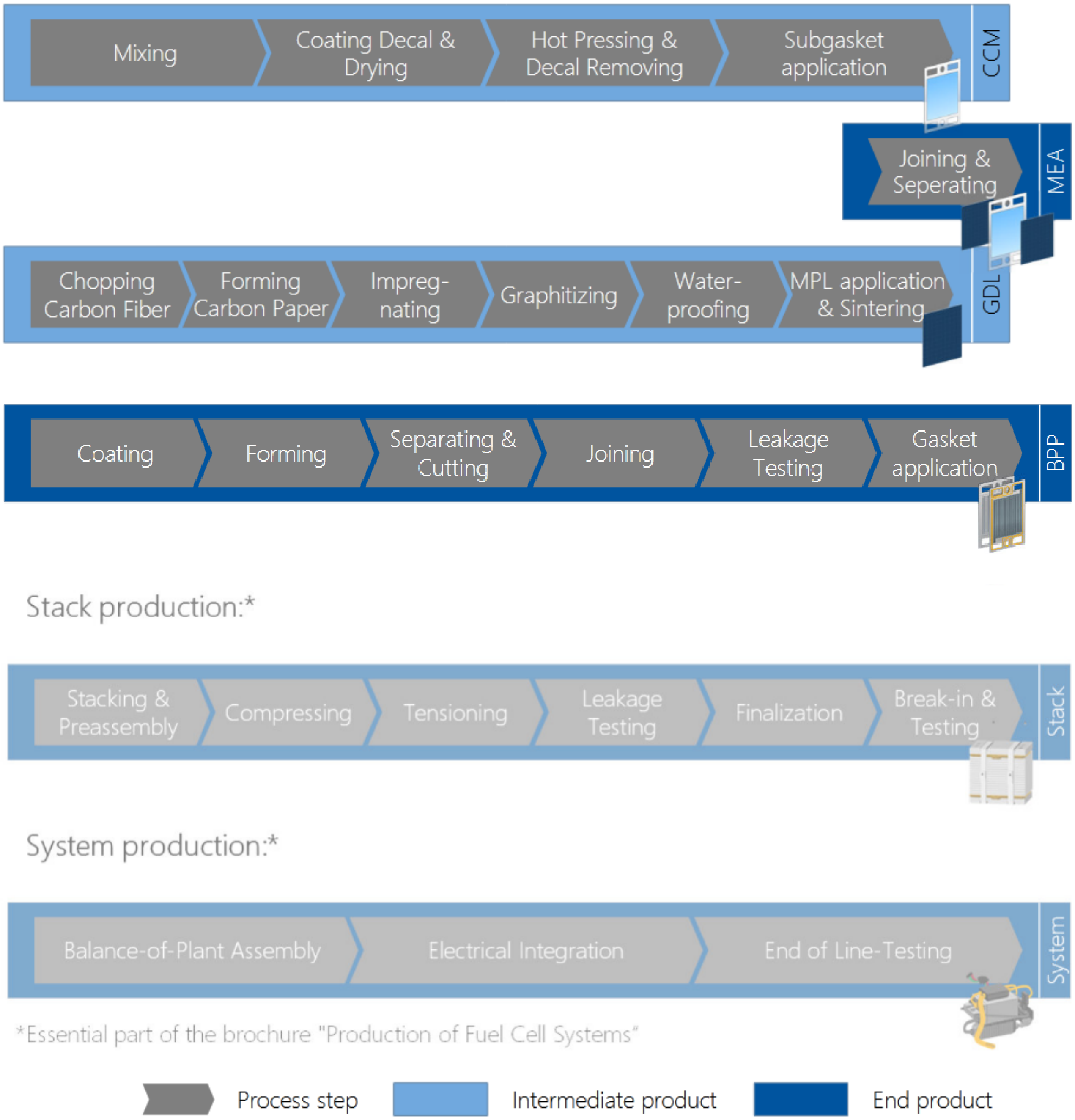
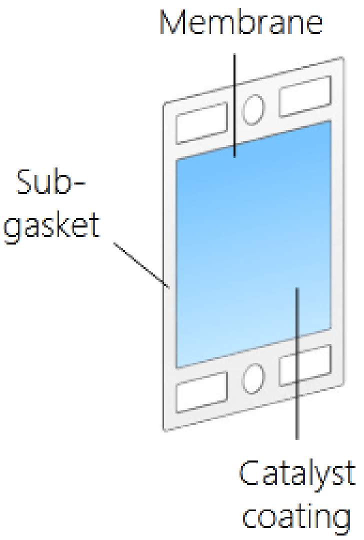


Fig. 40: Production process of PEM fuel cell components

36 Overview of PEM fuel cell components

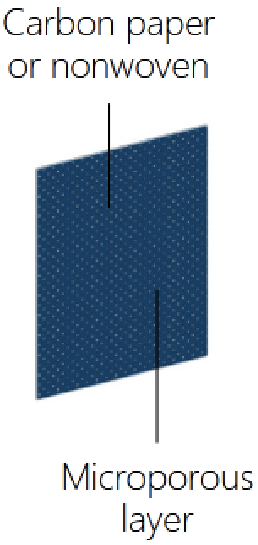
Catalyst coated membrane



- 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

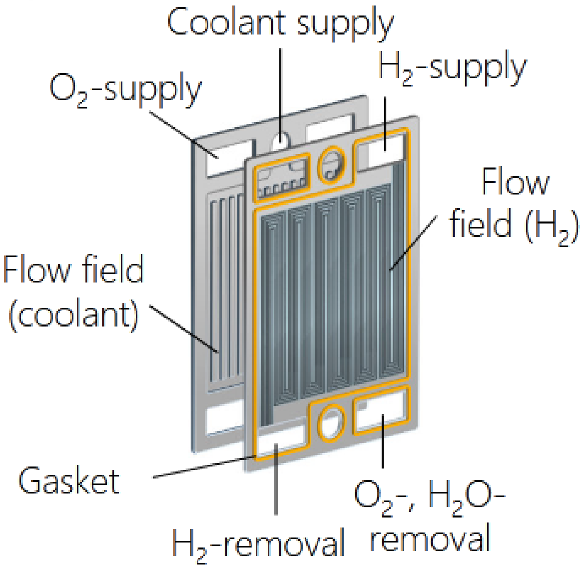
Gas diffusion layer



- 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

37 Thermal Engineering Performance Evaluation of a Polymer Electrolyte Membrane Fuel Cell Stack at Partial Load [53]

37.1 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,

$$P_{el} = V \times I \quad \textbf{(7)}$$

For a single cell, the cell efficiency

$$\eta_{cell} = \frac{V_{cell}}{V_{\max}} = \frac{V_{cell}}{1.482} \quad \textbf{(8)}$$

Thus, the stack efficiency was evaluated using

$$\eta_{stack} = \frac{V_{stack,measured}}{V_{stack,rated}} = \frac{V_{stack,measured}}{48V} \quad \textbf{(9)}$$

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,

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[53] file:///C:/Users/admin/AppData/Local/Temp/ThermalEngineeringPerfEvaluationofaPEMFCstackatpartialload.pdf

$$\dot{Q}_{cw} = \dot{m}_{cw}.C_{p,cw}.\left(T_{cw,e} - T_{cw,i}\right) \qquad \textbf{(10)}$$

Air energy changes,

$$\dot{Q}_{a} = \dot{m}_{a}.C_{p,a}.\left(T_{a,e} - T_{a,i}\right) \qquad \textbf{(11)}$$

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,

$$\dot{Q}_{stack} = \frac{m_{stack}.C_{stack}.\Delta T_{stack}}{\Delta t} \qquad \textbf{(12)}$$

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

$$Q_{nc} = h.A_{surface}\ (T_{surface} - T_{ambient}) \qquad \textbf{(13)}$$

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

$$Q_{r} = \varepsilon.\Sigma A_{s}.\sigma.\left(T_{s}^{4} - T_{ambient}^{4}\right) \qquad \textbf{(14)}$$

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,

$$\varepsilon = \frac{\dot{Q}_{actual}}{\dot{Q}_{\max}} \qquad (18)$$

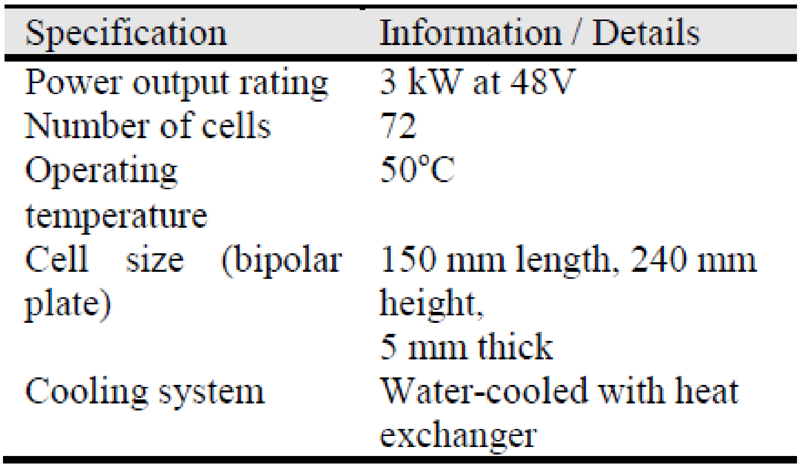
The maximum possible cooling rate in a heat exchanger is

$$\dot{Q}_{\max} = C_{\min}(T_{hot,in} - T_{cold,in}) \qquad (19)$$

where C_{min} is the smaller of $C_h = \dot{m}_h C_{p,h}$ and $C_c = \dot{m}_c C_{p,c}$.

