بسم الله الرحمن الرحيم

MASTER THESIS

In Order to Obtain the

Research Master

of

Physics of Radiation-Matter Interaction

Presented and defended by:

Mariam Mourad

On Friday, November 30, 2020

Title

Laser Based Flue Gas Detection

Supervisor

Dr. Ahmad Osman

Reviewers

Dr. Salah Al Falou

Dr. Ahmad Ahmad

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Acknowledgements

First, I thank Allah the Almighty for everything.
Then, I thank my father, Dr. Samir Mourad, the director of AECENAR research center, Tripoli, where this research has been undergone, for been patient with me as Master Student and daughter in Corona times. Thank you, Dr. Ahmad Osman for supervising me. Thank you all my lecturers Prof.Dr. Adnan Naja and all. You enabled me to be in this state. In a state where I can help our community with science and technology.
Thank you also Eng. Mahmoud Zohby for preparing the Melexis Camera with the Arduino and Abdurrahman Mourad for helping me with Arduino.
Thank you, Abdullah Mourad for supporting me as chemical student. He was responsible for the safety while the chemical experiments.
Finally, yet importantly, I want to thank AECENARs employees, Siham Aisha, Maysaa Kamar Adin and Maryam Abd Alkarim for your preliminary work, and Eng. Mahmoud Zohby, Osman Dhaybi and Samer Yusuf for assisting me during the final test at the municipal waste incineration power plant.

Abstract

This master thesis is the construction of an experimental setup. Starting from the idea of TDLAS (Tunable diode laser absorption spectroscopy), we construct a test stand consisting of a DFB Laser diode in a LD mount controlled by a LD and a temperature controller. The radiation of the Laser in constant power mode was detected from a Melexis IR camera (16x4).
The aim is to prove that the AECENAR municipal waste incineration power plant is environmentally friendly. Until now, just a LD of 1550nm is available. Therefore, we just studied the interaction of that laser radiation with the carbon monoxide CO, which absorb this wavelength. Before we go to an in-sito test at the power plant, we made indoor experiments. During these experiments, the Arduino program was developed. To produce a known concentration of CO, the dehydration of formic acid with sulfuric acid as catalyzer, was used.

INTRODUCTION

The AECENAR[1] power plant converts municipal waste to electric energy. Certainly, there are different types of filters in use. Nevertheless, we have to take measurements at the flue gas after the filters to prove that it is environmentally friendly. In this thesis, the carbon monoxide (CO) is studied. CO is a dangerous gas which attacks the health. A CO - air mixture is even explosive. To detect CO we chose to use the TDLAS method. A corresponding LASER radiation is directed to the gas. If the gas absorbs a part of the energy, we can say that there is CO. The energy gap, which is the difference of two signals detected before and after the gas, indicates the concentration of CO.

If the CO concentration is under the limit (20mg/m^3), the incineration power plant is environmentally friendly, corresponding the CO. [14]

If not, the O_2 saturation during incineration has to be increased. An incomplete combustion is a reason of CO existents.

In chapter I, we will take a look at the different methods of Laser spectroscopy, the Lasers themselves and characteristics of CO and its interaction with Laser interaction.

In chapter II, we will see the initially planned experiment. Why we had to find an alternative. Also, the alternative setup and its development, especially of the Arduino program, and the results of the indoor experiments. Finally, the preparations and the implementation of the measurement at the power plant is presented.

In chapter III, you will find the results of the outdoor experiment.

The Conclusion and future prospects are mentioned in chapter IV.

If you want to have a closer look at the devices you can refer to the Appendixes “Elements in detail”.

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[1] AECENAR: Association for Economical and Technological Cooperation in the Euro-Asian and North-African Region, Karlsruhe/Germany and Tripoli/Lebanon, www.AECENAR.com. AECENAR is a German association with a branch in Tripoli/Lebanon. AECENAR is registered in Germany with the following number: Reg. VR103464 MANNHEIM, Germany

1 CHAPTER I: STATE OF THE ART

There are many different methods of gas measurement via Laser and much more for CO measurement with or without Laser.

1.1 CO measurement types

Here you will see the Laser methods, which detect gas contents concentrations and a few of those even the temperature of molecules. The methods, which are capable to detect the CO, are mentioned. From these methods, we chose the TDLAS. The reasons of selection will be clear after the comparison of the different methods.

1.1.1NDIR (Non-dispersive infrared)

NDIR compares the transmission of absorbing and non- absorbing regions.
Two infrared sources radiate throw two samples. One contains N_2 as reference. The second contains the studied gas [1]

1.1.2FTIR (Fourier Transform Infrared spectroscopy)

The basic element of a FTIR is the interferometer. The IR beam of the source is split into two equal beams. One of them reflects in a moving mirror, the other in a fixed one. The interferogram results when the two beams interfere back at the beam splitter. It passes the sample and arrive at the detector. A Fourier program transforms the interferogram to a frequency spectrum. [2](P.24)

1.1.3DOAS (Differential Optical Absorption Spectroscopy)

The DOAS is a method to determine the concentrations and total amounts of gases from remote sensing measurements of light in the UV, visible, and NIR spectral range. The basic principle is absorption spectroscopy. Light travelling through the sample is partly absorbed by trace constituents along the way following Lambert Beer's law of absorption. [3]

1.1.4LIF (Laser-induced fluorescence)

LIF is a two-step process: First, a laser photon is absorbed. An emission of a fluorescence photon from the excited state follows. Only a fraction of these excited molecules fluoresces, the rest relaxes without light emission. A filter selects fluorescence light at the emission wavelength.
LIF allow to identify the gas species. From the intensity of the excitation spectrum the concentrations of atoms / molecules is deduced. And the temperature from the spectral distribution. [4]

1.1.5CRDS (cavity ring down spectroscopy)

A pulsed absorption CRDS technique was developed by O’ Keefe and Deacon, 1988.

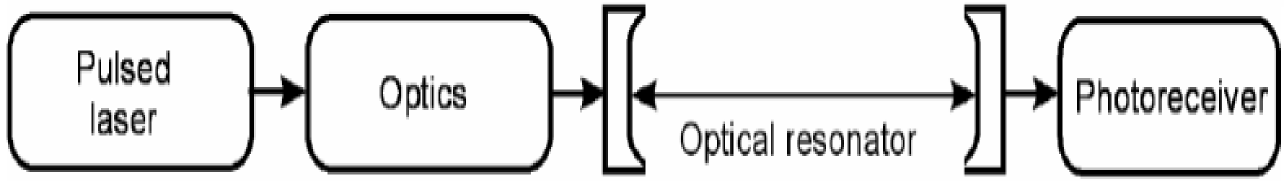


Figure 1 CRDS Principle

CRDS bases upon a measurement of radiation's decay time. The radiation is captured in an optical resonator with a high quality factor. The radiation's decay time is measured once when the cavity is empty and next when the absorber fills out the cavity. [5] (P.1)

1.1.6CEAS (Cavity enhanced absorption spectroscopy)

Cavity enhanced absorption spectroscopy (CEAS) is a development of CRDS technique. The optical cavity is in an off-axis arrangement. The mirrors reflect the light repeatedly. However, the reflection points are spatially separated. [5] (P.2)

1.1.7TDLAS (Tunable diode laser absorption spectroscopy)

A diode laser radiation is directed through a gas mixture. The laser is tuned over a small frequency range around a molecular or atomic transition of the target species. It results an attenuation of the intensity caused by absorption. The intensity of the light transmitted through the sample is recorded.

In that way, you can measure the energy absorbed by the atoms/molecules at the transition, relative to the baseline, further away from the transition, where no energy is absorbed.

The Beer-Lambert Law describes the variation in intensity. This law is the basis for the theory of absorption spectroscopy.

1.1.7.1Advantages

- Online, in-situ, rapid response
- Non-intrusive
- Sensitive species-specific detection
- Calibration-free
- Measure concentration and gas temperature

1.1.7.2Limitations

- Although asserts to be calibration-free, TDLAS implementation still depends on good knowledge of molecular and atomic spectroscopic parameters (such as line strength), absorption path length, and averages over possible inhomogeneous conditions along the radiation path. Comparison to other techniques might be still necessary as validation.
- At high pressures, the absorption spectrum is broadened.
- Particles is the gas cause extinction of laser beam at longer path length
- H_2 cannot be measured

• A challenging application for laser spectroscopy is the Gasification. Due to the presence of a significant number of compounds, each of them with different cross sections, the strong light attenuation of product gas, and the high temperature of application. [2] (P.49)

1.1.7.3Applications

• Medical:
Ergospirometry: Breath analysis - pulmonary diagnostics
• Environmental:
Continuous Emissions Monitoring (CEM), biogas, natural gas, fugitive emissions, leak detection
• Process control:
SCR in power generation and engine development, agriculture, carbonitriding of steel
• Research:
Environmental studies, climate control [6] (P.4)

1.1.8Comparison

In the tables below you can see a comparison of the main methods according to the gases and to important properties.

	TDLS	NDIR	FTIR	E-Chem
Performance & Reliability				
High selectivity	+	=	+	-
High stability and reliability in the field	+	=	+	-
Cost				
Low initial investment	=	=	-	+
Low cost of ownership	+	=	=	=
Flexibility				
Hot gas measurement	+	=	+	-
Multigas Sensing	=	+	+	+

Table 1 Properties comparison of different methods [6] (P.5)

As we see in table 1, TDLAS has a higher selectivity, stability and reliability in the field as NDIR and E-Chem. In addition, it has a lower initial investment as FTIR, and lower costs of ownership as the others. TDLAS has a high flexibility with hot gas measurements, and multigas sensing.
As we see in the table below (table2) TDLAS can detect the highest number of molecules. CO is also under these gases.

Measurement method	Measurement system	Gas molecular species
Points	Self-emission spectrum	OH, CH, C^2
Points	CARS	N^2, O^2
Line	Raman scattering method	OH, NO, NO^2, C^2, CH...etc
Line	TDLAS	CH^4, CO, CO^2, O^2, HCl, NH^3, HC...etc

Area	PLIF	OH, C, NO, O^2, CO

Table 2 Comparison of methods with respect to the detected gases [7]

1.2 Laser types

There are many types of Lasers: liquid, gas and solid Lasers. We just have a look at few semiconductor Lasers, which belong to the category of solid laser. Because the SC react to current and temperature variations, it is simply tunable.

1.2.1TDL (Tunable diode lasers)

There are many types of TDLs. Like VCSEL, FP, DBR and DBF. [8] I will give a short definition of every one. However, just the DFB is utilized for the carbon monoxide measurement. Therefore, I will describe it in few sentence.
In general, diode lasers with the combination InGaAsP/InP are tunable over 900 nm to 1.6 µm. Those with an InGaAsP/InAsP combination are tunable over 1.6 µm to 2.2 µm. [22]

1.2.1.1VCSEL (Vertical Cavity Surface Emitting Lasers)

In contrast to other SC lasers, the coherent energy of VCSEL was emitted perpendicular to the boundaries between the layers.
The active medium is of very short length. Therefore, it follows a small gain. Therefor the mirrors are fabricated with a high reflectivity to give a sufficient gain. [9] (P. 435)

1.2.1.2FP (Fabry-Perot)

FP (Resonator) consists of two plane mirrors, which are parallel to each other. The condition between them is $L=n\lambda/2$. This condition leads to resonant frequencies of $\nu = n(c/2L)$. [9] (P. 180)

1.2.1.3DBR (Distributed Bragg reflector)

The grating of a DBR laser is fabricated separately from the active layer. This let the integration with other dives be simpler. Like the fabrication itself.
Temperature variations lead sometimes to a switch of adjacent modes. This is why the DFB laser is more used than the DBR laser. [9] (P. 434)

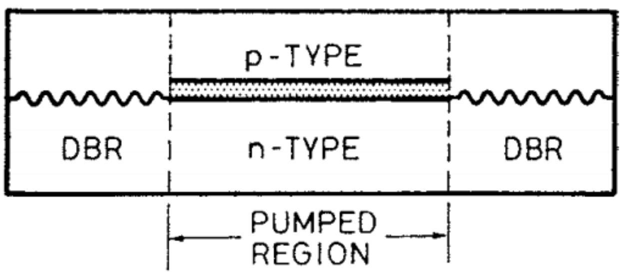


Figure 2 Distributed Bragg reflector (DBR) SC Laser [9] (P. 434 of PDF)

1.2.1.4DFB (Distributed-feedback laser)

The resonators structure is periodic. It plays the role of a distributed reflector.
There are two types of DFBs: fiber Lasers and semiconductor Lasers.
These single-frequency fiber Lasers are simple and compact. Their robustness brings low intensity and phase noise level.

In our study, we use the SC DFB Laser.

SC DFB Lasers can be constructed by integrating grating structure – this takes time and is complicated- or by arrange laterally coupled structures. Here, the gratings are on both sides of the active matter.

They are able to emit in different spectral regions: from 0.8 µm to 2.8 µm. The output power is typically some tens of milliwatts. The linewidth is about few hundred MHz. you are able to tune the wavelength over several nm.

With a Temperature controller, a high wavelength stability can be reached. [10]

1.2.2 Comparison

In the graph below we can see that the DFB laser have a stable drift in comparison to the VCSEL and FP lasers.

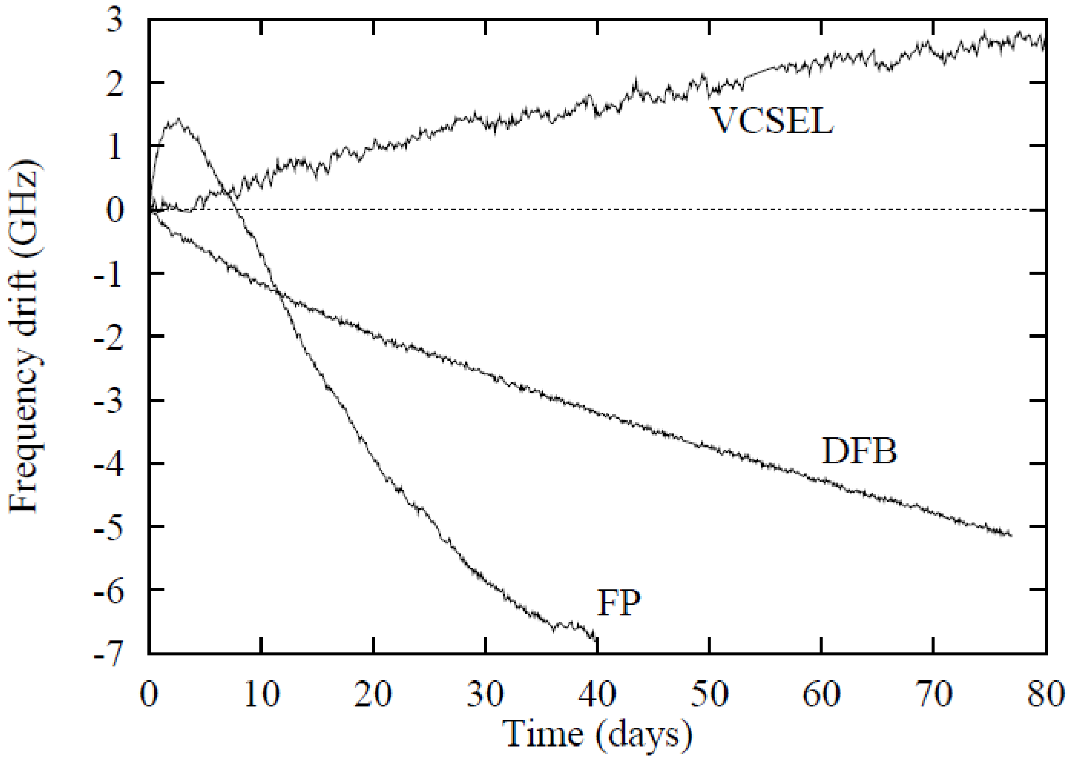


Figure 3 Graph compare the frequency drift of FP, VCSEL and DFB at 760nm [8] (P.5)

In the table below (table 4) we see that according to CO, the typical wavelength is 1.56 µm, it is not the single one. We use a laser diode of a near wavelength 1.55 µm. CO absorb it either.

The method used by them was DFB. We used the same.

The detection limit is set hear by 20 ppmm for the CO. In our setup, it is easier to use another concentration unit mg/m^3. The limit is also 20 mg/m^3.

In this table, you see that DFB can be used to measure all the mentioned gases. That let it be a good choice.

Gas	Laser type	Wavelength /µm	Detection limit /ppm·m
O_2	FP, DFB, VCSEL	0.764, 0.760	1000
HF	DFB	1.28, 1.30	0.03
NH_3	DFB, DBR	1.51	0.2
CO	DFB	1.56	20
H_2S	DFB	1.57	5
HCl	DFB	1.74	0.1
NO	DFB	1.81	5

Table 3 detection limits and typical wavelengths of gas molecules. Measured with techniques described in [8] (P.6)

After all what is a Laser physically, and how interact it with CO. What are actually the properties of CO?

1.3 LASER-CO INTERACTION

The Laser is a Light Amplification by Stimulated Emission of Radiation. It is a coherent electromagnetic radiation. [11]
CO, the carbon monoxide, is a molecule with a triple liaison between the carbon and the oxygen atoms. [12] It is colorless, odorless and tasteless.
In human body and in all living beings whose respiration is based on hemoglobin (Hb), the CO form with the Hb, carboxyhaemoglobin (COHb). Therefore, the O_2 cannot bind on the Hb. All the organs need O_2 especially the brain and the heart. Their disfunction leads to death. [14]

Most of the interesting trace gases absorb on their fundamental rotational/vibrational modes in the middle infrared. The strong absorption requires a high spectral resolution that avoid interference between species.
The CO goes in an excitation mode by absorbing the laser's energy. [8] It reemits the energy in different directions. According to Beer's law, the concentration of the CO is proportional to the detected absorption peak. [17]
1550nm have an energy, which fits to the transmission between the $A^2\Pi$ levels represented in the picture below.

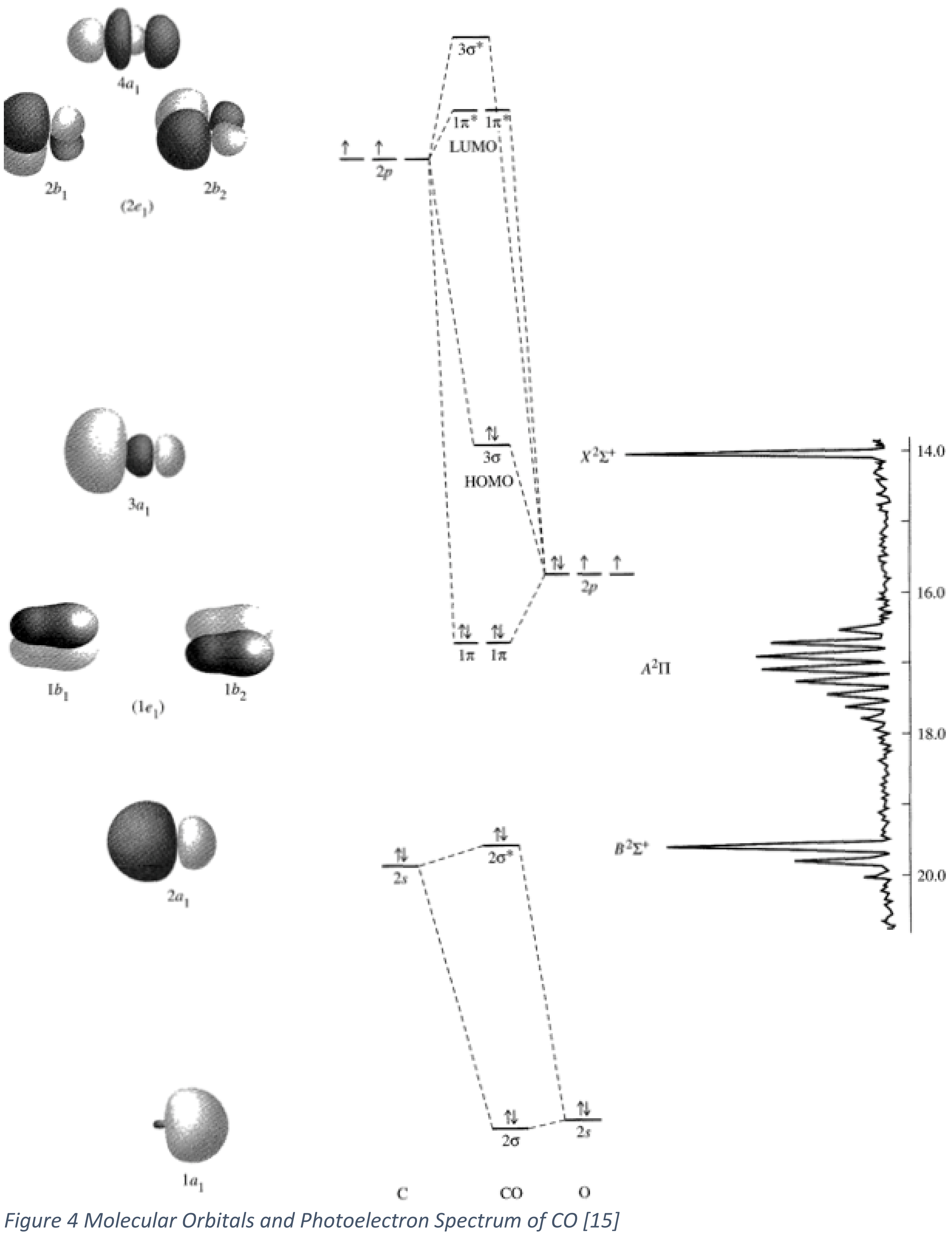


Figure 4 Molecular Orbitals and Photoelectron Spectrum of CO [15]

2 CHAPTER II: CONTRIBUTION

In this chapter, you will find a short description of the initially planned setup. The alternative implementation. Its development. The indoor experiments with results and the outdoor experiment. Its result is mentioned and discussed in the chapter after.

2.1 First planed experiment

In the experiment illustrated below (Figure 5 planed test), the current controller establish the current in CC mode or the power in CP mode of the LD. The temperature controller prohibits the LD from overheating. The aspheric lens let a Laser be a Laser by directing the rays parallel to each other.
To be able to measure the influence of the gas against the laser wavelength, power, or intensity, there is a detector, a PD, placed before and after the flue gas.
For this reason, the splitter split the radiation into two. The isolator ensures that the laser ray do not reflect and go back to the LD. The radiation enters to the gas through an optical window and exits through a spherical lens a focusing lens. To rebound the radiation that be distracted in the gas mixture.
The synchronic detector compares the two signals. The two signals can be amplified, to have a better-scaled result.
The result can be displayed on an oscilloscope or on a Laptop. A program can also replace the synchronic Detector.
The Table below (Table 4 5) shows the main devices for each gas with the information that able you to order them or have a look at the manual.