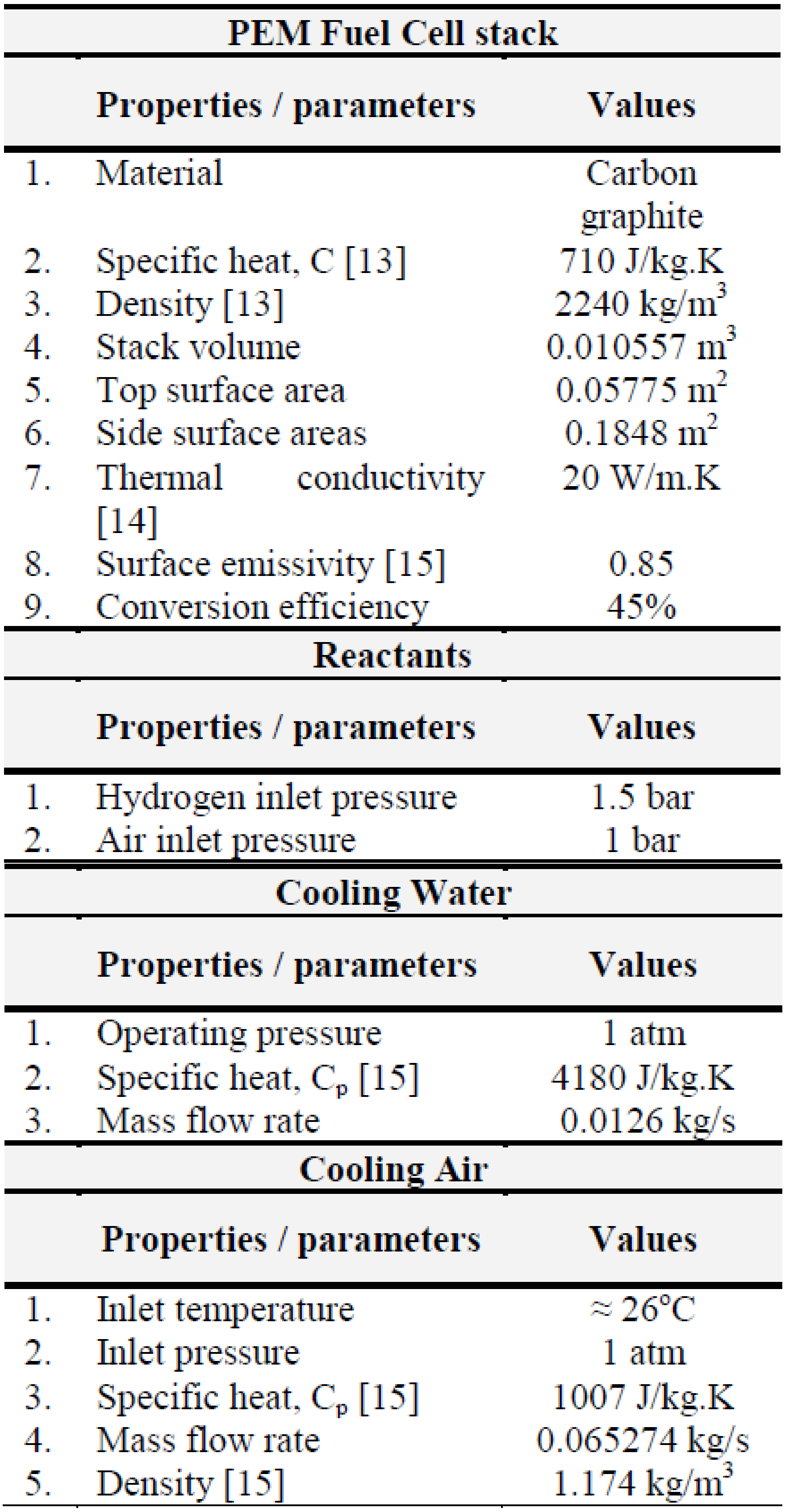
37.2 Experimental Method

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

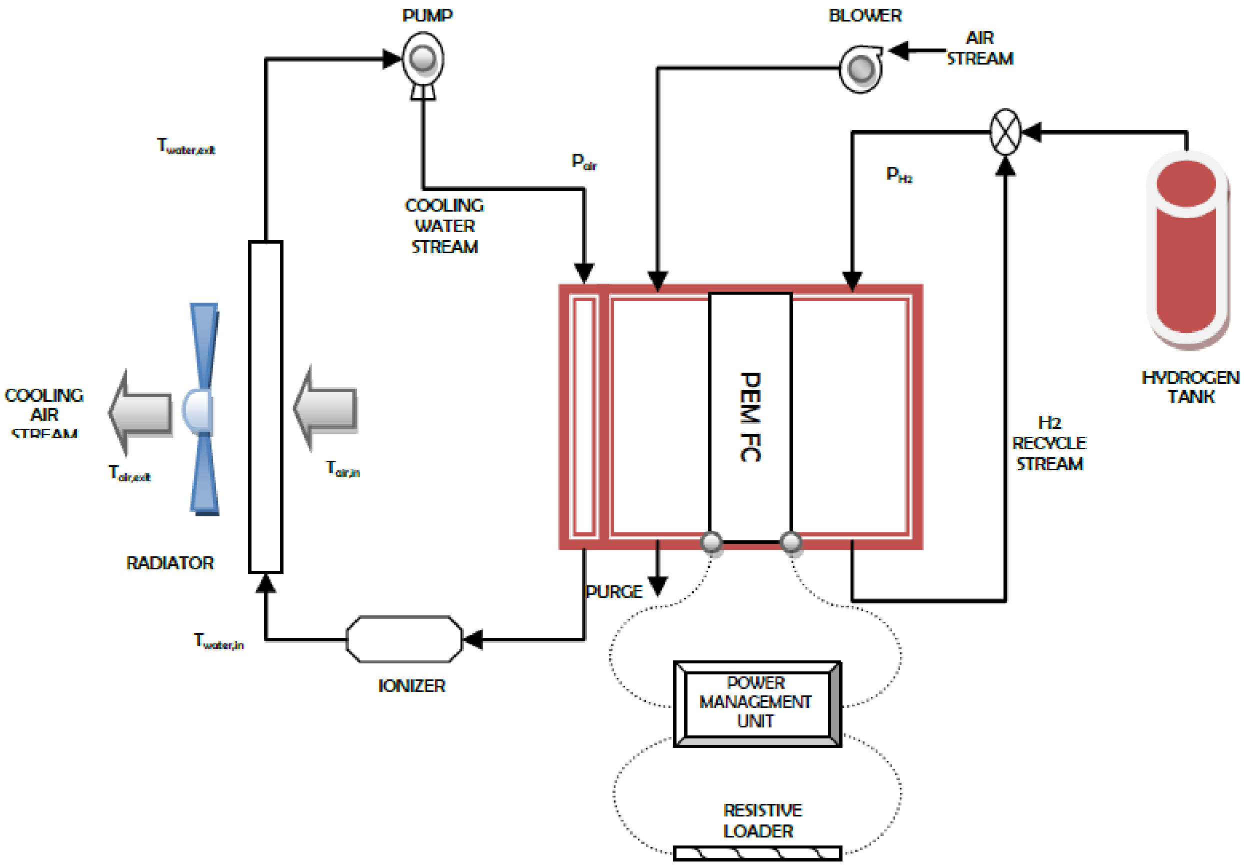


Fig. 46: The fuel cell system schematic

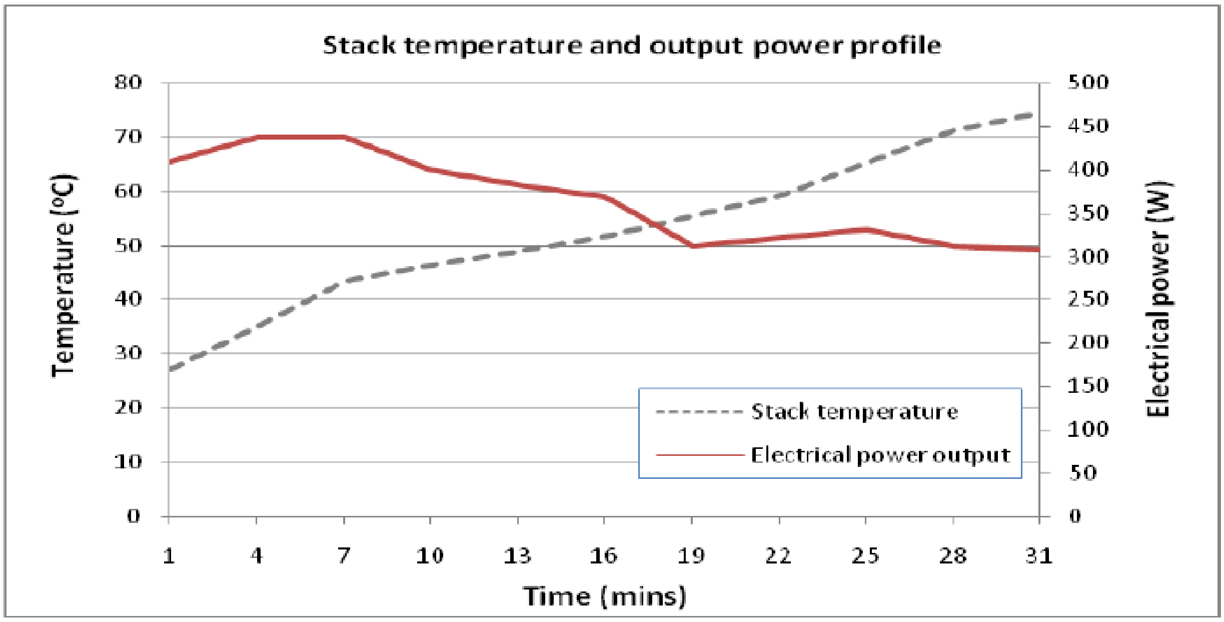


Fig. 47: Relation of stack temperature to electrical power

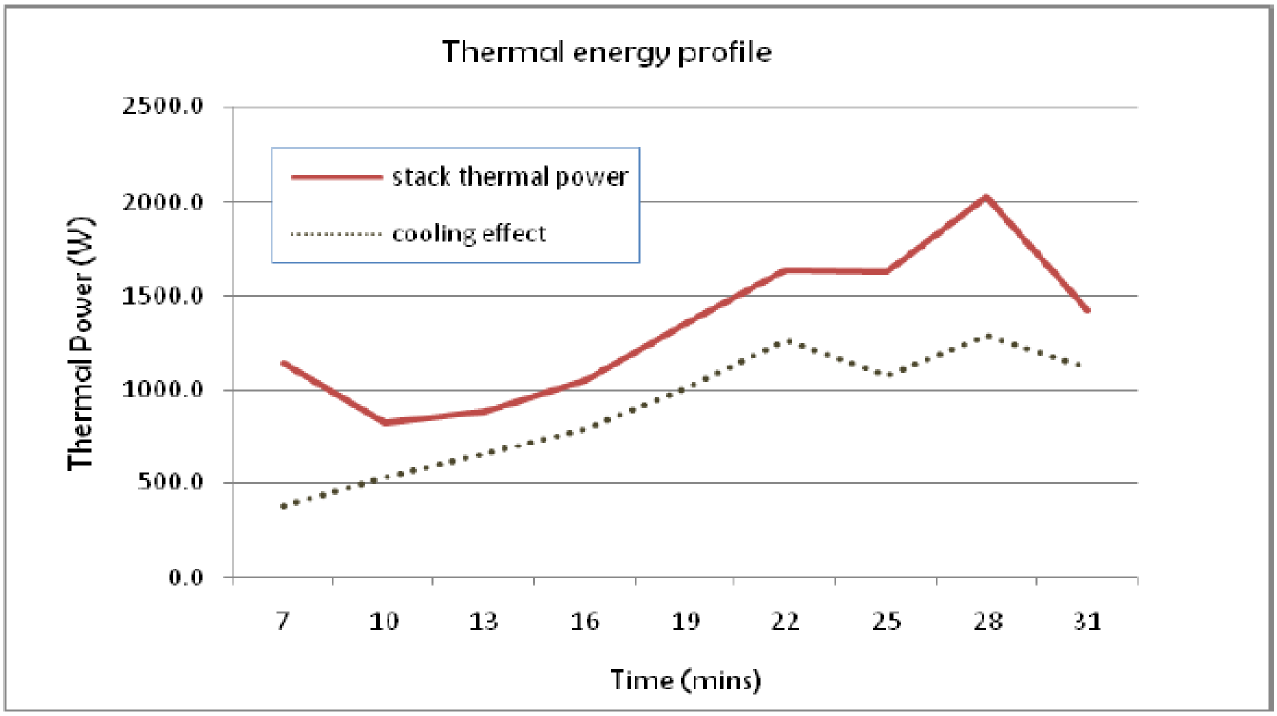


Fig. 48:The total stack thermal energy compared to combined cooling effects

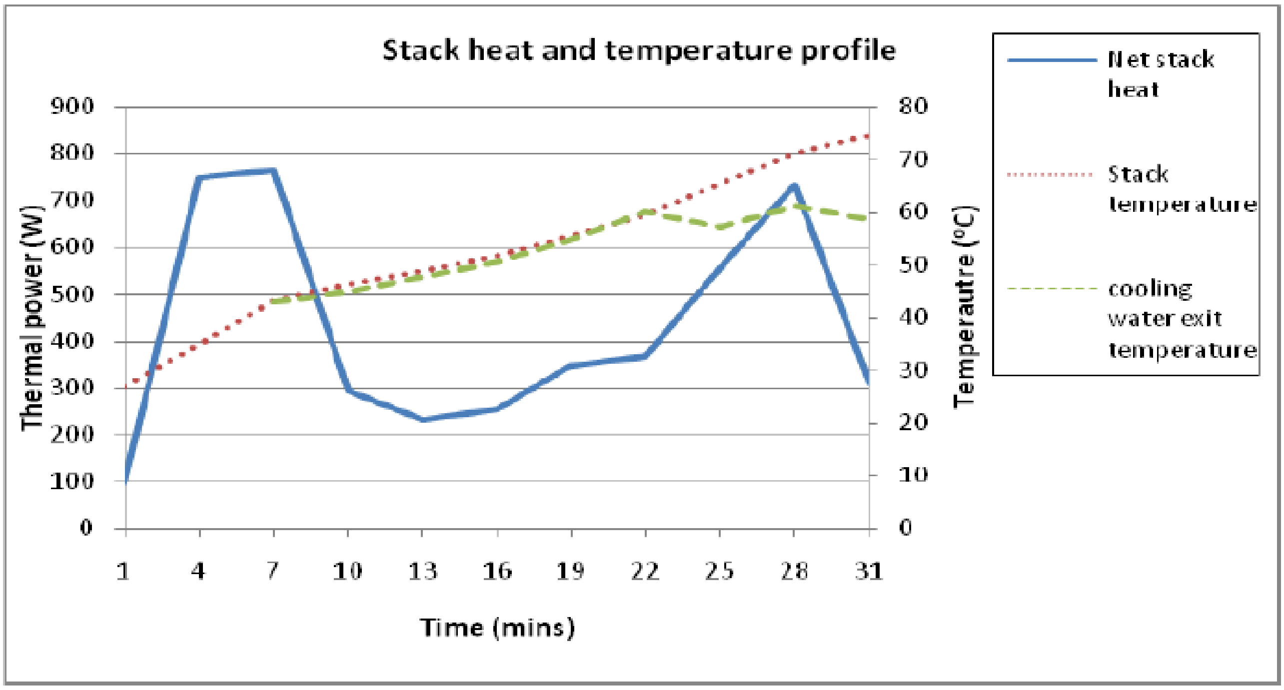


Fig. 49: Relation of stack heat and stack-to-cooling water temperature profile

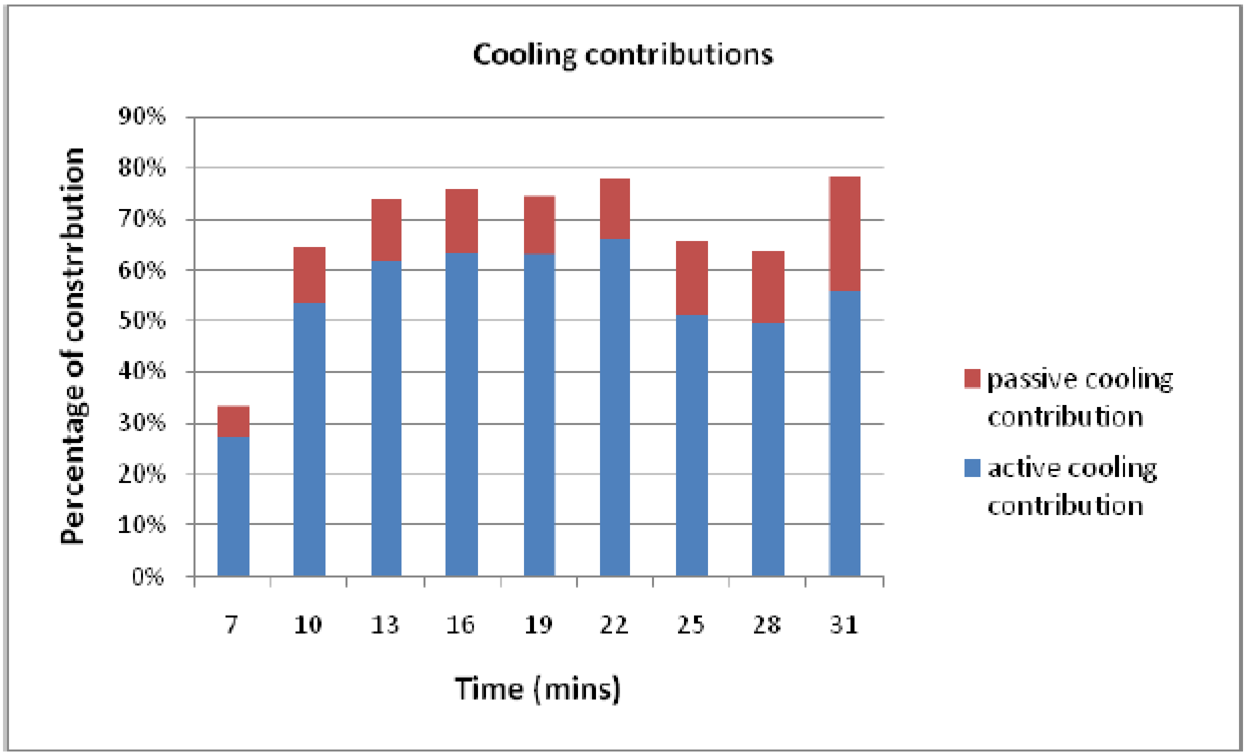


Fig. 50: Active and passive cooling contribution percentages

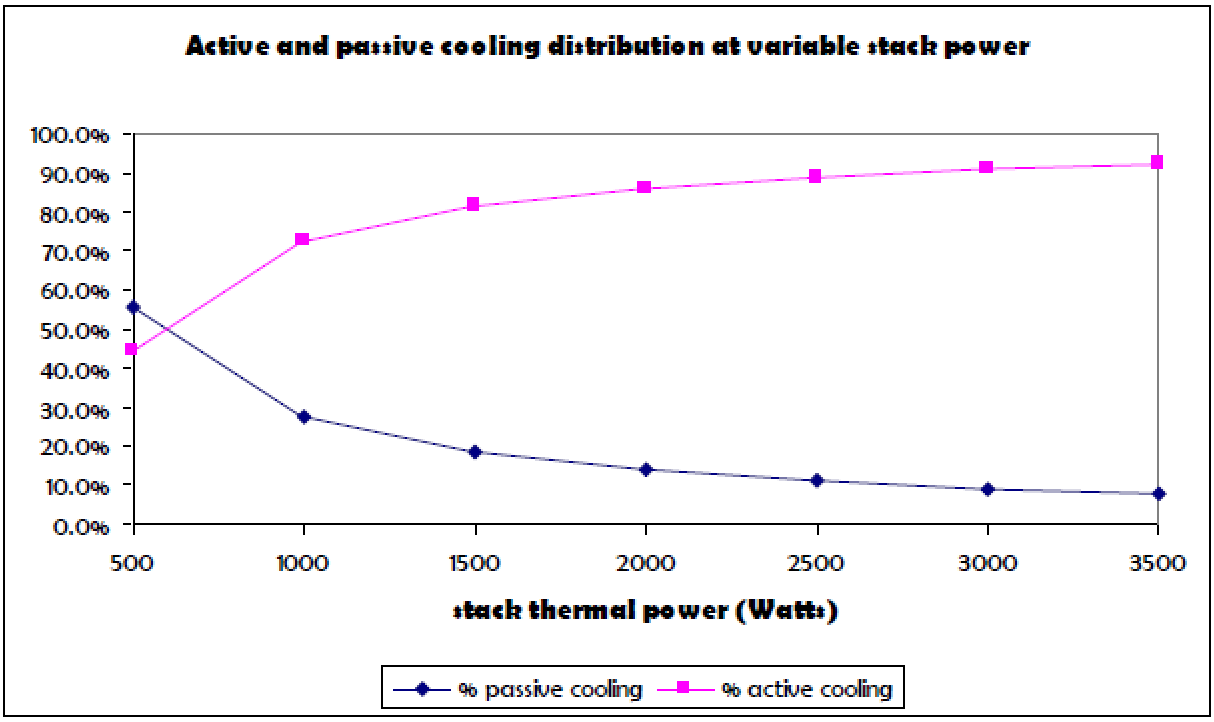


Fig. 51: Theoretical optimum cooling contributions of passive and active cooling

37.3 Cooling Performance

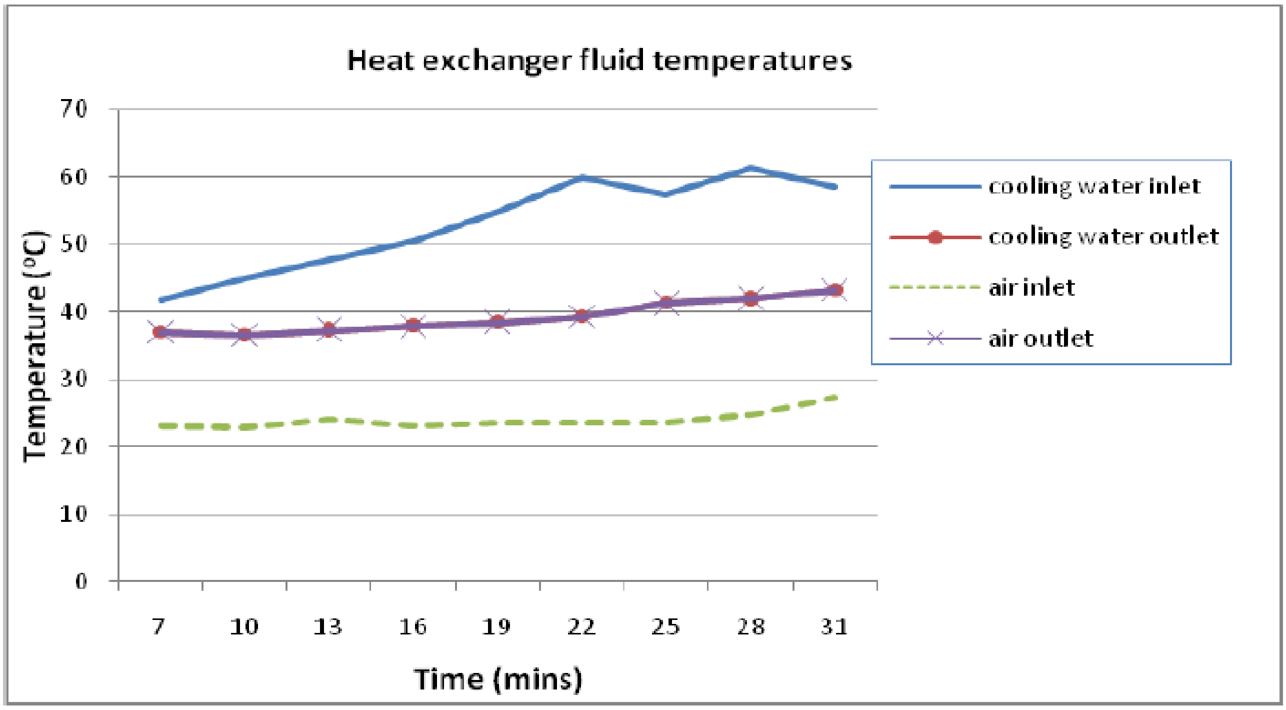


Fig. 52: Temperature profile at heat exchanger

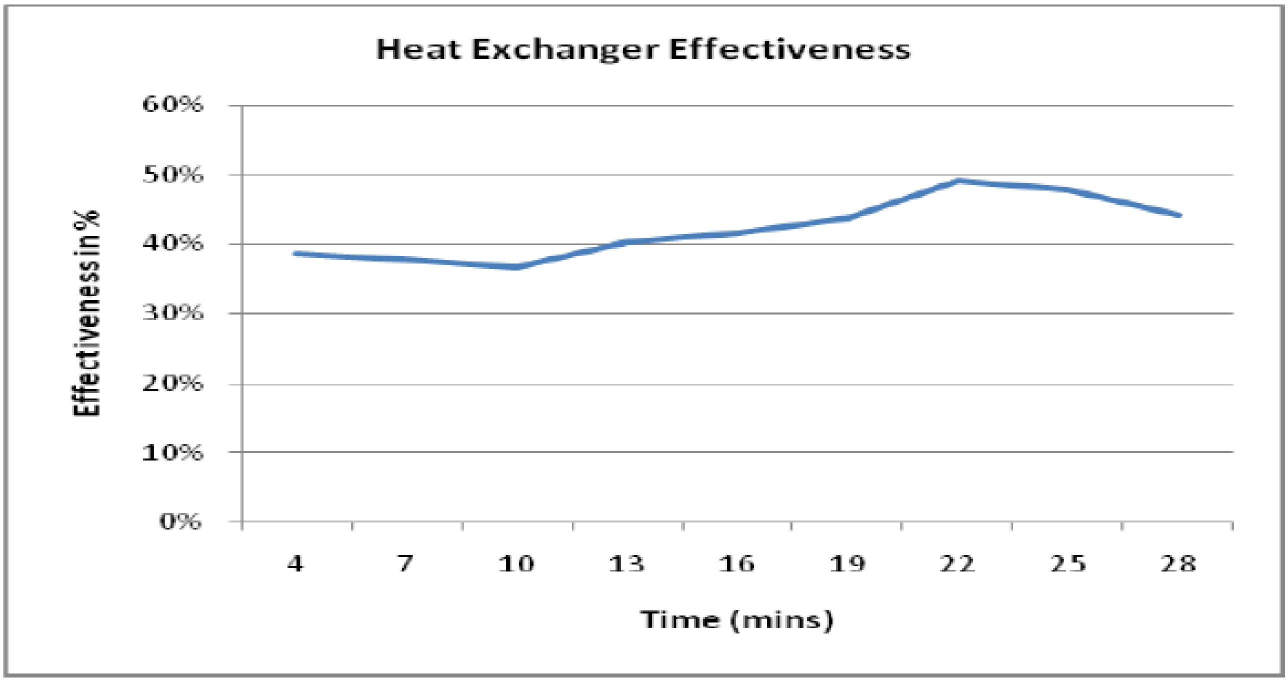


Fig. 53: Effectiveness of the heat exchanger at steady-state

37.4 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.

38 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.

38.1 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:

$$W_{FC} = V_{st} \cdot I \qquad (20)$$

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:

$$I = i * A_{cell} \qquad (21)$$

The cell potential and the current density are related by the polarization curve:

$$V_{cell} = f(i) \qquad (22)$$

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.

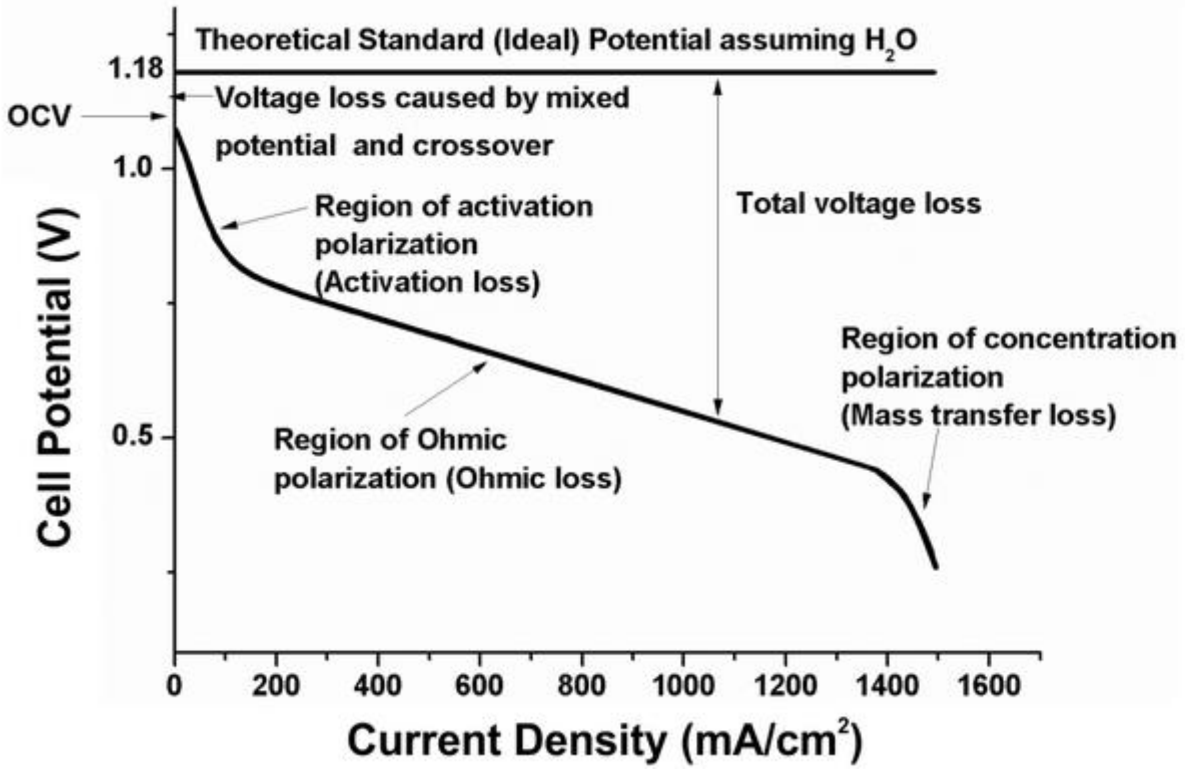


Fig. 54: Typical polarization curve for a PEM fuel cell stack.

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.

38.2 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:

$$\eta_{stack} = \frac{V_{cell}}{1.482} \qquad \textbf{(24)}$$

38.3 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.

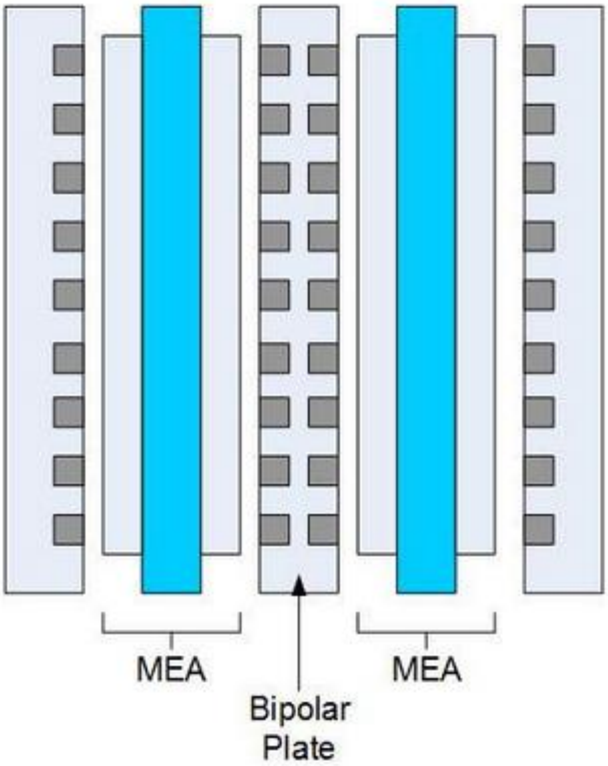
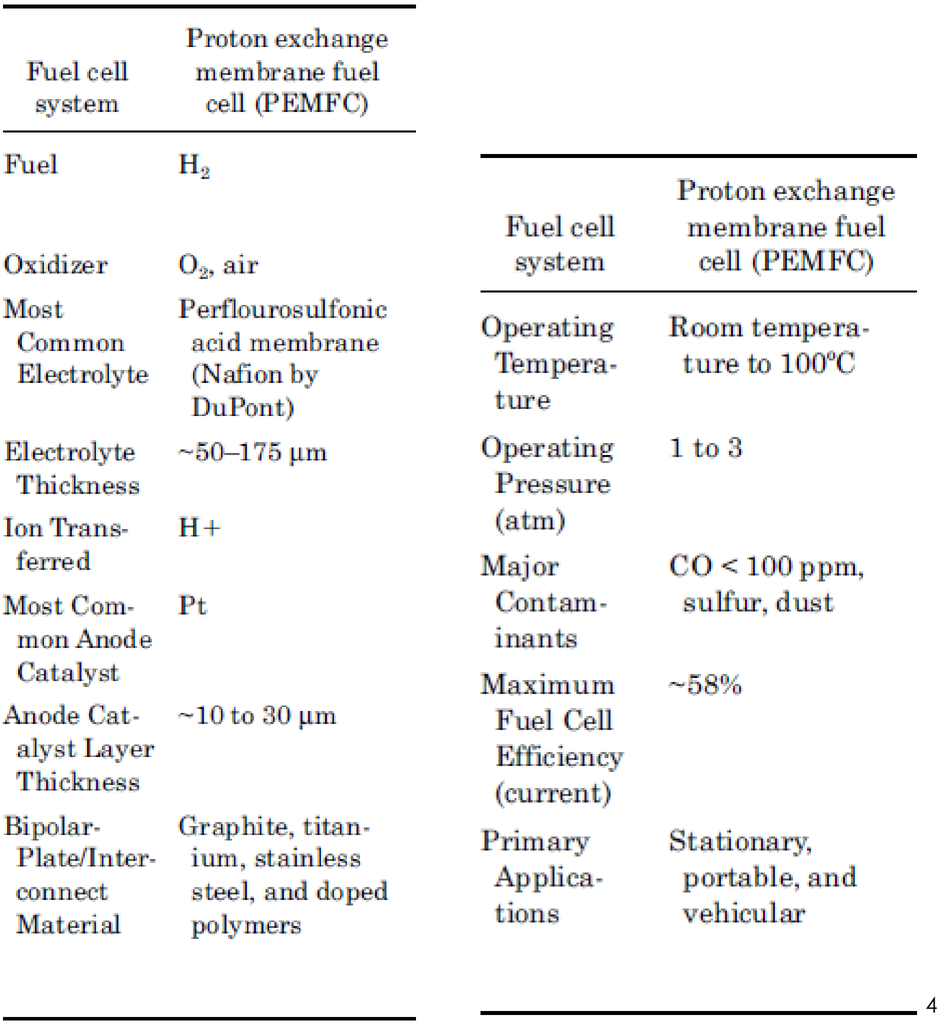


Fig. 55: Typical fuel cell stack configuration (a two-cell stack)

39 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)

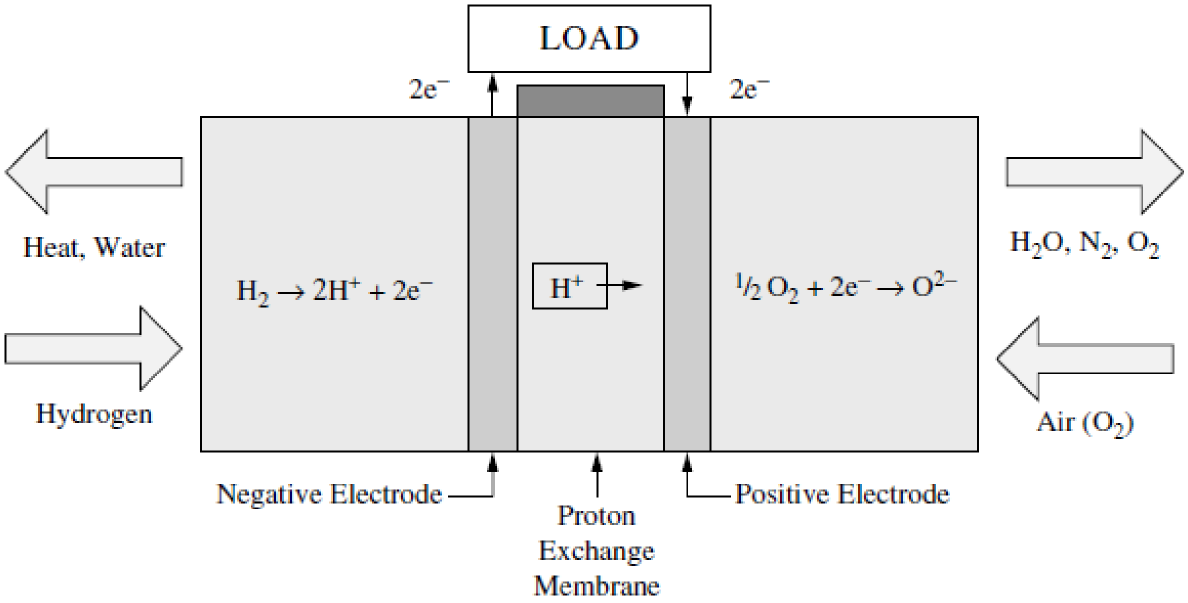


Fig. 57: The polymer electrolyte fuel cell (PEMFC) [4]

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].

39.1 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 $$\eta_{total} = \frac{P_{net} + Q_{net}}{HHV_{fuel} * n_{fuel}} \qquad \textbf{\textit{(26)}}$$

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:

$$\eta_{total} = \sum \eta - \xi_p \qquad \textbf{\textit{(27)}}$$

The electrical efficiency of the stationary fuel system is:

$$\eta_{electrical} = \frac{P_{net}}{HHV_{fuel} * n_{fuel}} \qquad \textbf{\textit{(28)}}$$

Where $$P_{net} = P_{AC} - P_{aux\_equipment} \qquad \textbf{\textit{(29)}}$$

And $$P_{aux\_equipment} = P_{compressor} + P_{pump} + P_{control} \qquad \textbf{\textit{(30)}}$$

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:

$$\eta_{thermal} = \frac{Q_{net}}{HHV_{fuel} * n_{fuel}} \qquad \textbf{\textit{(31)}}$$

If the stationary fuel cell system uses a fuel processor, the efficiency of the fuel processor is:

$$\eta_{fuel\_processor} = \frac{HHV_{H_2} * n_{H_2}}{HHV_{fuel} * n_{fuel}} \qquad \textbf{\textit{(32)}}$$

The DC/AC efficiency of the stationary fuel cell system is:

$$\eta_{DC/AC} = \frac{P_{AC}}{P_{stack}} \qquad \textbf{\textit{(33)}}$$

For any auxiliary equipment used, the efficiency is:

$$\eta_{aux\_equipment} = \frac{P_{stack} - P_{aux\_equipment}}{P_{stack}} \qquad \textbf{\textit{(34)}}$$

The efficiency of the fuel cell stack is:

$$\eta_{stack} = \frac{P_{net}}{HHV_{H_2} * n_{H_2}} \qquad \textbf{\textit{(35)}}$$

1.1. 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]:

$$V(i) = V_{rev} - V_{irrev} \qquad \textbf{(36)}$$

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:

$$W_{elec} = -\Delta G \qquad \textbf{(37)}$$

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:

$$W_{elec} = \Delta G = \Delta H - T\Delta S \qquad \textbf{(38)}$$

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:

$$\Delta H = \sum_i m_i h_i - \sum_j m_j h_j \qquad \textbf{(39)}$$

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]:

$$W_{elec} = EQ \qquad \textbf{(40)}$$

If the charge is assumed to be carried out by electrons:

$$Q = nF \qquad \textbf{(41)}$$

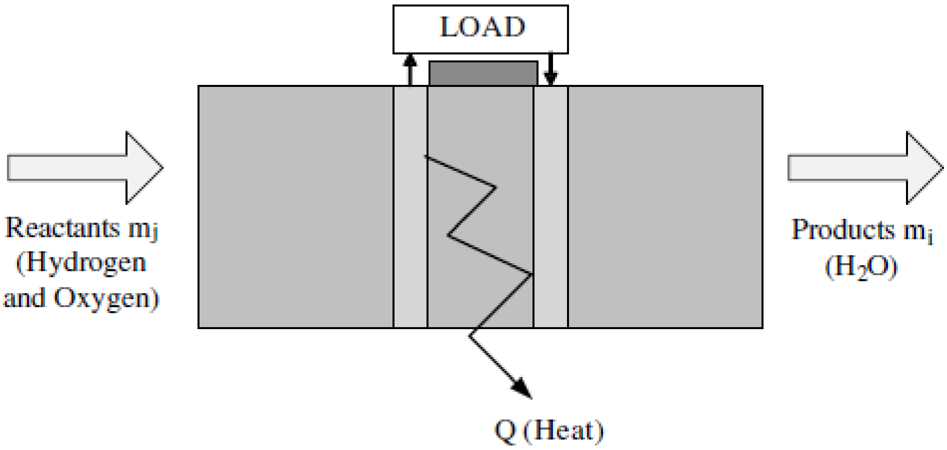


Fig. 58: Fuel cell heat and mass balance

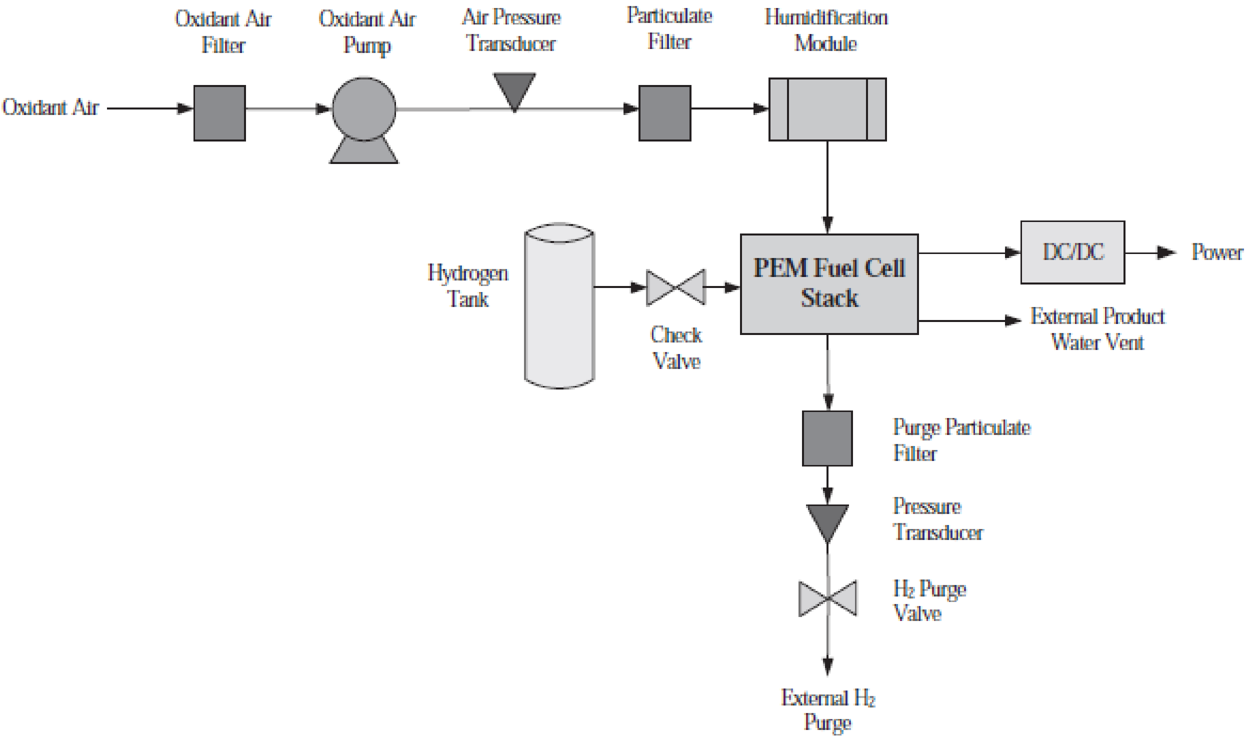
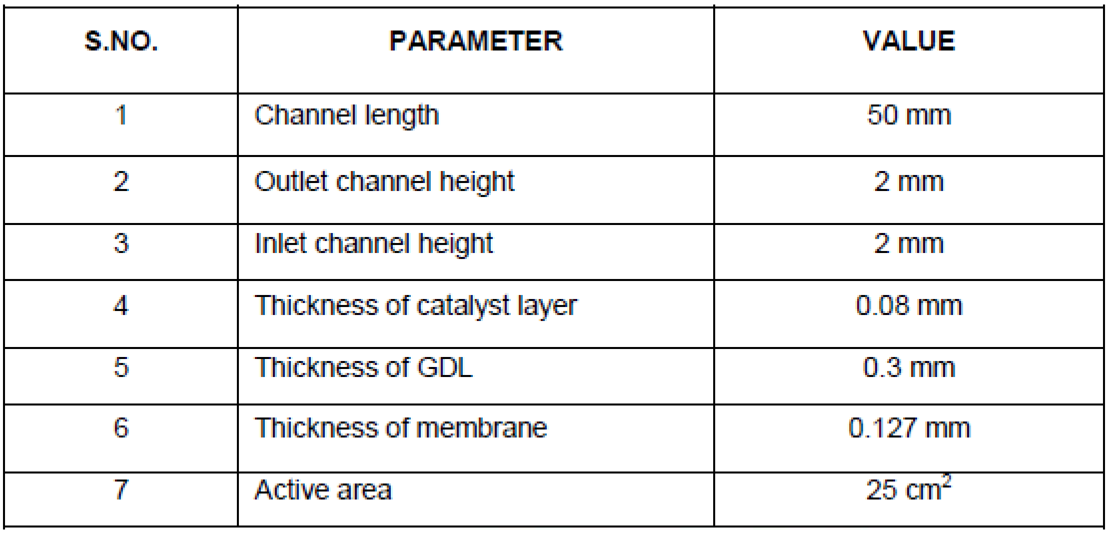


Fig. 59: Simple PEM fuel cell system [5]

40 Model creation of PEM fuel cell [54]



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

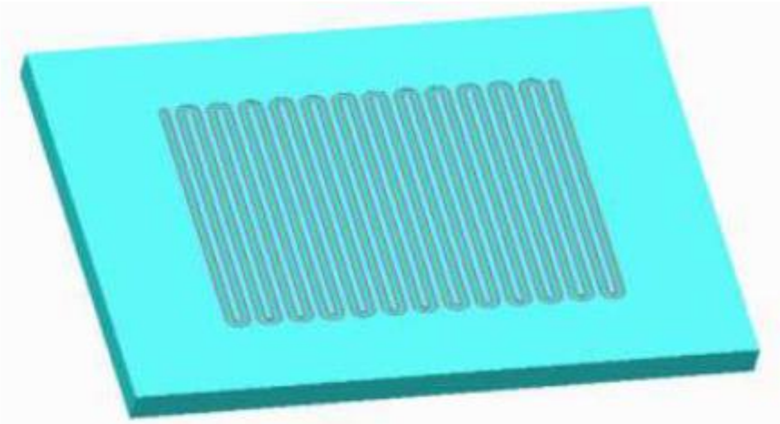
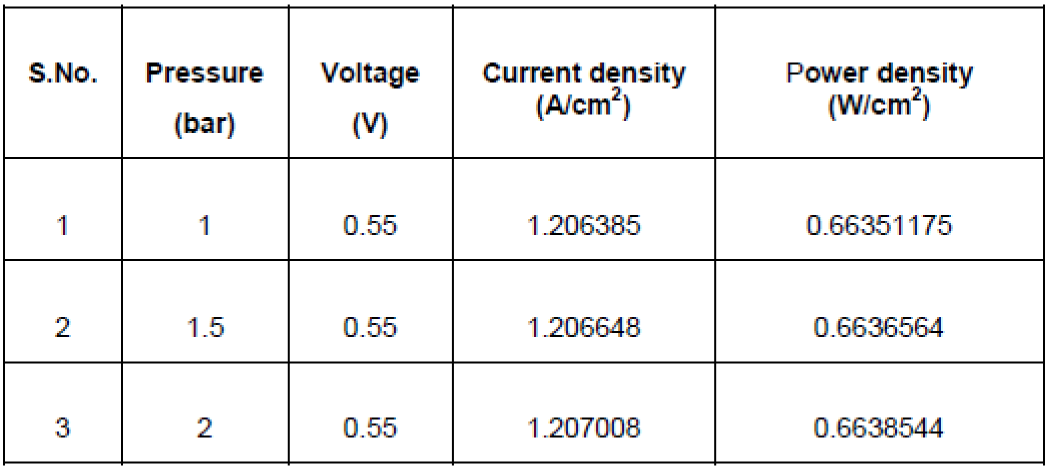


Fig. 61: Model of serpentine channel flow field of PEM fuel cell



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

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[54] https://www.researchgate.net/publication/341095046_IMPACT_OF_PRESSURE_ON_THE_PERFORMANCE_OF_PROTON_EXCHANGE_MEMBRANE_FUEL_CELL

40.1 Material and assembly (exp) [55]

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.

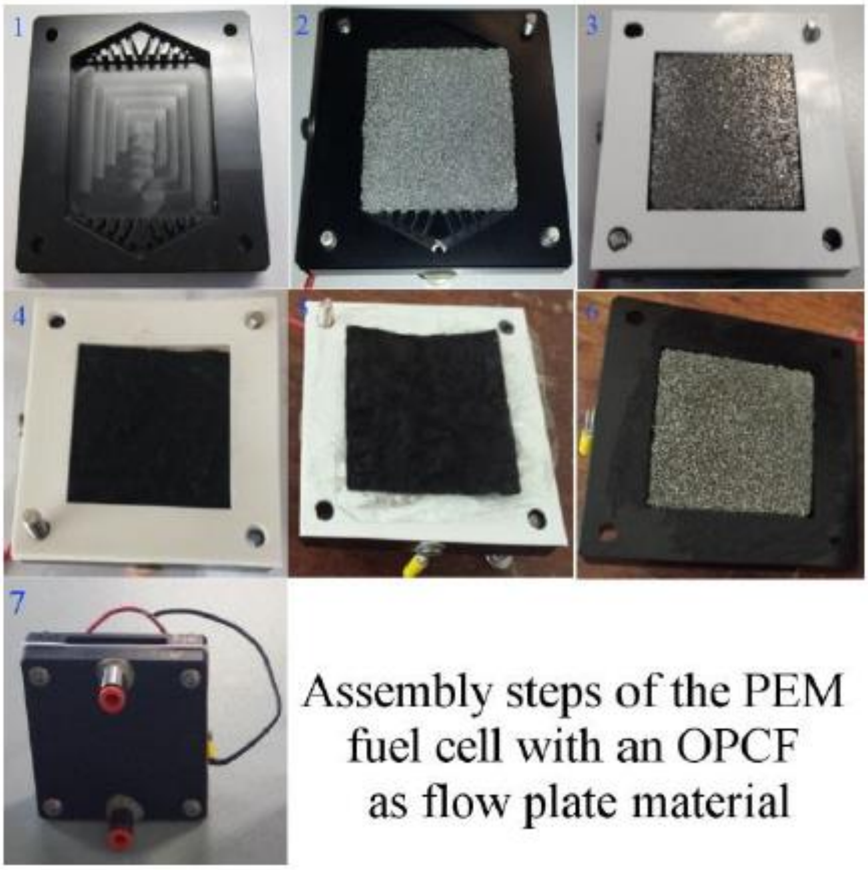

Fig. 63: Assembly steps of the PEM fuel cell

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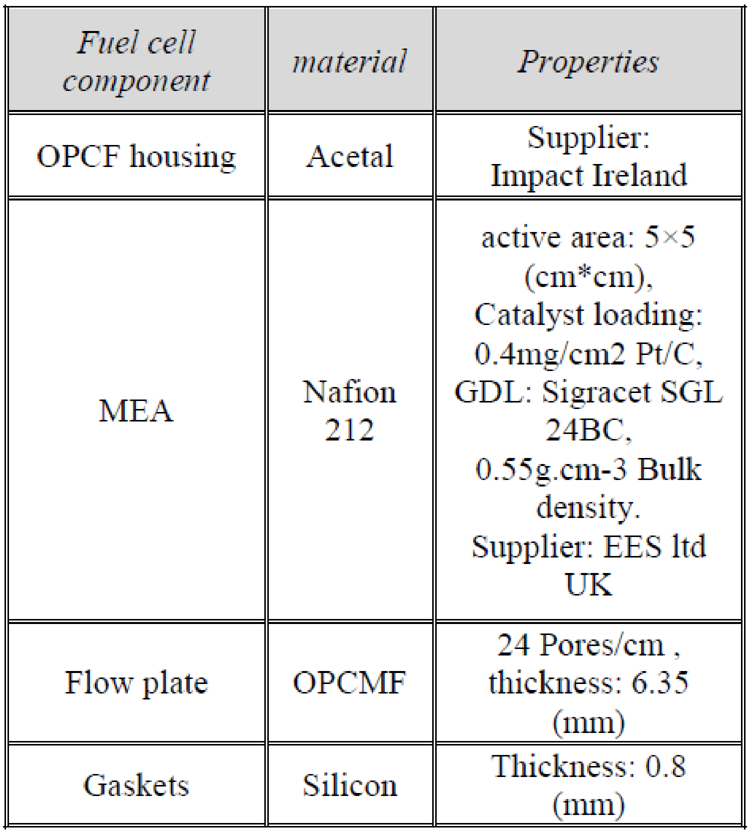
[55] https://www.researchgate.net/publication/265412592_Design_and_Development_of_Proton_Exchange_Membrane_Fuel_Cell_using_Open_Pore_Cellular_Foam_as_Flow_Plate_Material/download



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

40.2 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.

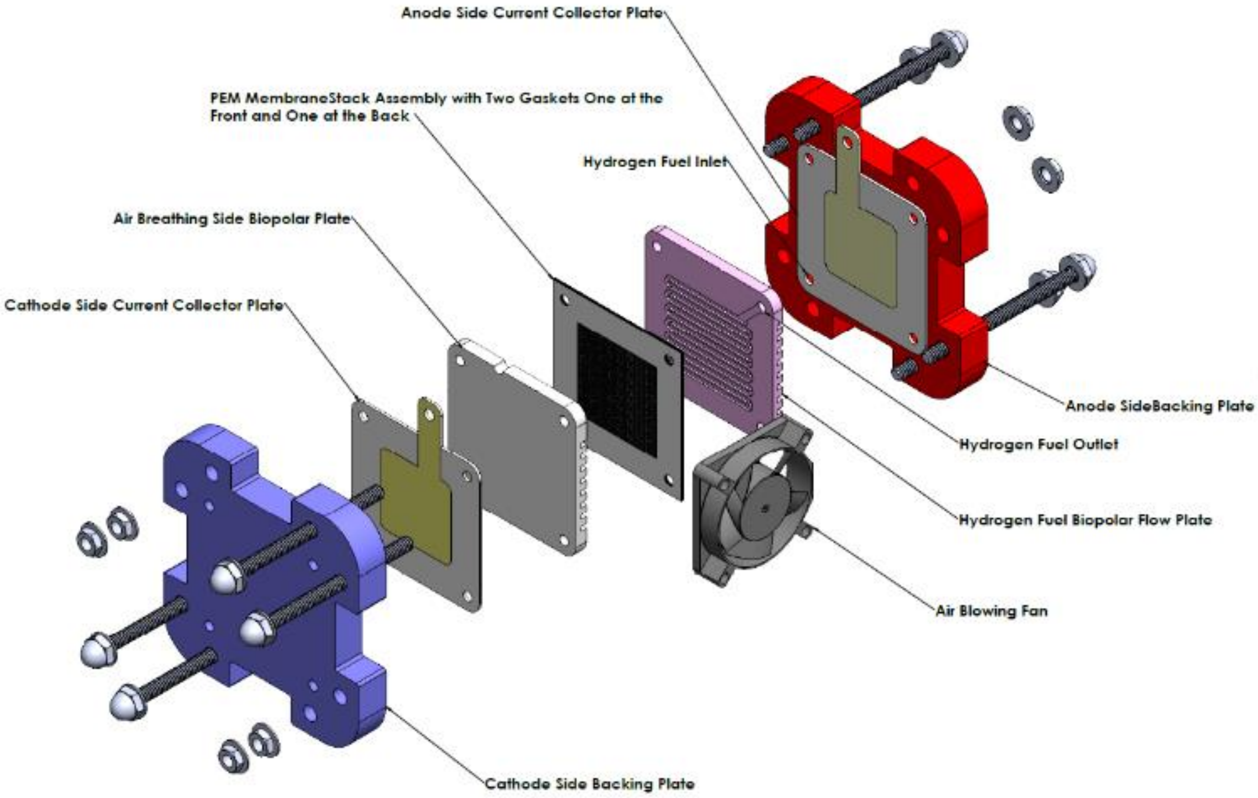


Fig. 65: The Polymer Electrolyte Membrane Fuel Cell (PEMFC)[56]

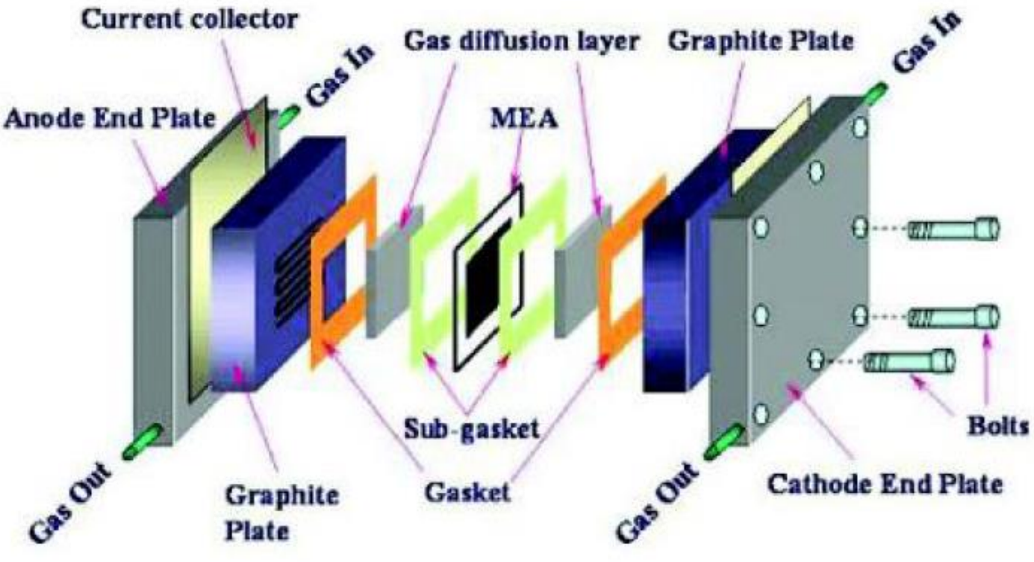


Fig. 66: Schematic of Polymer Electrolyte Membrane Fuel Cell showing different components [57]

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[56] 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

[57] https://www.researchgate.net/publication/282896560_Proton_Exchange_Membrane_Fuel_Cell_Technology_India's_Perspective/download

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

41 Study of PEM Fuel Cell End Plate Design by Structural Analysis Based on Contact Pressure [58]

41.1 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 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].

41.2 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.

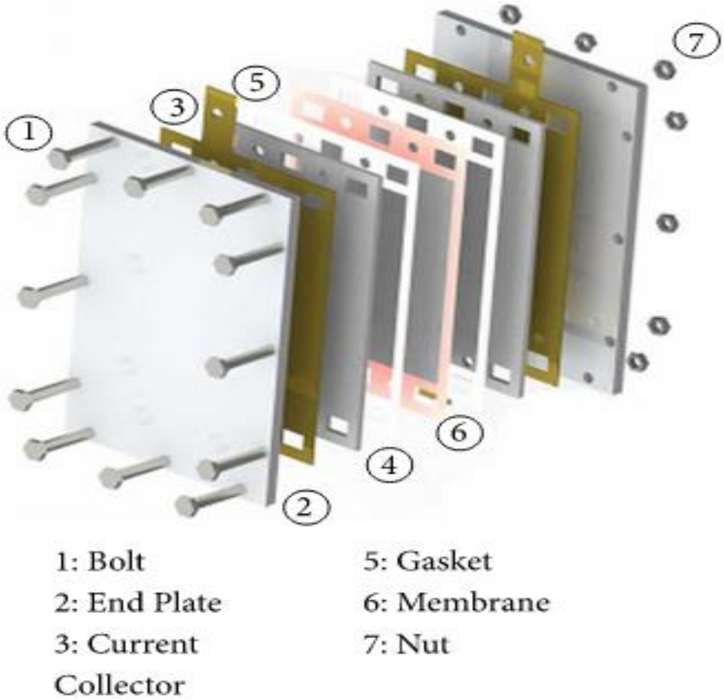

Fig. 68: Schematic geometry of PEMFC

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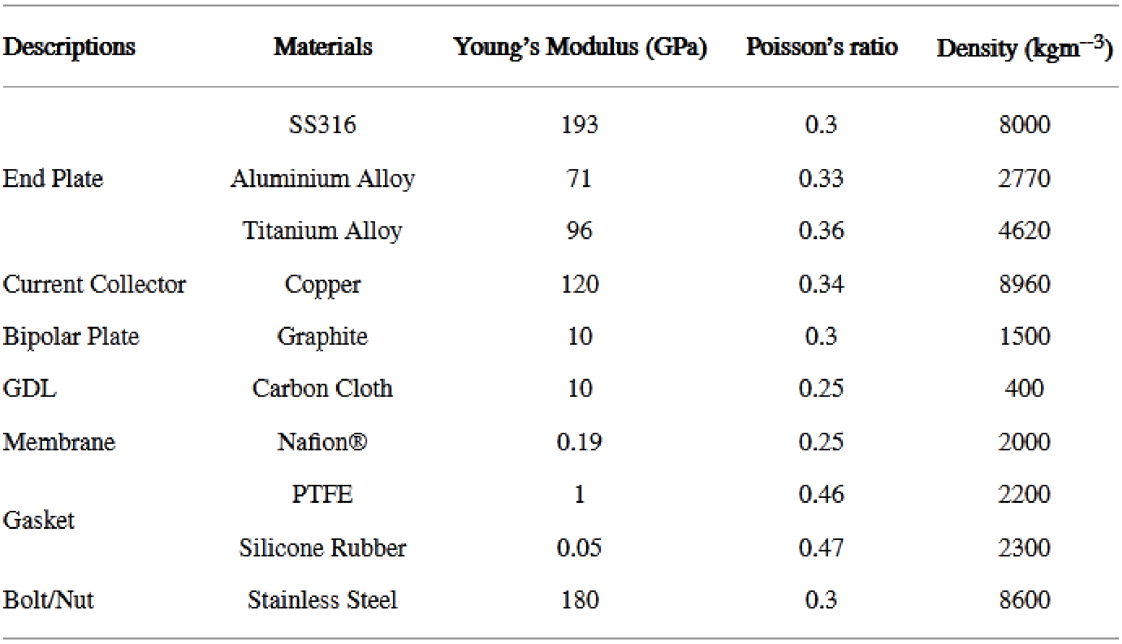
[58] https://www.hindawi.com/journals/jen/2019/3821082/



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

$$\mathrm{d} = \frac{L}{n+1}$$

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.

41.3 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.

42 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 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.

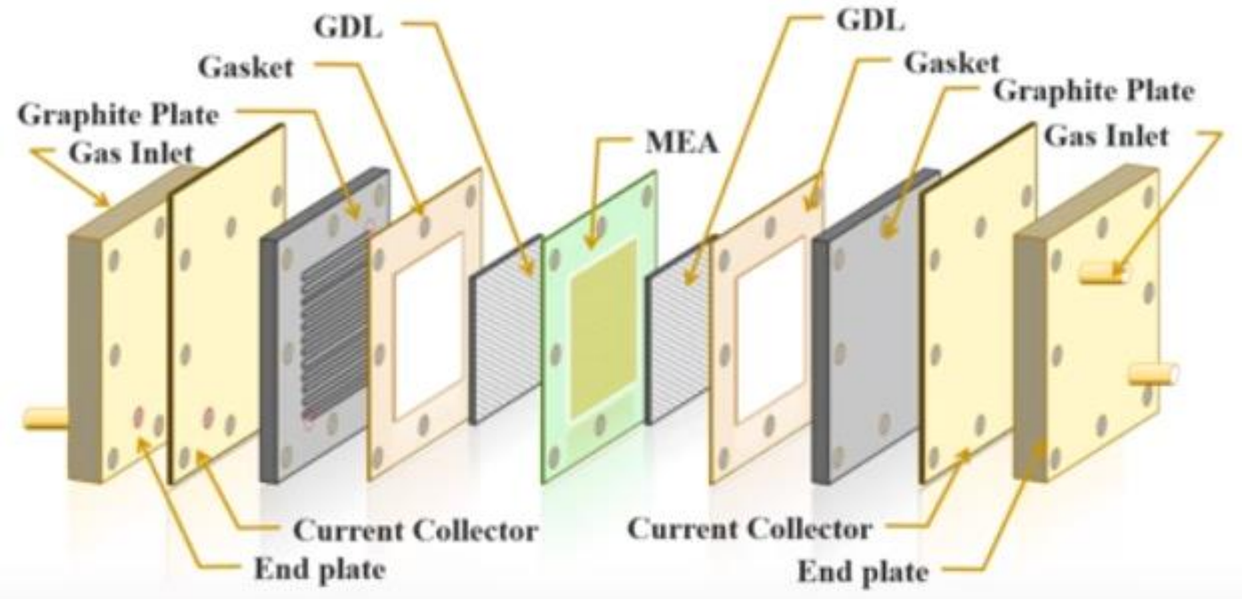
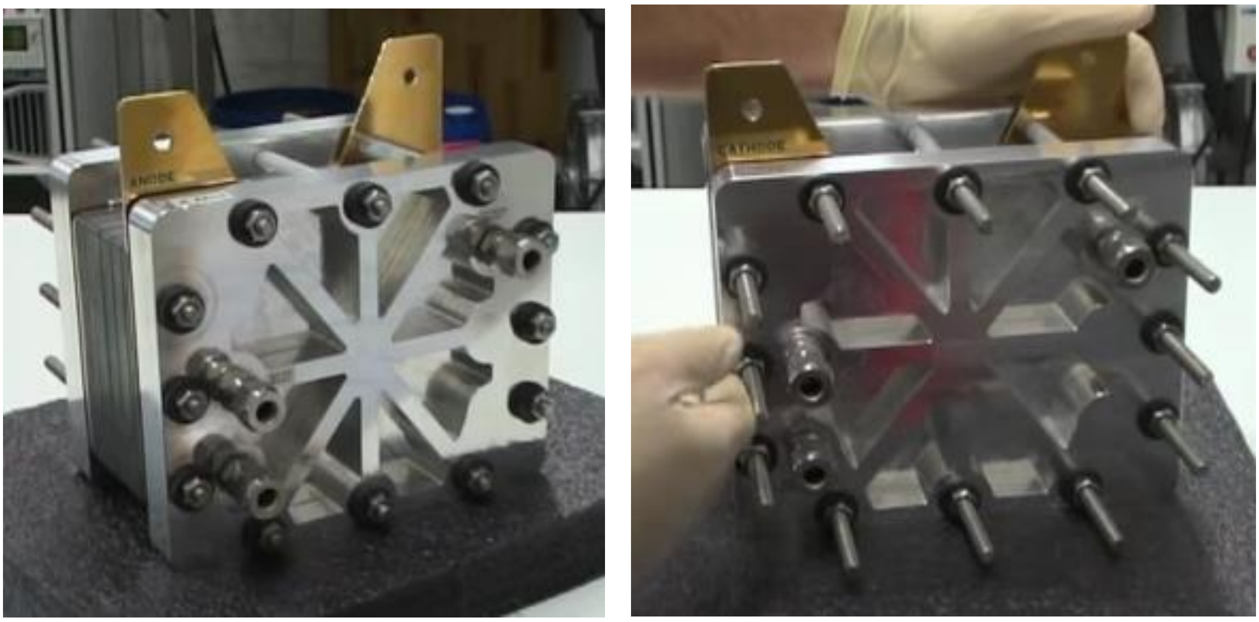


Fig. 70: Components in a single cell

43 Fuel cell stack

43.1 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

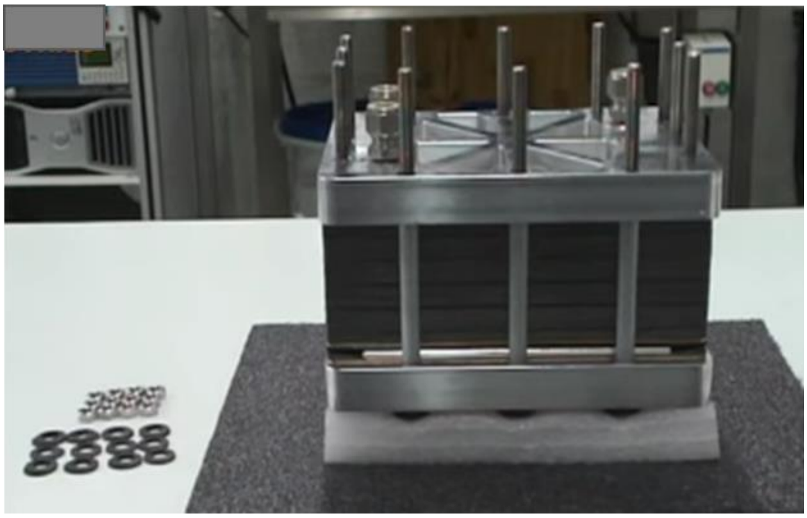


Fig. 72: Remove the bolts and nuts from stack

Then we remove the end plate

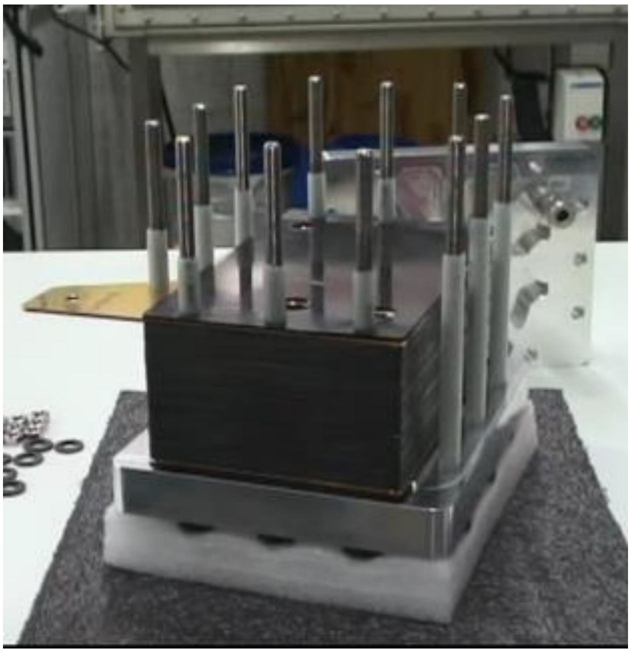


Fig. 73: Remove the end plate from the stack

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

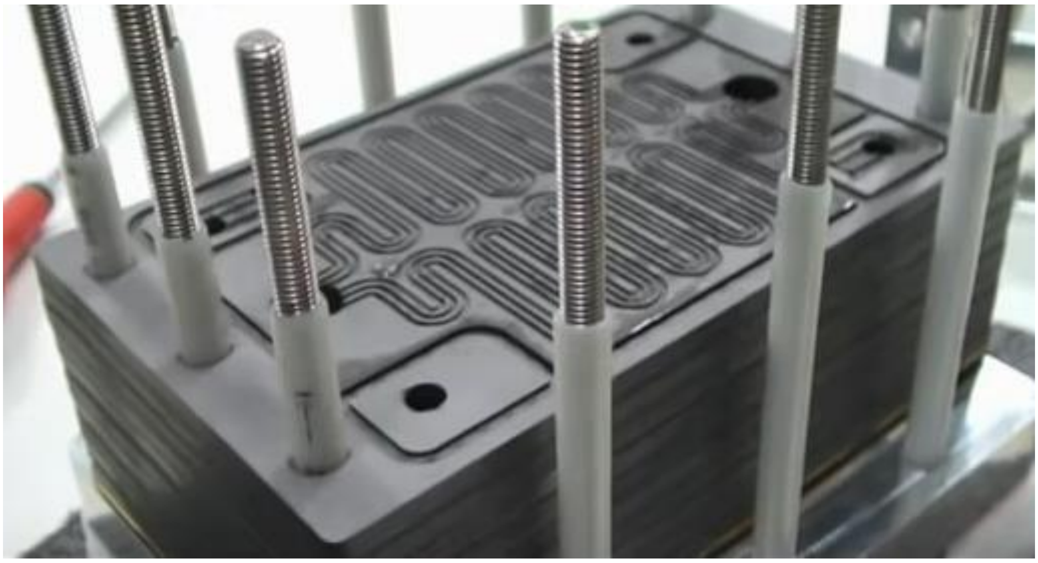


Fig. 75: First cell next to the current collector

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).

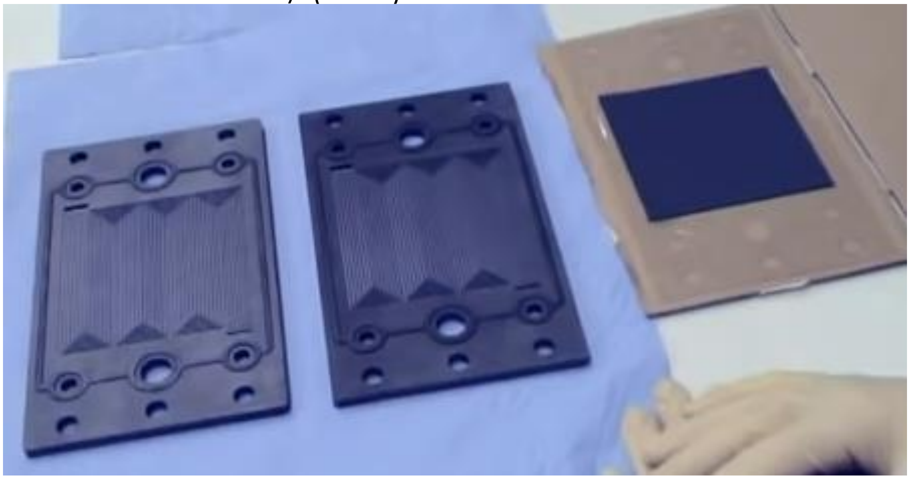


Fig. 76: Overview of a single cell (Two graphite plate and one MEA)

We can see the gasket layers and the subgasket use two support the electrolytic membrane

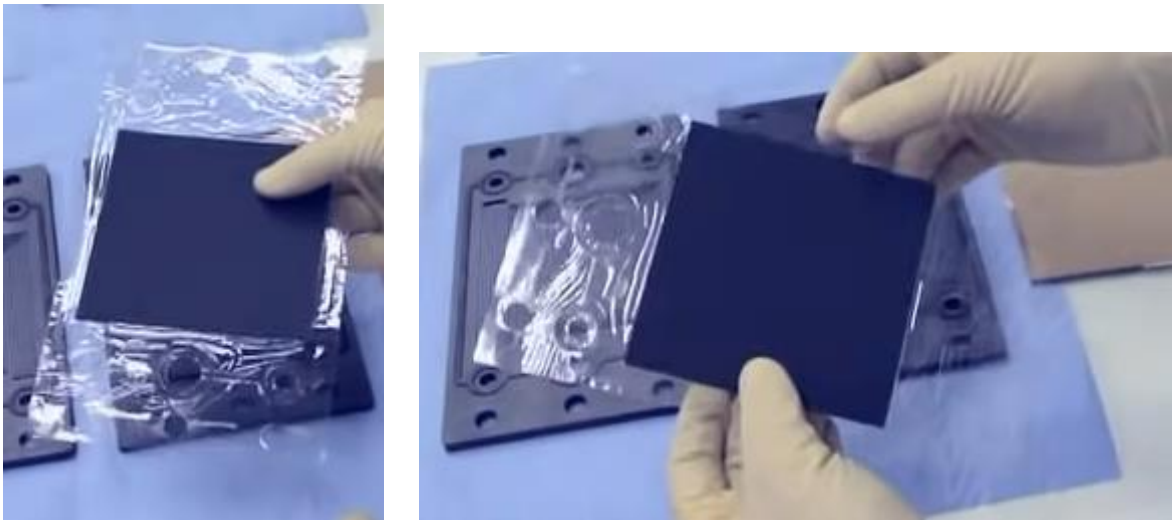


Fig. 77: The MEA layer

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.

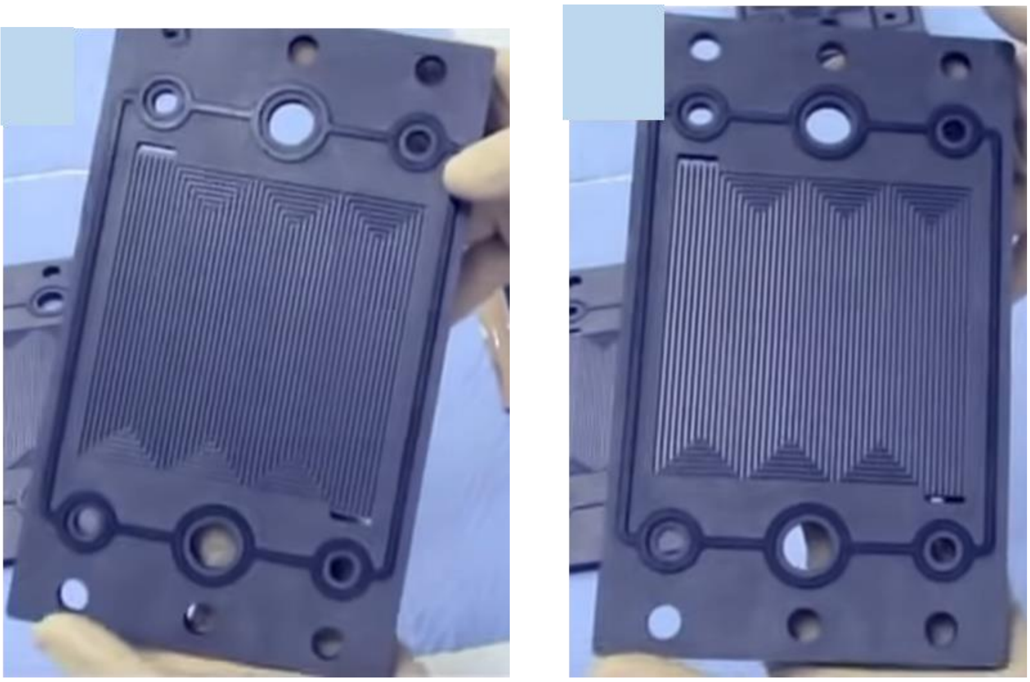


Fig. 78: Gas distribution channel with multiple support flow field, and field gasket at the front side

We turn the plate, we can see the hole is connected through the plate.

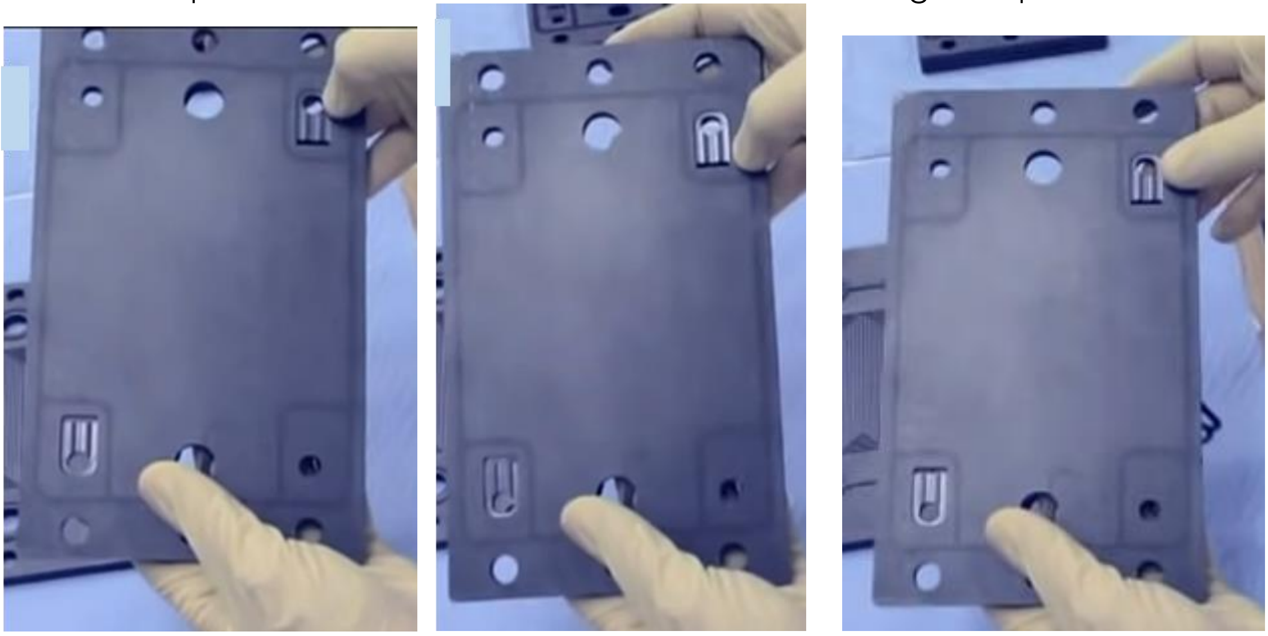


Fig. 79: Gas distribution channel with multiple support flow field, and field gasket at the back side

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.