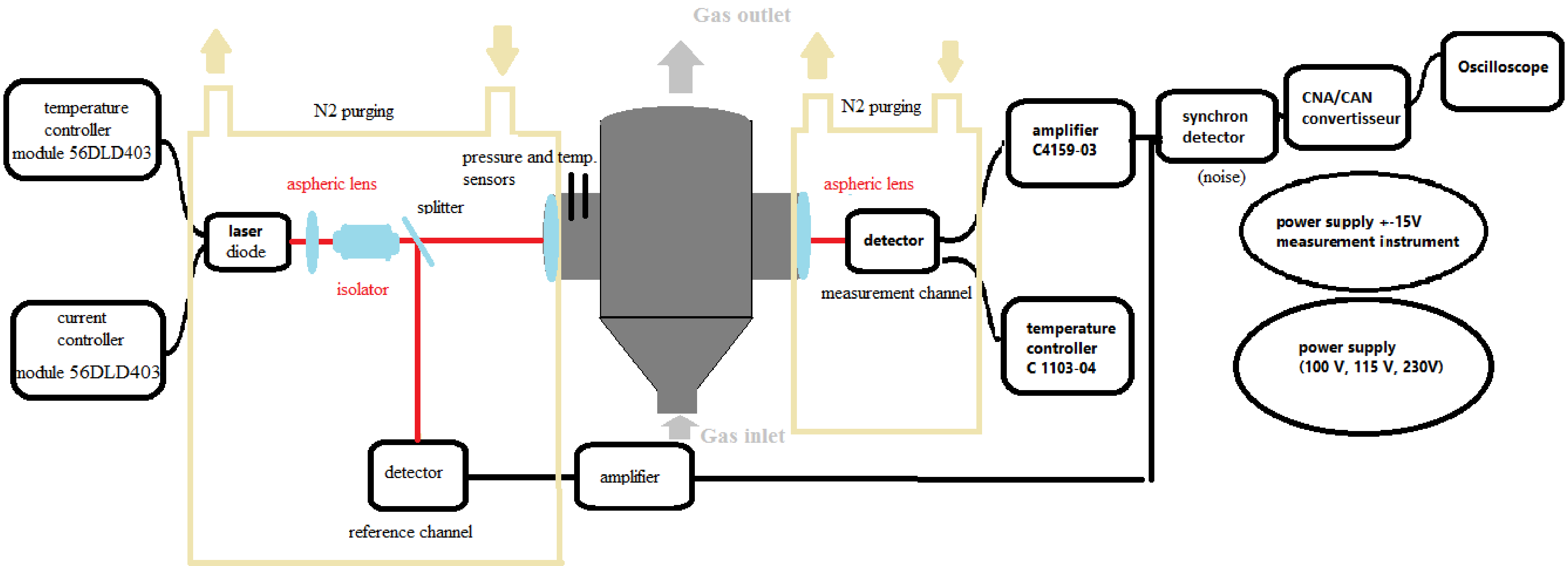


Figure 5 planed test stand [18]

Gas	Device	Company	Nb	Link	Same as for /Note	Price
CO	Two T controller	Thorlabs	TED200C	https://www.thorlabs.com/thorproduct.cfm?partnumber=TED200C	Bought one	$1,069.13
	Current controller	Thorlabs	LDC205C	https://www.thorlabs.com/thorproduct.cfm?partnumber=LDC205C	Bought	$1,091.86
	LD 1550nm	Thorlabs	L1550P5DFB lens cap	https://www.thorlabs.com/thorproduct.cfm?partnumber=L1550P5DFB	Bought	$84.14
			ML925B45F	https://www.thorlabs.com/thorproduct.cfm?partnumber=ML925B45F	Bought	$52.48
	Aspheric lens Collimator	Thorlabs	C230TMD-C	https://www.thorlabs.com/thorproduct.cfm?partnumber=C230TMD-C	Bought	$73.05
	Isolator	Thorlabs	IOT-4-1550-VLP	https://www.thorlabs.com/thorproduct.cfm?partnumber=IOT-4-1550-VLP		$1,560.42
	Splitter	Thorlabs	CM1-BP108	https://www.thorlabs.com/thorproduct.cfm?partnumber=CM1-BP108		$255.38
	Two Detectors PD	Thorlabs	PDA10D2	https://www.thorlabs.com/thorproduct.cfm?partnumber=PDA10D2		2* $568.12
	Spherical lens Focusing lens	Thorlabs	LBF254-200-C	https://www.thorlabs.com/thorproduct.cfm?partnumber=LBF254-200-C		$60.59
NO	Two T controller					
	Current controller					
	LD	Nanoplus or		https://nanoplus.com/fileadmin/user_upload/Data_sheets/nanoplus_DFB_1650-1850nm.pdf		
		LD-PD INC	PL-DFB-1814-A-A81-SA	http://www.ld-pd.com/?a=cpinfo&id=592		
	Aspheric lens Collimator					
	Isolator	Thorlabs	I2300C4	https://www.thorlabs.com/thorproduct.cfm?partnumber=I2300C4		$2,227.89
	Splitter	Thorlabs	CM1-BP108	https://www.thorlabs.com/thorproduct.cfm?partnumber=CM1-BP108		$255.38
	Focusing lens	DPMphotonics	02-024-2000	https://www.dpmphotonics.com/product_detail.php?id=246		
			02-025-2000	https://www.dpmphotonics.com/product_detail.php?id=247		
	Two Detectors PD	Thorlabs	PDA10D2	https://www.thorlabs.com/thorproduct.cfm?partnumber=PDA10D2	CO	2* $568.12
HF	Two T controller	Thorlabs	TED200C	https://www.thorlabs.com/thorproduct.cfm?partnumber=TED200C	CO	$1,069.13
	Current controller	Thorlabs	LDC205C	https://www.thorlabs.com/thorproduct.cfm?partnumber=LDC205C	CO	$1,091.86
	LD 1280nm	NanoPlus		https://nanoplus.com/en/products/distributed-feedback-lasers/1100-nm-1300-nm/		
	Aspheric lens Collimator	Thorlabs	LTN330-C	https://www.thorlabs.com/thorproduct.cfm?partnumber=LTN330-C		$252.13

	Isolator	Thorlabs	IO-4-1310-VLP	https://www.thorlabs.com/thorproduct.cfm?partnumber=IO-4-1310-VLP		$947.94
	Splitter	Thorlabs	CM1-BP108	https://www.thorlabs.com/thorproduct.cfm?partnumber=CM1-BP108		$255.38
	Focusing lens	Thorlabs	LBF254-200-C	https://www.thorlabs.com/thorproduct.cfm?partnumber=LBF254-200-C		$60.59
	Two Detectors PD	Thorlabs	PDA10D2	https://www.thorlabs.com/thorproduct.cfm?partnumber=PDA10D2	CO	2* $568.12
SO_2	Two T controller					
	Current controller					
	LD 2460 nm	NanoPlus		https://nanoplus.com/fileadmin/user_upload/Data_sheets/nanoplus_DFB_2200-2600nm.pdf		
	Aspheric lens Collimator					
	Isolator	Thorlabs	I2500C4	https://www.thorlabs.com/thorproduct.cfm?partnumber=I2500C4		$3,193.31
	Splitter					
	Two Detectors PD	Thorlabs	PDA10D2	https://www.thorlabs.com/thorproduct.cfm?partnumber=PDA10D2	CO	2* $568.12
HCl	Two T controller					
	Current controller					
	LD 1742 nm	Nanoplus		https://nanoplus.com/en/products/top-wavelengths/17420-nm/		
	Aspheric lens Collimator					
	Isolator					
	Splitter					
	Focusing lens					
	Two Detectors PD	Thorlabs	PDA10D2	https://www.thorlabs.com/thorproduct.cfm?partnumber=PDA10D2	CO	2* $568.12

Table 4 List of Main elements of the planed experiment, for each gas. The company and the link where it is found. Its serial number and price. Moreover, a note if it is bought yet or if it is the same used for other gases. Partially from [18]

The synchronal detector can be simply replaced by a program, which compare the values measured from the two detectors.
Additionally, we have in the laboratory a CAN converter, an oscilloscope and a 15V power supply. The amplifiers were not included in the preliminary examination. On the other hand, there was many detailed material parts concerning the adapting or mounting of the main optical elements.

2.2 Problem

Because of the Corona pandemic, we are not able to order the rest elements of the planed experiment. We have only what we ordered before. The LD controller, the temperature controller, the LD mount and the LD for CO measurement with a corresponding collimator.
Therefore, we can just study CO instead of four gases.

Moreover, we need necessarily a detector. These elements are without at minimum one detector, useless.

2.3 The search of a solution

First, we looked hopefully to the month before us. We want to prepare all we can while waiting for a chance to get the remaining devices. Therefore, I trained myself in WPF, Windows Forms and C#. The aim was to prepare the interface between the detector and the laptop.
Soon we change our strategy toward instructing a detector or finding one, which is including in an ordinary device.
We were looking for an IR sensor in the middle IR. Most of the daily devices, which use IR, like the remote control, reach only 950nm. [19]
A technical device that I hope to be the solution was the parking sensor of cars. It is in common use and few devices manuals announce to detect over the IR interval (1550nm too). [20] Other device internet sites do not give an information about the wavelength. Therefore, we have to experiment with the parking sensor that is present in the market. Unfortunately, the sensors used here, work with ultrasonic waves (40 KHz)
I suggest installing the bought sensor seen in Appendix 2 as parking or security sensor at the power plant.

In July, we found that we perhaps could use the IR camera as detector.
The MELEXIS IR camera was used before for the safety valve of the incinerator.

2.4 Alternative Experiment

With just one detector, I propose to compare the cases: “with” and “without” gas between laser and camera. Instead of the results of two detectors: one before and one after the gas. Therefore, we do not need a splitter nor an isolator.

Figure 6 actually setup

Figure 6 represents the alternative experimental setup. Current/LD and temperature controllers control the LD in the LD mount. The IR camera detect the Laser radiation. The Arduino processes the information and display them on the Laptop. For a detailed description of the elements, see the appendix 1(P.62).

2.5 Indoor Experiments

The indoor experiment has one problem. How to produce CO without increasing the temperature around the camera. The CO in the power plant comes an O_2 rear combustion.
CO is also a result from a chemical reaction:

Equation 1 $$HCOOH \xrightarrow{H_2SO_4} H_2O + CO$$

The formic acid HCOOH with his catalyzer, the sulfuric acid H_2SO_4 dehydrate and gives carbon monoxide CO. This reaction is unfortunately also used for suicides in closed cars.
The aim from this experiment was to make a table: we now the quantity of CO and get the reaction of the camera. To use this table in the contrary direction. We will see by the power plant the resulting graph and conclude the concentration of CO.
After the first experiment with CO, I see that this is not realizable. The reaction of the camera is very small.
The first experiment was with the limit concentration of CO that is allowed in the air. I want to take this line as limit line. However, it is too near to the main oscillation of the laser signal without CO in the air.
First, we repeated the experiment with a high concentration to see a noticeable result. I hope that the experiments with higher concentrations allow us to conclude the influence of low concentration on the camera.
We encountered two problems: we have to put the powder (HCOOH) and the liquid (H2SO4) far from each other, to avoid the reaction before closing the container hermetically. Because the CO is very toxic. Than we mix the two. However, we cannot be secure that all the powder reacts with all the liquid. Especially because their rest powder in the bottom. Therefore, we can say that there is a high concentration of CO. We know her approximately, but the exactitude is not enough for low concentrations.
The second problem was that the CO takes volume. Our volume is fix. Therefore, the pressure will rise. Moreover, we do not know how much our glass container endures.
The solution that we could realize was to let the Arduino calculate the concentration. For a program, small variations are not a problem. At minimum, what we need.
There was one difficulty: The Arduino do not save the results. That is why; we can only compare the old value with the new, by creating an additional variable and by define the main variable at the beginning of the program, outside the loop.

2.5.1 First Experiment: activate Melexis with Arduino

20.8.20.

To run an Arduino program, you have to verify the program with the √ button then upload it with the -> button. First time the Program run without errors (**Error! Reference source not found.**). M ake sure that all three files: get temperatures, MLX90621.cpp and MLX90621.h are in the same folder and open.

The laser is off yet.

Program 1 first time the program run

Go to Tools -> Serial Monitor

```
Reading sensor...
Time taken: 59
[24.47, 25.46, 26.50, 24.00, 25.41, 26.87, 26.95, 24.56, 26.97, 25.63, 26.56, 25.22, 25.83, 26.41, 26.47, 25.46]
[27.00, 26.03, 26.50, 26.02, 26.00, 25.85, 27.18, 25.86, 25.92, 26.67, 26.62, 26.35, 25.78, 25.73, 26.37, 26.00]
[26.67, 25.85, 26.63, 25.34, 25.71, 26.19, 26.52, 26.11, 27.06, 25.82, 27.16, 25.98, 25.74, 25.67, 26.77, 25.75]
[26.37, 26.05, 25.07, 25.34, 25.47, 26.39, 26.13, 26.26, 25.21, 25.10, 25.59, 25.72, 27.09, 25.86, 26.74, 26.17]
Ambient temperature: 28.03°C
```

Serial Monitor 1

As you see in Serial Monitor 1, the ambient temperature is 28. 03 °C. It is the average of the 16x4=64 temperatures. The program takes 59 ms to calculate it.

The Arduino is ready now. We can actuate the Laser.

2.5.2 Preparations to activate the Laser: Grounding the devices

We have to ground it first. For human and devices' safety, this is necessary.

On the 22.8.2020, the Grounding was completed. Like you can see in the images below.

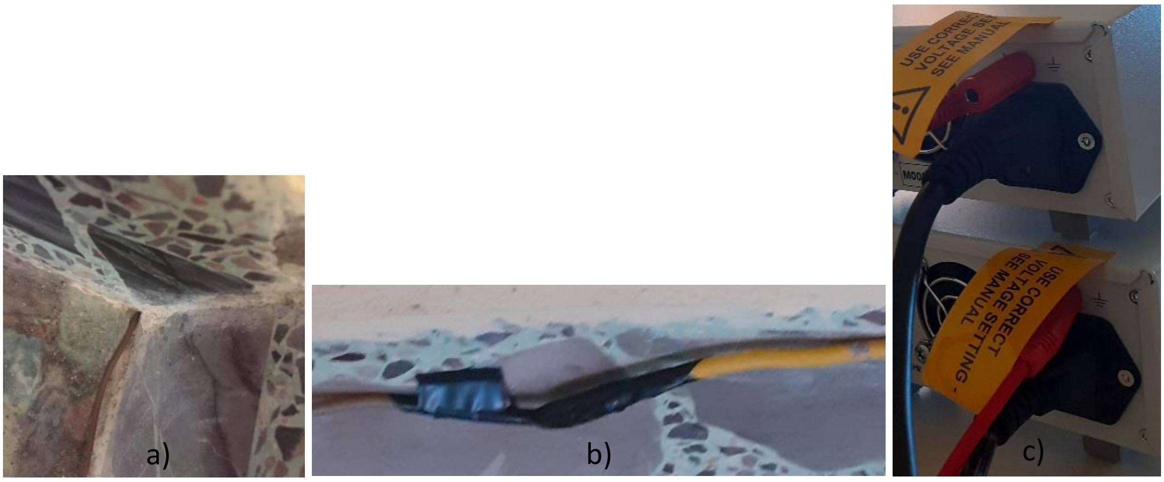


Figure 7 a) Plug in the corner between tiles. b) Connection to a longer cable. c) Labor cables in the grounding place of the two controllers.

Grounding completed as shown in Figure 7.

2.5.3Second Experiment:

22.8.20
Aim: See the influence of the Laser at the serial monitor.
For this reason, we compare the monitor when the Laser is off and when it is on.
Without Laser:

```
Reading sensor...
Time taken: 59
[25.94, 25.46, 26.51, 24.47, 25.89, 25.24, 26.73, 26.08, 25.99, 26.15, 26.01, 26.37, 26.25, 27.44, 26.52, 25.95]
[26.67, 27.25, 26.86, 26.50, 25.81, 26.20, 27.23, 26.54, 26.07, 27.02, 27.15, 26.80, 26.91, 26.37, 26.43, 26.36]
[26.92, 26.58, 26.39, 26.55, 26.40, 27.02, 26.58, 27.08, 26.56, 26.55, 27.60, 26.34, 26.63, 26.12, 26.91, 26.88]
[26.41, 26.40, 26.04, 26.50, 25.62, 26.64, 26.39, 25.93, 26.68, 26.02, 27.07, 25.62, 26.73, 26.36, 25.58, 24.97]
Ambient temperature: 28.14°C
```

Serial Monitor 2 Serial Monitor when the Laser is off yet to compare it when it is on

Laser on:
The distance between laser and detector was 24 cm. I_{LD}=30mA.
There is no difference. The reason is that P_{LD} reach only 0.2mW.
I change the LD. I substituted the ML925B45F with I1550P5DFB. To see if the LD was the problem.
NO both reach only 0.2mW even though the current is set at 20mA or even at $I_{Lim,}$ 50mW by ML925B45F and 40mW by I1550P5DFB. This is one difference of the two LDs. The other is that I1550P5DFB is studied.
To solve the problem, I communicate with Thorlabs. I chat with them as Samir Mourad, because he is their official costumer.
They told me to change to CP mode.

2.5.4 Third experiment: CC vs CP

Laser off:

```
Reading sensor...
Time taken: 59
[24.94, 24.71, 26.09, 24.80, 26.26, 26.19, 27.81, 26.20, 27.40, 26.22, 25.83, 26.45, 26.36, 26.37, 26.21, 26.10]
[26.62, 26.63, 26.65, 26.41, 25.85, 26.39, 26.73, 26.34, 27.36, 26.80, 26.84, 27.30, 26.60, 26.25, 26.86, 26.57]
[26.62, 26.55, 26.56, 26.13, 26.41, 26.32, 26.36, 26.46, 26.69, 27.20, 26.62, 27.06, 26.64, 26.91, 27.19, 25.93]
[26.00, 26.29, 26.55, 25.98, 26.23, 26.23, 26.72, 25.64, 25.78, 26.60, 26.78, 25.82, 25.67, 25.48, 26.24, 25.09]
Ambient temperature: 27.71°C
```

Serial Monitor 3 when the laser is off

We always take a new screenshot of the serial monitor, when the laser is off, as reference for each experiment.

2.5.4.1 Laser on in CP mode

Figure 8 the CP mode, LD is cathode grounded and the PD is anode grounded

```
Reading sensor...
Time taken: 59
[27.62, 27.05, 28.32, 26.20, 28.27, 27.84, 28.68, 27.71, 27.79, 27.48, 27.34, 27.34, 26.42, 27.42, 28.43, 27.15]
[27.64, 27.90, 27.31, 27.69, 27.24, 27.67, 27.82, 27.93, 26.94, 27.89, 28.21, 27.38, 26.90, 28.11, 27.50, 27.95]
[28.31, 27.83, 28.22, 28.04, 28.21, 28.08, 28.76, 28.34, 28.49, 40.00, 77.70, 28.53, 28.02, 27.79, 30.81, 28.17]
[27.37, 27.57, 27.72, 27.46, 26.82, 27.30, 27.36, 27.36, 27.17, 27.65, 27.48, 27.66, 27.32, 27.91, 27.97, 27.93]
Ambient temperature: 29.17°C
```

Serial Monitor 4 while the LD is on CP mode

Success!
The constant power mode has an influence to the IR camera. As seen in Serial Monitor 1, in this case, two pixels detect the laser. One of them detect the main radiation and is heated to 77.7 °C, the other pixel detects a lower power. Therefore, it displays just 40 °C.
Note:
This consequence was noticed after Experiment 4. In this experiment here, the increase of the ambient temperature was noticed as Laser influence.

2.5.4.2 Laser on CC mode

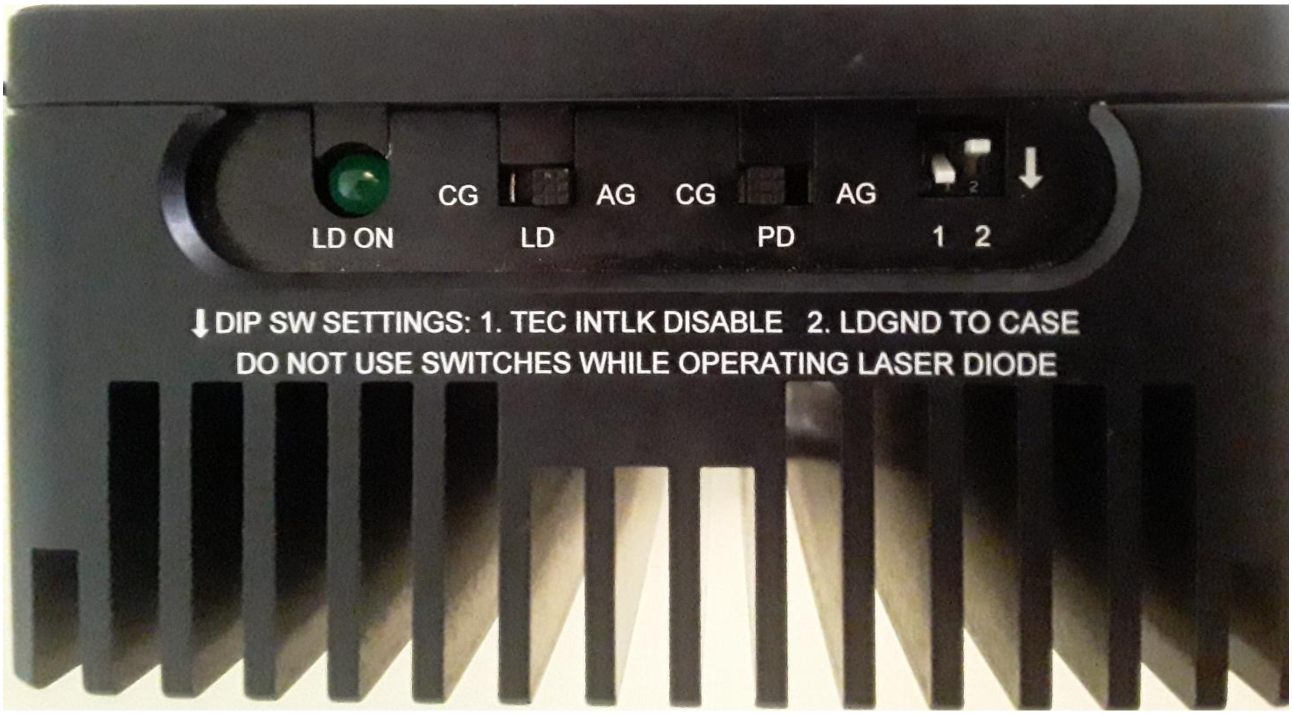


Figure 9 CC mode, the LD is anode grounded and the PD is cathode grounded

```
Reading sensor...
Time taken: 58
[26.84, 27.04, 28.46, 26.05, 27.78, 28.00, 27.73, 27.33, 27.25, 27.78, 27.86, 27.63, 26.59, 27.27, 27.78, 28.00]
[27.45, 27.77, 27.50, 27.01, 26.85, 27.76, 27.53, 27.28, 27.34, 27.68, 27.93, 27.16, 27.41, 27.92, 27.87, 27.62]
[27.86, 28.12, 27.28, 28.53, 27.76, 27.69, 28.48, 27.52, 27.37, 28.09, 27.98, 27.49, 28.21, 27.69, 28.16, 28.56]
[27.11, 27.07, 26.89, 26.64, 27.11, 27.68, 27.75, 27.65, 27.70, 28.04, 27.77, 27.94, 27.11, 26.93, 27.78, 27.15]
Ambient temperature: 29.42°C
```

Serial Monitor 5 while CC mode

There is no reaction. In the monitor above (Serial Monitor 5), no pixel is heated. Nevertheless, the ambient temperature is 29.42°C higher than in the monitor without Laser influence (Serial Monitor 3). This is the consequences of the Laser in CP mode (actuate just before this) and not from the Laser in CC mode. It is assumed that the CC mode have an influence at the detector that detect intensities. However, this detector is an IR camera.
I continued in CP mode.

2.5.5 Experiment 4

I_{LD}=12.05mA, P_{LD}=11.2 mW, I_{PD}=0.130mA

```
[28.29, 27.07, 28.92, 26.98, 27.65, 28.31, 28.16, 27.38, 28.27, 27.83, 28.26, 28.18, 28.33, 28.76, 28.16, 27.95]
[28.70, 28.37, 28.39, 28.58, 29.07, 28.72, 28.65, 28.29, 28.74, 29.41, 28.39, 28.24, 28.87, 28.28, 28.41, 28.51]
[28.98, 29.41, 29.69, 28.70, 28.88, 31.08, 31.32, 30.00, 31.06, 81.66, 190.81, 31.56, 29.41, 32.28, 43.76, 30.12]
[27.95, 29.80, 29.77, 29.12, 28.74, 28.57, 29.17, 28.29, 28.23, 28.32, 29.90, 28.24, 28.55, 27.69, 28.08, 28.65]
Ambient temperature: 29.53°C
```

Serial Monitor 6 while P_{LD}=11.2mW

We see in the middle of each IR photo, a very high temperature. Here 190 °C and 81/82 °C.
This is the Lasers consequence!

2.5.6Plan for the experiment with CO

For the indoor Experiment with CO, we can use chemically produced CO.

Equation 1 $$\mathrm{HCOOH} \longrightarrow \mathrm{H_2O} + \mathrm{CO}$$

We revoke the water from the formic acid by adding sulfuric acid to it.
We will obtain CO, without an increase in temperature. Which would be a grand error.
Formic acid will cost 75 000 LL / l. It costs 25 000 LL for 211 g of powder.

The table below (Table 5) is from this excel file. It aids the documentation of future experiments.

EXPsheet.xlsx

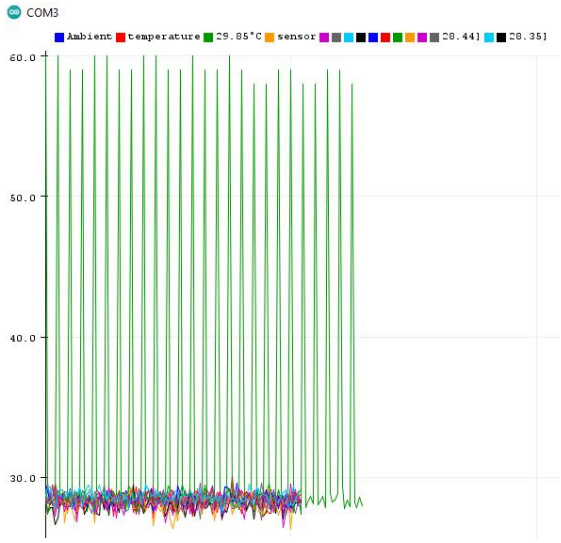
EXP	**LD type**			**CO**				
Nr.	ML925B45F	l1550P5DFB		x/√	quantity	d_{LD}	d_C	
1								
	LD controller							
					const		LD POL	
Nr.	I_{LIM}	I_{LD}	P_{LD}	I_{PD}	I	P	AG	CG
1								
	T controller							
Nr.	I_{LIM}	T_{SET}	T_{ACT}	I_{TEC}	PID cal x/√	Sensor		
1								
	LD Mount							
	LD		PD		1		2	
Nr.	CG	AG	CG	AG	up	down	Up	Down
1								
	Results							
	Camera	Arduino						
Nr.	D	T_{max}	T_{av}					
1								

Table 5 Table avail the documentation of the planed experiments

1.9.20

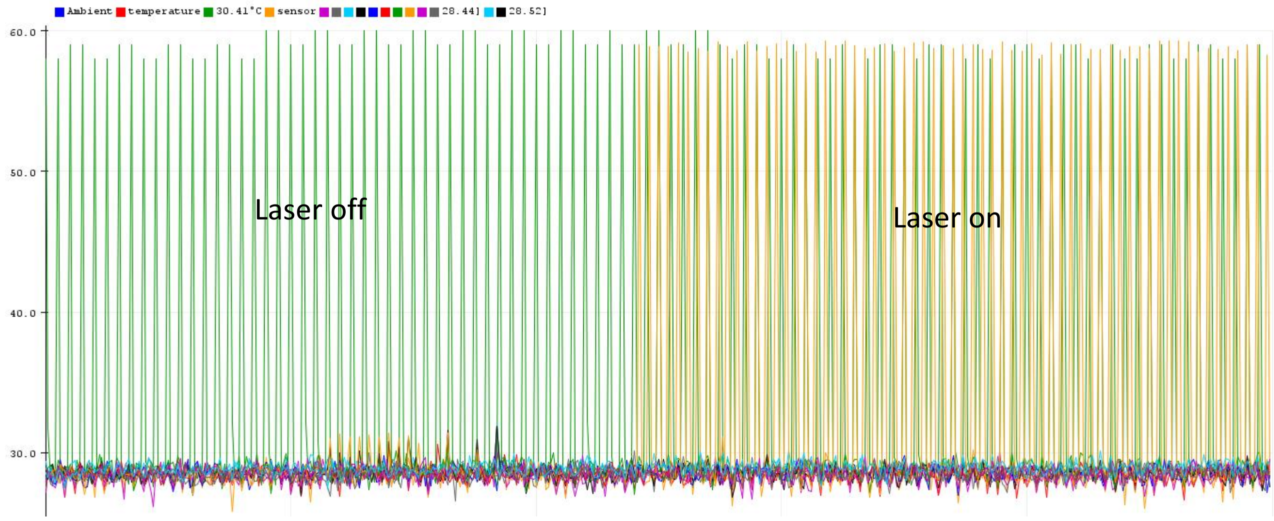
2.5.7Experiment 5 Plotter

There must exist a method in Arduino to program a plot (graph). The Arduino itself have serial plotter.
Arduino ->Tools-> Serial Plotter
Work?



Serial Plotter 1 First time the serial plotter is displayed

Yes.
With laser?
D_{lc}=10cm



Serial Plotter 2 shown the difference if the Laser is on or not

The serial plotter plots every “serial. Print” order. Therefore, the all unneeded graphs must be cleaned form the plotter to have a noticeably graph of the laser’s radiation.

2.5.8 Experiments for Plotter development

2.5.8.1 Experiment 6

To control the scale of the y axes of the plot, you can at the lower and the upper border as serial.println() orders (Figure 10 left). They will be printed in the serial monitor without sense. The Y-axes is now scaled but the 200°C are always plotted (Figure 10 right).

```
Serial.print("Time taken: ");
Serial.println(time_taken);

for(int y=0;y<64;y+=16){ //go through all the rows

    Serial.print('[');
    for(int x=0;x<16;x++){ //go through all the columns
        Serial.print(temperatures[y+x], 2);

        if (x < 15) {
            Serial.print(", ");
        }
    }

    Serial.println(']');

}
Serial.println(200);
Serial.println(0);
```

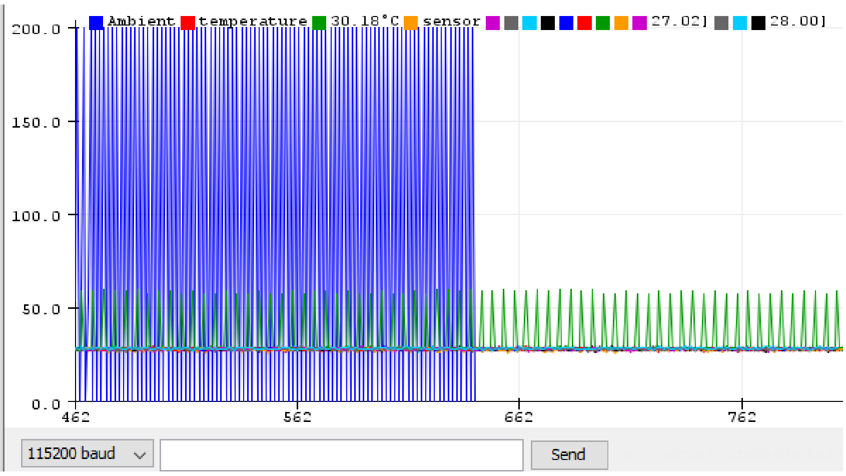


Figure 10 Arduino program at the left. Serial plotter at the right

To change the graph of 200 to white, you have, according to [23], to go to the theme of Arduino (Arduino-1.8.11-> lib -> theme) and change there the plotting advices.
"200" is the first print advice so it is the first plotted graph. Its color have a hex code of #0000FF. Changing it to #FFFFFF, which correspond to white [24], let the unneeded in Figure 10 right, blue graph disappear.
Note:
I have to create an administrator account to be able to change something in the theme of Arduino (Figure 11).

```
# GUI - PLOTTING
plotting.bgcolor = #ffffff
plotting.color = #ffffff
plotting.gridcolor = #f0f0f0
plotting.boundscolor = #000000
plotting.graphcolor.size = 8
plotting.graphcolor.00 = #0000FF
plotting.graphcolor.01 = #FF0000
plotting.graphcolor.02 = #009900
plotting.graphcolor.03 = #FF9900
plotting.graphcolor.04 = #CC00CC
plotting.graphcolor.05 = #666666
plotting.graphcolor.06 = #000000
plotting.graphcolor.07 = #000000
```

theme - Notepad
File Edit Format View Help

```
buttons.status.color = #ffffff

# GUI - PLOTTING
plotting.bgcolor = #ffffff
plotting.color = #ffffff
plotting.gridcolor = #f0f0f0
plotting.boundscolor = #000000
plotting.graphcolor.size = 8
plotting.graphcolor.00 = #FFFFFF
plotting.graphcolor.01 = #FF0000
plotting.graphcolor.02 = #FFFFFF
plotting.graphcolor.03 = #FF9900
plotting.graphcolor.04 = #CC00CC
plotting.graphcolor.05 = #666666
plotting.graphcolor.06 = #00CCFF
plotting.graphcolor.07 = #000000
```

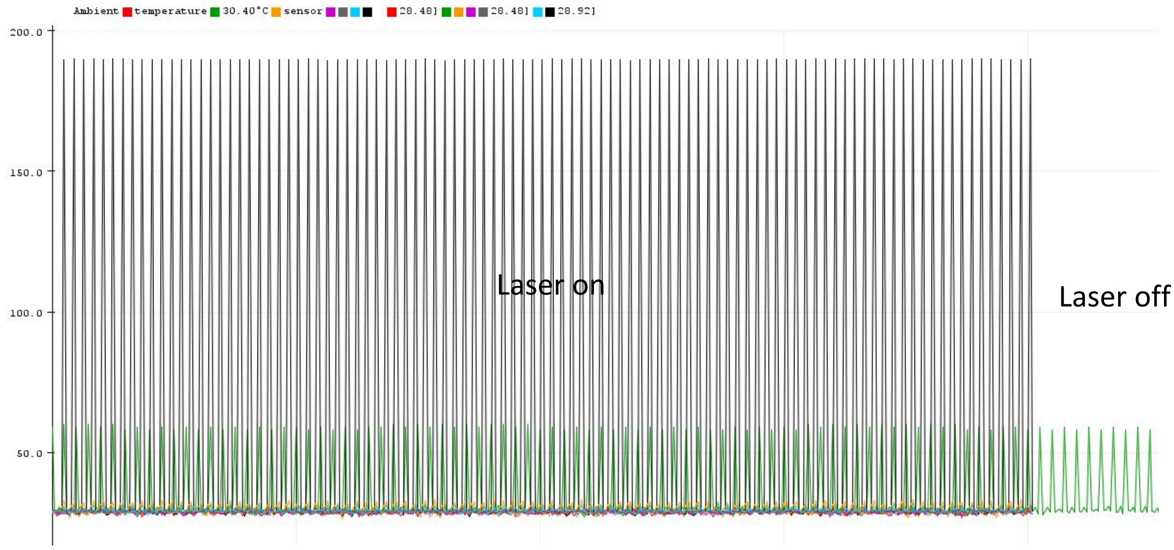
Figure 11 Arduino theme #0000FF-> #FFFFFF in experiment 6. #009900-> #FFFFFF in experiment 10

Nevertheless, there is a second unneeded curve (green). What is its origin?

Laser on:

I_{LD}=20mA, P_{LD}=27.6mW, I_{PD}=0.321mA.

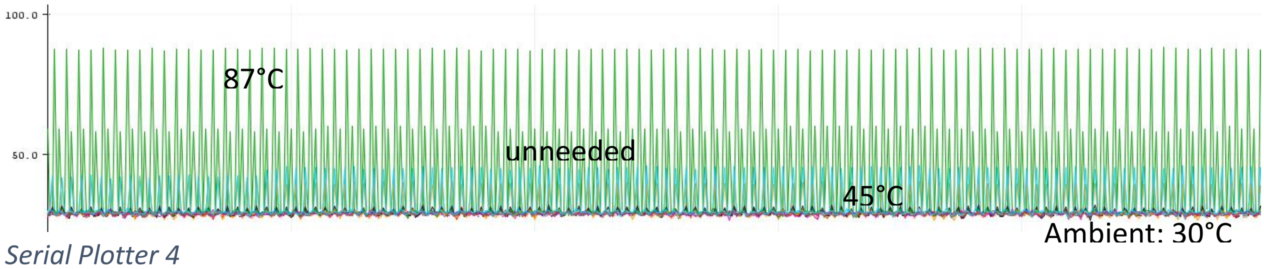
In Serial Plotter 3 the laser radiation in black you can see the black laser radiation more clearly than in Serial Plotter 2 **Error! Reference source not found.**.



Serial Plotter 3 the laser radiation in black

2.5.8.2Experiment 7

When the D_{Lc}: 10cm-> 22cm, the temperatures influenced of the laser radiation decrease. Tmax in Serial Plotter 2 is 190°C decrease to 87.82 °C in Serial Plotter 4.



Serial Plotter 4

```
[28.50, 27.50, 28.94, 27.72, 28.39, 28.36, 28.63, 27.31, 27.88, 27.95, 29.09, 27.68, 27.63, 28.28, 29.49, 29.10]
[29.65, 29.70, 28.28, 28.87, 28.65, 28.74, 29.36, 28.49, 28.46, 28.86, 29.28, 29.25, 28.41, 29.46, 29.66, 29.72]
[29.68, 29.37, 87.82, 39.19, 28.75, 29.90, 45.54, 31.09, 28.91, 29.15, 29.52, 29.38, 28.68, 28.77, 29.41, 28.80]
[27.45, 28.74, 28.48, 28.41, 28.35, 28.57, 29.87, 28.30, 28.13, 28.82, 29.30, 28.70, 28.77, 27.60, 28.09, 28.70]
Ambient temperature: 30.23°C
```

Serial Monitor 7

We see in Serial Plotter 4 that it is necessary to remove the unneeded green graph.

2.5.8.3Experiment 8

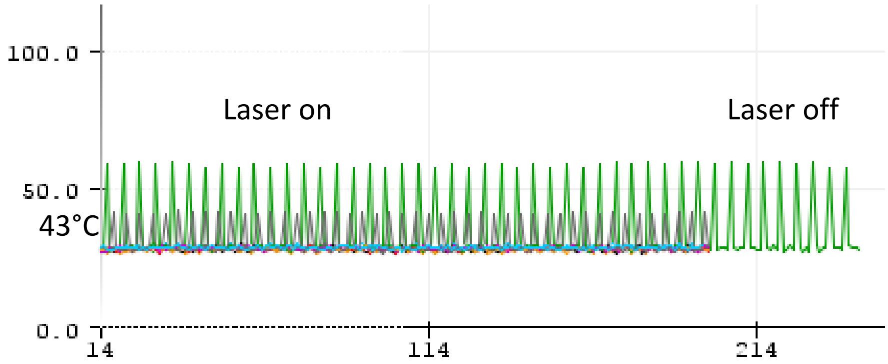
Still at d=22 cm

5mW is the typical power of the LD.

We decrease the P_{LD}: 27.6mW-> 5mW. T_{max} decrease from 87.8°C to 41°C. I_{LD} becomes 9.24mA.

```
[27.83, 28.48, 28.57, 26.57, 28.91, 28.28, 29.05, 28.15, 28.49, 28.96, 28.34, 28.10, 28.20, 28.54, 29.02, 29.70]
[28.52, 28.92, 28.74, 28.81, 29.15, 28.79, 29.31, 28.12, 28.51, 29.10, 29.23, 28.01, 28.46, 28.28, 28.44, 28.36]
[28.90, 28.67, 29.33, 28.74, 29.01, 41.35, 29.50, 28.25, 28.74, 28.73, 29.38, 29.73, 27.90, 28.52, 28.89, 28.10]
[28.38, 28.11, 28.63, 29.11, 28.84, 28.62, 29.41, 28.81, 27.83, 28.23, 28.81, 28.04, 29.20, 28.34, 29.07, 28.49]
Ambient temperature: 30.22°C
```

Serial Monitor 8 5mW d=22cm



Serial Plotter 5

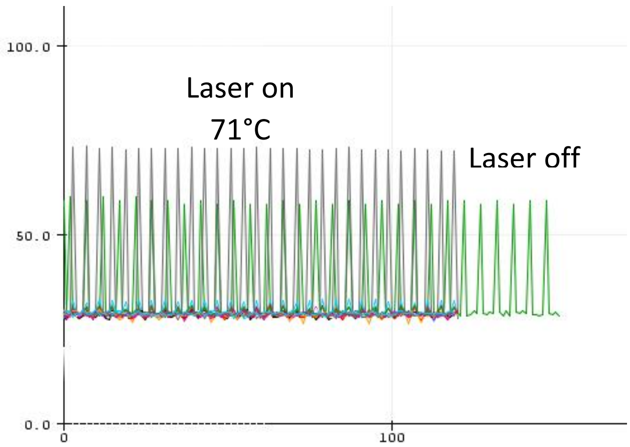
The Laser's influence is under the always-plotted graph!

2.5.8.4Experiment 9

The typically current of the LD is 20mA for 5mW.
I_{LD}=20 mA for a short time only, because if I rise the current the power rise automatically (Serial Monitor 9 and Serial Plotter 6). This is not preferable. The max power of the Photodiode is 10mW.

```
[27.28, 27.68, 28.11, 27.44, 27.63, 28.24, 28.88, 27.31, 28.59, 28.43, 28.40, 28.04, 28.41, 29.02, 29.67, 28.54]
[28.94, 28.53, 28.77, 28.11, 28.87, 28.62, 29.61, 27.95, 29.11, 28.93, 28.69, 28.53, 29.24, 29.14, 28.81, 28.59]
[29.35, 29.53, 28.79, 29.18, 28.63, 71.16, 32.42, 28.78, 28.89, 30.53, 30.14, 28.76, 28.76, 28.54, 29.57, 29.00]
[28.97, 28.32, 28.56, 28.72, 28.55, 28.65, 28.92, 29.56, 28.59, 29.55, 28.96, 28.70, 28.27, 28.40, 28.31, 28.84]
Ambient temperature: 30.16°C
```

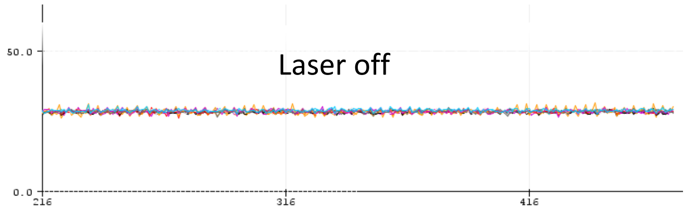
Serial Monitor 9 I_{LD}=20 mA, T_{max}= 71°C.



Serial Plotter 6 I_{LD}=20 mA

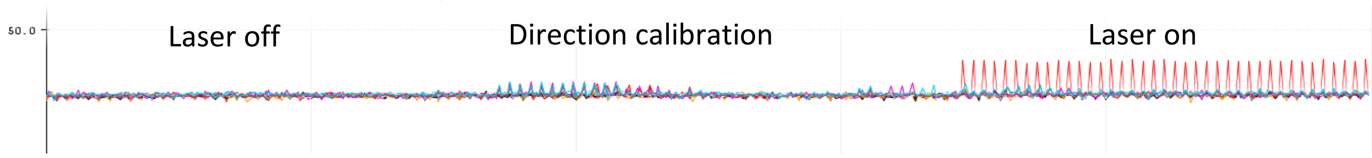
2.5.8.5Experiment 10

Color the second unneeded curve white.
The origin is probably: "float temperatures [64];" I say probably because it is not a print order. The Serial Plotter draw everything of the order print if it is a number. Nevertheless, the number 64 fits.
I go throw all hex codes mentioned in the Arduino theme and compare their colors with the color of the useless plot.
The color of this graph is dark lime green [25]. Its Hex code is #009900. In the theme of Arduino, you can change it to #FFFFFF, white, if you are the admin.
While the LASER is turned off, you can see in the graph below, only the ambient temperature.



Serial Plotter 7 first clear plot laser off

The Laser is reset to 5mW. In this graph, the Laser is seen clearly.



Serial Plotter 8 with clear laser plot

```
[27.79, 28.37, 28.57, 27.20, 28.66, 29.06, 28.50, 27.86, 28.20, 28.77, 27.67, 28.15, 28.68, 28.86, 27.75, 28.72]
[28.92, 28.05, 28.50, 28.26, 29.05, 28.73, 28.77, 27.67, 28.95, 28.75, 29.06, 28.75, 28.76, 28.40, 29.35, 27.60]
[29.50, 29.16, 29.44, 28.40, 29.09, 30.07, 29.42, 28.31, 29.26, 38.98, 57.57, 29.39, 29.62, 29.44, 29.78, 29.48]
[28.05, 28.54, 28.49, 29.01, 28.84, 28.38, 28.55, 28.61, 28.09, 27.78, 28.81, 28.45, 27.76, 28.59, 29.11, 28.47]
Ambient temperature: 29.74°C
```

Serial Monitor 10: 4 min after Serial Plotter 8

2.5.9Experiment 11

Approaching the camera from the Laser

D: 22cm -> 15.5cm. Two pixels have a temperature of 54°C instead of one 57°C.

```
[27.59, 27.88, 28.69, 27.18, 28.94, 28.10, 28.84, 28.23, 28.18, 28.86, 28.34, 28.24, 28.26, 29.49, 28.97, 28.80]
[28.54, 28.34, 28.06, 28.98, 28.35, 28.91, 29.31, 28.78, 29.37, 28.92, 29.04, 29.12, 28.63, 28.84, 29.05, 28.90]
[29.48, 28.76, 29.04, 28.48, 28.75, 29.58, 30.04, 29.79, 30.30, 32.62, 33.06, 28.97, 30.11, 54.71, 54.19, 29.77]
[29.45, 29.98, 29.75, 28.54, 28.26, 29.27, 30.28, 29.51, 29.35, 28.51, 29.76, 28.90, 28.99, 27.53, 29.55, 28.44]
Ambient temperature: 29.76°C
```

Serial Monitor 11 D=15.5cm

2.5.10 Experiment 12

Approaching the camera to the laser. D:15.5-> 10cm.

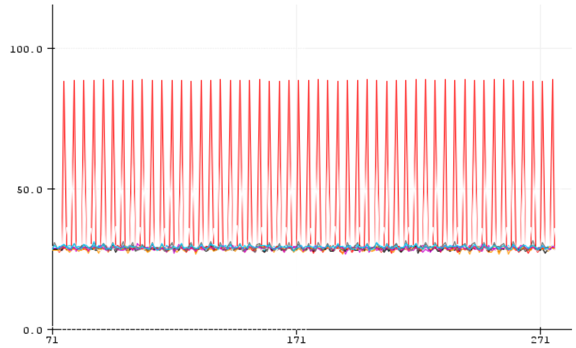
Increase to the max power of the LD: 5mW->11mW.