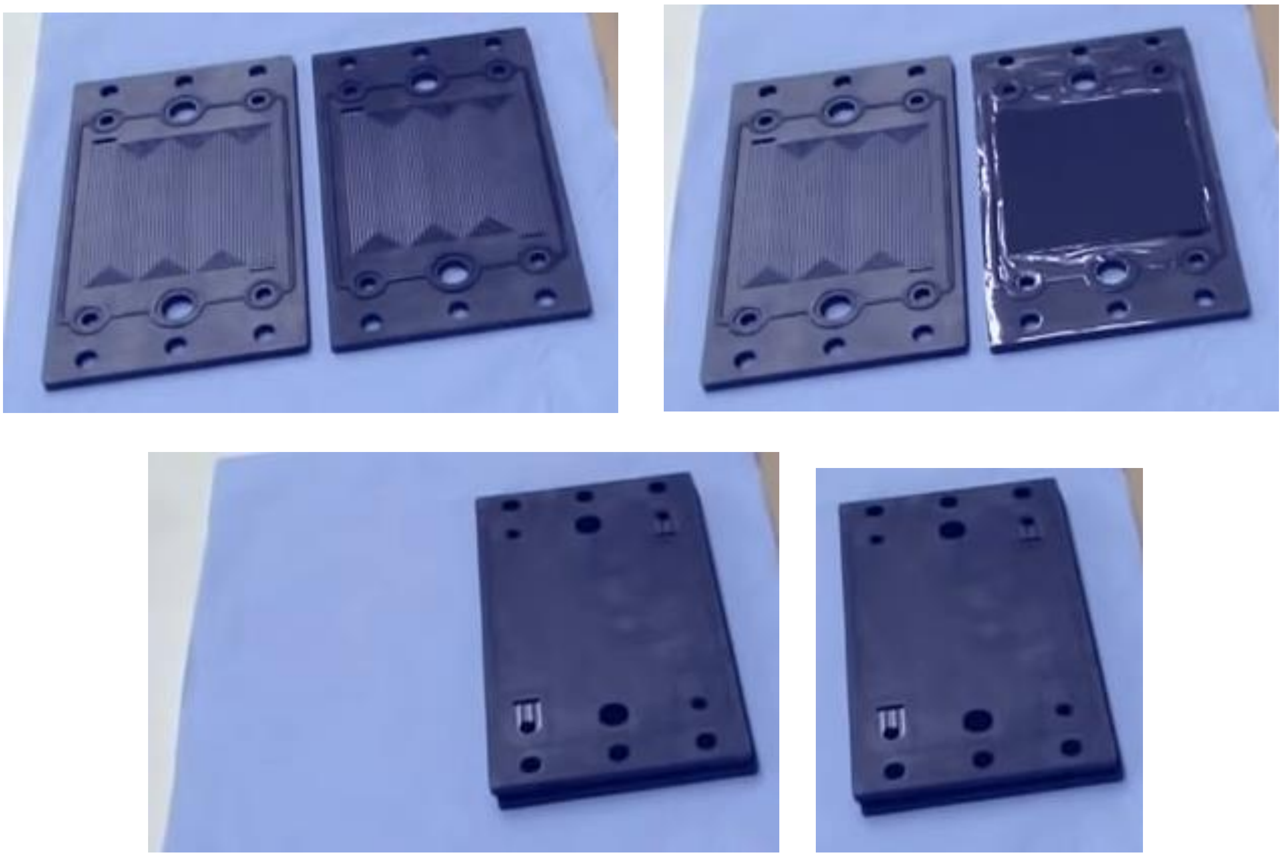
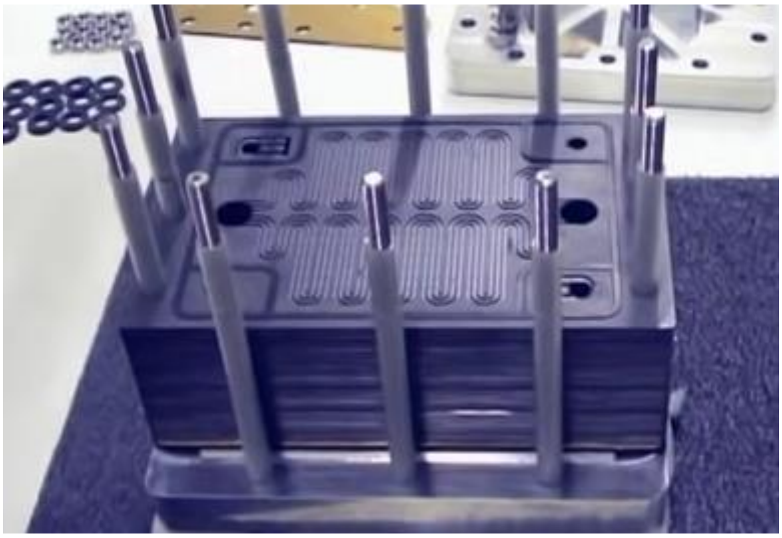


Fig. 80: Steps to build a cell

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.

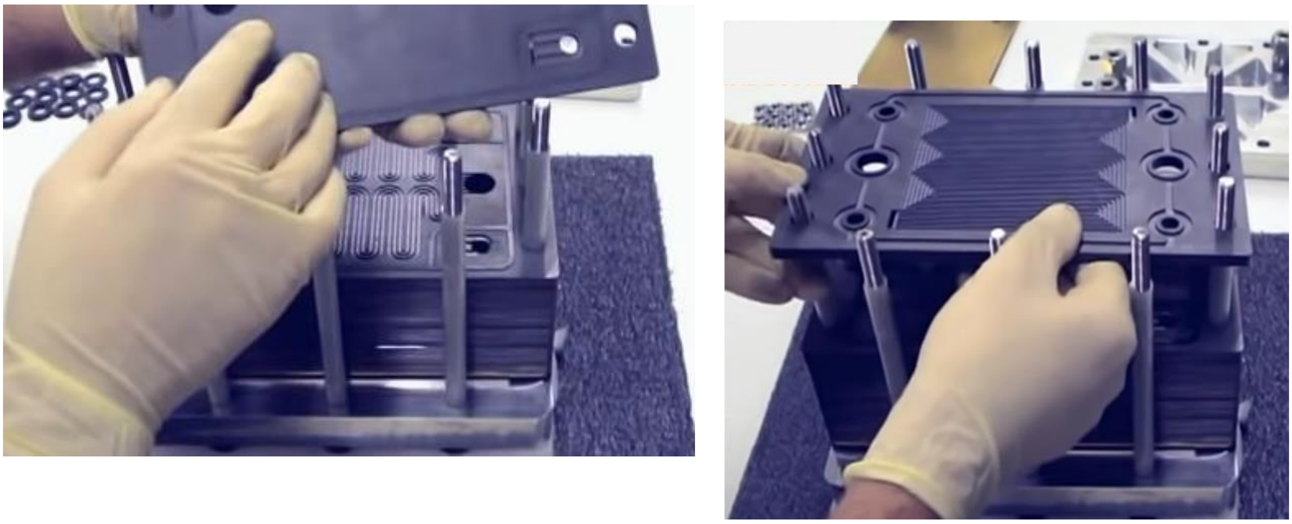


Fig. 81: Add the plate in the appropriate direction to the stack

Add the gasket

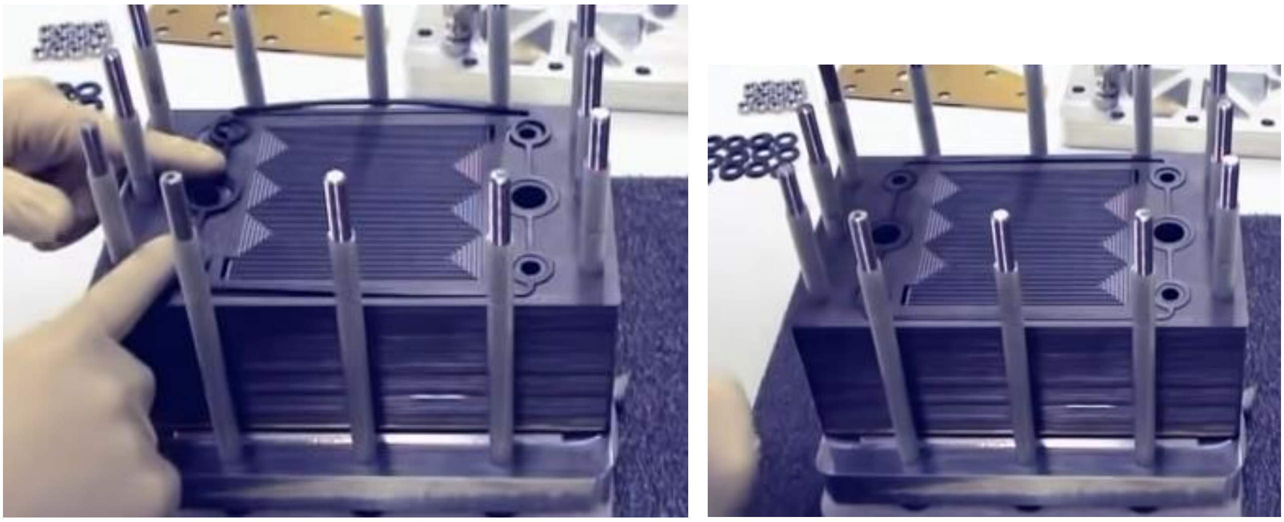


Fig. 82: Add the gasket

Now we added the MEA

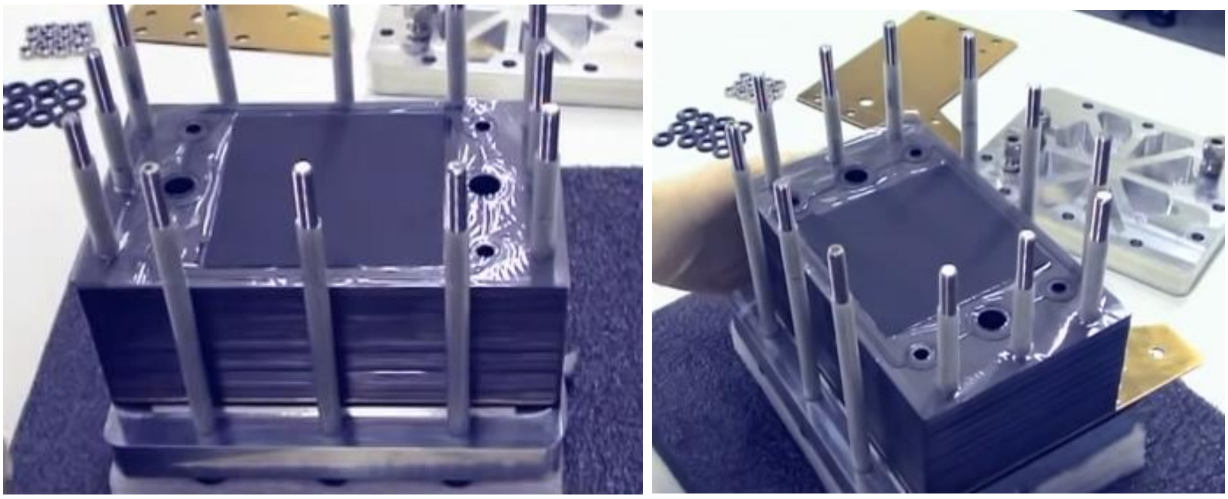


Fig. 83: Add the MEA

And add the gasket

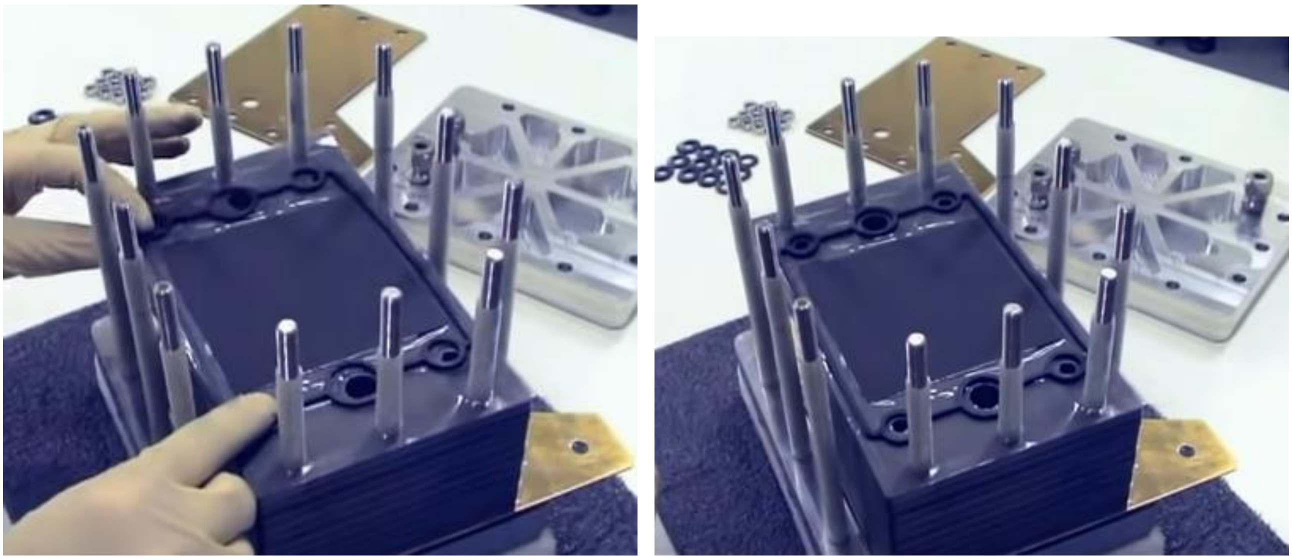


Fig. 84: Add the second gasket

And emplacing the plate through the tie rod.

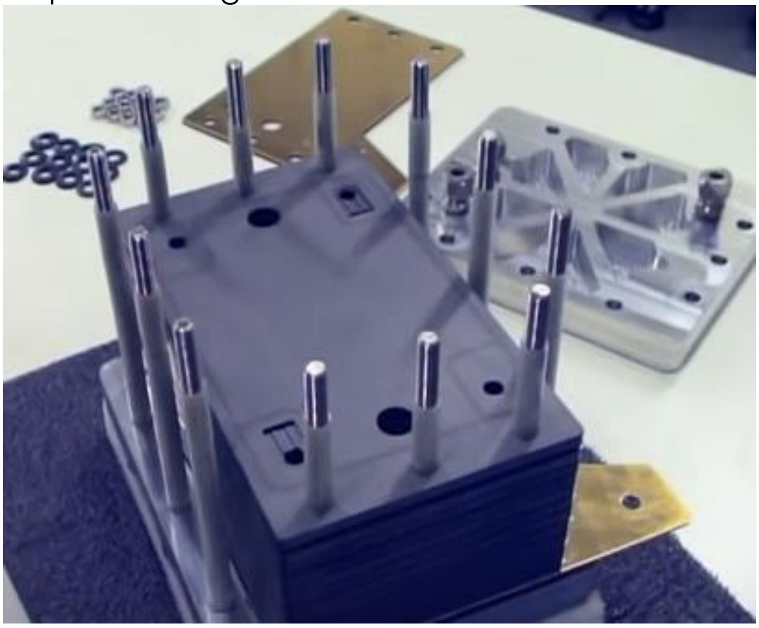


Fig. 85: Emplacing the plate through the tie rod

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

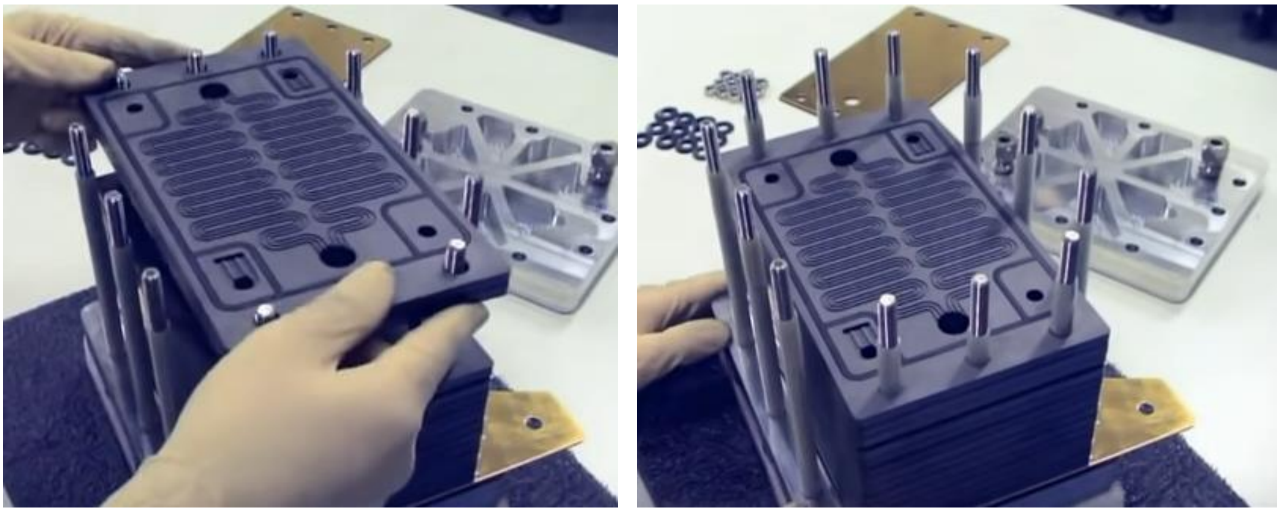


Fig. 86: Add the second cell

Now what i need is again the current collector. We placed back.

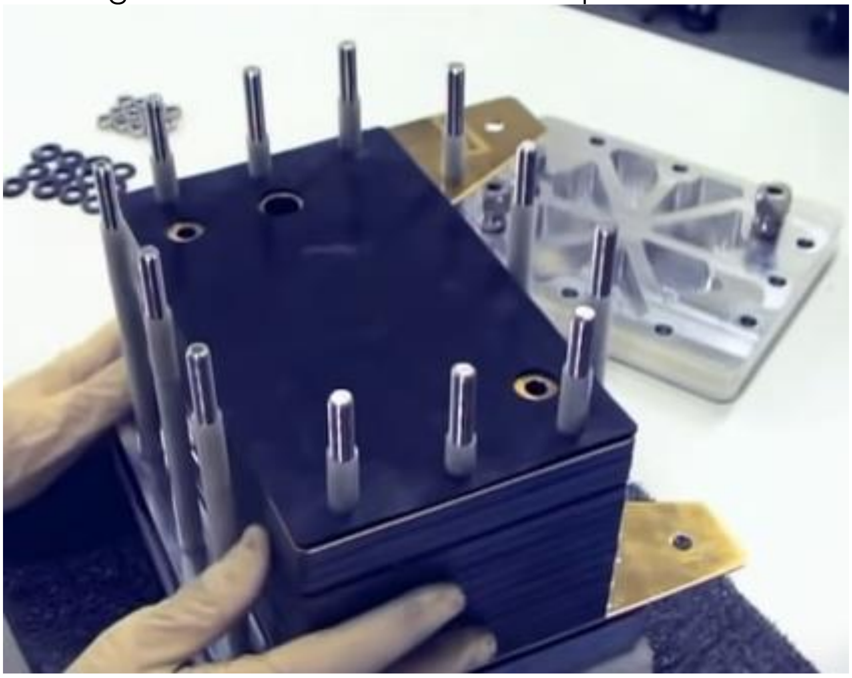


Fig. 87: Placed back the current collector

And go nicely to placed the end plate

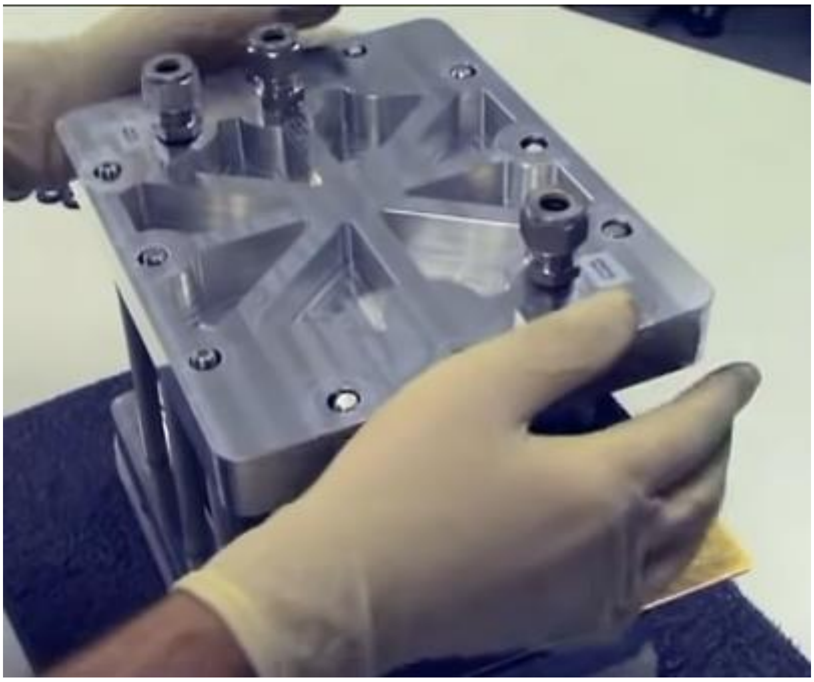


Fig. 88: Placed back the end plate

43.2 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, 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.

Fuel cell stack

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.

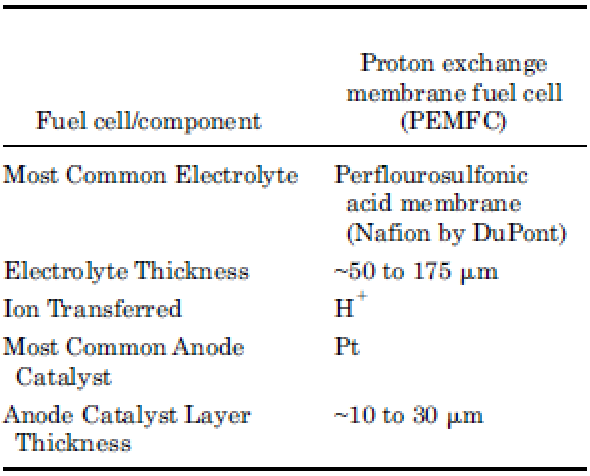
As a result the lower electrode is negative or is an anode and the upper electrode is positive or in other words is cathode. in some time, there even condensed some water on the upper part of my setup which is a main by-product of this battery. My cell generates 0.7 V out of 1.3 theoretically possible. 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.

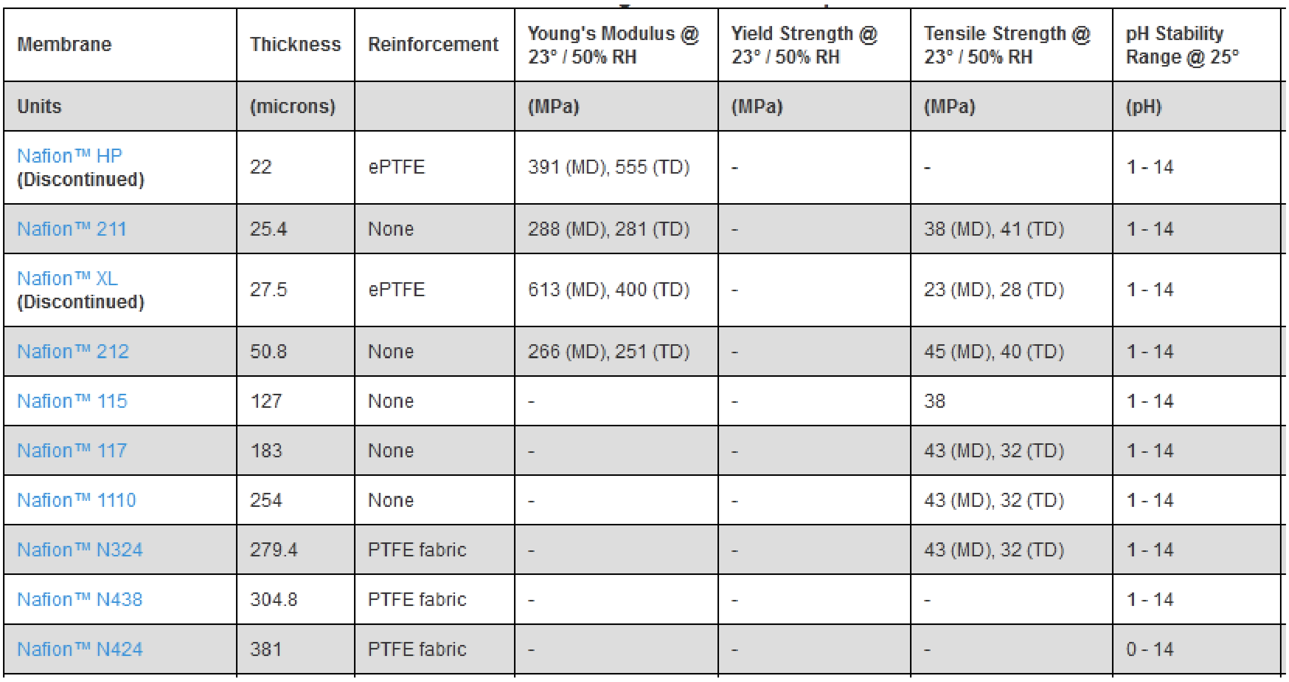
44 Fuel Cell Materials

44.1 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 [59]

44.2 Fuel Cell Electrode Layers - PEMFC catalysts

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[59] 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-lr/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

44.3 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.

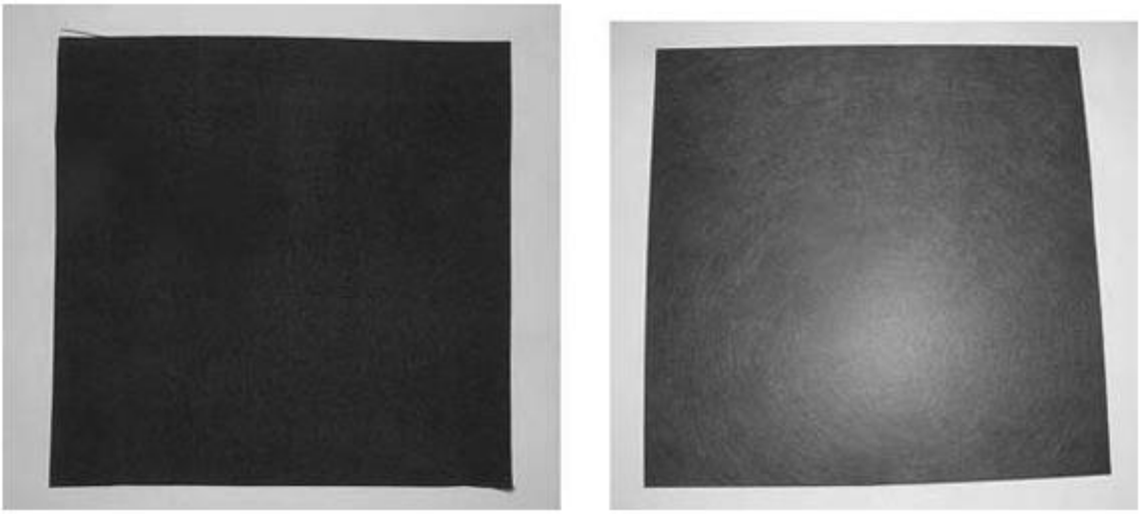


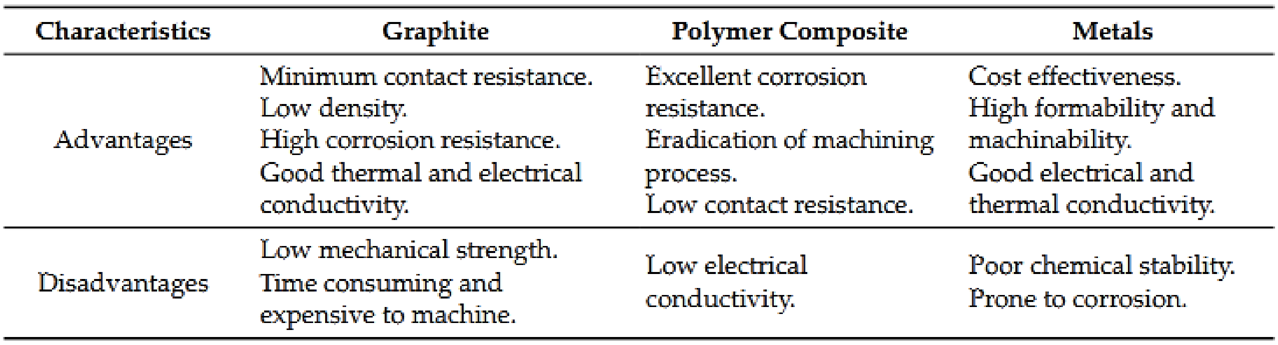
Fig. 92: Carbon cloth and toray paper (picture courtesy of Fuel Cell Scientific)

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

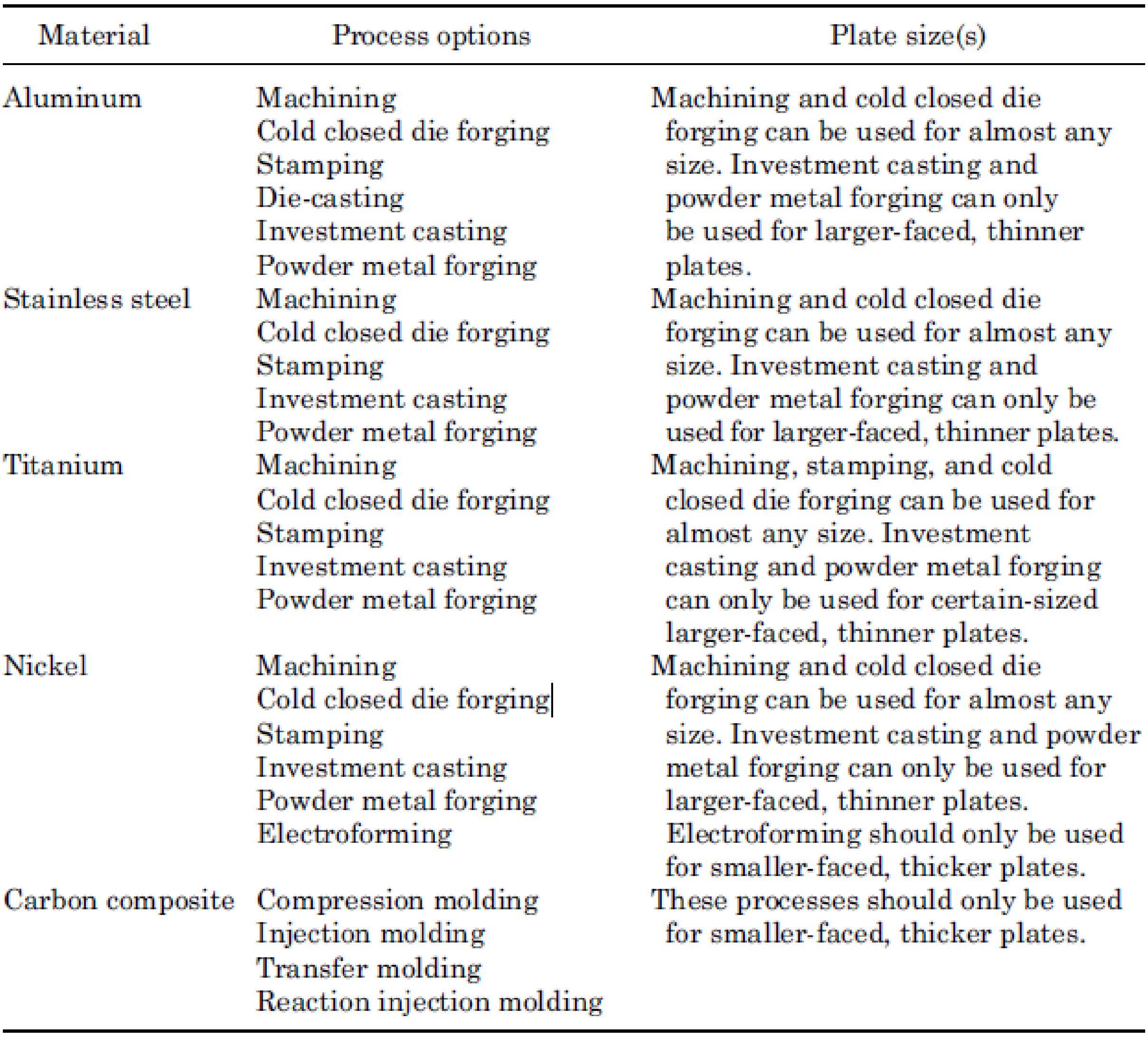
45 Constructing the Fuel Cell Bipolar Plates, Gaskets, End Plates, and Current Collectors

45.1 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 [60]



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

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[60] https://www.mdpi.com/1996-1073/11/11/3203/htm

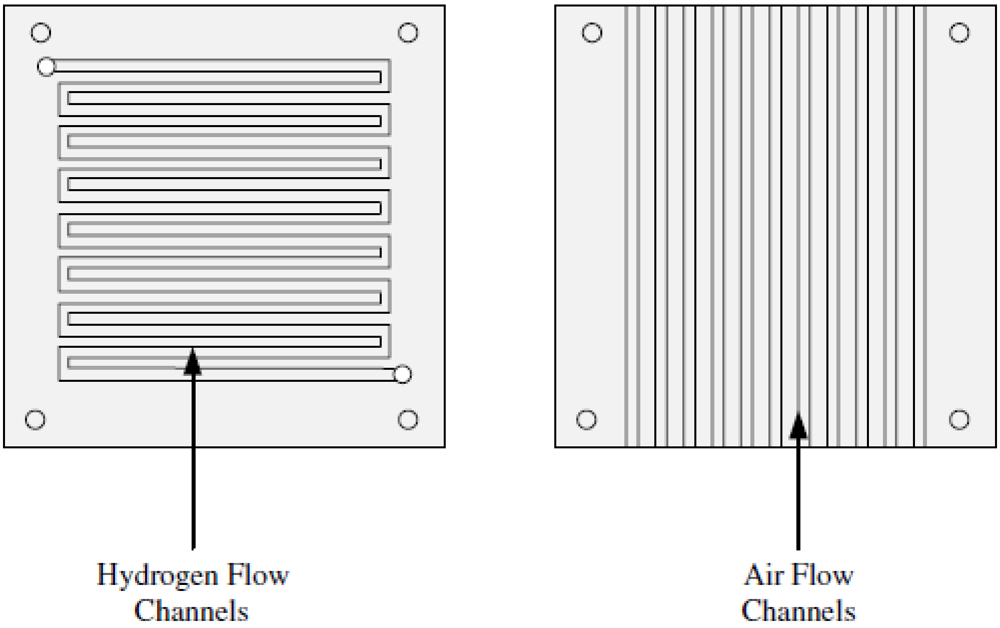


Fig. 96: Bipolar plate design for hydrogen and air flow channels for a PEMFC

45.2 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.