The I_{LD}=12.14mA

```
[27.17, 28.01, 28.82, 27.76, 29.53, 28.49, 29.46, 28.49, 28.03, 29.47, 28.23, 28.00, 27.87, 29.07, 29.40, 27.93]
[29.72, 28.47, 28.39, 28.15, 28.48, 29.13, 29.44, 28.80, 29.16, 29.52, 28.70, 28.25, 28.86, 31.20, 30.26, 28.82]
[29.70, 88.62, 35.89, 30.03, 29.19, 29.13, 29.61, 29.31, 30.00, 29.51, 29.40, 28.69, 28.90, 28.27, 29.40, 29.36]
[28.15, 27.95, 27.68, 28.45, 27.72, 28.17, 29.38, 27.08, 27.61, 28.10, 28.36, 28.07, 27.99, 27.43, 28.15, 27.25]
Ambient temperature: 29.83°C
```

Serial Monitor 12

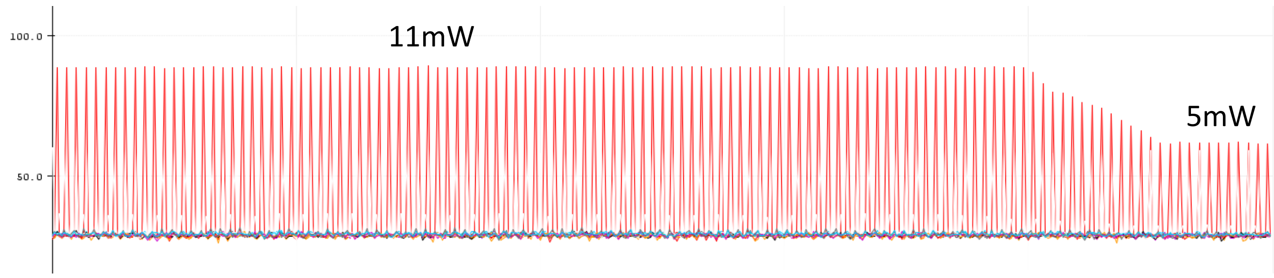
Comparing the Serial Monitor 11 and Serial Monitor 12. Tmax increase from 54°C to 88°C.



Serial Plotter 9 laser on 11mW at 10cm. T_{max}=88°C

2.5.11 Experiment 13

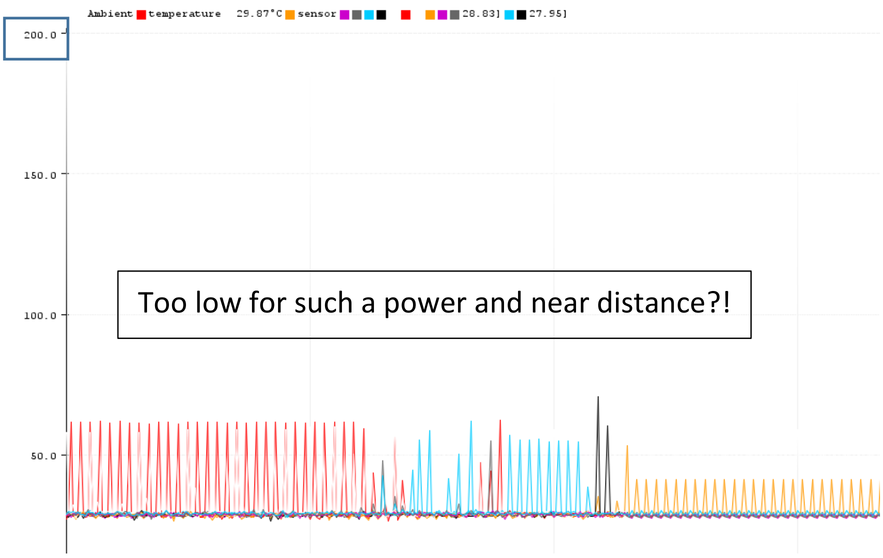
Decrease the power from 11mW to 5mW. The needed current becomes 9.36mA.



Serial Plotter 10: 11mW-> 5mW

2.5.12 Experiment 14

Decrease the distance between camera and LD. D: 10cm -> 5cm.
Increase the current to 27 mA. Aimed was the current near the limit 40mA.
The I_{PD} is 0.483mA.
Expected is a very high temperature and many influenced pixels.



Serial Plotter 11

```
200
0
[30.50, 29.62, 29.58, 29.31, 30.38, 29.88, 31.08, 29.47, 31.51, 30.34, 30.42, 30.11, 30.62, 31.14, 31.06, 30.17]
[32.08, 31.60, 30.74, 30.60, 32.61, 30.80, 31.60, 31.36, 32.13, 33.77, 32.75, 31.43, 36.74, 38.77, 36.56, 32.61]
[89.32, 284.34, 41.06, 35.65, 88.52, 299.37, 40.86, 34.40, 37.47, 38.92, 36.75, 32.67, 33.76, 34.28, 33.32, 31.71]
[31.97, 32.13, 31.66, 30.97, 31.06, 30.72, 29.92, 29.91, 31.24, 29.84, 30.56, 30.24, 31.14, 29.86, 29.94, 30.05]
Ambient temperature: 29.79°C
```

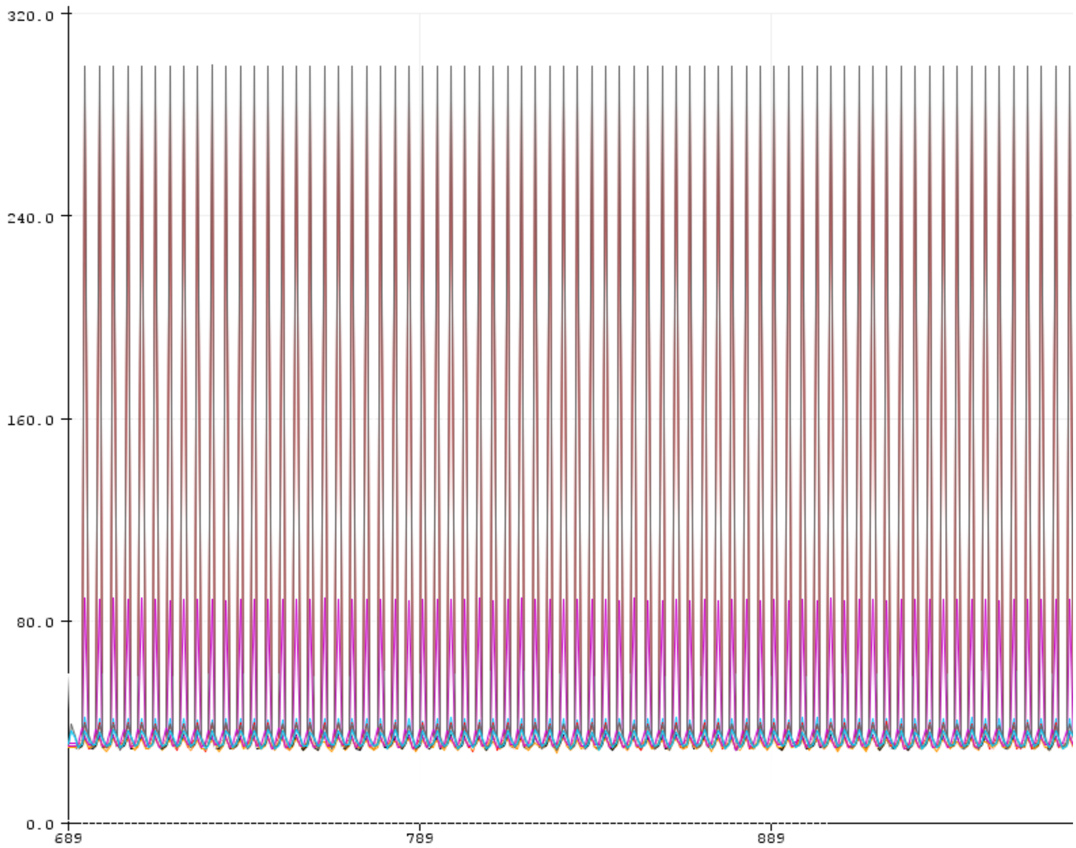
Serial Monitor 13 corresponding the Serial Plotter 11

In the serial monitor Serial Monitor 13 corresponding the Serial Plotter 11 are very high temperatures displayed. 299°C is higher than 200 the upper border of the serial plotter. Therefor the serial plotter do not plot this temperature.
We have to rise the y-axis to 300.

```
    Serial.print("Time taken: ");
    Serial.println(time_taken);
Serial.println(300);
Serial.println(0);
    for(int y=0;y<64;y+=16){ //go through all the rows
        Serial.print('[');
        for(int x=0;x<16;x++){ //go through all the columns
```

Program 2 Arduino program. Changing the upper border of the serial plotter from 200 to 300

The 299°C is now plotted. See Serial Plotter 12.



Serial Plotter 12

The MLX90621 is calibrated from -40˚C to 85˚C for the ambient temperature sensor and from - 50˚C to 300˚C for the object temperature.

NOTE: The sensor is able to detect higher temperatures, but it is not calibrated for temperatures above 300°C. [26]

2.5.13 Calculus for Experiment with CO

Equation 1 $$HCOOH \xrightarrow{H_2SO_4} H_2O + CO$$

2.5.13.1 Sulfuric acid properties:

Liquid 250ml
98%
1L -> 1.84 kg
MW = 98.08 g/mol
We ensure that we can use the micropipette with the sulfuric acid. The micropipette is from Pigmented Polypropylene, which is acid resistant at least for a short time. [16]

2.5.13.2 Formic acid properties

Solid powder 200 g
MW = 46 g/mol
We have with 200g, 4.3 mol.

2.5.13.3 Reaction

1mol HCOOH ———> 1mol CO

2.5.13.4 Concentration of CO

Equation 2 $$[\boldsymbol{CO}] = \frac{nM}{V}$$

[28]

M=28 g/mol [27]
We fixe V and change n by changing the masse of HCOOH.
We use:
https://www.lenntech.com/calculators/ppm/converter-parts-per-million.htm
to convert our concentration, which is in mg/m^3, into ppm (V).
There are different limits for CO depend on the country. From 50 ppm to 20ppm. We take the lowest one as limit: 20mg/m^3. Since we found a limit in mg/m^3, the link above is not necessary yet.

The volume of the cylinder of a height h of 11cm and a radius r of 3cm is.
Equation 3 $$V = \pi r^2 h$$

The volume occupied from the CO gas is
Equation 4 $$V_{CO} = \Pi r^2 (h - h_{HCOOH})$$

In the excel sheet you will find the calculation for many cases

CO8.9.20.xlsx

To produce the limit concentration of CO, the mass of the formic acid, , will be in micrograms, which is in reality not measurable.
Alternatively, we can control the sulfuric acid instead of the formic acid.
We can do this because we have a micropipette but no balance under 10 mg.
It is assumed that 1mol sulfuric acid catalyze 1mol formic acid.
It is no problem that we use virgin propylene with concentrated sulfuric acid.

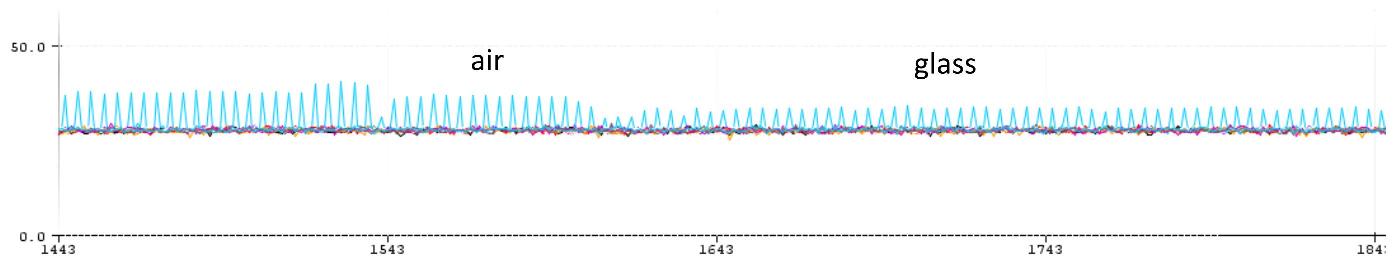
1L-> $1.84 * 10^3$ g
0.053304L<-98.08g
1 mol-> 0.053304L
! $1.366 * 10^{-6}$ mol ->$7.245 * 10^{-8}$ L=0.073µL

It keeps too small.
Therefore, we have to enlarge the volume!
We want to see the limit, the border of the CO concentration permitted.
We have a Volume of $13 * 10^{-3}$ m^3
We calculated it by using the fact that 1kg water =1l.
According to the excel calculus we need:
0.002626929 g from HCOOH, which we cannot measure.
Alternatively, 3.04404E-06 l of H_2SO_4, which we can God thanks control with the micropipette.

2.5.14 Experiment 15 Container Influence

What is the influence of the green convergent glass?

The volume of the container let us take a distance of 30cm between laser and detector.
The Laser is turned on at 5mW

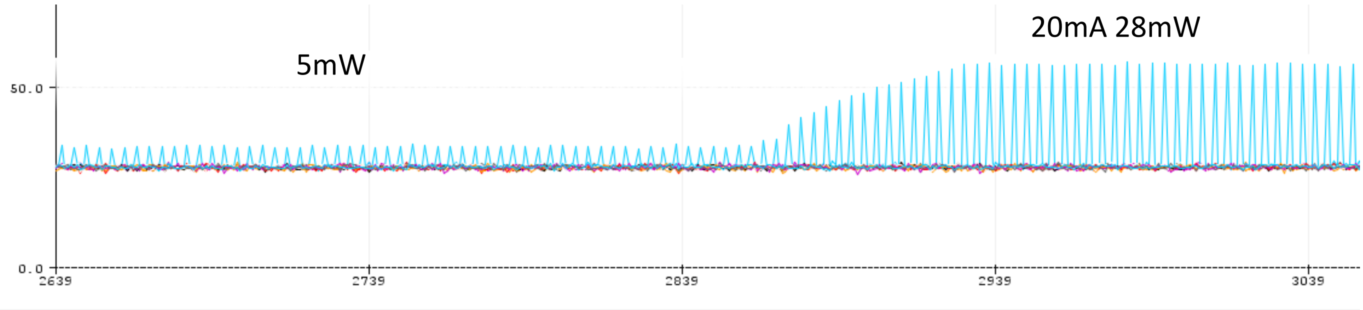


Serial Plotter 13 influence of glass at the radiation

The influence of the container is clearly seen.

2.5.14.1 Experiment 16

The current of the LD is increased to 20mA
Its power increase automaticaly from 5mW to 28mW
The glass container still between laser and detector.



Serial Plotter 14

2.5.15 Prepare the CO

9.9.20

3.4 µl of sulfuric acid (Figure 13 a) b)) and 0.5g of formic acid (Figure 13 c) d)) were taken to produce the limit concentration of CO in the green glass container.

Figure 13 a) sulfuric acid b) micropipette c) formic acid d) balance e) putting them in the volume f) hermetic closure of container

We put the powder and the liquid far from each other (Figure 13 e)).
After closing it hermetically (Figure 13 f)), we mixed it.

2.5.16 Experiment 17

Just camera

```
[27.81, 27.71, 27.59, 27.72, 29.11, 28.98, 27.69, 27.50, 28.73, 27.46, 27.62, 28.19, 27.78, 27.66, 28.09, 28.08]
[28.32, 28.00, 27.99, 28.00, 27.97, 28.20, 27.82, 28.31, 27.31, 27.91, 27.45, 27.12, 27.55, 28.30, 28.30, 28.01]
[28.51, 27.83, 27.83, 27.69, 27.88, 27.42, 28.01, 27.59, 28.07, 27.72, 28.28, 28.39, 31.18, 29.96, 29.04, 28.72]
[28.72, 30.06, 29.97, 29.25, 28.31, 28.08, 28.29, 27.56, 27.84, 27.54, 28.27, 28.12, 27.83, 27.39, 28.40, 27.20]
Ambient temperature: 28.29°C
```

Serial Monitor 14

Laser on 5mW

```
[28.61, 28.30, 28.72, 28.00, 28.61, 29.14, 27.62, 29.12, 28.88, 27.77, 28.51, 27.64, 28.59, 27.97, 28.51, 27.83]
[28.98, 28.84, 27.80, 27.79, 28.51, 29.11, 28.62, 28.32, 27.62, 29.20, 28.25, 28.14, 27.65, 28.62, 28.26, 28.22]
[28.09, 28.53, 27.88, 48.24, 29.14, 28.03, 28.80, 28.01, 28.38, 28.42, 28.69, 28.40, 28.32, 28.14, 28.02, 27.95]
[27.05, 27.24, 27.69, 28.02, 27.95, 28.40, 28.39, 29.14, 28.97, 28.72, 28.58, 28.30, 28.39, 29.19, 28.47, 28.28]
Ambient temperature: 28.70°C
```

Serial Monitor 15

With glass

```
[28.62, 29.38, 28.17, 28.01, 29.40, 28.08, 28.87, 28.21, 28.47, 28.15, 27.83, 28.87, 27.96, 28.85, 29.86, 28.73]
[29.00, 28.74, 28.12, 28.12, 29.08, 28.34, 28.54, 28.43, 27.63, 28.63, 28.92, 28.36, 27.56, 28.26, 28.36, 28.13]
[28.84, 28.36, 29.01, 33.25, 28.52, 28.33, 29.09, 28.33, 28.61, 28.62, 28.52, 28.72, 28.33, 28.16, 28.61, 28.72]
[28.50, 27.45, 27.90, 28.36, 28.86, 28.21, 28.61, 29.15, 28.40, 28.09, 28.27, 28.43, 29.15, 29.09, 28.25, 28.29]
Ambient temperature: 28.74°C
```

Serial Monitor 16

2.5.16.1 Experiment 18

Laser on 9mW

```
[29.66, 27.84, 29.30, 27.86, 29.07, 29.68, 28.52, 27.95, 28.89, 28.28, 27.51, 28.52, 28.35, 28.55, 28.76, 29.42]
[28.54, 28.35, 28.05, 27.72, 29.44, 28.28, 28.29, 27.75, 28.88, 28.38, 28.02, 27.69, 28.01, 28.01, 27.86, 28.58]
[28.66, 28.77, 28.12, 59.47, 28.14, 28.18, 28.48, 28.87, 28.31, 27.81, 28.46, 29.15, 28.78, 28.49, 28.55, 28.64]
[27.86, 27.68, 27.94, 28.28, 27.66, 28.24, 28.33, 28.13, 27.83, 27.79, 28.40, 28.57, 28.16, 27.62, 28.27, 28.43]
Ambient temperature: 28.81°C
```

Serial Monitor 17

With glass

```
[29.85, 28.80, 29.20, 29.67, 28.48, 29.61, 28.58, 29.06, 29.08, 29.19, 28.27, 28.34, 28.54, 29.28, 28.43, 28.06]
[29.67, 28.96, 28.95, 28.34, 28.62, 28.95, 28.00, 28.14, 29.07, 28.76, 29.42, 29.07, 29.26, 28.48, 28.50, 28.66]
[29.57, 28.39, 27.93, 32.47, 28.63, 28.65, 27.82, 30.25, 28.82, 29.13, 28.55, 28.83, 29.48, 29.06, 29.50, 29.04]
[28.60, 29.15, 28.72, 29.23, 28.29, 28.32, 28.83, 28.89, 28.37, 28.30, 28.59, 28.52, 29.48, 28.16, 29.62, 28.35]
Ambient temperature: 29.01°C
```

Serial Monitor 18

2.5.17 Experiment 19

Laser on 10mW 11mA 0.118mA

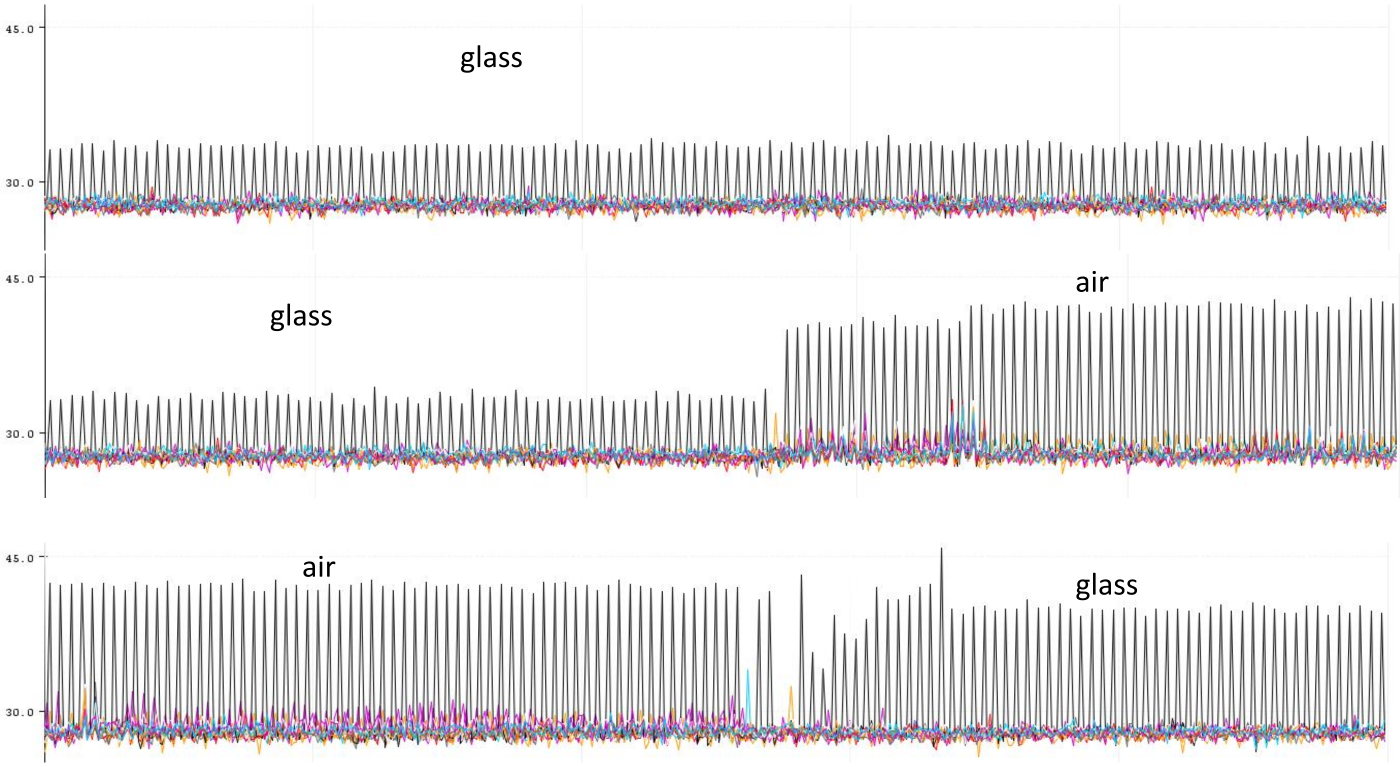
```
[27.70, 28.47, 27.47, 27.42, 28.46, 27.56, 27.91, 27.83, 27.79, 26.96, 26.94, 28.05, 27.46, 27.80, 27.32, 27.32]
[28.91, 27.84, 27.35, 27.20, 27.99, 28.09, 28.78, 27.86, 27.67, 27.61, 27.37, 27.30, 27.92, 27.84, 28.24, 27.67]
[28.98, 27.75, 28.41, 30.11, 28.25, 27.81, 27.93, 38.81, 28.43, 28.11, 28.38, 28.16, 27.75, 28.11, 28.28, 28.11]
[27.43, 28.29, 28.35, 28.07, 27.78, 27.74, 27.50, 27.56, 28.19, 27.91, 28.20, 28.34, 28.05, 28.10, 27.93, 26.72]
Ambient temperature: 28.87°C
```