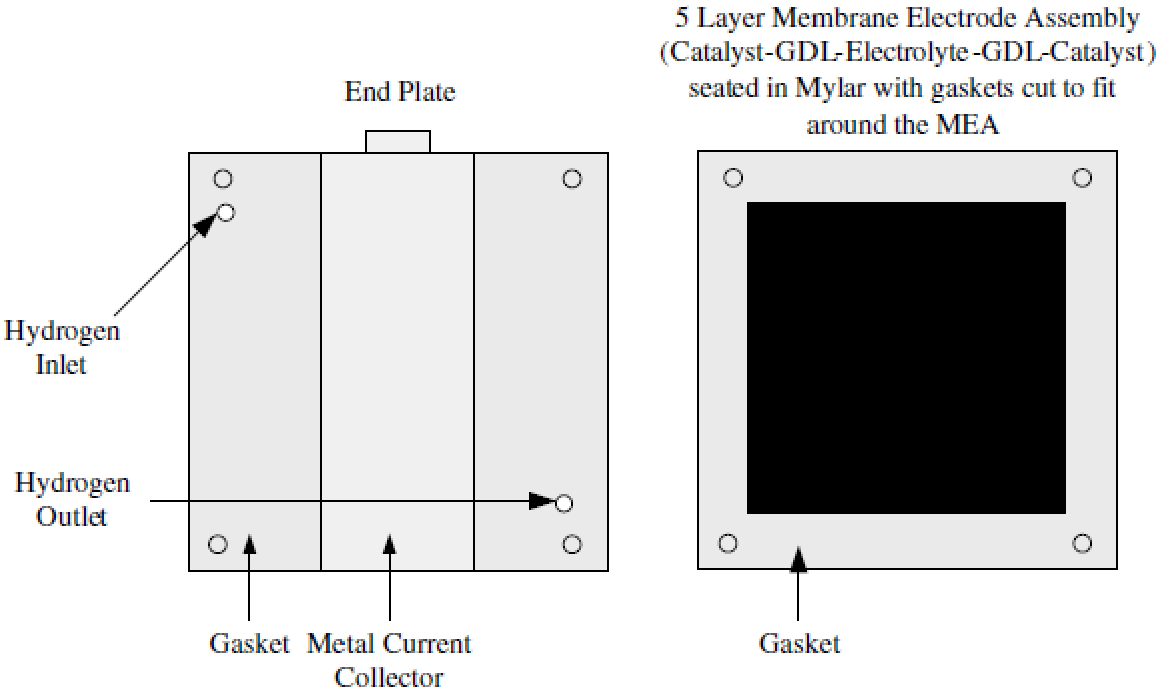


Fig. 97: Gaskets, end plate, and MEA for PEMFC

45.3 End plates

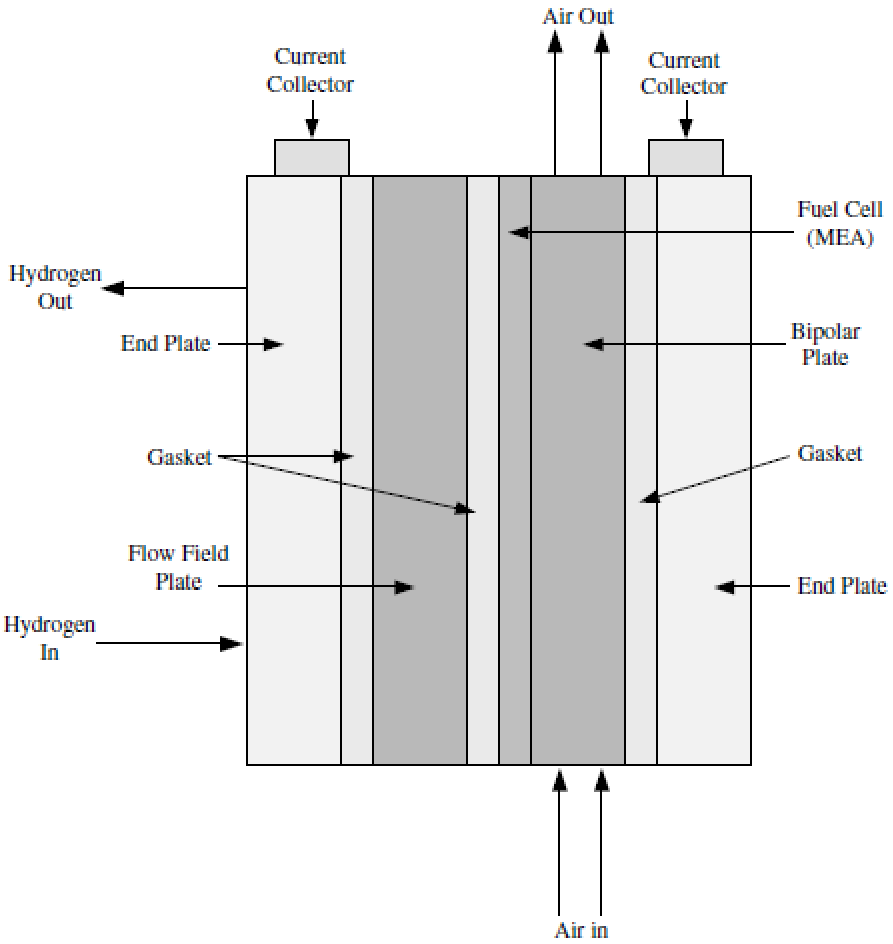


Fig. 98: End and flow field plates, gaskets, current collectors, and MEA for a single-cell PEMFC stack

46 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

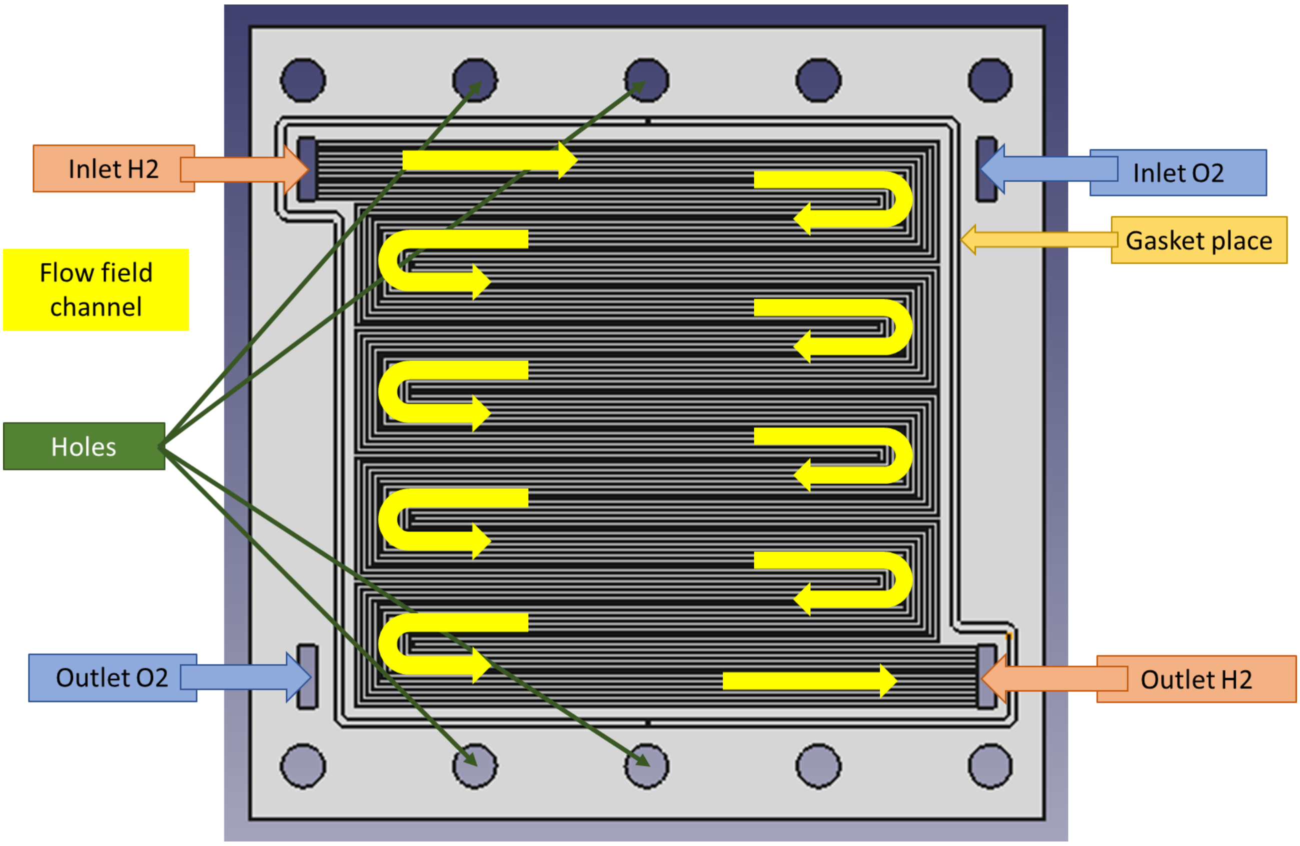
47 Bipolar plate design

bipolar plate _
square design.FCSt

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



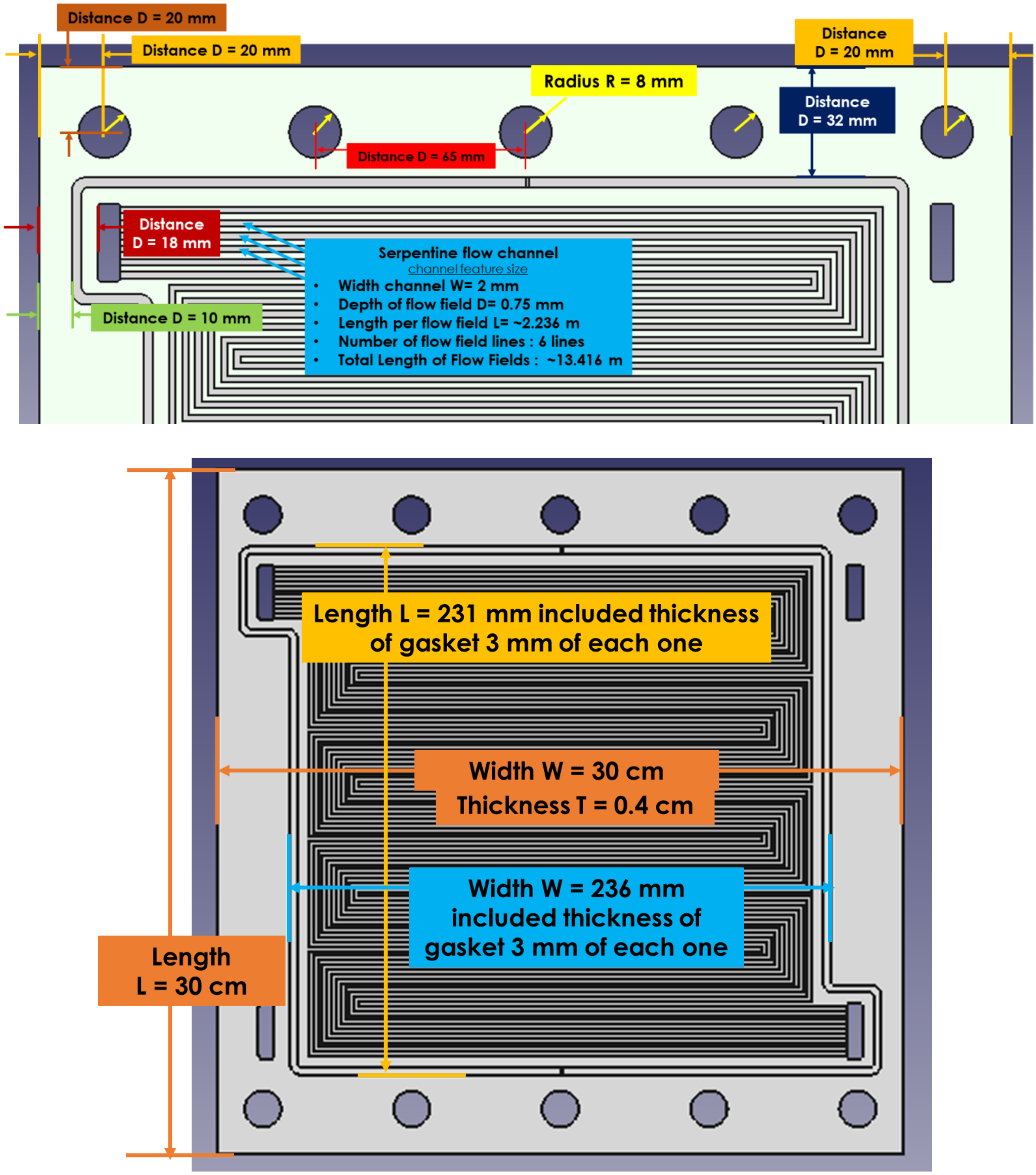
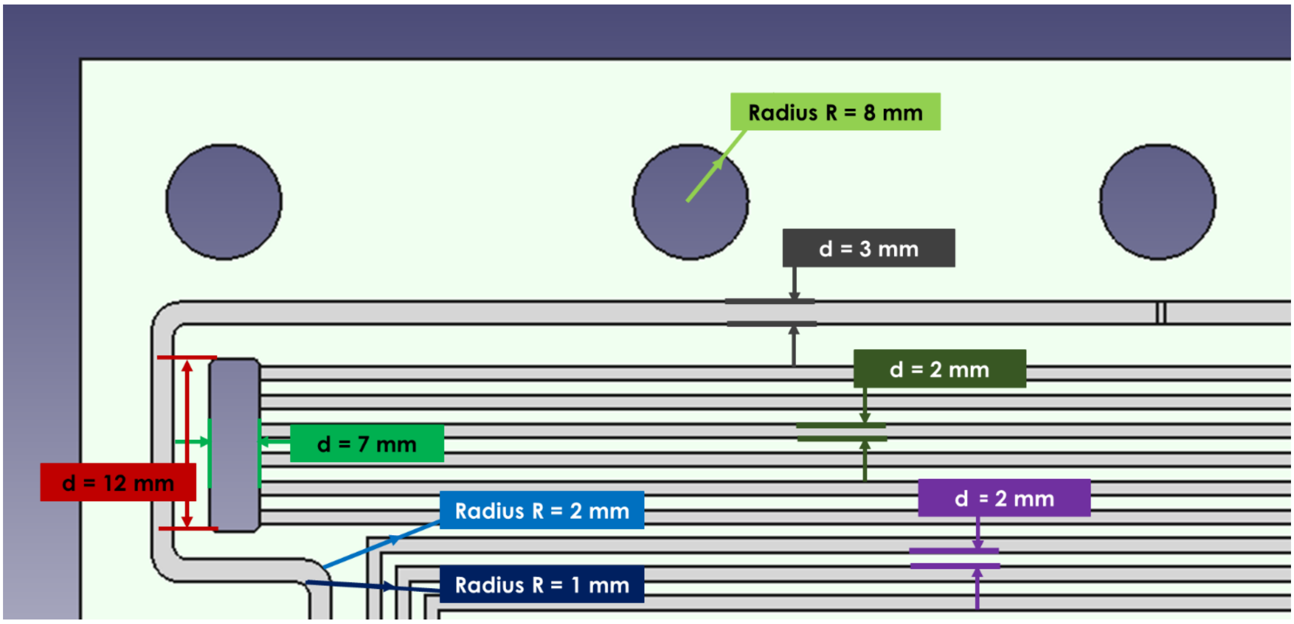
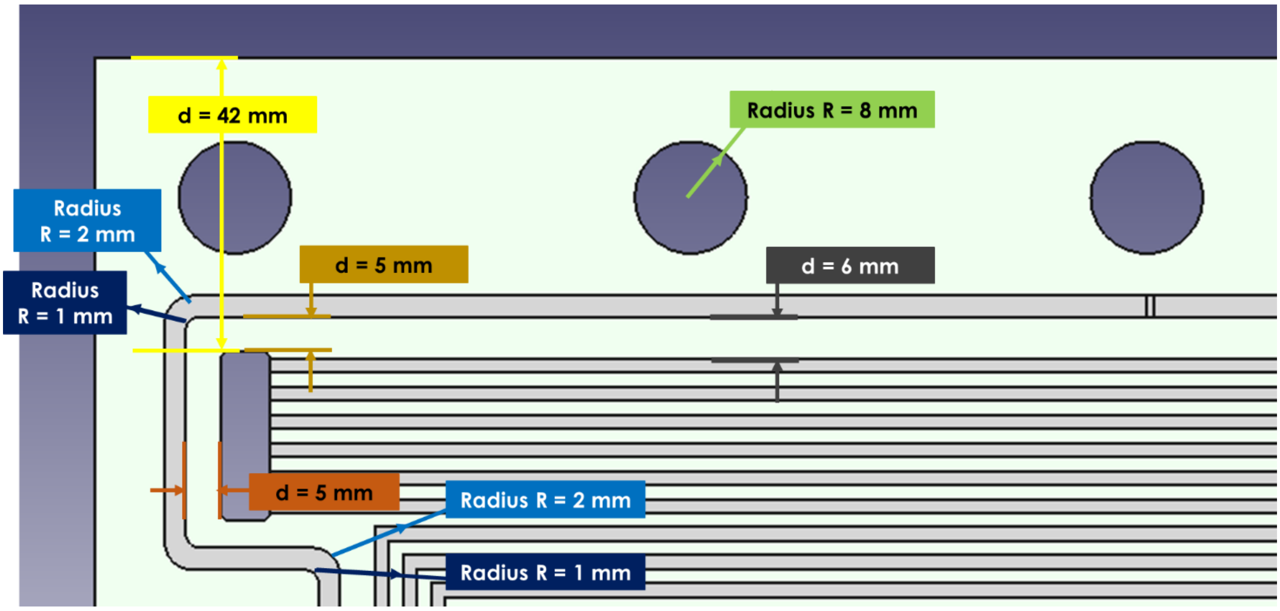
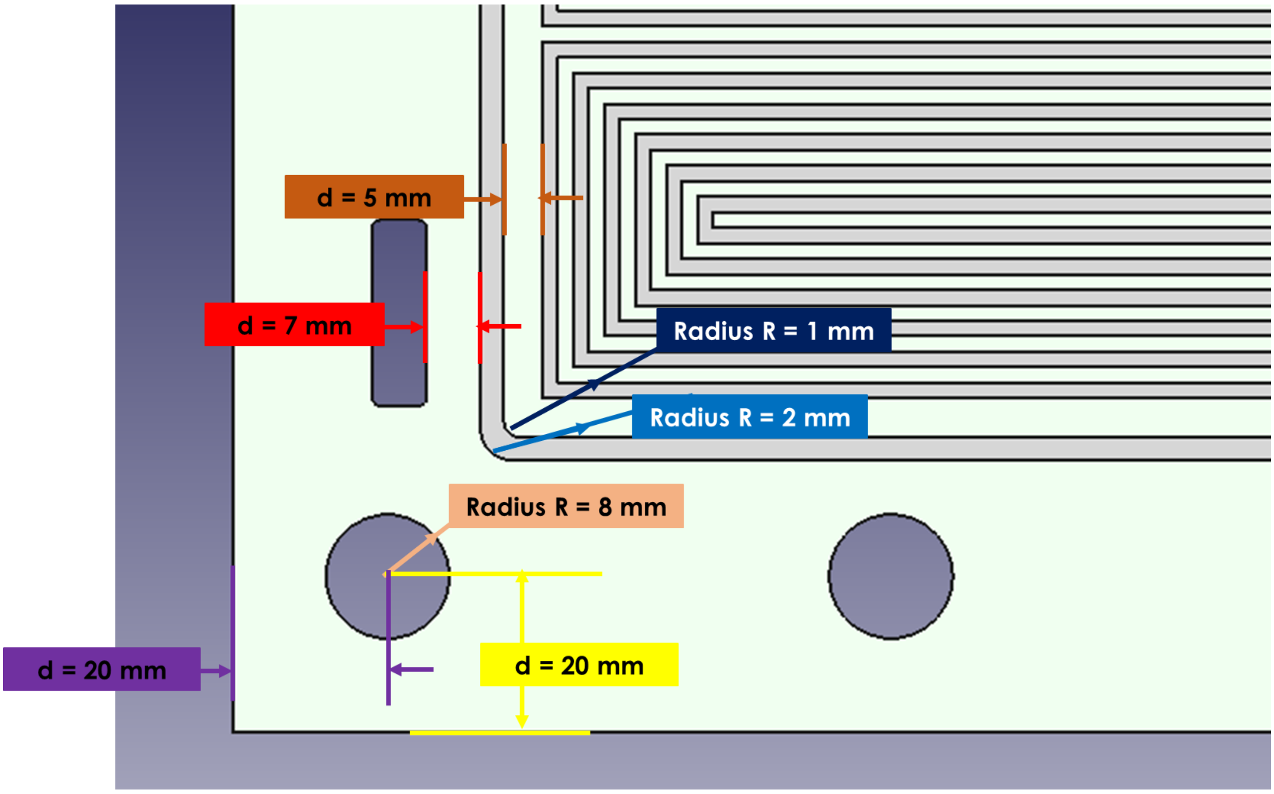


Fig. 100: Sizing of our fuel cell design

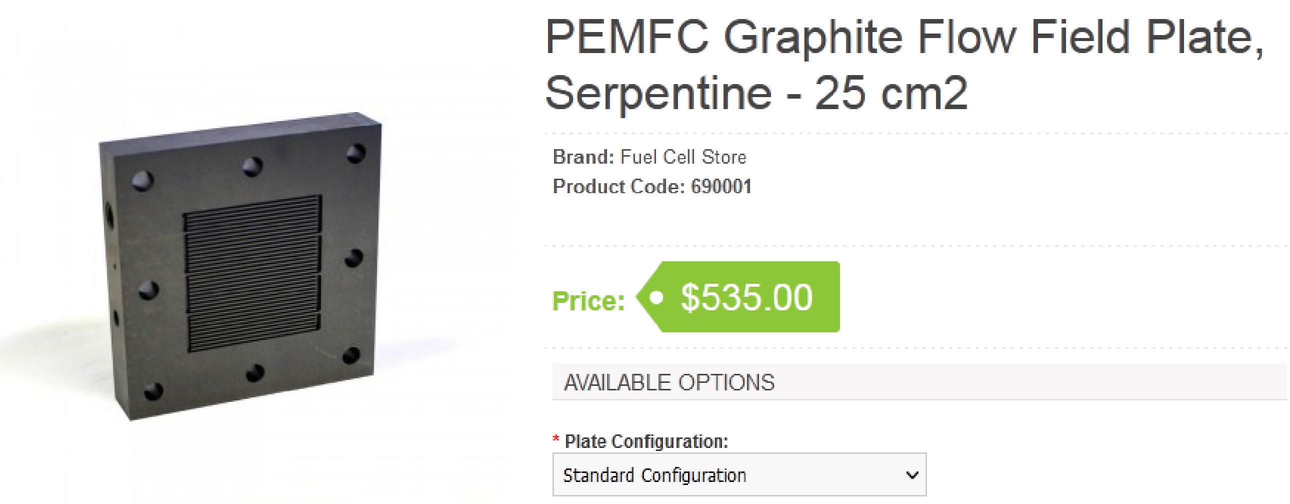

Radius R = 8 mm
d = 3 mm
d = 2 mm
d = 7 mm
d = 12 mm
Radius R = 2 mm
d = 2 mm
Radius R = 1 mm


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


d = 5 mm
d = 7 mm
Radius R = 1 mm
Radius R = 2 mm
Radius R = 8 mm
d = 20 mm
d = 20 mm

48 Components costs of one cell

48.1 PEMFC



PEMFC Graphite Flow Field Plate, Serpentine - 25 cm2

Brand: Fuel Cell Store

Product Code: 690001

Price: $535.00

AVAILABLE OPTIONS

* 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)

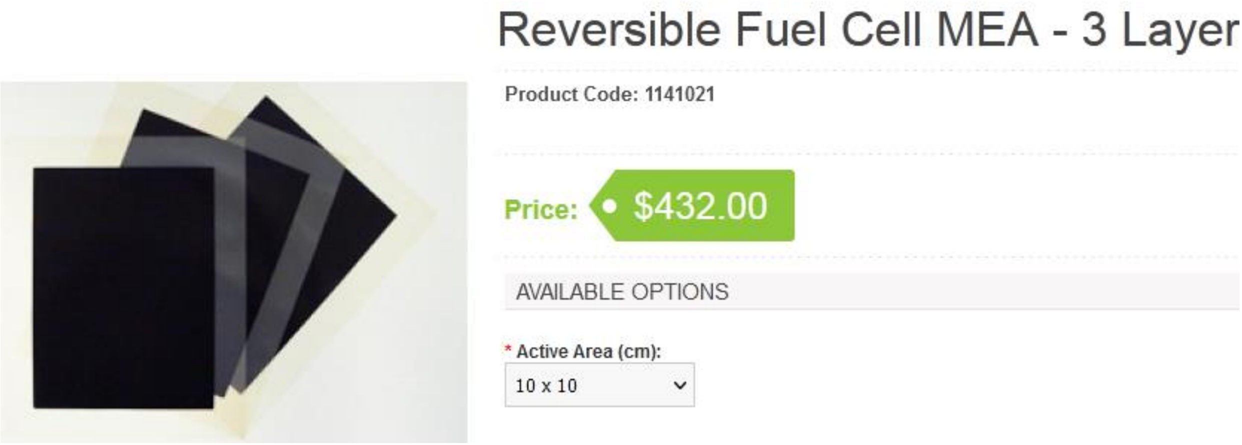
Flow Pattern or Channel Design: Serpentine (5-channels)

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")

48.2 MEA

Item #1:



Reversible Fuel Cell MEA - 3 Layer

Product Code: 1141021

Price: $432.00

AVAILABLE OPTIONS

* Active Area (cm): 10 x 10

[61]

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

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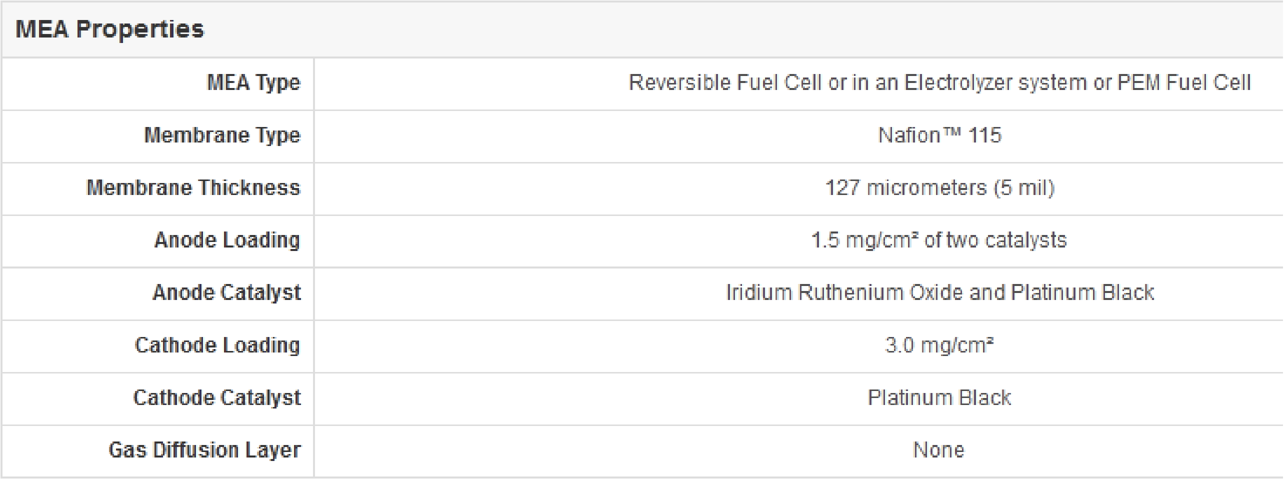
[61] https://www.fuelcellstore.com/fuel-cell-components/membrane-electrode-assembly/reversible-fuel-cell-ccm

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:

Hydrogen Air CCM - 3 Layer

Product Code: 2014013

Price: $232.00

AVAILABLE OPTIONS

* Active Area (cm):

10 x 10

[62]

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.