Serial Monitor 19

With glass

```
[29.59, 28.74, 30.27, 28.58, 29.19, 28.77, 28.67, 28.36, 29.17, 28.20, 29.27, 28.55, 28.50, 29.26, 28.62, 28.25]
[28.58, 28.42, 28.02, 28.32, 28.93, 29.23, 28.38, 28.12, 28.05, 27.97, 28.29, 27.46, 28.50, 28.76, 29.04, 28.65]
[28.82, 27.73, 28.67, 28.64, 28.41, 28.07, 29.03, 35.44, 28.80, 28.74, 28.54, 28.21, 28.84, 28.47, 29.11, 28.48]
[28.03, 28.06, 28.21, 28.88, 28.16, 28.92, 28.71, 28.86, 28.34, 28.28, 29.22, 28.24, 28.44, 27.90, 29.01, 28.44]
Ambient temperature: 29.08°C
```

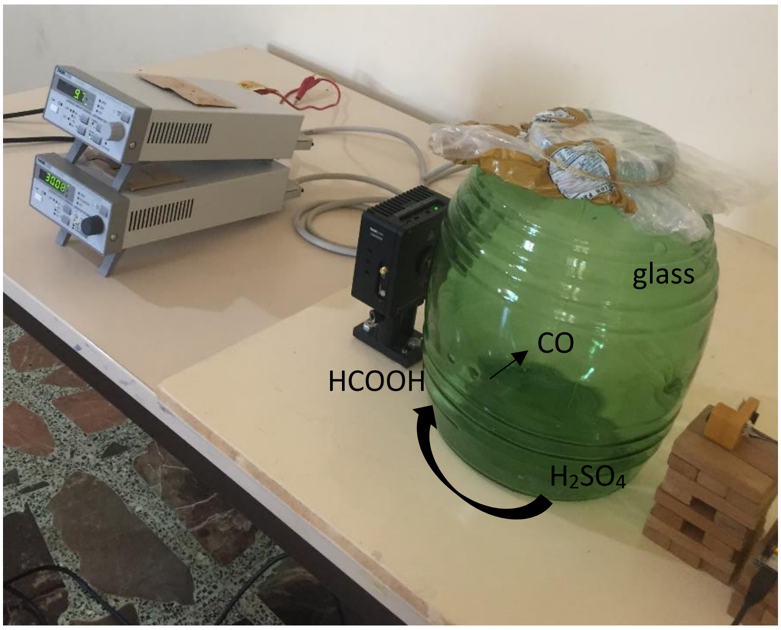
Serial Monitor 20



Serial Plotter 15

The glass container was placed in a way that allow the maximum of radiation to reach the detector. (Serial Plotter 15)

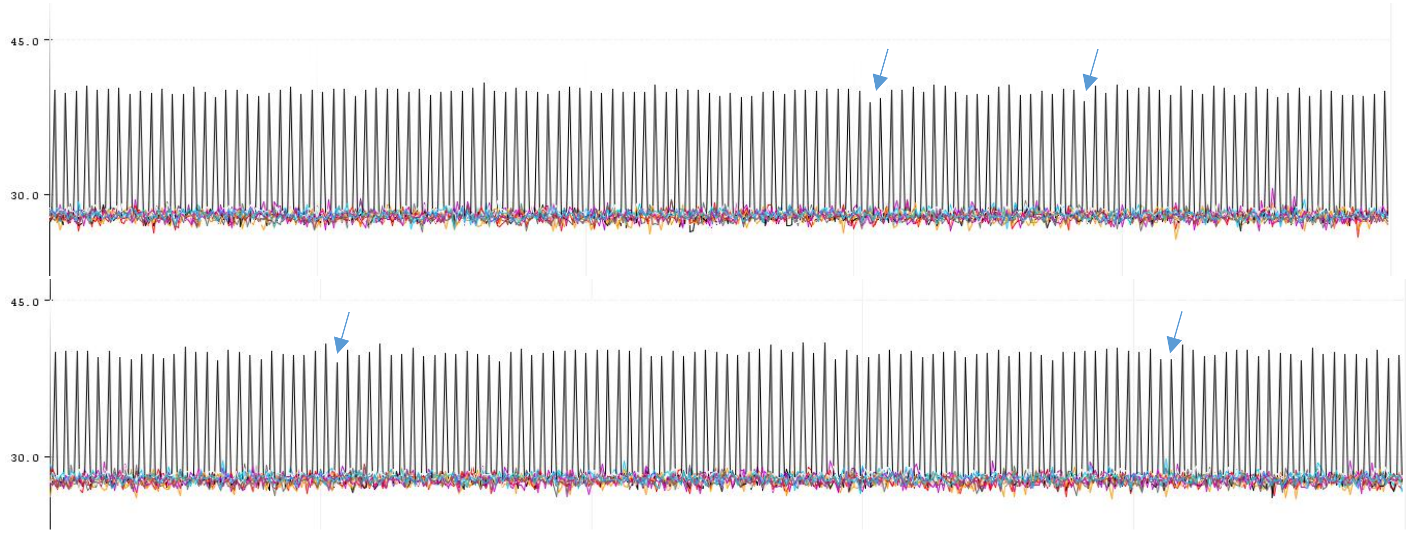
2.5.18 Experiment 20 With CO at limit concentration



```
[27.59, 27.93, 27.69, 26.30, 29.16, 26.82, 27.49, 26.57, 28.70, 28.85, 27.48, 27.63, 26.75, 27.55, 28.12, 27.62]
[27.56, 27.17, 28.24, 27.06, 27.95, 27.57, 28.38, 27.11, 27.86, 27.20, 28.48, 26.87, 27.67, 27.14, 28.03, 27.85]
[28.01, 27.82, 27.55, 27.94, 27.59, 27.60, 28.19, 40.23, 27.97, 27.70, 28.55, 27.93, 27.41, 27.30, 28.83, 28.29]
[27.28, 27.08, 26.71, 27.70, 27.18, 27.61, 27.37, 26.81, 27.45, 27.45, 27.94, 27.58, 28.13, 28.06, 27.06, 27.33]
Ambient temperature: 28.94°C
```

Serial Monitor 21 with CO in limit concentration

The variations and absorptions are better seen in a graph than in a monitor.

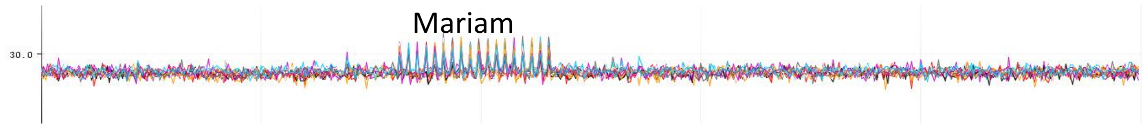


Serial Plotter 16 with CO in limit concentration

In Serial Plotter 16 there are anomalies. The Laser radiation is no more a clear sinusoidal curve. Nevertheless, we do not see the absorption clearly.
Therefore, we will repeat the experiment with a higher concentration of CO

2.5.19 Influence of human corps in front of camera

Laser off



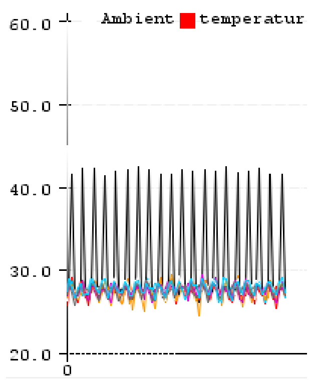
Serial Plotter 17 human temperature

When I was direct in front of the detector, it mesure my temperature.Serial Plotter 17

2.5.20 Preparation of higher concentration of CO

To see a clear absorption peak, a higher concentration of CO is produced. As you see in Figure 14, 10g of formic acid were taken. We put them in a small cylinder to have a higher concentration.

Laser on with glass in its path.
This is the influence of the small empty reservoir.



Serial Plotter 18 influence of small cylinder to the radiation

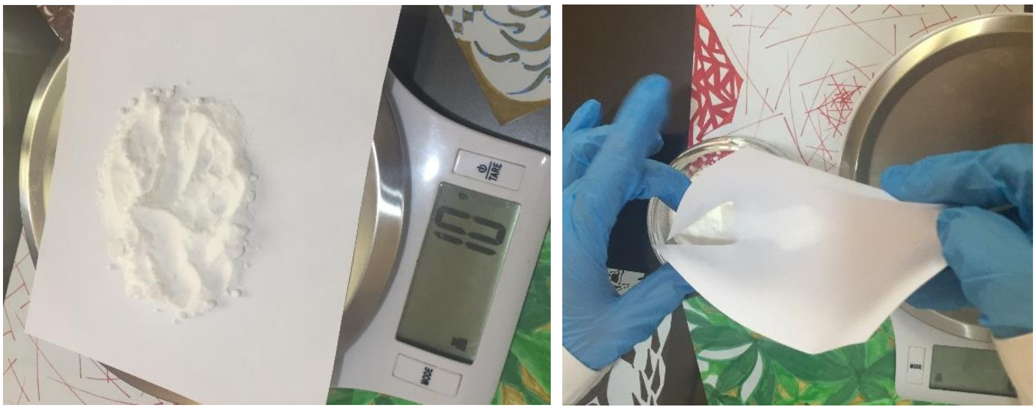
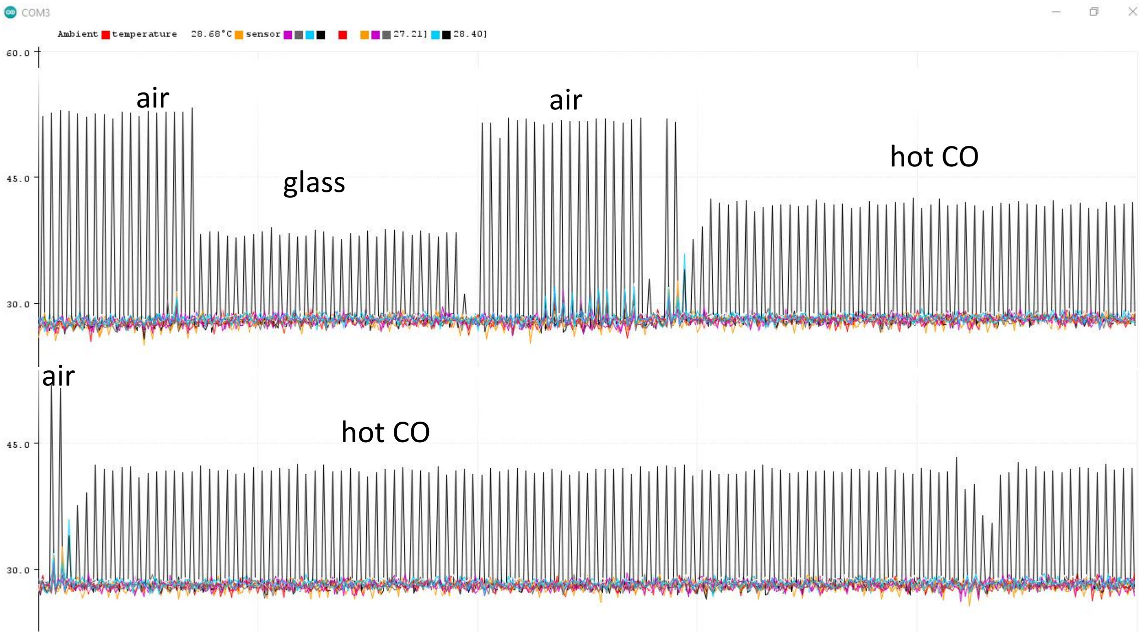


Figure 14

But the gas has also its own volume. Calculated it becomes ca. 4l.
To calculate it we use the molar volume V_m=22.4 L/mol [29].
This volume is too small for 4 liter of gas.
Therefore, we put it in the same big reservoir.

2.5.21 Experiment 21 CO in green big reservoir

The Laser radiation go first just throw air. Then the green big reservoir is put in its path. Its influence is clearly seen. The reservoir is shaken to activate the reaction that produce the CO. The container with the new produced CO is put in the Laser path. Its influence is regarded in the Serial Plotter 19



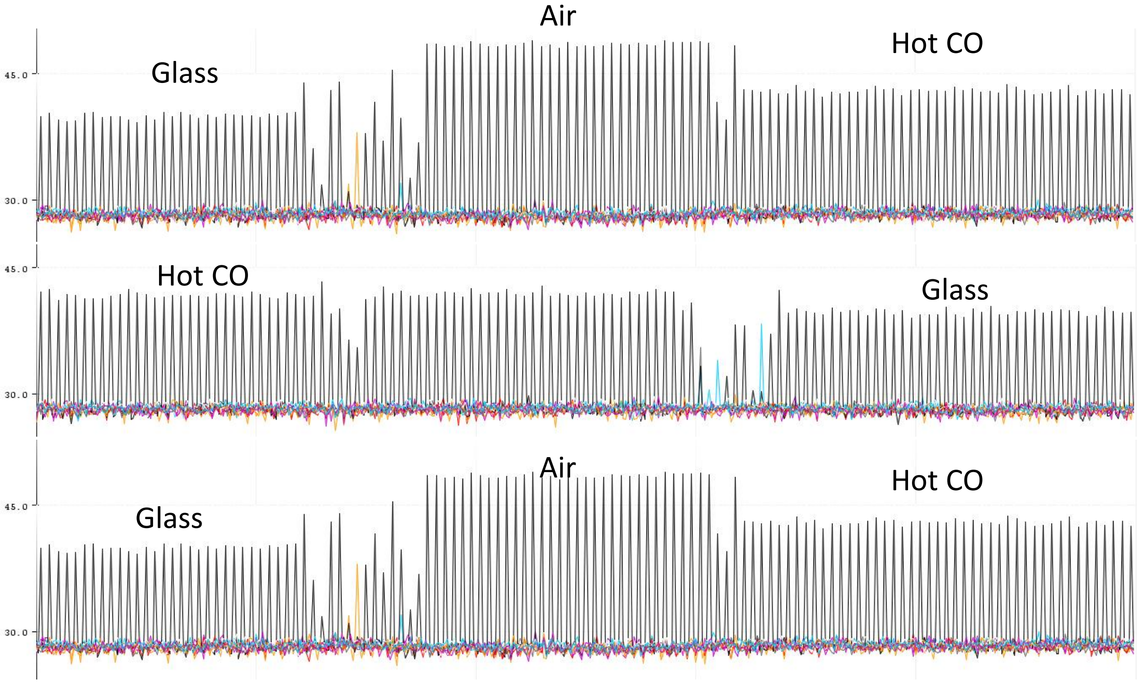
Serial Plotter 19

The graph goes up instead of going down!!

2.5.22 Experiment 22 CO repeated

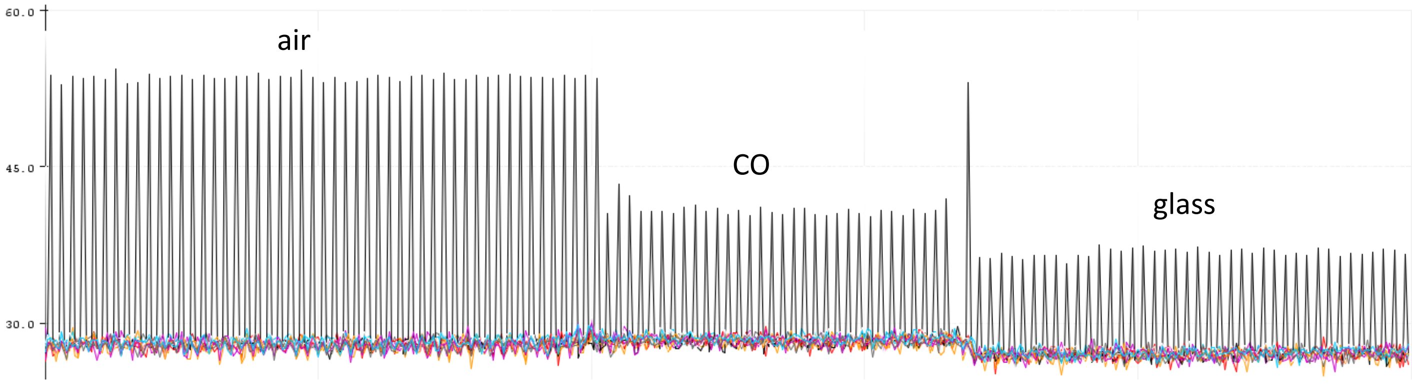
Figure 15

We use an identical reservoir to compare between CO and air but with the influence of the glass (Figure 15).



Serial Plotter 20 repeated switch between the reservoir with and without CO

The two containers are switches several times to insure the unsuspected result (Serial Plotter 20). In Serial Plotter 21 you can see clearly that the temperature detected after the CO is higher than that detected after a path throw the empty glass container.



Serial Plotter 21

Serial Monitor 22 correspond to the case were the CO is in the Laser's path. The temperature detected is 43°C is higher than 31°C detected in the case of the empty glass container (Serial Monitor 23).

```
[27.50, 27.73, 28.79, 26.40, 28.01, 27.35, 28.11, 28.29, 29.09, 27.54, 28.31, 27.15, 27.52, 28.46, 27.54, 28.09]
[28.53, 28.27, 27.88, 28.27, 28.09, 28.21, 28.34, 28.39, 27.21, 28.52, 29.10, 28.03, 28.35, 28.06, 28.83, 27.39]
[28.26, 28.07, 28.54, 28.60, 28.68, 27.94, 28.62, 43.28, 28.86, 27.95, 28.70, 28.68, 28.59, 27.94, 29.17, 28.22]
[27.76, 28.32, 27.77, 28.17, 28.66, 27.76, 28.35, 27.88, 28.17, 27.70, 28.08, 28.54, 28.88, 28.08, 28.37, 27.71]
Ambient temperature: 29.18°C
```

Serial Monitor 22

```
[25.93, 27.65, 28.44, 26.78, 26.83, 28.77, 27.69, 27.03, 28.06, 27.97, 26.65, 27.47, 27.08, 27.88, 27.40, 27.61]
[27.53, 27.07, 27.23, 27.71, 27.14, 28.39, 28.42, 27.43, 27.74, 27.91, 28.05, 27.50, 28.00, 27.66, 28.17, 26.54]
[28.01, 27.49, 27.31, 27.95, 27.71, 27.92, 27.95, 31.35, 27.75, 27.83, 28.11, 28.25, 27.63, 27.23, 27.42, 27.97]
[27.83, 27.20, 26.93, 27.70, 27.06, 27.21, 27.69, 27.60, 27.06, 27.12, 27.71, 27.66, 28.21, 26.07, 27.27, 26.99]
Ambient temperature: 29.25°C
```

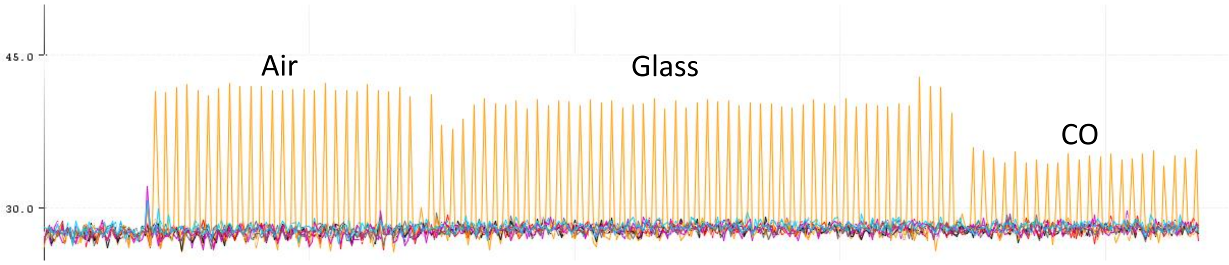
Serial Monitor 23

This for the first view unaccountable result is explainable. The chemical reaction is exothermic!

2.5.23 Experiment 23 CO after cooling

Since the chemical reaction was an exothermic one, the results must be like there was expected after cooling.

2.5.23.1 Main Result

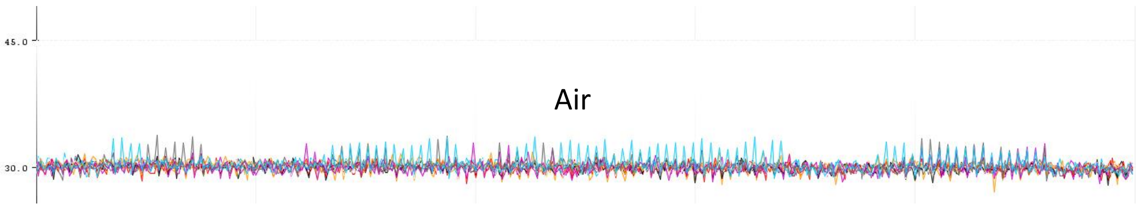


Serial Plotter 22 expected result with cool CO

In the graph above, you see clearly the absorption of wave's energy from the CO molecules

2.5.24 Experiment 24 CC VS CP mode again

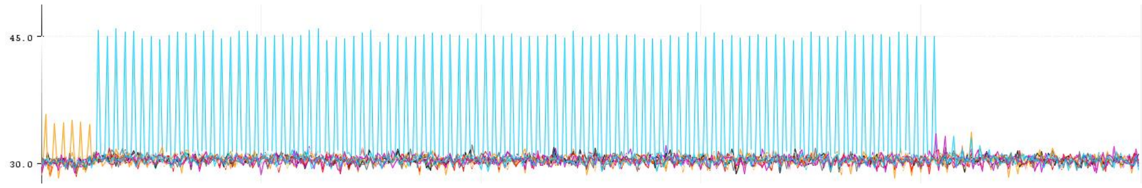
Laser on CC mode 30mA 0.2mW



Serial Plotter 23

In the Third experiment: CC vs CP the laser on 20mA has no influence at the IR camera. Here the camera detects the Laser but it keeps too feeble.

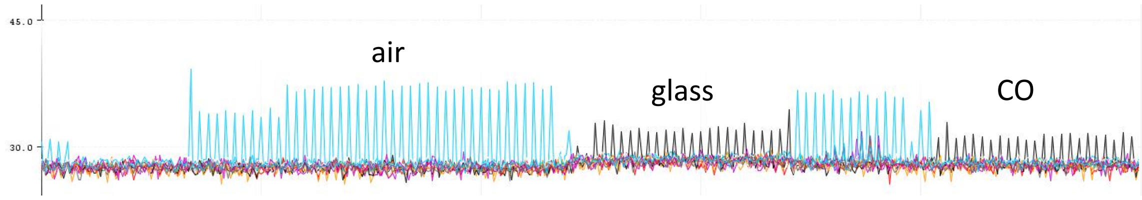
Laser on the usual CP mode



Serial Plotter 24

2.5.25 Experiment 25 CO container after two days

How does the container in which the CO was prisoned react to the laser?



There is no difference between the reaction to the glass and the reservoir, which contains CO, two days ago.
The reaction $CO + O_2 \rightarrow CO_2$ is the reason. [30]

Note:
Make sure that the camera is directed right!
That the LD is its seat.
Move the containers carefully, so that the camera stays in its place.