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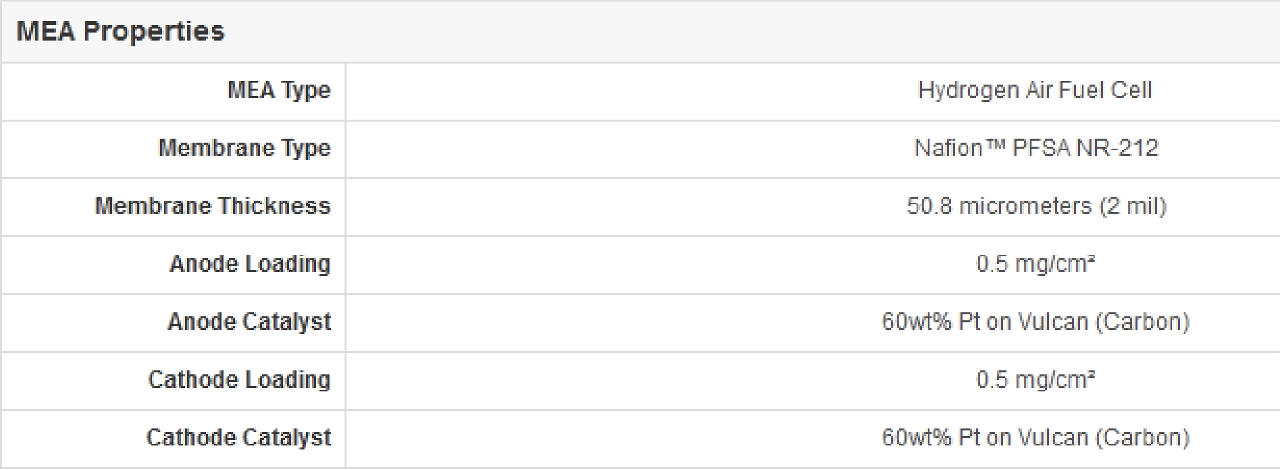
[62] https://www.fuelcellstore.com/fuel-cell-components/membrane-electrode-assembly/ha-ccm

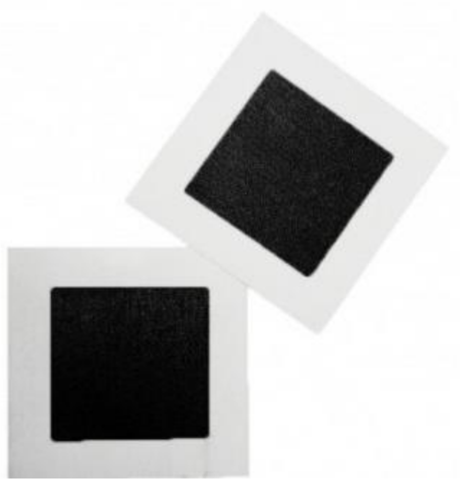
Components costs of one cell

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:



MEA for PEM Research Test Cell - 250cm²

Product Code: 550029

Price: $381.00

[63]

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%

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[63] https://www.fuelcellstore.com/fuel-cell-components/membrane-electrode-assembly/mea-pem-research-test-cell-250cm

- 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

[64]

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 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 $

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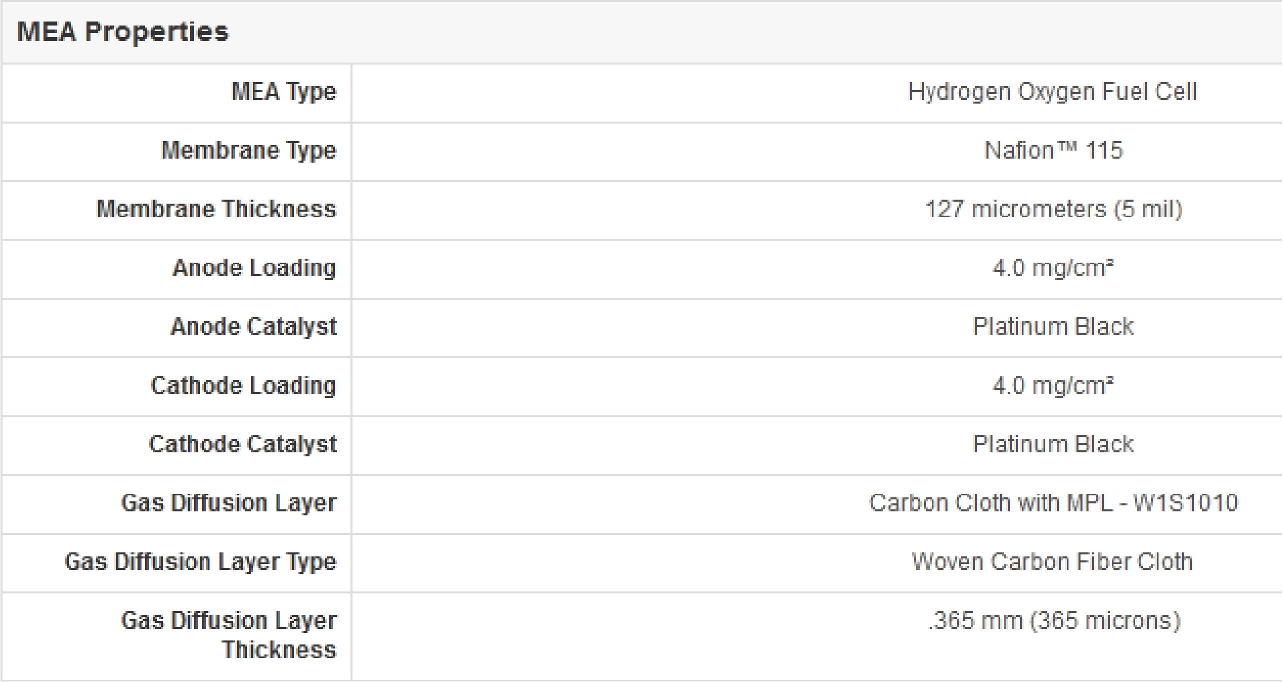
[64] https://www.fuelcellstore.com/fuel-cell-components/membrane-electrode-assembly/hydrogen-oxygen-mea

Components costs of one cell



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)

48.2.1 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

[65]

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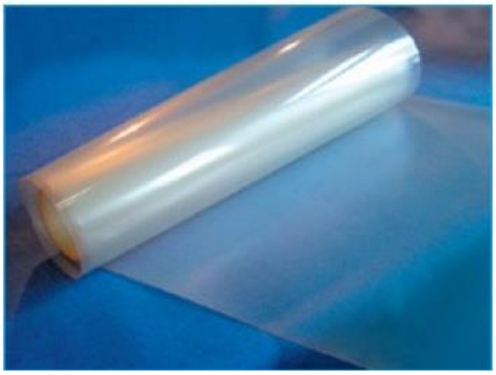
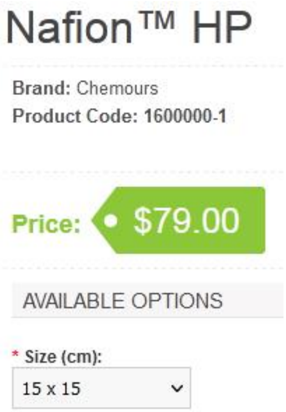
[65] https://www.fuelcellstore.com/fuel-cell-components/nafion-hp?sort=p.sort_order&order=ASC





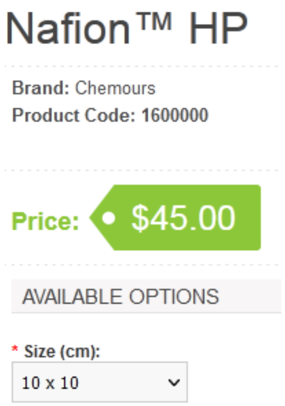
Nafion™ HP

Brand: Chemours
Product Code: 1600000-1

Price: $79.00

AVAILABLE OPTIONS

* Size (cm):
15 x 15



Nafion™ HP

Brand: Chemours
Product Code: 1600000

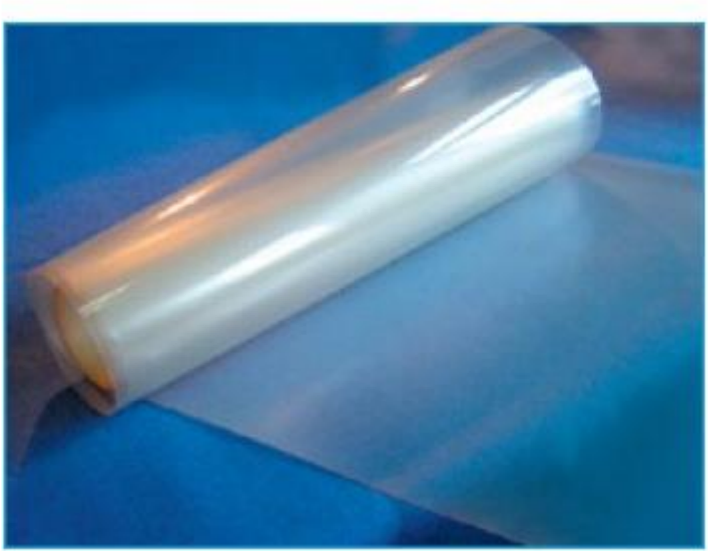
Price: $45.00

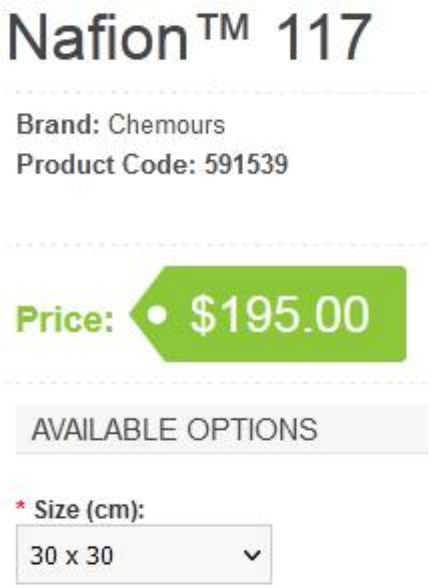
AVAILABLE OPTIONS

* 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

[66]

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[66] https://www.fuelcellstore.com/nafion-117

Components costs of one cell

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

[67]

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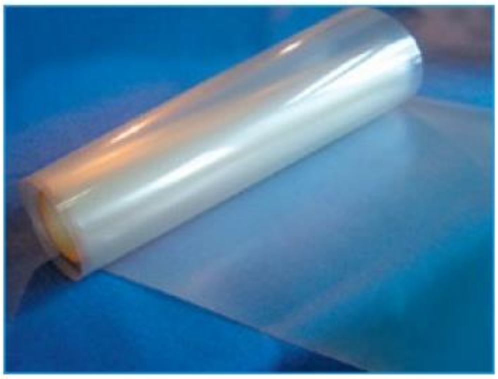
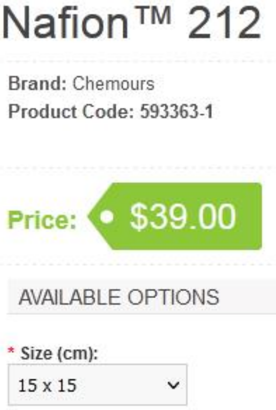
[67] https://www.fuelcellstore.com/nafion-212





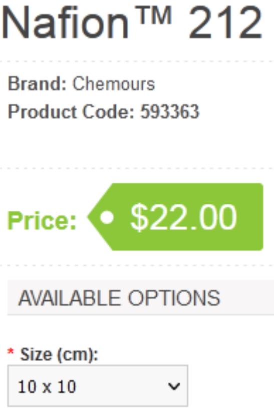
Nafion™ 212

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

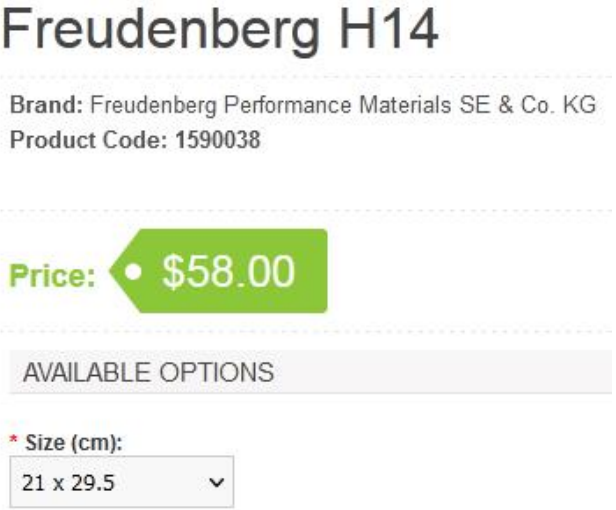
AVAILABLE OPTIONS

* **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.

48.2.2 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

[68]

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[68] https://www.fuelcellstore.com/fuel-cell-components/freudenberg-h1410?sort=p.model&order=ASC

Components costs of one cell

Freudenberg H14

Brand: Freudenberg Performance Materials SE & Co. KG
Product Code: 1590039

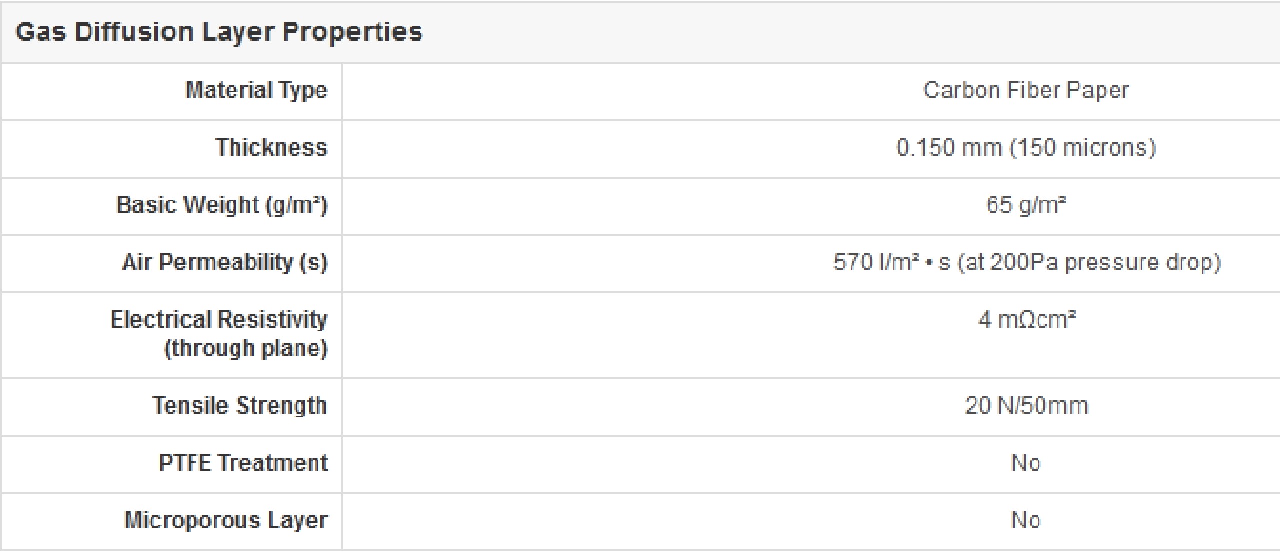
Price: $92.00

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

48.2.3 21.2.3. GDL+Catalyst

0.2 mg/cm^2 20% Platinum on Vulcan - Carbon Cloth Electrode (W1S1010)

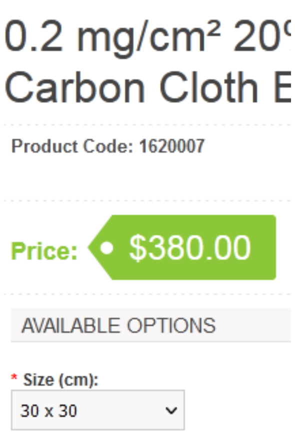
Product Code: 1620007-1

Price: $634.00

AVAILABLE OPTIONS

* Size (cm): 40 x 40

[69]



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 E

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).

48.3 Bipolar plate

Item #1:

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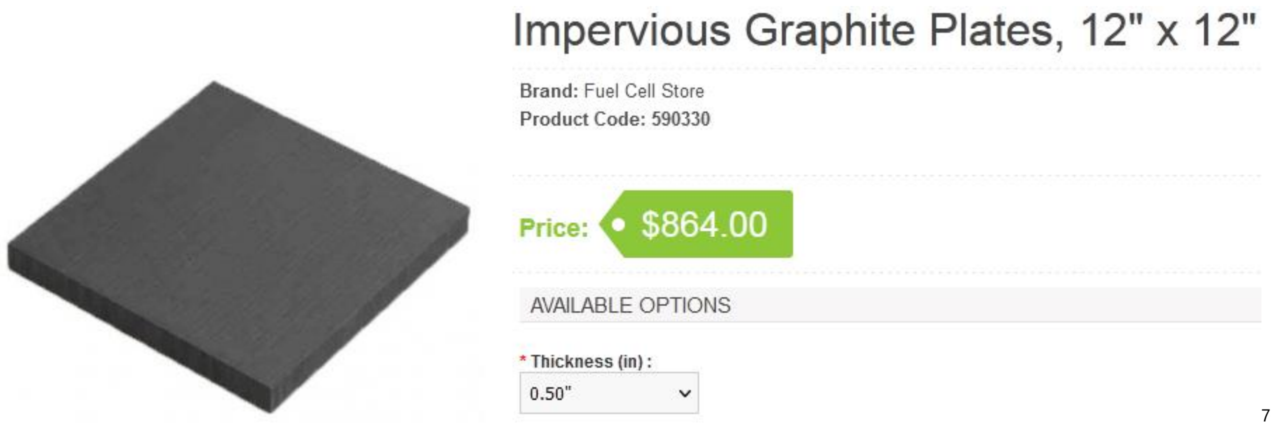
[69] https://www.fuelcellstore.com/fuel-cell-components/carbon-cloth-02-ptc-gas-diffusion-electrode-w1s1010?sort=p.sort_order&order=ASC

Components costs of one cell



Impervious Graphite Plates, 12" x 12"

Brand: Fuel Cell Store
Product Code: 590330

Price: $864.00

AVAILABLE OPTIONS

* **Thickness (in) :** 0.50"

[70]

Impervious Graphite Plates, 12" x 12"

Brand: Fuel Cell Store
Product Code: 590329

Price: $452.00

AVAILABLE OPTIONS

* **Thickness (in) :** 0.25"

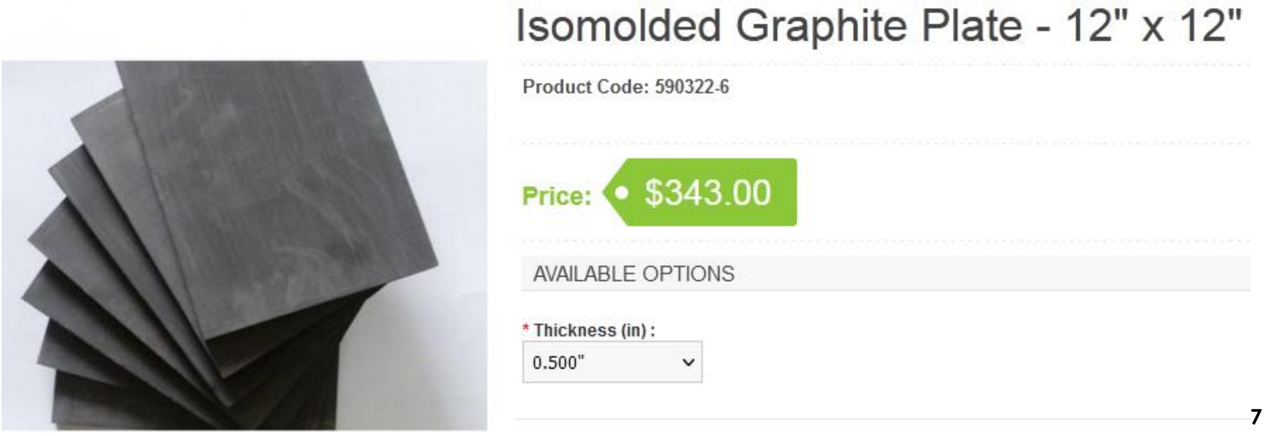
Fuel Cell Grade Graphite Plates can be machined on both sides to be used as bi-polar plates. These plates exhibit high electrical and thermal conductivity, incredible resistance to chemicals, and are densified and resin-filled for low permeability.

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"

[71]

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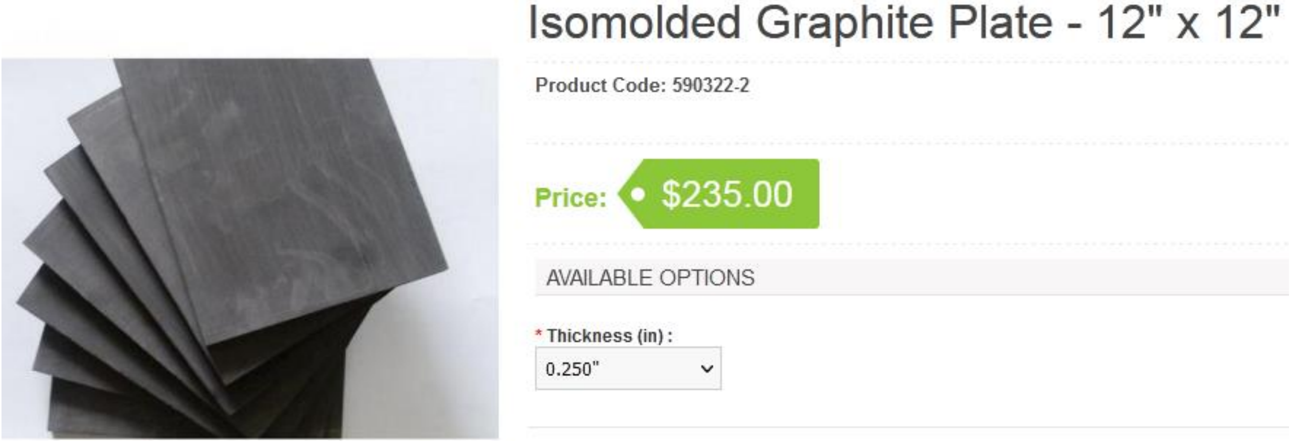
[70] https://www.fuelcellstore.com/impervious-bipolar-graphite-plates

[71] 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"

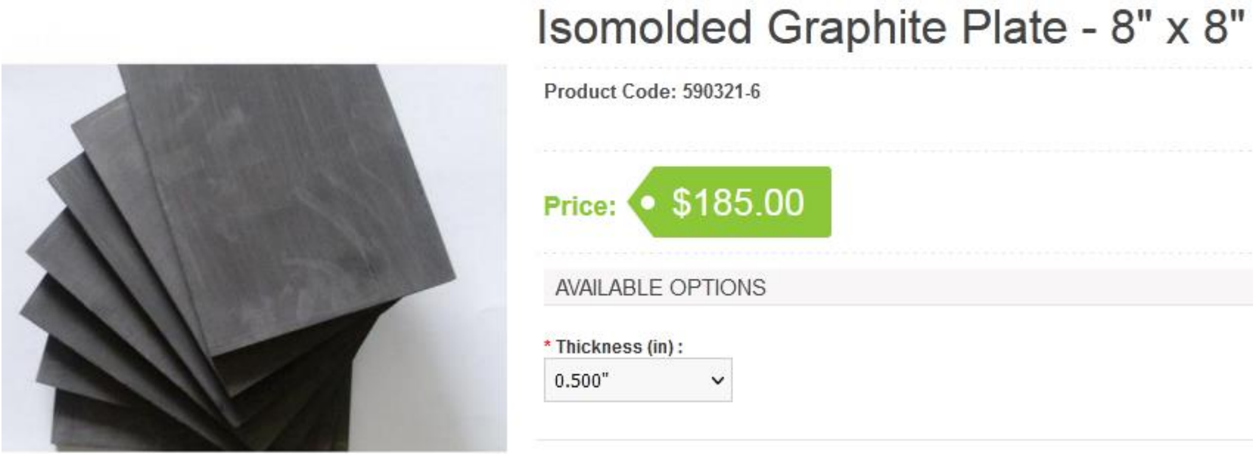
These Isomolded Graphite Plates can be machined on both sides. Isomolded plates are made out of very fine grain, high strength and density graphite. These plates are Isostatically pressed.

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"

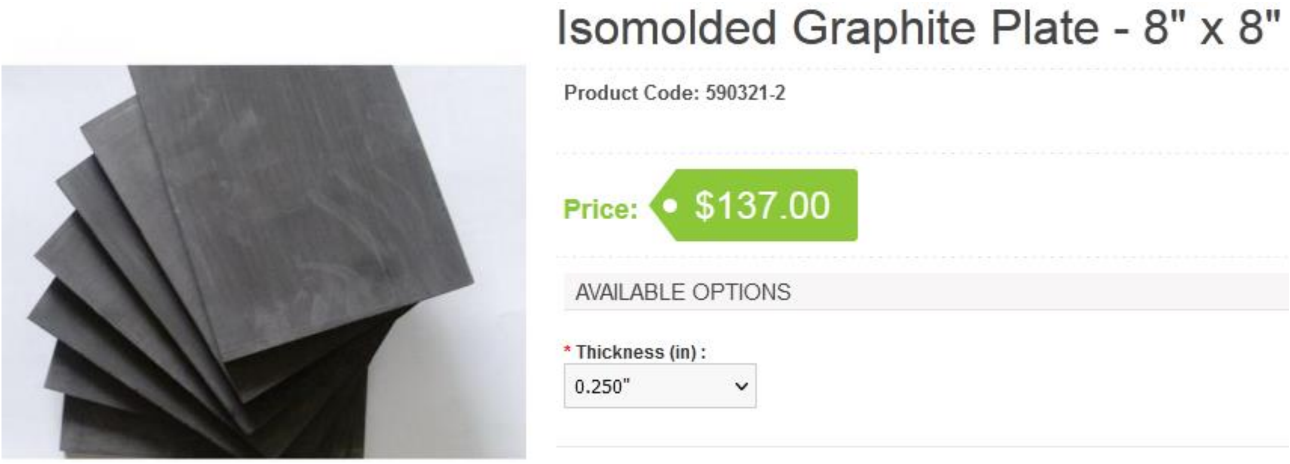
Product Code: 590321-6

Price: $185.00

AVAILABLE OPTIONS

* Thickness (in) : 0.500"

[72]



Isomolded Graphite Plate - 8" x 8"

Product Code: 590321-2

Price: $137.00

AVAILABLE OPTIONS

* Thickness (in) : 0.250"

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[72] https://www.fuelcellstore.com/isomolded-plate-064

Components costs of one cell

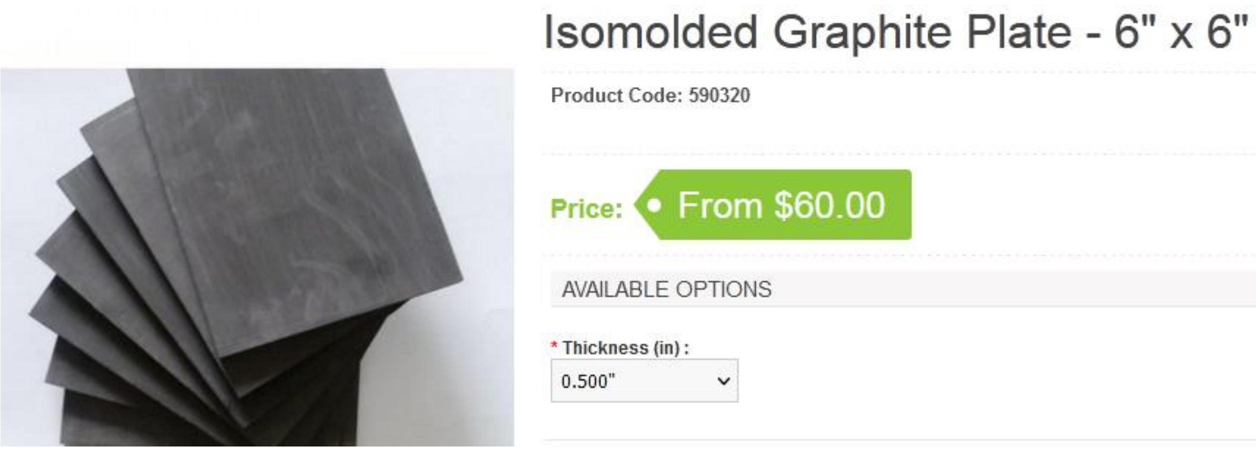
These Isomolded Graphite Plates can be machined on both sides. Isomolded plates are made out of very fine grain, high strength and density graphite. These plates are Isostatically pressed.

Size - 8.0" x 8.0"

Thickness Tolerance +/- 0.001"

Length and Width Tolerance +/- 0.005"

Item #4:



Isomolded Graphite Plate - 6" x 6"

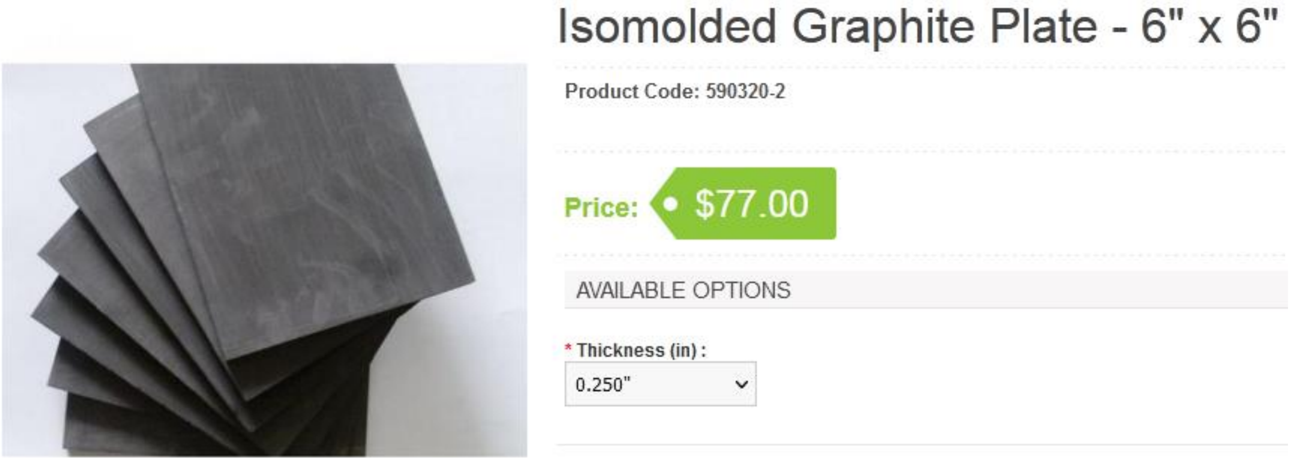
Product Code: 590320

Price: From $60.00

AVAILABLE OPTIONS

* Thickness (in) : 0.500"

[73]



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"

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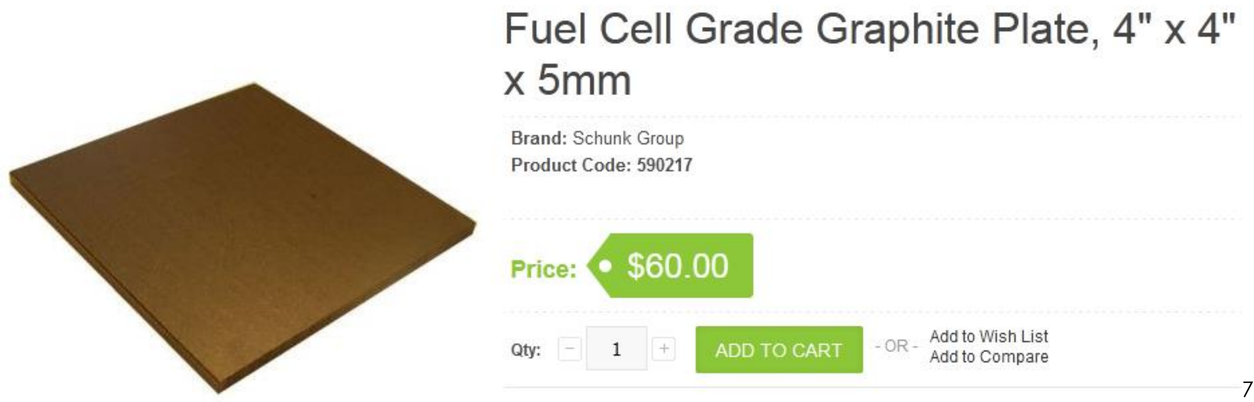
[73] https://www.fuelcellstore.com/isomolded-plate-036

Item #5:



Fuel Cell Grade Graphite Plate, 4" x 4" x 5mm

Brand: Schunk Group
Product Code: 590217

Price: $60.00

Qty: 1

[74]

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

[75]

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

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[74] https://www.fuelcellstore.com/bipolar-plate-5mm

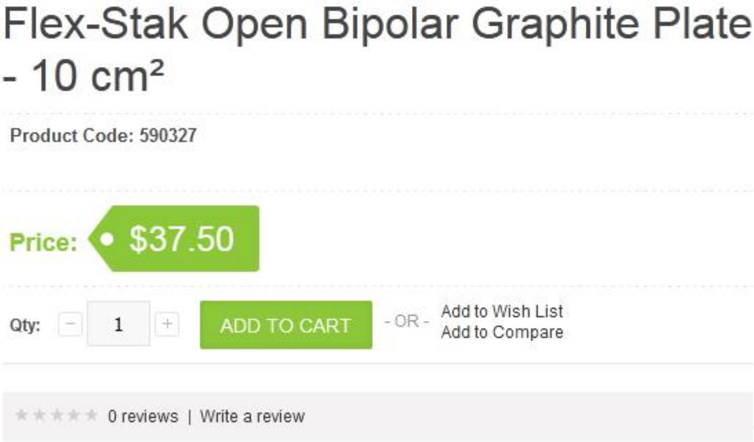
[75] https://www.fuelcellstore.com/flex-stak-anode-bipolar-plate?search=Bipolar%20Graphite%20Plate

Components costs of one cell

Graphite Plate Specifications:

- 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

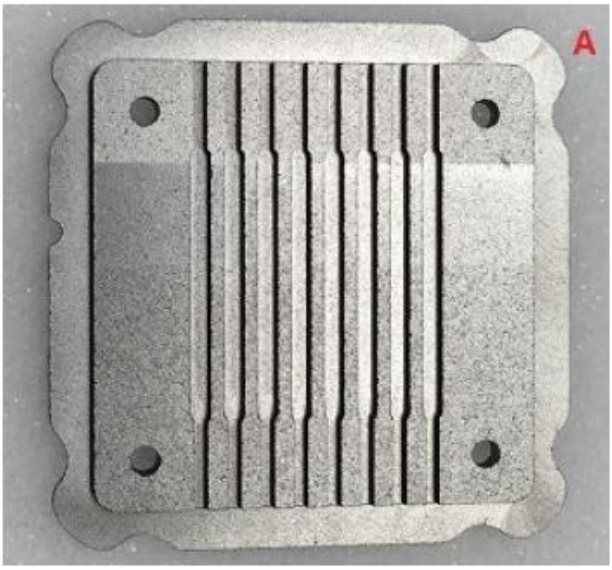
Product Code: 590327

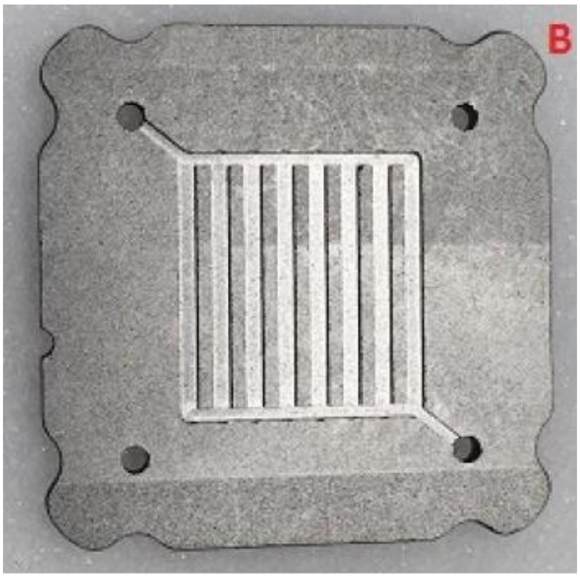
Price: $37.50

Qty: 1 ADD TO CART - OR - Add to Wish List Add to Compare

0 reviews | Write a review

[76]





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

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[76] https://www.fuelcellstore.com/fuel-cell-components/plates/flex-stack-bipolar-graphite-plate

Overall Dimensions (L x W x D): 6.3 x 6.3 x 0.4 cm

Graphite Plate Side A:	**Graphite Plate Side B:**
• Depth of Flow Fields: 2 mm	• Depth of Flow Fields: 0.75 mm
• Length Per Flow Field: 54 mm	• Length Per Flow Field: 30 mm
• Number of Flow Field Lines: 8	• Number of Flow Field Lines: 8
• Total Length of Flow Fields: 432 mm	• Total Length of Flow Fields: 240 mm

48.4 Gaskets

Item #1:

Silicone Gasketing - 12" x 12"

Product Code: 590363

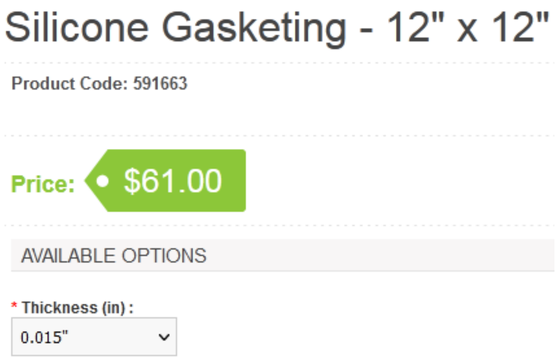
Price: $57.00

AVAILABLE OPTIONS

* Thickness (in) :

0.010"

[77]



Silicone Gasketing - 12" x 12"

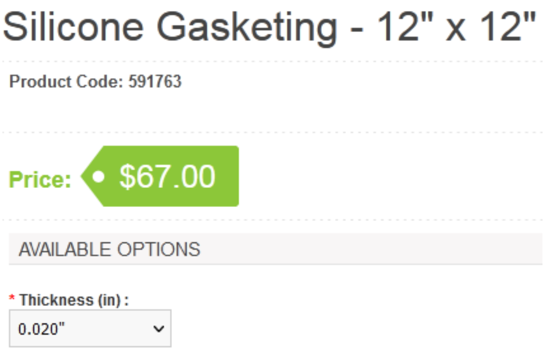
Product Code: 591663

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).

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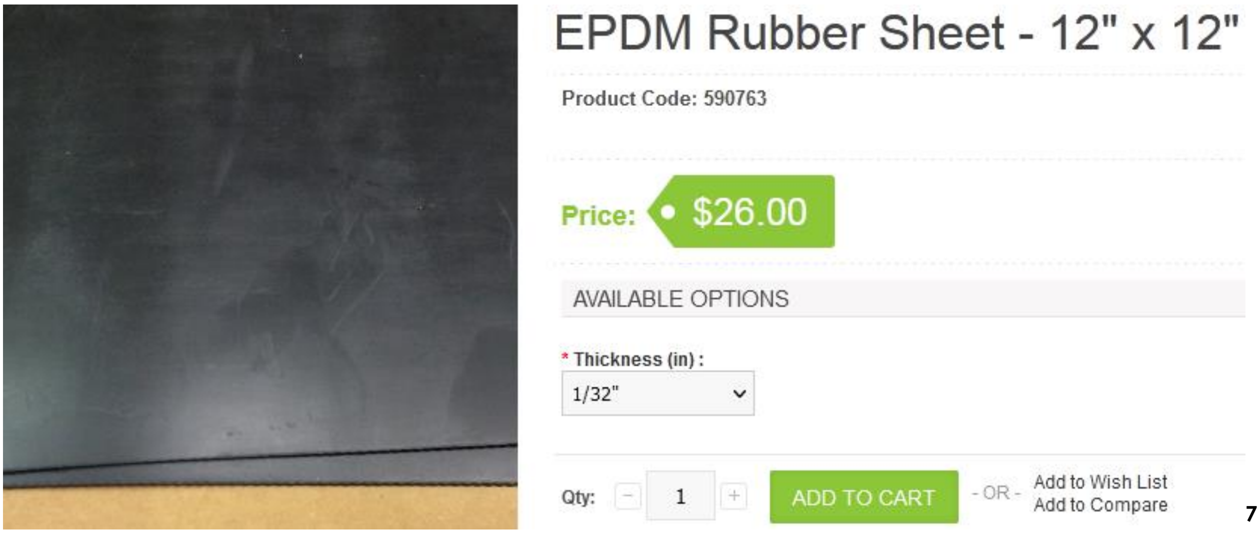
[77] https://www.fuelcellstore.com/fuel-cell-components/gaskets/silicone-gasket-35a?sort=p.model&order=ASC

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.

Item #2:


EPDM Rubber Sheet - 12" x 12"

Product Code: 590763

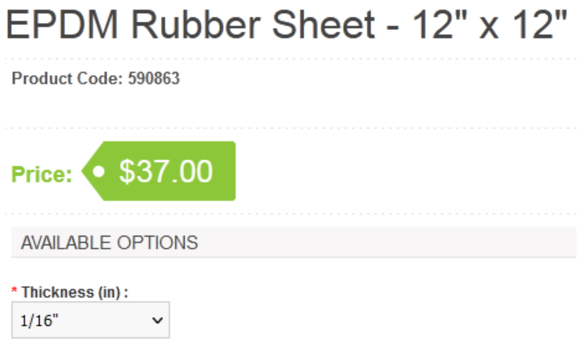
Price: $26.00

AVAILABLE OPTIONS

* Thickness (in) : 1/32"

Qty: 1

[78]

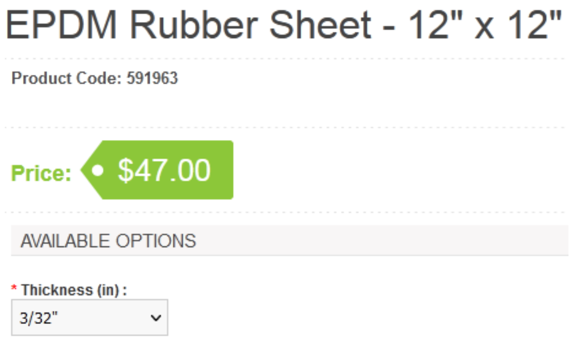

EPDM Rubber Sheet - 12" x 12"

Product Code: 590863

Price: $37.00

AVAILABLE OPTIONS

* Thickness (in) : 1/16"

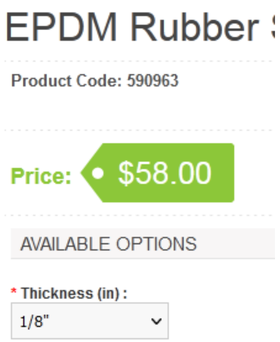

EPDM Rubber Sheet - 12" x 12"

Product Code: 591963

Price: $47.00

AVAILABLE OPTIONS

* Thickness (in) : 3/32"

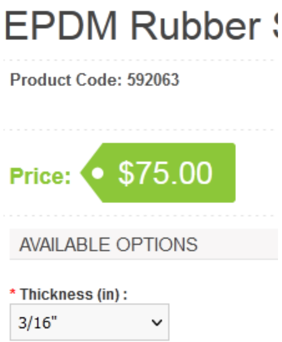

EPDM Rubber

Product Code: 590963

Price: $58.00

AVAILABLE OPTIONS

* Thickness (in) : 1/8"

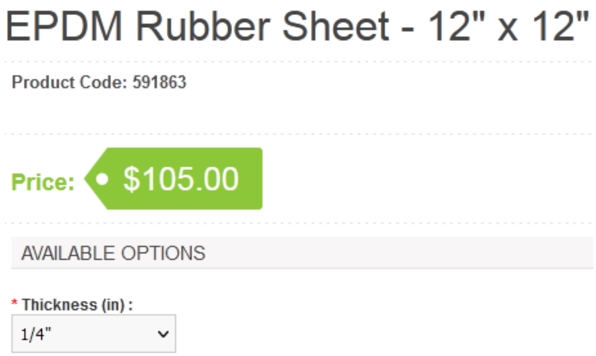

EPDM Rubber

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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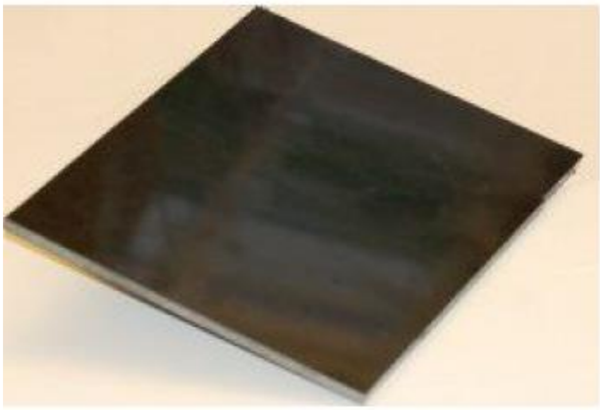
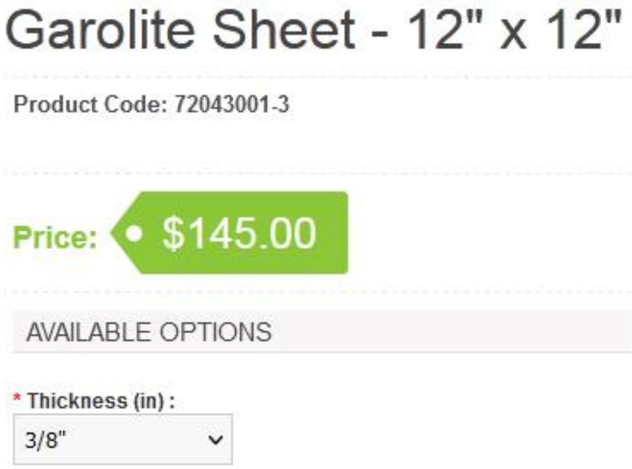
[78] https://www.fuelcellstore.com/epdm-rubber-50A

48.5 Current plate

48.6 End plate





Garolite Sheet - 12" x 12"

Product Code: 72043001-3

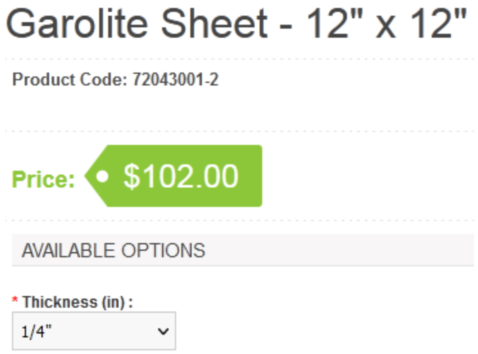
Price: $145.00

AVAILABLE OPTIONS

* Thickness (in) :

3/8"

[79]



Garolite Sheet - 12" x 12"

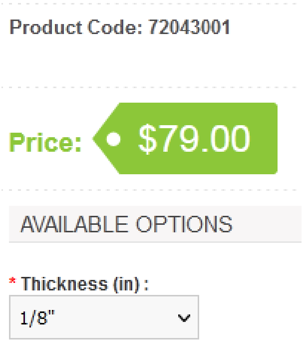
Product Code: 72043001-2

Price: $102.00

AVAILABLE OPTIONS

* Thickness (in) :

1/4"



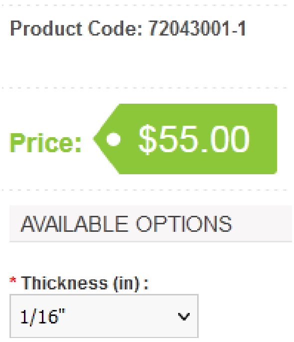
Product Code: 72043001

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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[79] https://www.fuelcellstore.com/fuel-cell-components/plates/end-plates/garolite-sheet-144

Components costs of one cell

Garolite Sheet - 6" x 6"

Product Code: 72043000-3

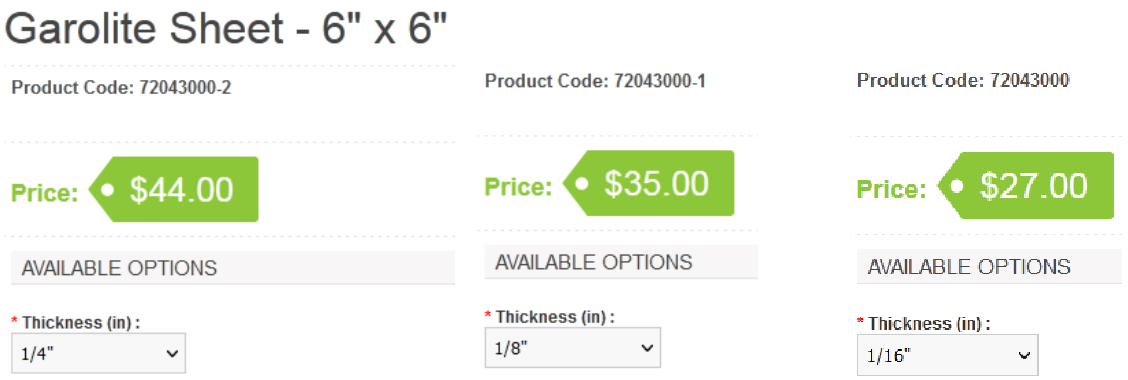
Price: $58.00

AVAILABLE OPTIONS

* Thickness (in) :

3/8"

[80]



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"

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[80] https://www.fuelcellstore.com/fuel-cell-components/plates/end-plates/garolite-sheet-036

49 Description of our prototype fuel cell system

49.1 Existing electrical system

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

49.2 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.

49.2.1 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.

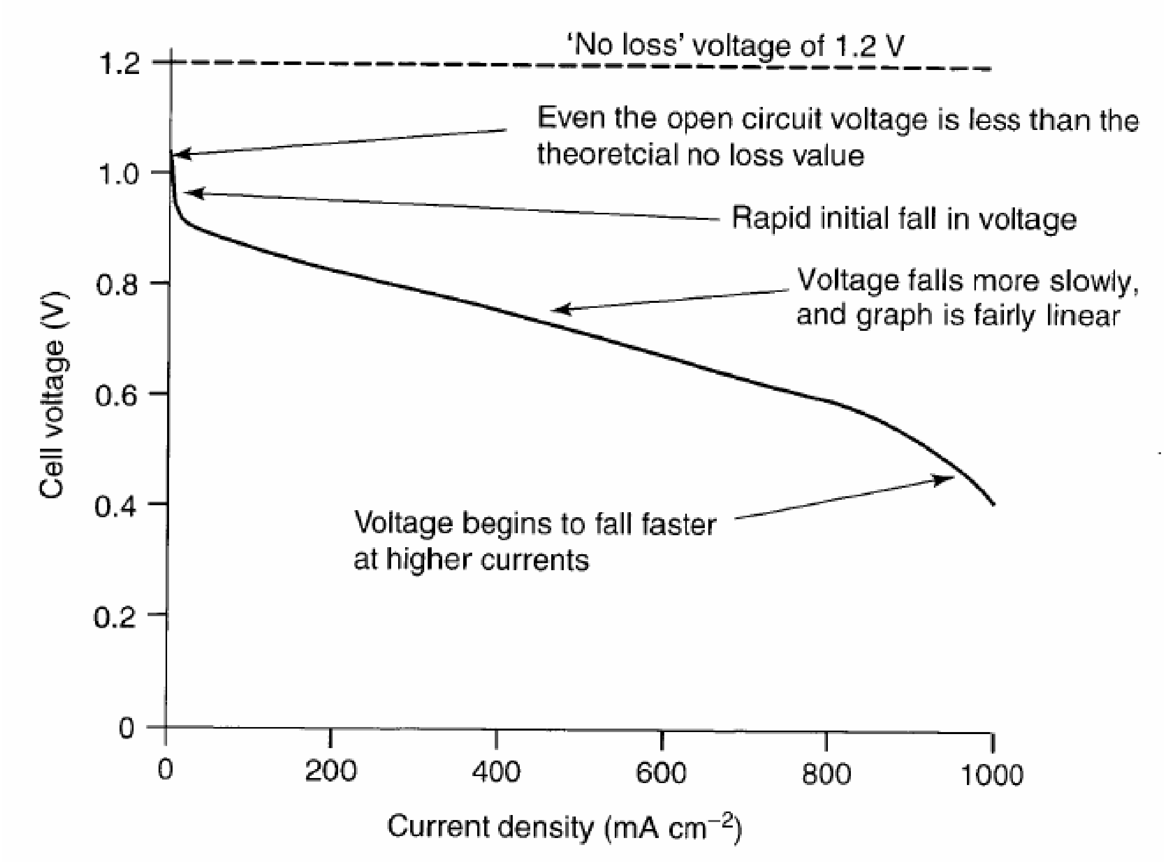


Fig. 101:
Voltage-current density diagram for a low temperature, air pressure fuel cell

The total current from the stack when supplying the maximum power can now be calculated.

$$P = U \times I \quad \longrightarrow \quad I = \frac{P}{U} = \frac{1000}{12*18} = 4.63\text{ A} \qquad \textbf{(42)}$$

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).

$$A = \frac{I}{J} = \frac{4.63}{0.55} = 8.42\ \text{cm}^2 \qquad \textbf{\textit{(43)}}$$

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.

49.2.2 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.

49.3 Converters

49.3.1 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.

49.3.2 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.

49.4 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.

49.5 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.

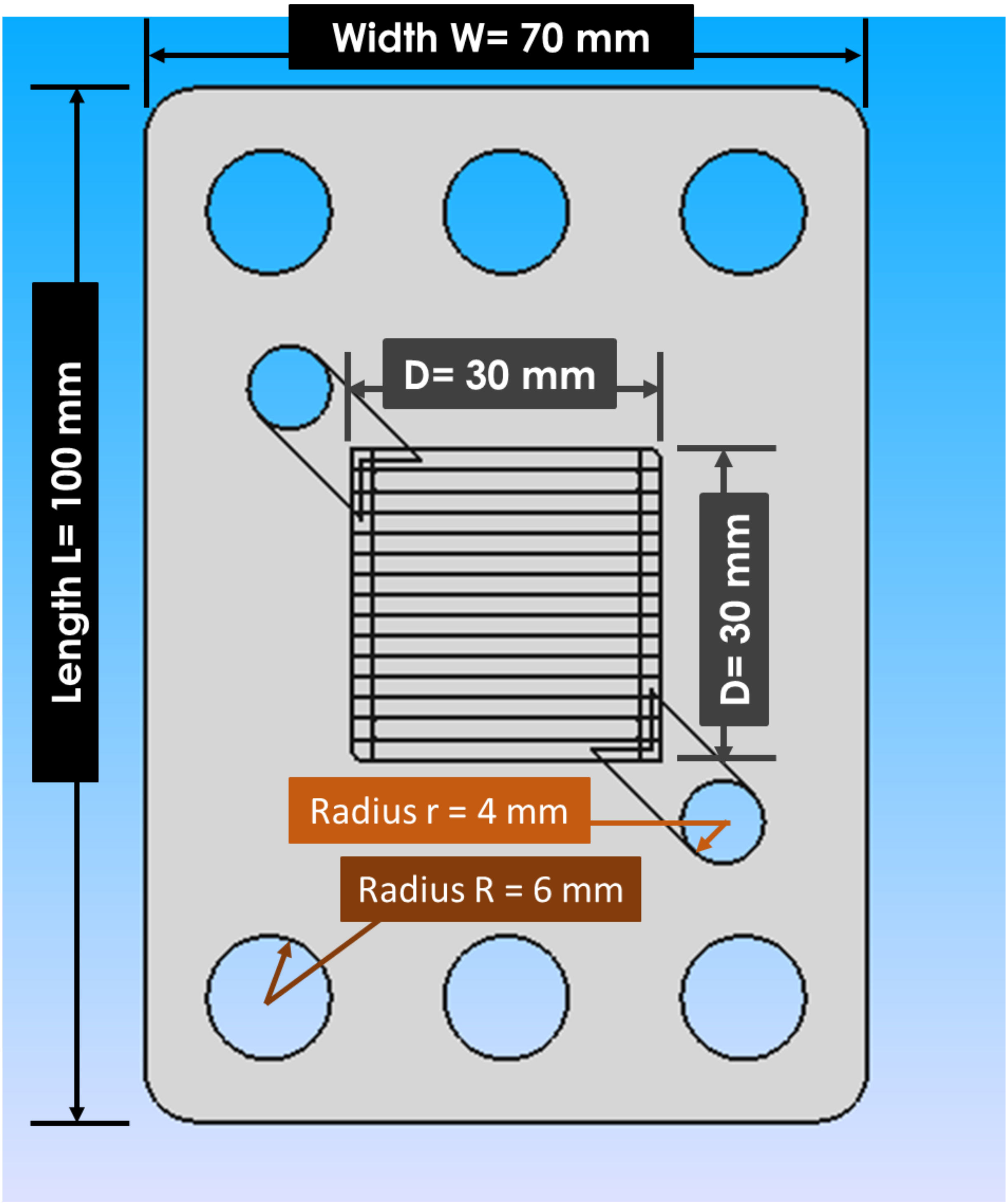
if hydrogen gas is available at a pressure of 200 bar. At this pressure the volume needed for 15 kg of H_2 is 1 m^3. It is easy to see that the mass needed for one day has a volume of 0.087 m3 (87 dm^3) with this pressure.