2.6 Wavelength/Power to temperature

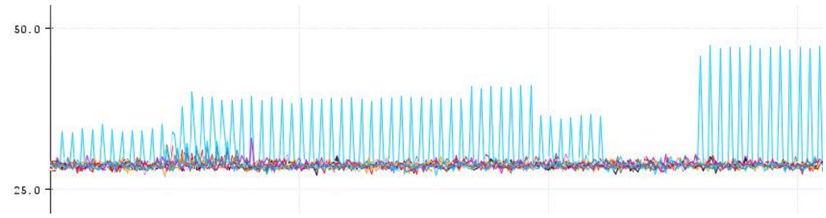
The graphs are not comparable at low concentrations of CO.
The chemical reaction is not so save
In addition, we have to mix the acids after closing the reservoirs. The consequence is that we do not know if HCOOH react totally with its catalyzer H_2SO_4.
So the planed table CO concentration <-> graph is not realizable.
We have to go back to a mix of experiment and theory. The Program must be developed to be able to say us directly if the concentration of CO is acceptable or not.

2.6.1 Experiment 26: T(P)?

15.9.20
Ambient T 29.15 °C
See excel

Energie
CO16.9.20.xlsx

On 5mW the Laser is calibrated.



Serial Plotter 25 plotter calibration

To gain the characteristic Table 6 the power is variated in 1mW steps. The maximum temperature is read from the corresponding serial monitors among all temperatures.

P(mW)	T(°C)
9.9	46
9	45
8	44
7	42
6	40
5	38
4	36.7
3	34.5
2	33
1	31
0.5	30

Table 6 T(P) characteristic

2.6.2 Developing Arduino: Tmax?

16.9.20

```
 //T Max?
 int y=0;
 float Tmax;
 if (y==0){
Tmax= max(temperatures[y],temperatures[y+1]);
 }
   for(int y=2;y<64;y++){ //go through all T

      Tmax= max(temperatures[y],Tmax);

         }



 Serial.print("Ambient temperature: ");
 Serial.print(sensor.get_ambient_temperature());
 Serial.println("°C");

Serial.print("Tmax:");
Serial.print(Tmax,2);
Serial.println("°C");
```

Program 3 T_{max}

The Program 3 search the T_{max} from the temperatures and displays it.

2.6.2.1 Experiment 27

Laser off

```
[28.45, 28.31, 27.94, 27.97, 29.10, 29.01, 28.03, 27.92, 28.92, 28.26, 28.57, 28.52, 28.43, 27.54, 27.75, 28.43]
[28.74, 28.91, 28.36, 27.77, 29.12, 28.63, 28.02, 28.27, 28.32, 28.32, 27.73, 28.56, 27.10, 28.02, 27.73, 28.46]
[28.49, 27.45, 27.82, 27.65, 28.06, 27.53, 28.28, 28.35, 28.49, 28.01, 28.10, 28.34, 27.55, 27.94, 28.10, 27.52]
[27.52, 27.84, 27.22, 28.39, 27.32, 27.63, 27.42, 27.97, 28.13, 27.21, 28.28, 28.20, 28.69, 28.00, 28.22, 27.36]
Ambient temperature: 27.58°C
Tmax:29.12°C
```

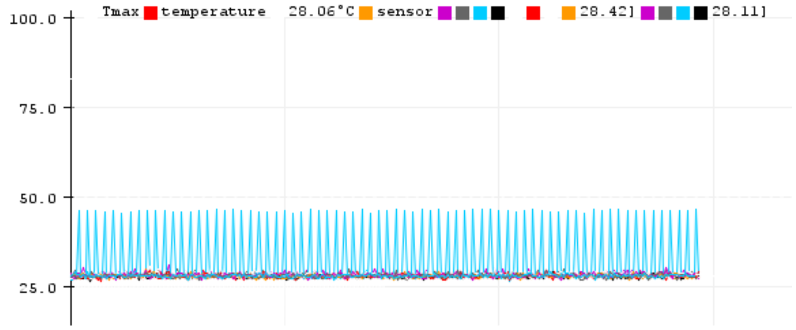
Serial Monitor 24

Laser on

```
[29.65, 27.84, 28.95, 27.83, 29.40, 29.97, 28.21, 27.69, 28.11, 28.08, 27.84, 27.71, 27.82, 27.73, 28.25, 28.50]
[28.56, 28.26, 27.73, 27.53, 28.41, 27.74, 28.60, 27.84, 28.29, 28.03, 28.03, 28.15, 28.47, 27.55, 28.02, 27.84]
[28.67, 27.93, 28.12, 28.15, 28.25, 27.34, 45.66, 28.24, 27.39, 27.73, 27.44, 27.92, 27.95, 27.15, 27.62, 27.49]
[28.04, 27.93, 27.41, 28.57, 27.73, 27.92, 28.24, 27.21, 27.37, 28.05, 27.70, 28.49, 28.24, 28.87, 27.82, 28.18]
Ambient temperature: 27.91°C
Tmax:45.66°C
```

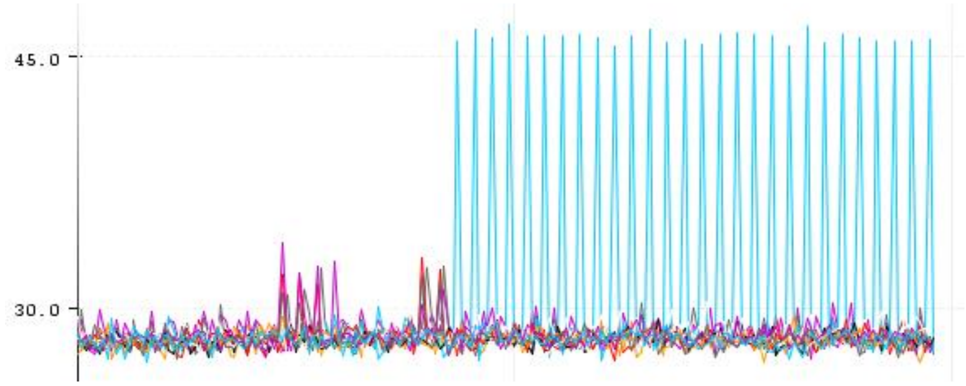
Serial Monitor 25

The program works (Serial Monitor 24 Serial Monitor 25). It does not ruin the Serial Plotter 26.



Serial Plotter 26

The plotter can be scaled better Serial Plotter 27.



Serial Plotter 27

Experiment 29 T(P) extacter

With the developed program the characteristic table T(P) can be performed. The experiment 28 is repeated but in 0.5 mW.

P(mW)	Tmax(°C)	P(mW)	Tmax(°C)
10	46.6	4.5	37
9.5	45.7	4	36
9	44.89	3.5	35.5
8.5	44	3	34.2
8	43	2.5	33
7.5	42.5	2	32.45
7	41.4	1.5	31.4
6.5	40.9	1	30.4
6	40	0.5	30
5.5	38.99	0.2	29.5
5	37.9	0	29.6

Table 7 T(P) 0.5mW steps

2.6.3 Developing Arduino: deltaT?

The variation of temperatures is the main indication of the concentration of CO. The Program 4 try to calculate this variation named delta T. But the delta T is always displays as zero (Serial Monitor 26). This is wrong.

```
//delta T?
float deltaT= Tmax - Tmax;
```

```
Serial.print("Ambient temperature: ");
Serial.print(sensor.get_ambient_temperature());
Serial.println("°C");

Serial.print("Tmax:");
Serial.print(Tmax,2);
Serial.println("°C");
Serial.print("deltaT:");
Serial.print(deltaT,2);
Serial.println("°C");
delay(500);
```

Program 4

2.6.3.1 Experiment 28

```
[29.94, 29.66, 29.80, 29.74, 30.00, 30.38, 29.23, 28.51, 28.82, 28.61, 28.01, 29.22, 28.89, 28.24, 29.87, 28.78]
[28.97, 29.28, 28.01, 28.56, 29.59, 29.30, 28.69, 28.74, 28.90, 28.80, 28.59, 28.93, 28.44, 28.69, 28.39, 28.03]
[29.37, 28.96, 28.21, 28.64, 29.16, 28.39, 28.76, 28.62, 29.07, 28.20, 28.95, 29.01, 28.65, 28.81, 28.00, 29.17]
[28.76, 28.31, 27.69, 29.06, 28.79, 28.10, 28.31, 28.54, 29.64, 28.44, 27.98, 28.66, 29.15, 28.58, 27.98, 28.86]
Ambient temperature: 28.13°C
Tmax:30.38°C
deltaT:0.00°C
```

Serial Monitor 26

The solution is to initialize Tmax before the setup and the loop. Moreover, to create Tmaxold before calculate the new Tmax. The library EEPROM.h is not necessary.

```
#include "Arduino.h"
#include <Wire.h>
#include "MLX90621.h"
//#include <EEPROM.h>

int refresh_rate = 16;
MLX90621 sensor;

float temperatures[64];
float Tmax;

void setup(){
    Serial.begin(115200);
```

```
float Tmaxold = Tmax;
 if (y==0){
Tmax= max(temperatures[y],temperatures[y+1]);

 }
   for(int y=2;y<64;y++){ //go through all T

      Tmax= max(temperatures[y],Tmax);

         }


        //delta T?
      float deltaT;
deltaT= Tmaxold-Tmax;


 Serial.print("Ambient temperature: ");
```

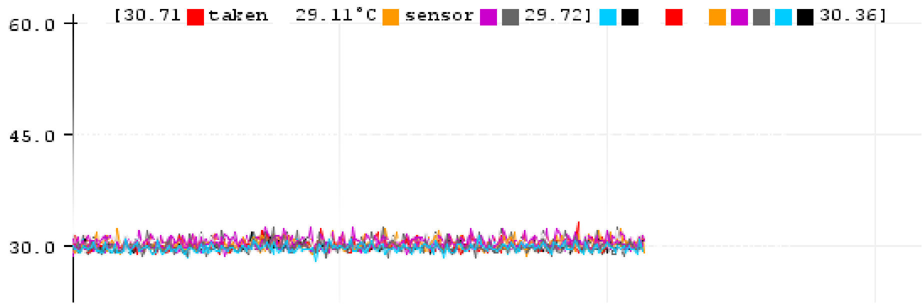
Program 5 deltaT

2.6.3.2 Experiment 29

The Serial Monitor 27 displays the variation of temperature different than zero. It prove that the Program 5 written write.

```
[30.85, 30.98, 31.61, 30.60, 31.17, 30.95, 29.93, 29.61, 30.21, 30.38, 28.83, 29.92, 30.74, 30.23, 30.36, 30.68]
[30.14, 30.18, 29.12, 29.05, 30.51, 29.89, 28.82, 29.34, 29.71, 29.78, 29.56, 29.34, 29.45, 29.19, 29.54, 30.33]
[29.76, 29.19, 29.46, 30.25, 30.06, 29.66, 30.28, 29.32, 29.76, 29.08, 30.29, 29.30, 29.76, 29.12, 29.08, 29.97]
[29.46, 29.31, 28.99, 30.08, 28.83, 29.21, 29.63, 29.01, 29.07, 28.60, 29.66, 29.93, 29.74, 29.51, 28.57, 29.16]
Ambient temperature: 28.82°C
Tmax:31.61°C
deltaT:0.24°C
```

Serial Monitor 27



Serial Plotter 28

The Serial Plotter 28 shows that the program do not destroy the plotter.

2.6.4Developing Arduino: deltaTmax?

The additional step in the program helps to see the variation of temperature that should happens to speak of an existence of CO molecules.

```
        //delta T?

  deltaT= Tmaxold-Tmax;

 deltaTmax=max(deltaT,deltaTmaxold);

   Serial.print("Ambient temperature: ");
   Serial.print(sensor.get_ambient_temperature());
   Serial.println("°C");

  Serial.print("Tmax:");
  Serial.print(Tmax,2);
  Serial.println("°C");

   Serial.print("deltaT:");
  Serial.print(deltaT,2);
  Serial.println("°C");

  Serial.print("deltaTmax:");
  Serial.print(deltaTmax);
  Serial.println("°C");

   delay(500);
```

Program 6

```
[31.57, 31.78, 31.55, 31.82, 32.14, 31.
[29.91, 30.53, 30.08, 29.83, 30.53, 29.
[29.80, 29.36, 29.26, 29.39, 30.00, 29.
[29.81, 29.46, 29.34, 30.32, 29.30, 29.
Ambient temperature: 29.16°C
Tmax:32.14°C
deltaT:0.63°C
deltaTmax:1.99°C
```

Serial Monitor 28

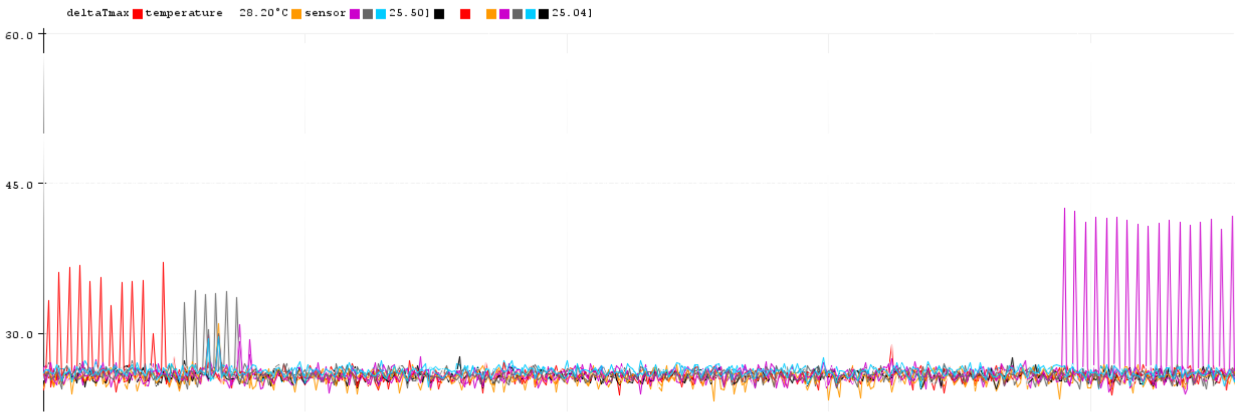
2.6.4.1Experiment 30

In 5 minutes running, the program reaches a constant deltaTmax of 1.99 °C.
This value perhaps changes in the environment of the incinerator.

2.6.5Calculus of [CO] in Arduino

I will now try to calculate [CO] in Arduino in a similar way as if I do it with excel.
I see now that the variation that took place when we detect the CO was 1.89°C.
If the Laser is on, do deltaTmax reach also 1.99°C?

2.6.5.1 Experiment 31 deltaTmax if Laser on



Serial Plotter 29

```
[26.03, 26.27, 26.22, 25.61, 26.13, 25.88, 26.16, 25.68,
[26.15, 26.28, 26.67, 25.69, 40.04, 26.04, 26.09, 26.24,
[26.61, 25.38, 26.03, 26.48, 25.59, 24.63, 25.62, 25.31,
Ambient temperature: 28.22°C
Tmax:40.04°C
deltaT:-0.26°C
deltaTmax:1.30°C
```

Serial Monitor 29

By 8.6mW

deltaTmax=1.30°C.

By 9.9 mW it reaches his saturation by 1.29°C.

When I calculate the [CO], do I have to substrate deltaTmax from deltaT, which is bigger than deltaTmax? No, because we are always compare two consecutives temperatures.

1.30 °C < 1.89 °C so all is logic.

We have to include the math library to use exp.

```
  // deltaTmax?
 deltaTmax=max(deltaT,deltaTmaxold);

 //calulation of nbCO
// 1.30 is deltaTmax if only Laser is on.

 if (deltaT > 1.30){
   // deltaT=deltaT-1.30; //right???? no!!
   float oneoverslope=0.57;   //see excel. should be calculate again!! just between the Ts which involved in the peak down of CO.
   float deltaP = oneoverslope*deltaT;
   int t=16; // = refresh_rate
   float deltaE= deltaP*t*exp(13)/1.6022; // in eV
   float Eco=0.8;
   float nbCO=deltaE/Eco;
   Serial.print("There is ");
   Serial.print(nbCO);
   Serial.println("CO molecules");
 }

  /* Serial.print("Ambient temperature: ");
   Serial.print(sensor.get_ambient_temperature());
   Serial.println("°C");*/

  Serial.print("Tmax:");
  Serial.print(Tmax,2);
  Serial.println("°C");

   Serial.print("deltaT:");
```

Program 7

The ambient Temperature is not necessary for our aims. The calculus is just a burden for the Program.
What is the relation between nbCO and [CO]?

2.6.5.2Relation between nbCO and [CO]

1 pixel (X) = 0.0264583333 cm [34]

Equation 5 *Surface= 1pixel(x)*1pixel(y) = 0.00070004340101388889 cm²*

Equation 6 *Volume = Surface * distance*

distance=21cm=25-2*2cm
V = 0.014700911421291666 69 cm³

special for the power plant chimney

N_A=6.022 x 10^23

Equation 7 *n=nbCO*N_A*

Equation 2 *[CO]=nM/V*

Int -> [CO](ppmV)
20 mg/m3
That is the average in European air.
So we don't need to convert to ppm.
[CO]lim=20mg/m³
n=[CO]V/M
nbCO=n/N_A

$\boxed{x10^{-3}}$ $\boxed{x10^{-2*3}}$

=>nbCOlim=20mg/m3*0.01470091142129166669 cm³/28g/mol/6.022 x 10^23mol

=>**nbCOlim =2.20827E-17**

2.7 Final Arduino Program

One of the main results of this thesis is the developed Arduino Program. It told the appraiser without detailed knowhow if the flue gas environmentally friendly or not.

```
// library: https://github.com/Leenix/MLX90621-Lite
#include "Arduino.h"
#include <Wire.h>
#include "MLX90621.h"
#include "Math.h"
int refresh_rate = 16;
MLX90621 sensor;
float temperatures[64];
float Tmax;
float deltaT;
float deltaTmax;
float nbCO=0;
float nbCOlim=2.20827*exp(-17);
void setup(){
  Serial.begin(115200);
  Serial.println("Starting MLX90621 thermopile sensor");
```

```
   pinMode(1, OUTPUT);
   digitalWrite(1, HIGH);
   Wire.begin();
    sensor.initialise(refresh_rate);
}
void loop(){
   Serial.println("\n\nReading sensor...");
   long start_time = millis();
   sensor.get_temperatures(temperatures);
   long time_taken = millis() - start_time;
   Serial.print("Time taken: ");
   Serial.println(time_taken);
   Serial.println(50);
   Serial.println(0);
      for(int y=0;y<64;y+=16){ //go through all the rows
      Serial.print('[');
      for(int x=0;x<16;x++){ //go through all the columns
         Serial.print(temperatures[y+x], 2);
         if (x < 15) {
            Serial.print(", ");
         }
      }
      Serial.println(']');
   }
    //T Max?
   int y=0;
       float Tmaxold = Tmax;
  float deltaTmaxold= deltaTmax;
   if (y==0){
  Tmax= max(temperatures[y],temperatures[y+1]);
         }
     for(int y=2;y<64;y++){ //go through all T
       Tmax= max(temperatures[y],Tmax);
         }
            //deltaT?
        deltaT= Tmaxold-Tmax;
  // deltaTmax?
 deltaTmax=max(deltaT,deltaTmaxold);
 //calulation of nbCO
// 1.30 is deltaTmax if only Laser is on.
 if (deltaT > 1.30){
  // deltaT=deltaT-1.30; //right???? No!!
   float oneoverslope=0.57;   //see excel. should be calculate again!! just between the Ts which
involved in the pic down of CO.
   float deltaP = oneoverslope*deltaT;
```

```
  int t=16; // = refresh_rate
  float deltaE= deltaP*t*exp(13)/1.6022; // in eV
  float Eco=0.8;
  float nbCO=deltaE/Eco;
  Serial.print("There is ");
  Serial.print(nbCO);
  Serial.println("CO molecules");
 }
    /* Serial.print("Ambient temperature: ");
  Serial.print(sensor.get_ambient_temperature());
  Serial.println("°C");*/
    Serial.print("Tmax:");
  Serial.print(Tmax,2);
  Serial.println("°C");
  Serial.print("deltaT:");
  Serial.print(deltaT,2);
  Serial.println("°C");
  Serial.print("deltaTmax:");
  Serial.print(deltaTmax);
  Serial.println("°C");
  if (nbCO < nbCOlim){
  Serial.print ("nbCO=");  Serial.print(nbCO); Serial.print ("<");  Serial.print(nbCOlim); Serial.print("= nbCOlim. The CO dose is environmentally friendly");
  }
  If (nbCO> nbCOlim) {
 Serial.print ("nbCO=");  Serial.print(nbCO);  Serial.print (">");  Serial.print(nbCOlim);   Serial.print ("=nbCOlim. The CO dose is over the lim. You have to increase the O2 supply");
  }
    delay(500);
}
```

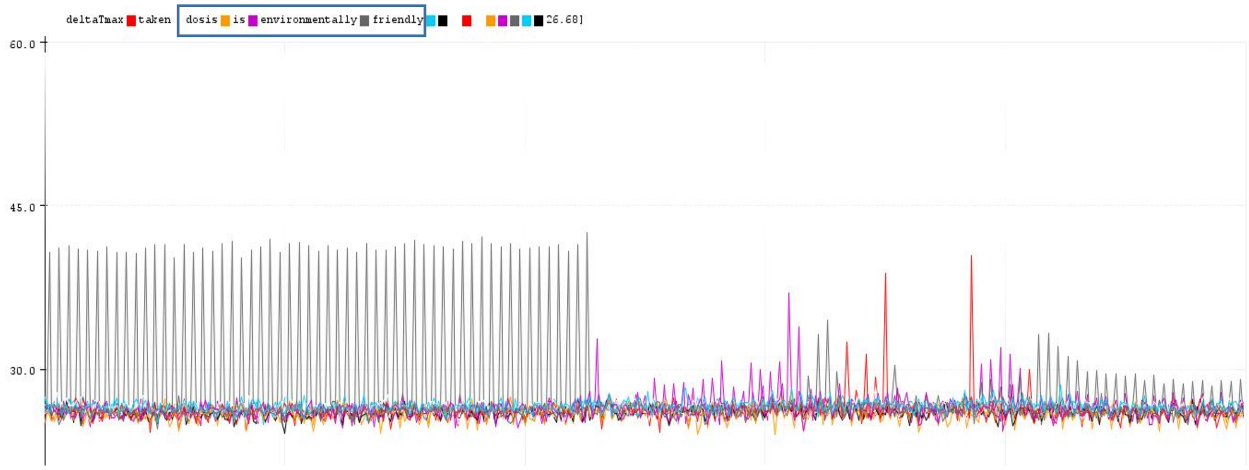
MLX90621.h   MLX90621.cpp   get_temperatures.ino

Get temperature is the developed program; MLX9061.h is a header file in C++ it is the library of the camera and MLX9061.cpp is the initially C++ program.

2.7.1 Experiment 32

```
[24.27, 25.22, 26.24, 24.67, 25.98, 25.63, 25.78, 24.97, 26.28, 26.31, 25.43, 24.92, 25.55, 26.42, 26.15, 25.48]
[26.94, 25.92, 25.86, 26.02, 25.57, 25.81, 26.26, 25.32, 25.61, 25.44, 25.51, 25.29, 26.76, 26.27, 25.93, 25.98]
[26.56, 25.89, 26.28, 26.07, 26.67, 26.05, 26.75, 25.98, 26.09, 26.16, 26.63, 25.55, 26.58, 25.13, 26.63, 26.09]
[25.27, 26.12, 26.18, 25.93, 25.72, 25.85, 25.70, 25.24, 26.11, 26.21, 25.95, 25.67, 25.26, 25.55, 25.85, 26.03]
Tmax:26.94°C
deltaT:0.14°C
deltaTmax:0.70°C
The CO dosis is environmentally friendly
```

Serial Monitor 30



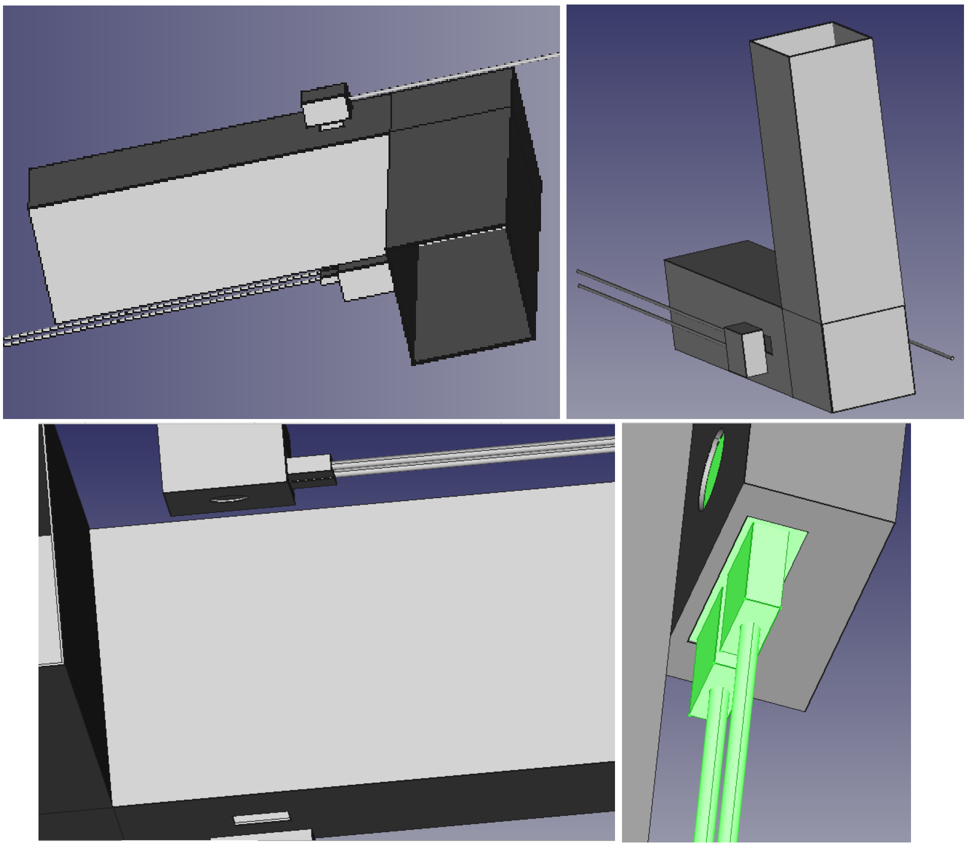
Serial Plotter 30

The program works. We have just to test it at the power plant.

2.8 Experiment at the Power Plant

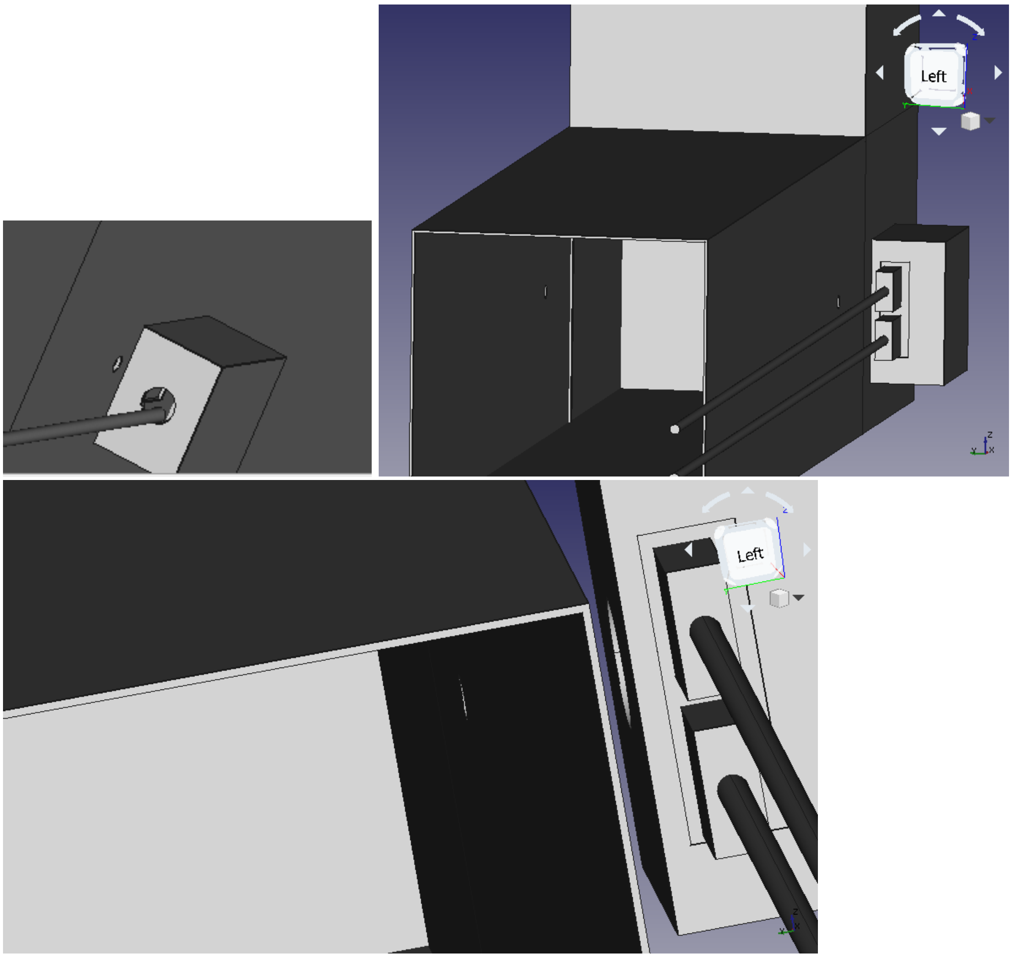
2.8.1FreeCad

Before constructing anything technical we have to sketch it in a 3D program.
In AECENAR, FreeCad is used. In the figures below, you can see the chimney after the last filter.
Planed is to open two opposite windows. On the one, the package continuing the IR camera is fixed.
On the other, the package continuing the LD mount.
Even the mount is remodeled to ensure that it fits in his package.

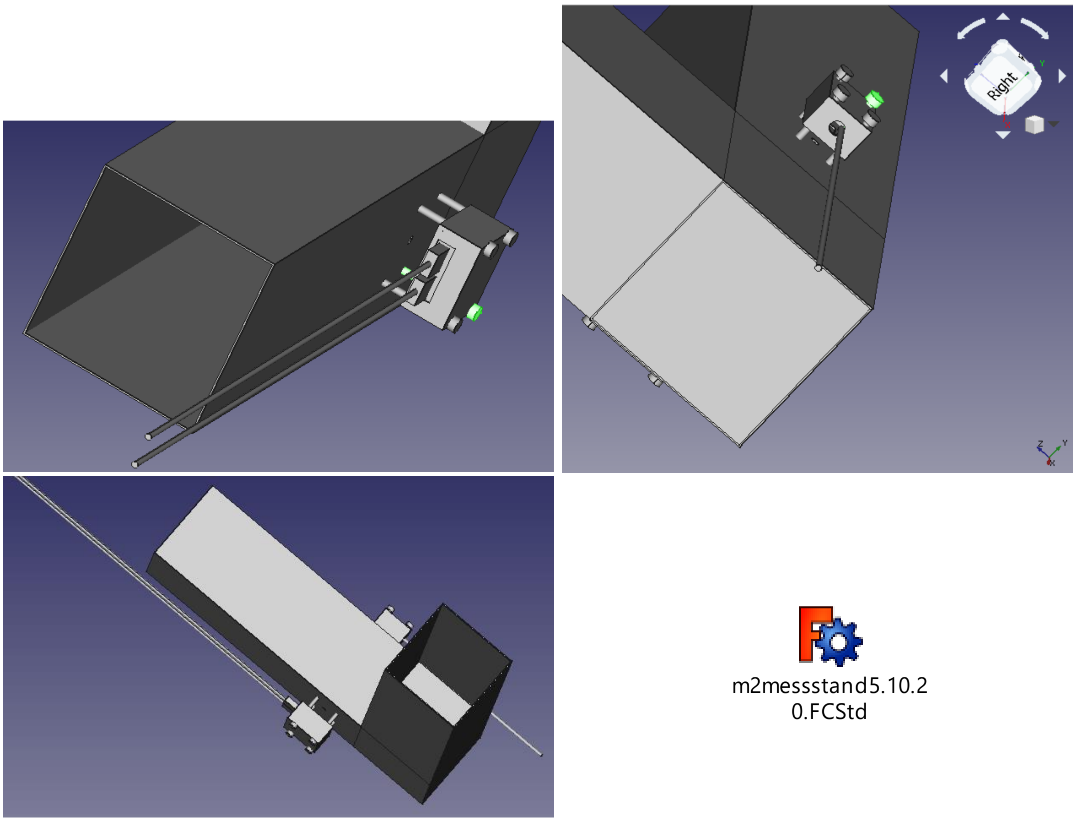


m2messstand30.9.20.FCStd

Freecad 1Model with cube windows



Freecad 2 Model adjusted to Figure 16 with 2 holes for the path of the laser



Freecad 3 fix proposal with screws

m2messstand5.10.2
0.FCStd

Nevertheless, even this model is just half-realizable. Because a single fault with the electro filter causes the damage of the LD. Therefore, we have to fix the experimental setup on the iron chimney without screws. Moreover, we have to isolate it at least for four cm. because the spark of the electrical filter reach at maximum 4cm.

2.8.2Preparation

5.10.2020

Figure 16

Instead of windows, we simply drill through the chimney. It is enough for the laser.

2.8.3Implementation

Figure 17 the power plant

Figure 17 shows the power plant. The heat treated waste in the black container, transform the water in the cylinder above to vapor. This steam hit the turbine and let it routine. The turbine transforms the mechanical energy to electrical energy.
The smoke goes throw four filters: an electrical, two cylindrical and a baghouse filter, before it goes out throw the chimney.

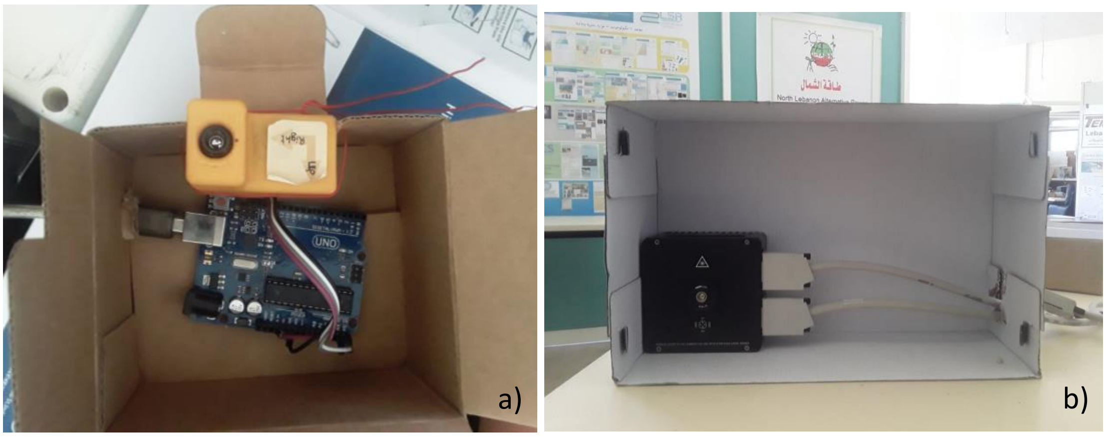


Figure 18 a) b)

The LD mount and the camera was fixed in cartons to protect them from dust Figure 18.
The LD mount and the detector were hold provisory on the corresponding holes.
The Laser diode I1550P5DFB is turn on at CP mode on 9.9 mW at T=35°C.
The results are shown in the next chapter: Results of outdoor experiment.

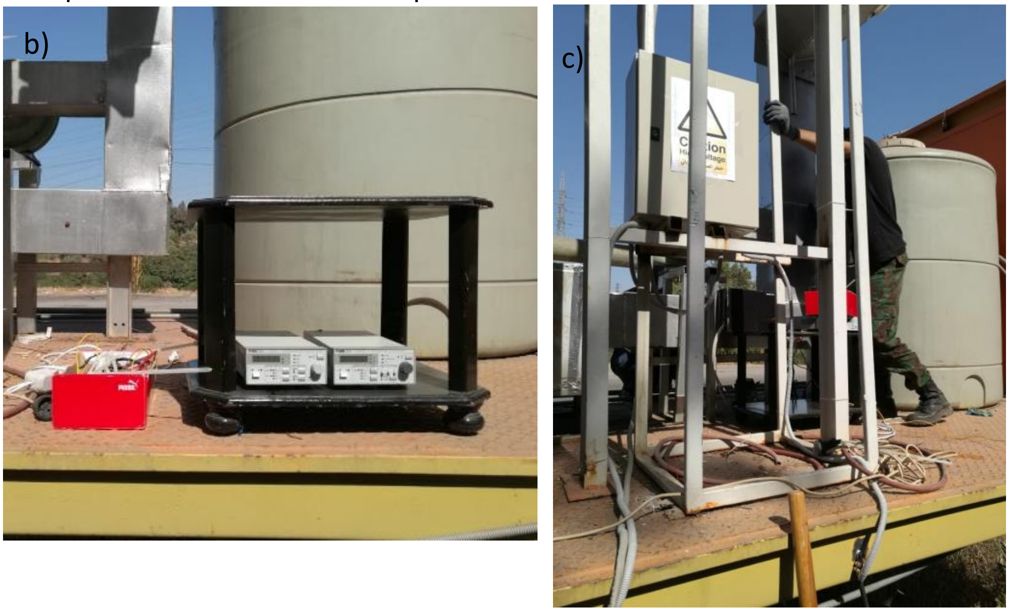


Figure 19 a) b) c)

Figure 20 a) before b) after

Figure 20 shows the waste before and after heat treatment.
Usually the incinerator reduces the rubbish to 10% of its volume and 30 % of its mass. [31]
In this test, for several reasons, we had to stop the test early.

The bottom ash can be used as road pavements. [32]
The filter ash presents a high potential for heavy metal recycling [33]

The LD mount and the detector were hold provisory on the corresponding holes.
After the test, the instruments were uninstalled and repacked (Figure 21).

Figure 21

Finish

3 CHAPTER III: RESULTS AND DISCUSSION

3.1 Results of indoor experiments

Are shown in the last chapter.

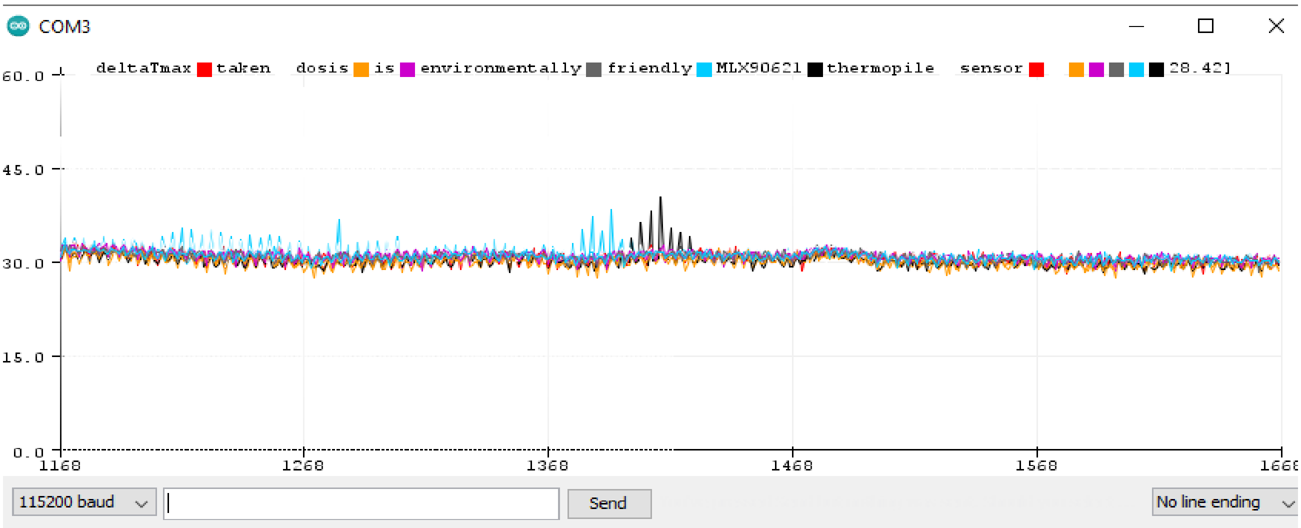
3.2 Results of outdoor experiment

```
deltaT:-0.26°C
deltaTmax:0.47°C
 The CO dosis is environmentally friendly

Reading sensor...
Time taken: 59
50
0
[32.15, 30.49, 32.96, 30.84, 33.75, 32.37, 32.91, 31.97, 33.13, 32.81, 32.17, 31.75, 32.74, 33.27, 33.04, 32.50]
[34.20, 32.56, 33.24, 32.17, 33.80, 33.06, 33.24, 33.17, 34.32, 33.80, 33.69, 33.10, 33.14, 33.60, 33.51, 32.59]
[34.34, 34.13, 33.51, 33.17, 33.64, 34.03, 34.36, 33.53, 34.02, 34.65, 34.18, 33.98, 34.06, 33.45, 33.92, 33.41]
[34.87, 33.90, 33.09, 33.57, 34.95, 34.18, 34.00, 33.59, 34.27, 33.55, 34.11, 34.35, 34.40, 34.35, 34.09, 33.50]
Tmax:34.95°C
deltaT:0.39°C
deltaTmax:0.47°C
 The CO dosis is environmentally friendly
```

Serial Monitor 31 at the power plant

```
deltaT:-0.26°C
deltaTmax:0.47°C
 The CO dosis is environmentally friendly

Reading sensor...
Time taken: 59
50
0
[32.15, 30.49, 32.96, 30.84, 33.75, 32.37, 32.91, 31.97, 33.13, 32.81, 32.17, 31.75, 32.74, 33.27, 33.04, 32.50]
[34.20, 32.56, 33.24, 32.17, 33.80, 33.06, 33.24, 33.17, 34.32, 33.80, 33.69, 33.10, 33.14, 33.60, 33.51, 32.59]
[34.34, 34.13, 33.51, 33.17, 33.64, 34.03, 34.36, 33.53, 34.02, 34.65, 34.18, 33.98, 34.06, 33.45, 33.92, 33.41]
[34.87, 33.90, 33.09, 33.57, 34.95, 34.18, 34.00, 33.59, 34.27, 33.55, 34.11, 34.35, 34.40, 34.35, 34.09, 33.50]
Tmax:34.95°C
deltaT:0.39°C
deltaTmax:0.47°C
 The CO dosis is environmentally friendly
```

Serial Monitor 32 at the power plant



Serial Plotter 31 result at the power plant

It is better to repeat the experiment to ensure the result.
The Temperature was 35 °C, and the Laser radiation causes a temperature under 50°C so the radiation was not clearly visualized.
Additionally, we have just 15 min to implement the instruments and take the results.
Nevertheless, during the measurement the program indicate always that the CO dose is environmentally friendly. As you can see in the Serial Monitor 31, Serial Monitor 32 and Serial Plotter 31.

4 CHAPTER IV: CONCLUSION AND PROSPECTS

4.1 Conclusion

Beginning from the idea of TDLAS (P.9) the laser was ordered. The Covid19 pandemic let us continued with an alternative setup. The MLX IR camera was used as detector. The influences of the different cases were compared on this one detector.
In the experiments 1-4(P.22), the setup was initialized. The different modes CC and CP was compared in experiment 3(P.24). Only with the serial monitor.
A clear heating of several pixels are mentioned as the influence of the Laser's radiation.
In the experiments 5-10 (P.27) the serial plotter was developed. It was cleaned from all disturbing graphs and scaled write.
Until experiment 14 (P.31), especially the serial plotter reaction to distance and power variations is studied.
The power of the Laser decrease with the distance more than expected.
After calculating the used quantities of the reactive species of the chemical reaction, which produce a known concentration of CO, and choosing the right reservoir, the influence of the container upon the laser radiation, in different power cases, is tested in experiment 15-19 (P.35).
The plot of experiment 20 (P.38) shows anomalies. This graph corresponds to the laser going throw the limit concentration of CO. This result is not enough. It is useless to use it as planned as limit line. This line was expected to be the reference. And to compare the absorption peaks of the unknown CO concentration with it.
After preparing a higher concentration of CO, the influence of this very high concentration is tested in experiment 21 (P.40). The result was unexpected. The plot goes up instead of going down to represent an absorption. The experiment was repeated to ensure the result (experiment 22 P.41).
The chemical reaction: dehydrating the formic acid with sulfuric acid is exothermic! This explain the results.
In this time, it must be cooling down. In experiment 23 (P.42), the container with the CO is put one more time in the path of the Laser. Now the absorption is seen very clear.
After two days, the same container with the prisoned CO, is done in the same Laser conditions (experiment 25 in P.43). No reaction. No absorption. Because the CO react with the O_2 from the air in the reservoir, giving CO_2. The Laser's wavelength 1550nm is only absorbed from CO molecules.

In Experiment 26(P.44) the characteristic curve T(P) of the setup is gained. This curve will help us knowing how much energy is absorbed. We can use this table back ward. We see a decreasing of temperature and conclude the increasing of power which is in a clear relation with the energy.

Due to the practical uncertainty that all the formic react with the sulfuric acid. And the fact that this reaction is exothermic, contradict with one of the aims of the indoor production of CO in a way that do not influence the environment thermally. The strategy was changed. We aimed now to let the program calculate the concentration of the CO and compare it to the limit.

From experiment 26 to 31(P.44) the Arduino program was developed. It is now able to calculate the maximum temperature Tmax, the variation between them deltaT, and the maximum variation of the maximum temperatures deltaTmax. The last one is necessary because the Laser have a

sinusoidal curve. That means not all variations in temperatures are from absorption. DeltaTmax is calculated when only the Laser is on, without anything in its path. Now any variation bigger than that comes from an absorption. If there is an absorption the program calculates the number of CO molecules (nbCO). Than it compares this value to the limit nbCO.
The setup is performed. Experiment 32 (P.52) show that.

A freecad model is made before we went to take measurements at the waste to energy plant.
Finally, the last experiment is done on the chimney of the power plant. The program displayed always that the gas was according to the CO, environmentally friendly.

After all this, we finally find a way to save the data from Arduino via python. This is a very big aid for future experiments (Appendix 3 Python program).

4.2 Prospects

Following Master Theses are conceivable, even a PhD.
The system can be developed to test the other flue gases.
This system can be studied especially.
Temperatures in function of the angle (camera, LASER)?
Why, by a near distance, there are two main high points, and inter them, ambient temperatures?
What is the detailed form of the LASER beam?

بحمد الله

5 APPENDIX

5.1 Appendix 1 Elements in detail

Before starting any device, make sure that the fuse in the back correspond to the power supply of your country.
Do not use mobile phones laptops or other electrical devices near the instruments and especially the LD. If you have to, use them only in flying mode.
They could cause interference or even damage.