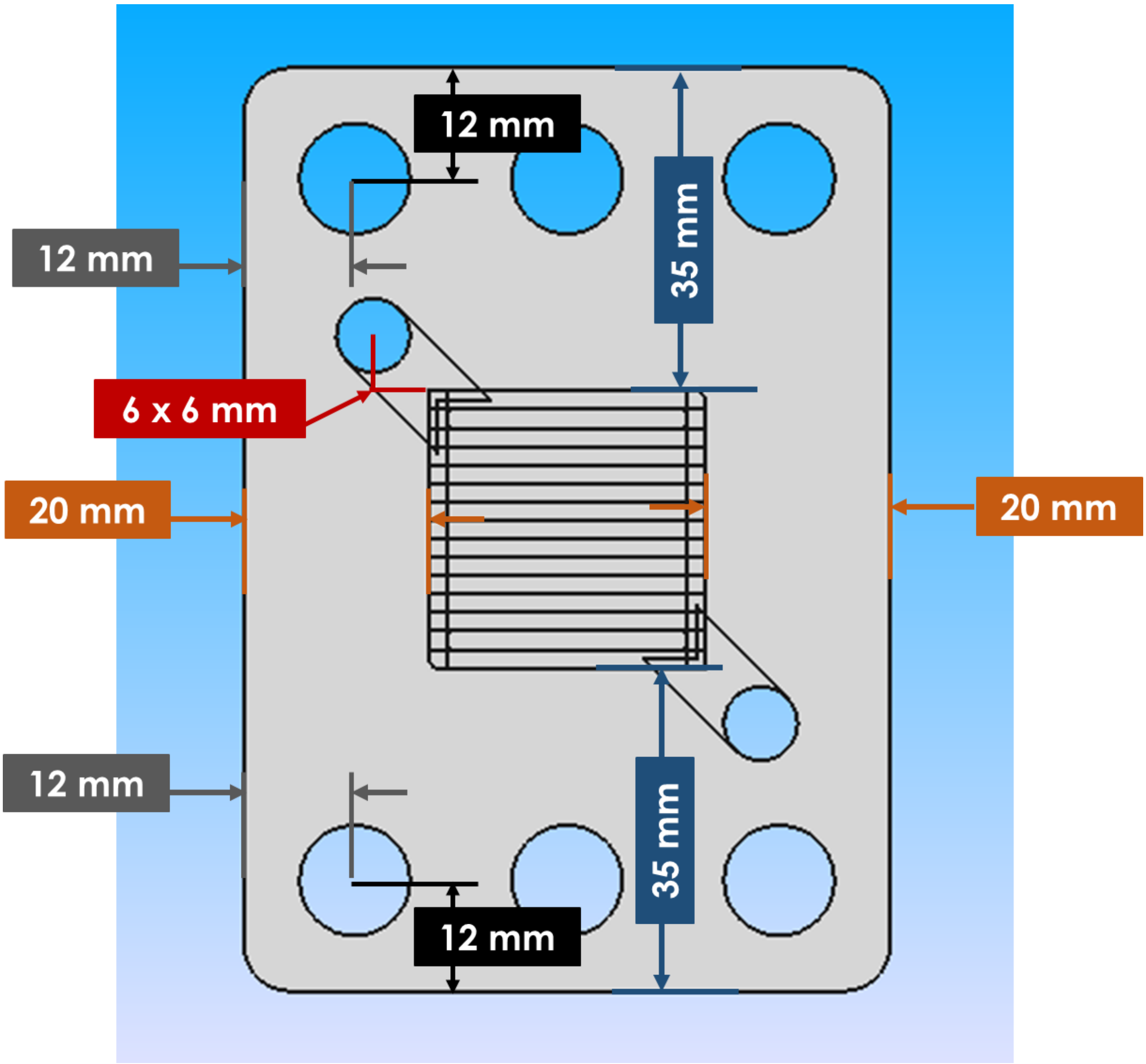
49.6 FreeCAD design

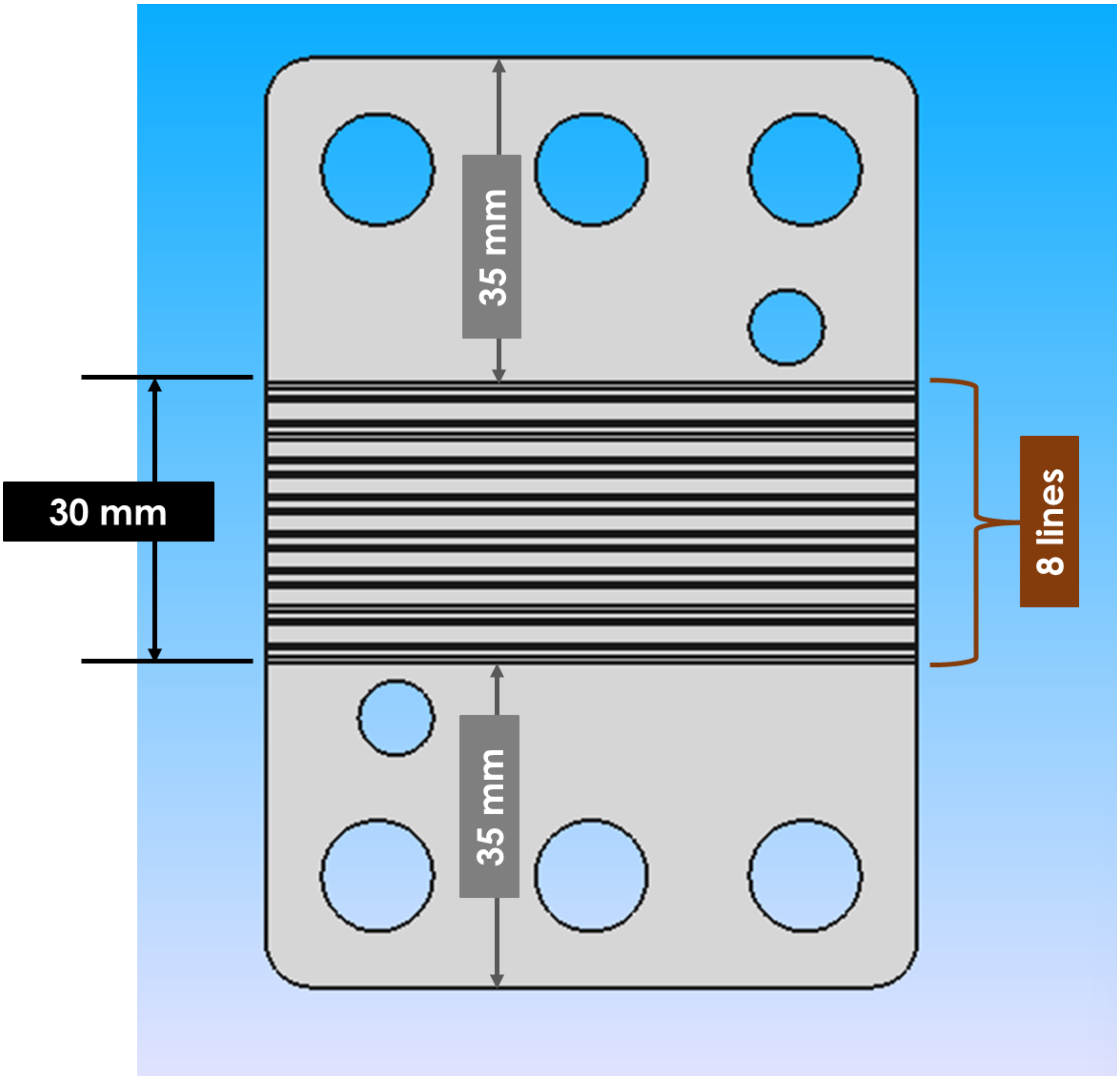
49.6.1 Bipolar plate design

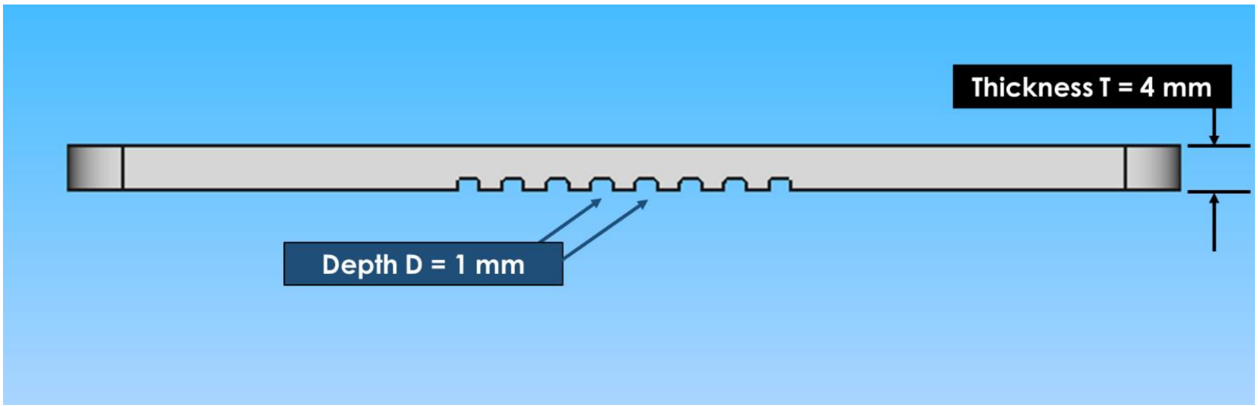
prototype
BBP.FCStd

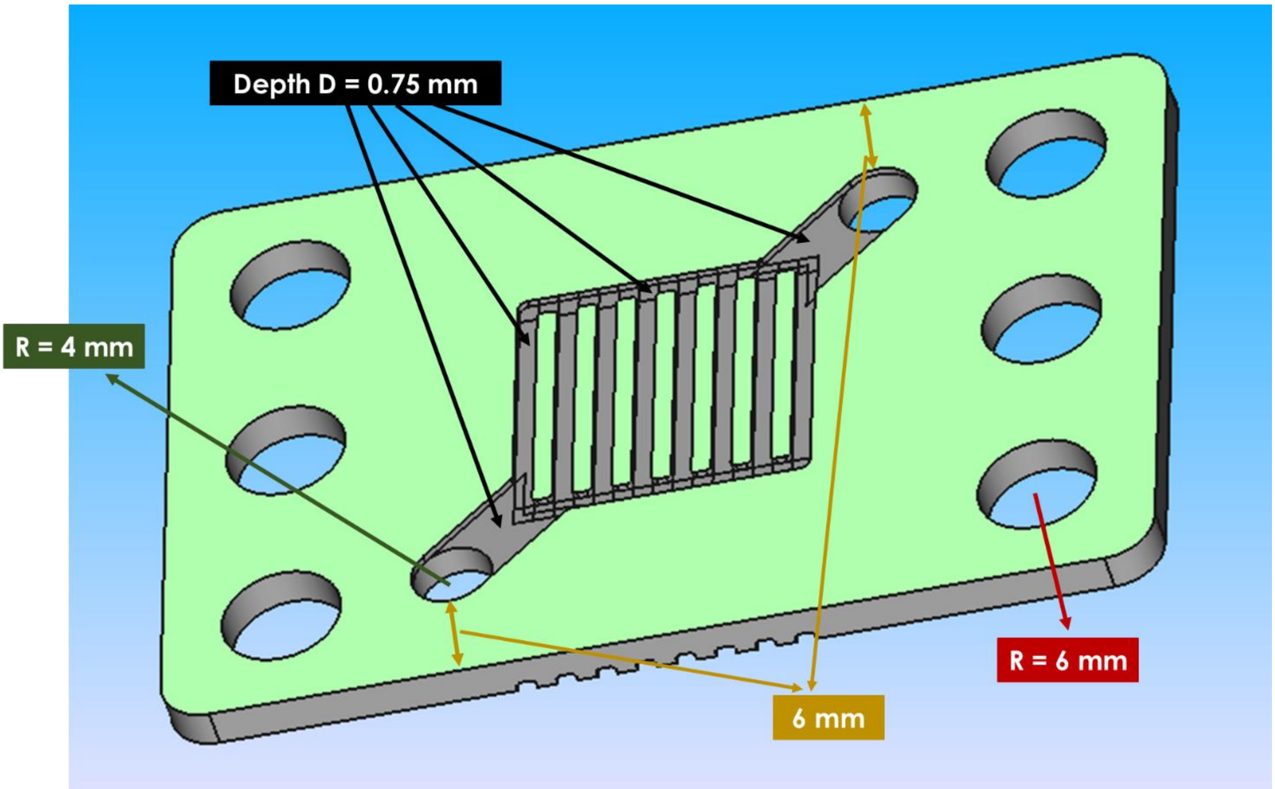
- **Design details**




12 mm
35 mm
12 mm
6 x 6 mm
20 mm
20 mm
12 mm
35 mm
12 mm


35 mm
30 mm
8 lines
35 mm

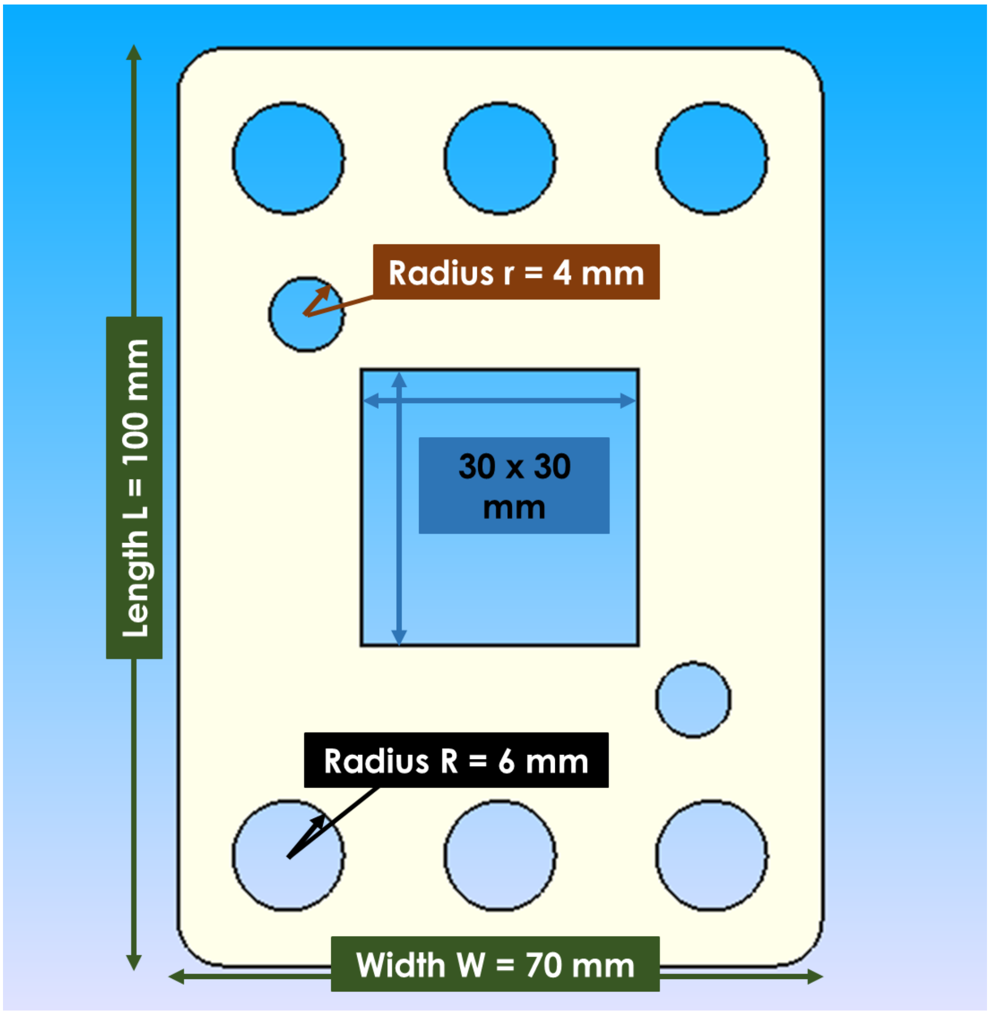

Thickness T = 4 mm
Depth D = 1 mm

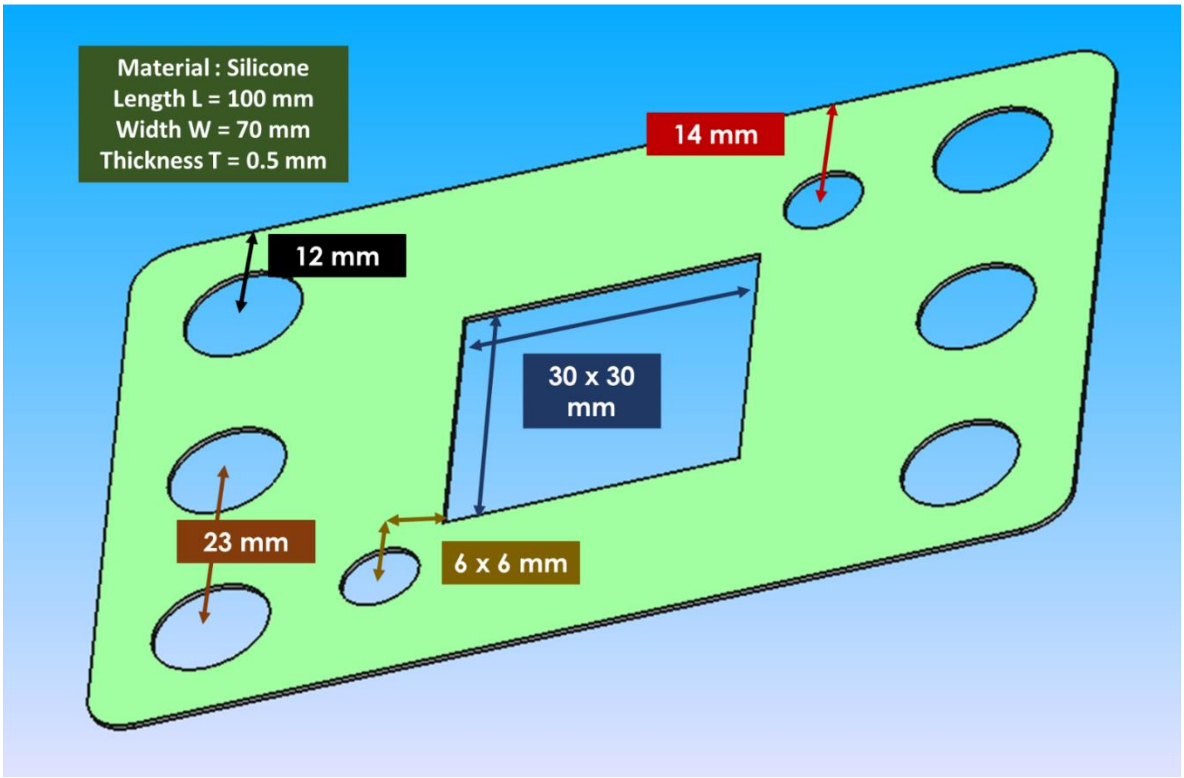


49.6.2 Gasket design

prototype
GASKET.FCStd

- **Design details**

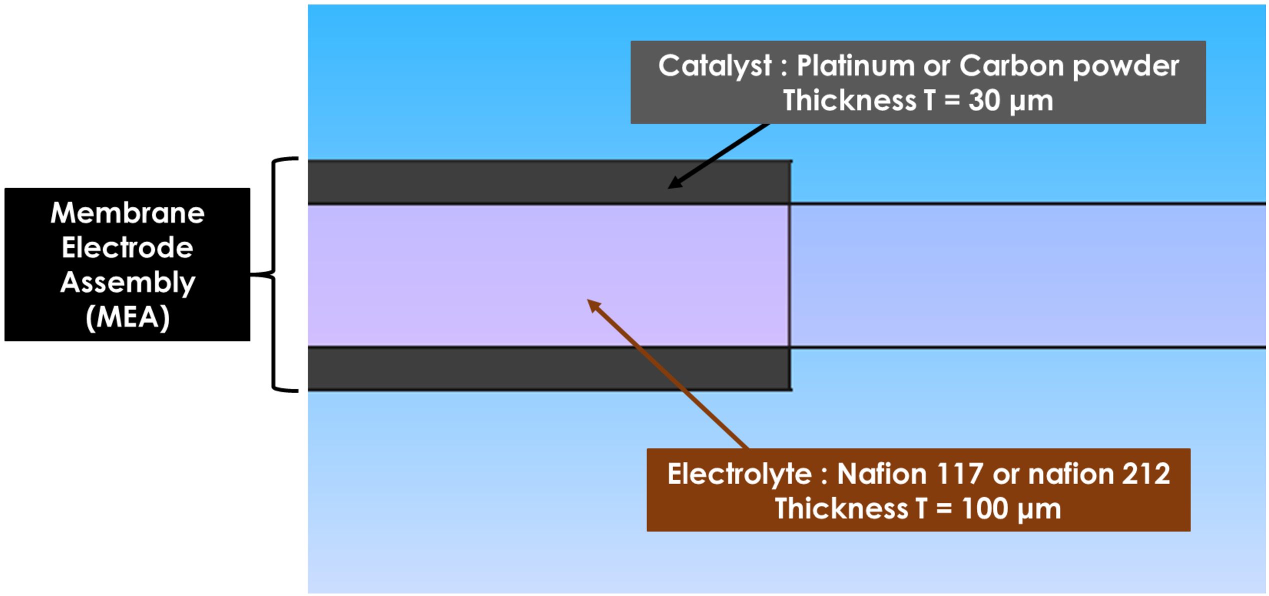

Radius r = 4 mm
Length L = 100 mm
30 x 30 mm
Radius R = 6 mm
Width W = 70 mm


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

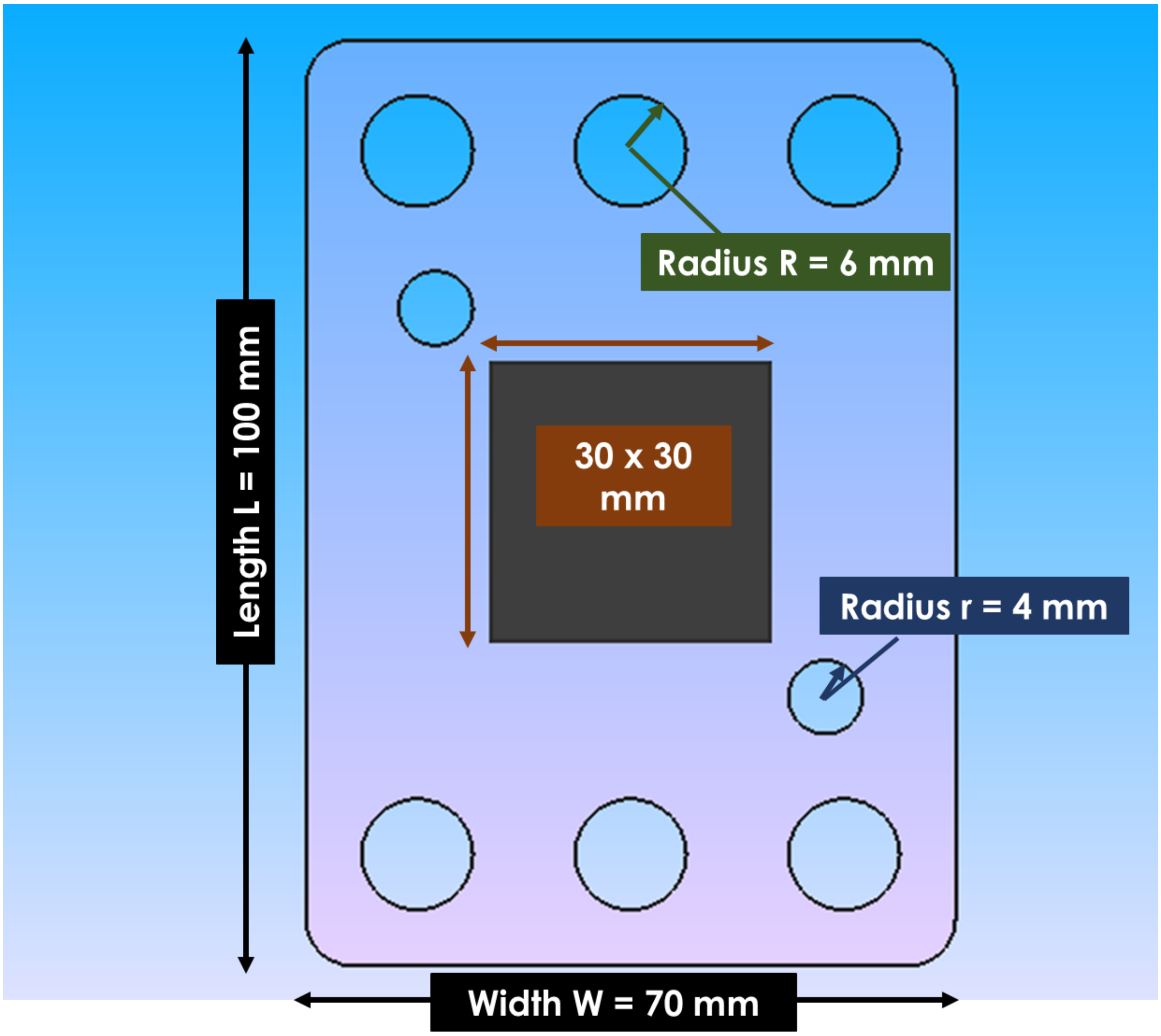
49.6.3 MEA design

prototype
MEA.FCStd

- **Design details**

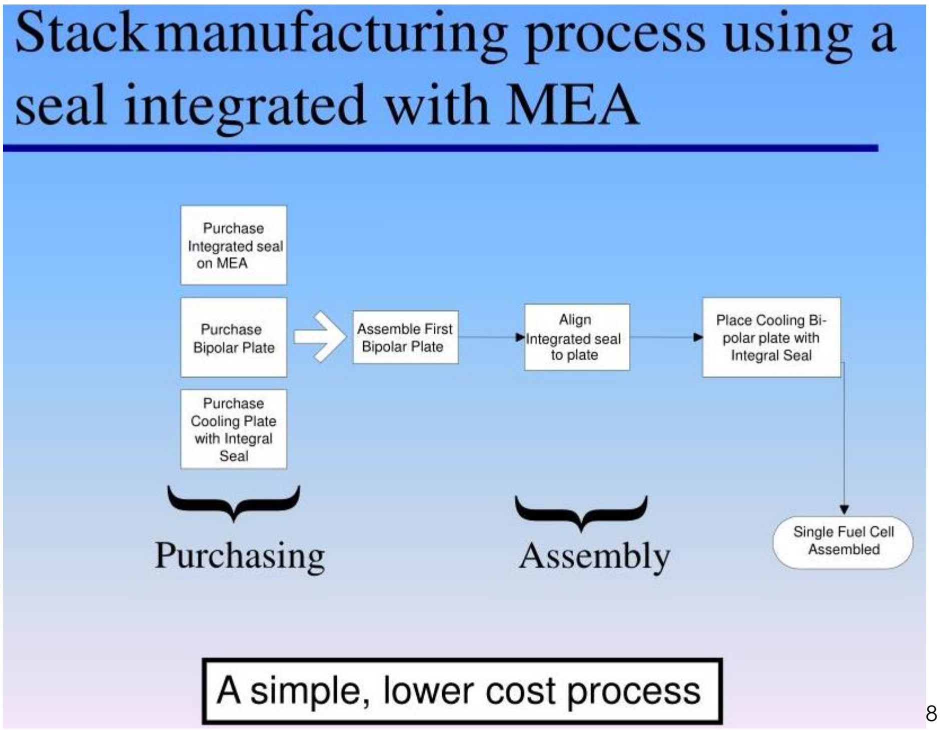


Description of our prototype fuel cell system



49.7 Specification of requirements

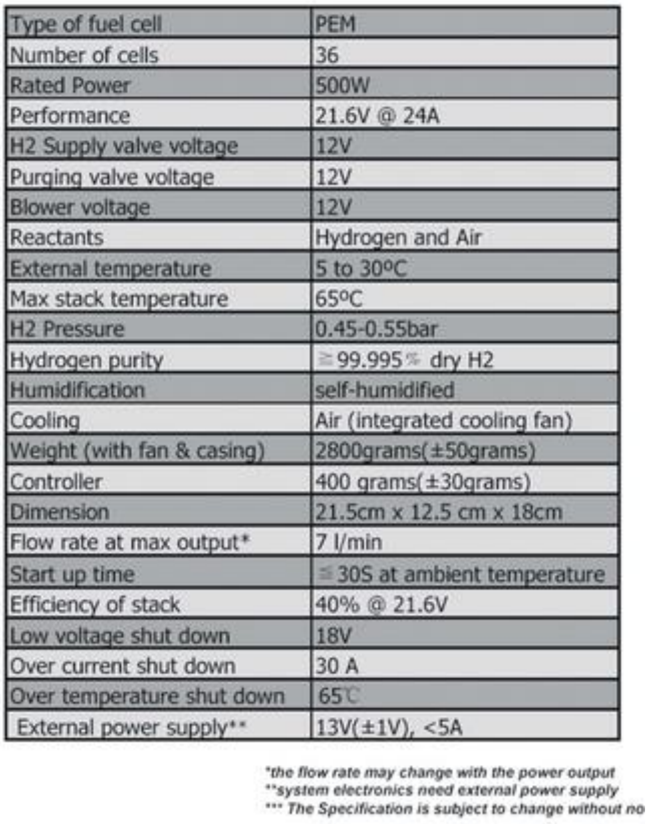
Description	Specifications
Power rating	1 kW
Output voltage	12 V
Fuel	H2
Fuel storage (per day)	13000 dm3 at 1 bar 87 dm3 at 200 bar



Stack manufacturing process using a seal integrated with MEA

A simple, lower cost process

[81]



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 30ºC
Max stack temperature	65ºC
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

[82]

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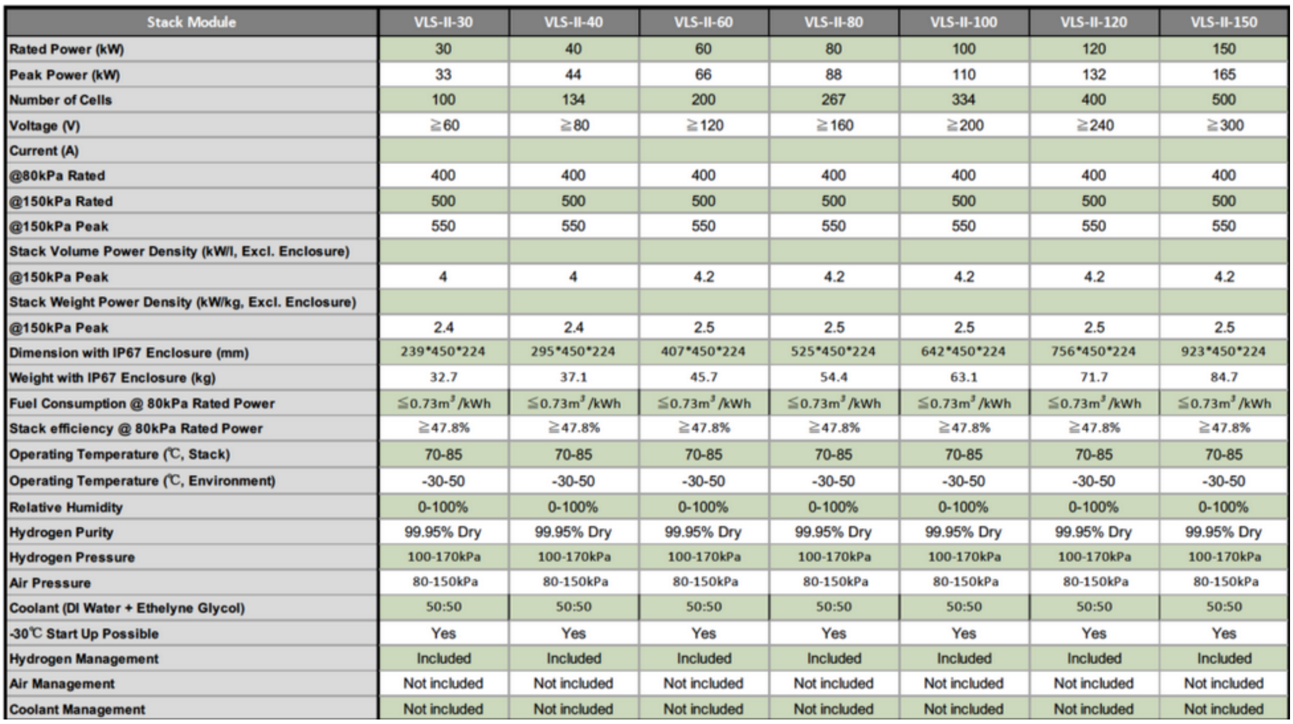
[81] https://www.slideserve.com/Mercy/pem-fuel-cell-stack-sealing-powerpoint-ppt-presentation

[82] 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

[83]

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[83] https://fuelcellsworks.com/news/throwback-thursday-spotlight-horizon-automotive-pem-fuel-cells-to-set-300kw-benchmark/

50 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.

Fuel Burner

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References

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