5.1.1 LD controller

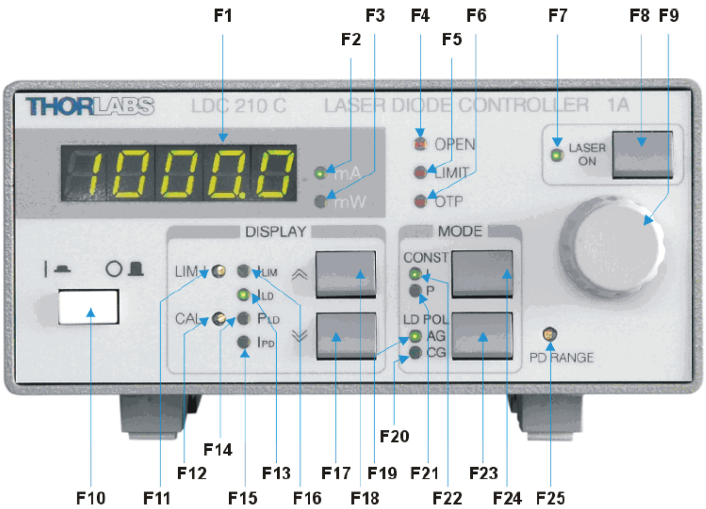


Figure 22

The Laser diode controller is the main instrument. It is responsible for the Laser radiation.
After turning on the LD controller with F10, the limit current I_{LIM} must be set, with a screwdriver, to protect the LD. The LD is in the LD mount. If the LDC is not connected to the LD mount or the mount is empty, F4 “OPEN” lights up.
There are two modes to run the Laser: CC constant current and CP constant Power.
While the CC process, the anode of the LD is grounded. Similarly, the cathode is grounded while the LD is run in CP mode.
During operation:
If the current I_{LD} exceed the I_{LIM} F5 “LIMIT” lights up.
If the LD is overheated, F6 “OTP” lights up.
F12 “CAL” calibrates via a screwdriver, P_{LD}, the LD’s power.
Also with a screwdriver, F25 “PD Range” can set I_{PD} more exactly. This is only in the CP mode relevant.
For more information, see the manual:
https://www.thorlabs.com/drawings/a9fbf9e34a0519a8-97F9F23E-ABBF-D66C-36398EC198AD207F/LDC205C-Manual.pdf

5.1.2Temperature controller

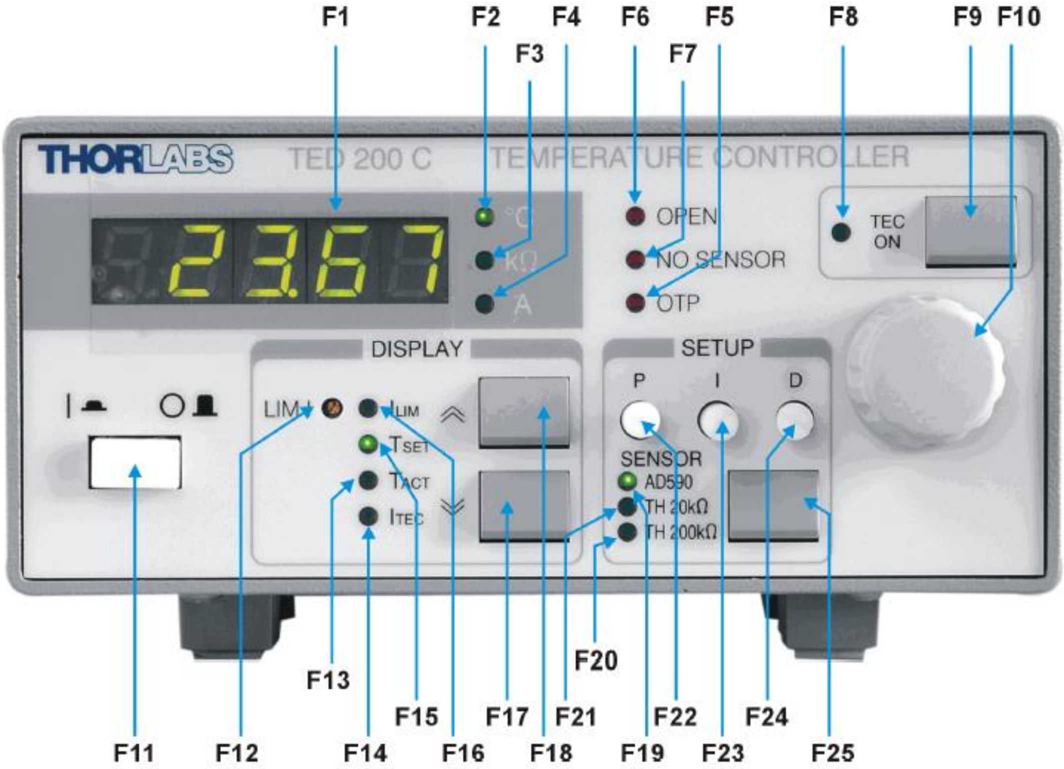


Figure 23

The Temperature controller provide a constant temperature around the ambient temperature.
This is necessary for the LD to be able to radiate a constant wavelength.
For this device, a grounding is very necessary for your and its safety.
Analogous to the LDC, the I_{LIM} must be set, just after turning the device on (F11)
Here also the LED "OPEN" light up if it is not connected rightly to the LD mount or if there is no sensor in the mount, or if the selection of the sensor do not correspond to the sensor used.
"OTP" lights up if the LD is over heated.
"NO SENSOR" lights up if there is no temperature sensor connected to it or if it is connected wrong.
The sensor used in the mount is AD590.
F20, F21 and F3 correspond to thermistors.
T_{act} is the actual (ambient (at the beginning)) temperature. T_{set} is the temperature you want to run the LD in. It cannot be very far from the T_{act}. The controller just holds the temperature constant to allow a stabile radiation.
The cycle PID regulate the temperature. To calibrate it, or for more information read the manual:
https://www.thorlabs.com/drawings/a9fbf9e34a0519a8-97F9F23E-ABBF-D66C-36398EC198AD207F/TED200C-Manual.pdf

5.1.3LD Mount

Figure 24

The LD mount is connected to the LD controller and the temperature controller. The connection cables are distinctive. Take attention how you set the LD in its seat!
The collimator is screwed above the LD.
As you see in the picture, you can switch between CC and CP mode. The configuration in the picture correspond to CC mode. The contrary correspond to CP mode. The switches "1" and "2" stay the same for the two modes.
How to set the switches depends from the type of the LD. In our case, Style D is used.

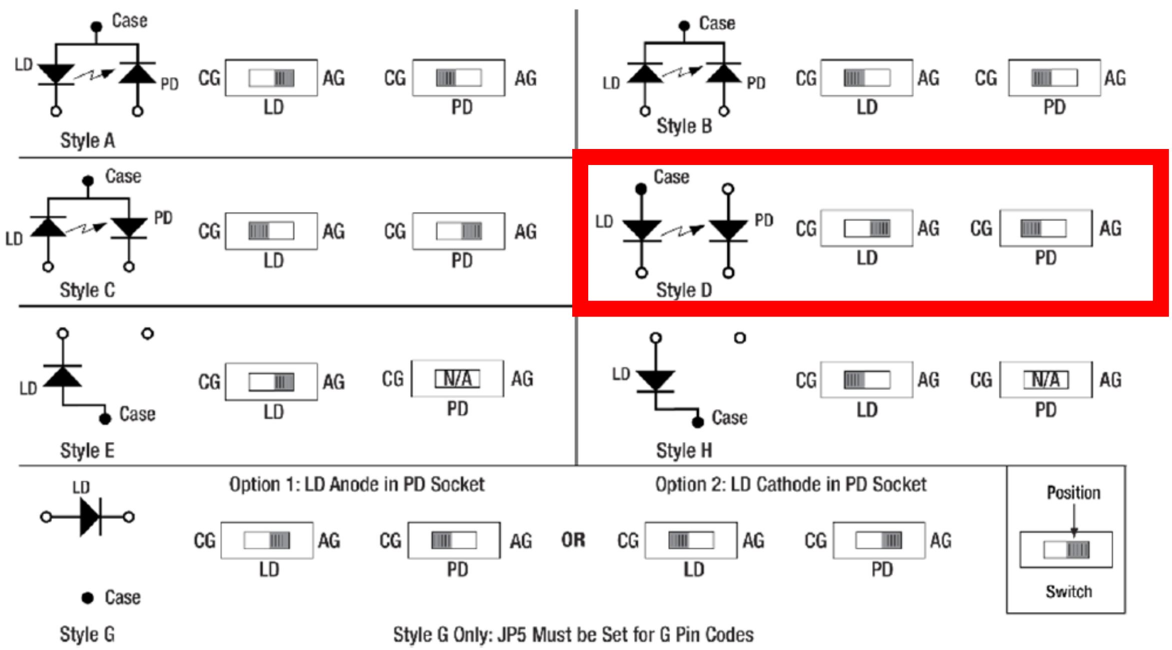


Figure 25 polarity switch settings

For more information, read the manual:
https://www.thorlabs.com/drawings/a9fbf9e34a0519a8-97F9F23E-ABBF-D66C-36398EC198AD207F/LDM56_M-Manual.pdf

5.1.4Laser Diodes

The laser diode is a PIN diode. " I" stands for a wide, undoped intrinsic semiconductor, which is sandwiched between a p-type semiconductor and an n-type semiconductor. Both are heavily doped.

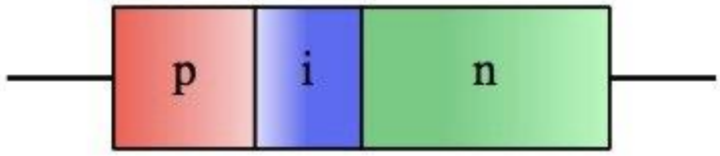


Figure 26

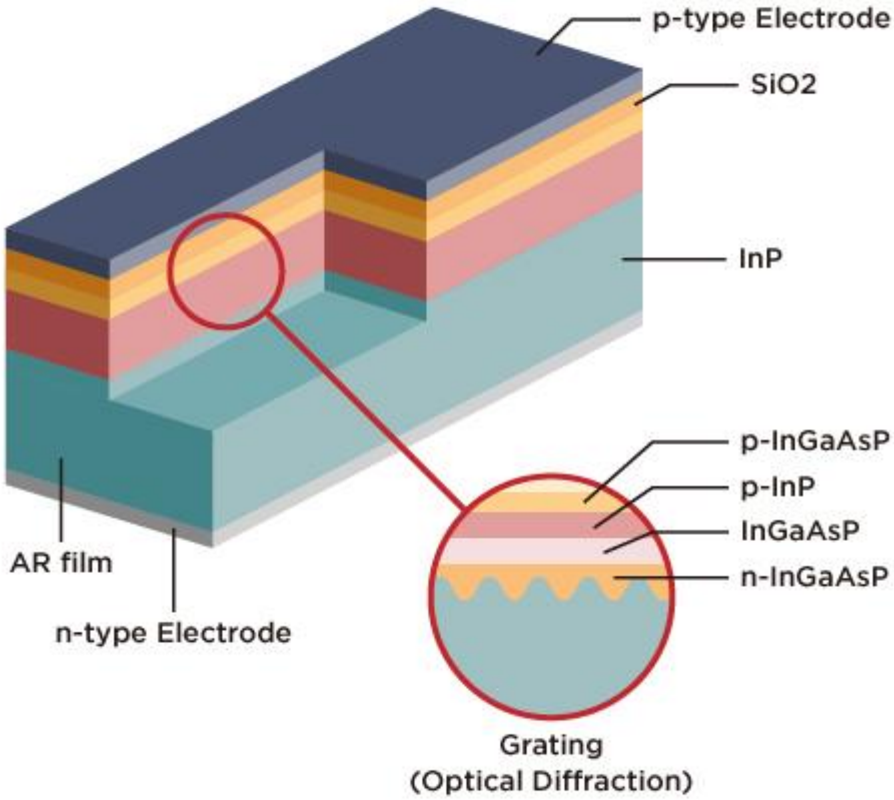


Figure 27

5.1.4.1ML925B45F

ML925B45F is an InGaAsP laser diode that provides a stable, single transverse mode oscillation with emission wavelength of 1550nm and standard continuous light output of 5mW and maximum power of 10mW.

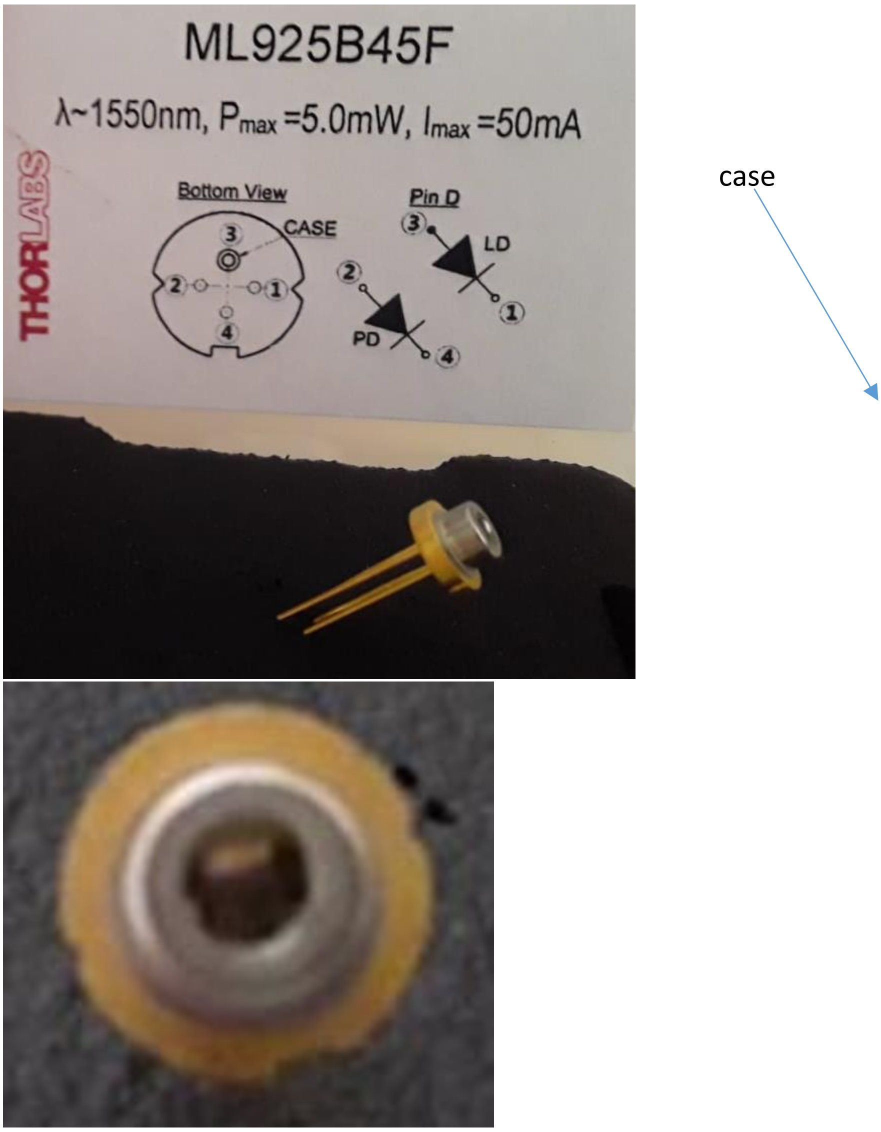


Figure 28

5.1.4.2L155P5DFB

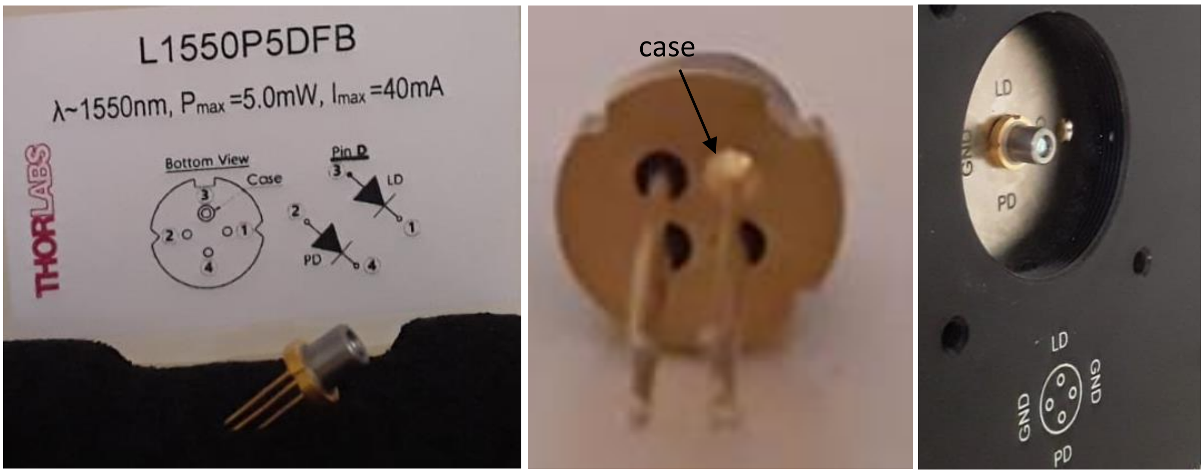


Figure 29

L155P5DFB is fabricated with a corresponding aspheric focusing lens. In addition, the characteristic curves are studied.

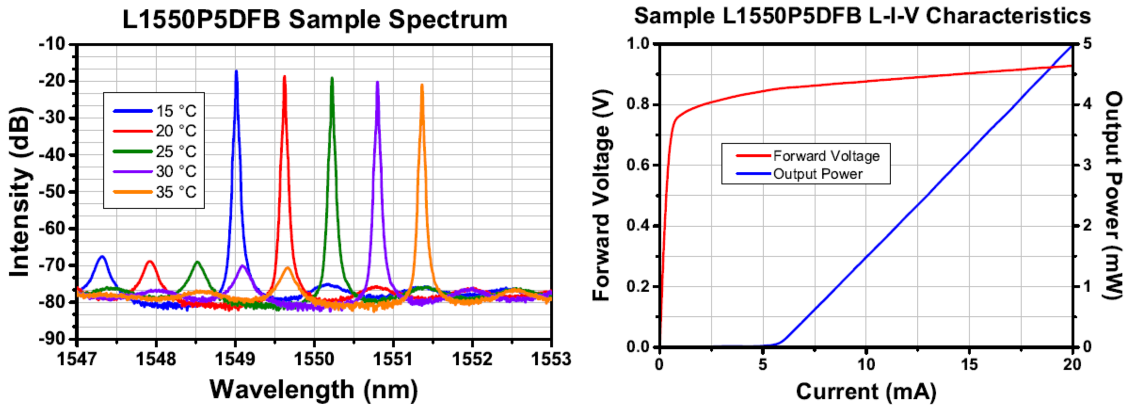


Figure 30

5.1.5Collimator

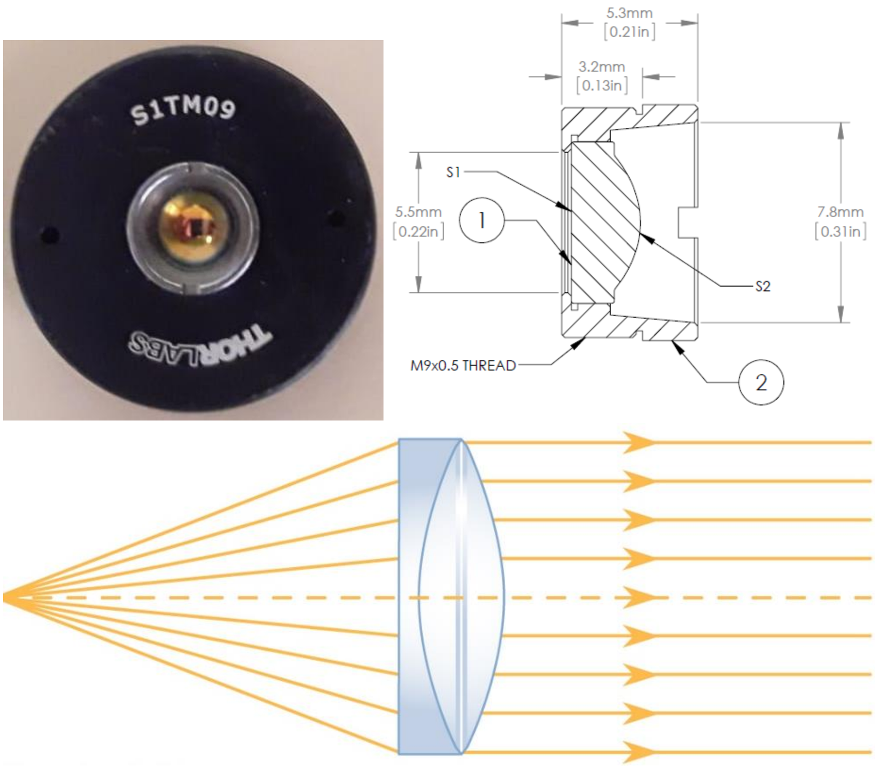


Figure 31

Without a collimator, there is no Laser beam. The collimator brings the radiation coming from the LD to a parallel direction.

5.1.6MELEXIS IR camera

The MLX90621 have 16x4 IR array of pixels. The camera withstands an ambient temperature between - 40˚C and 85˚C. Nevertheless, it is calibrated for an operating temperature i.e. the object’s temperature, between -50˚C and 300˚C. The sensor can detect above 300°C but it is not calibrated for.

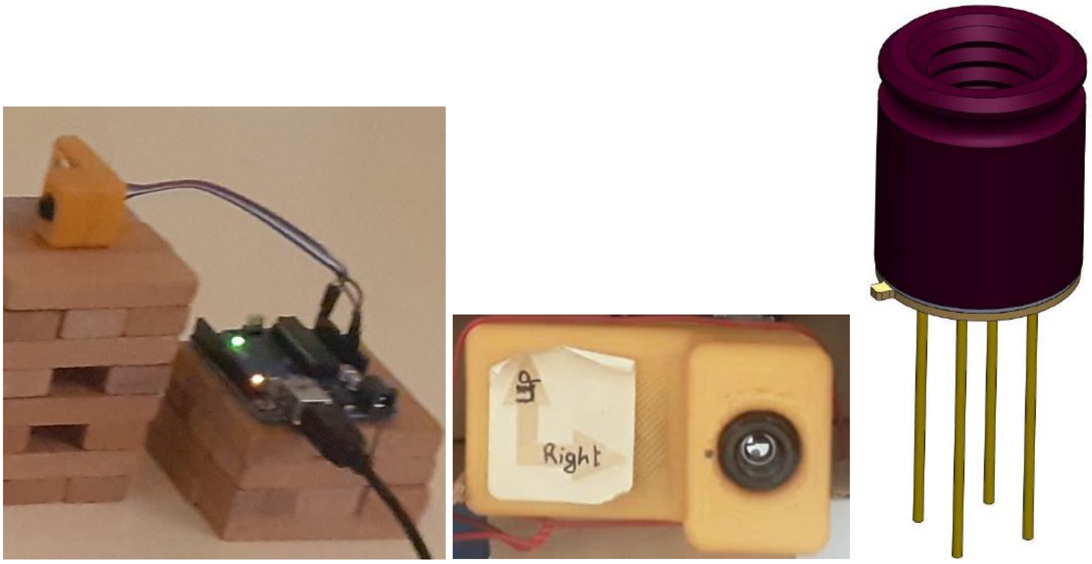
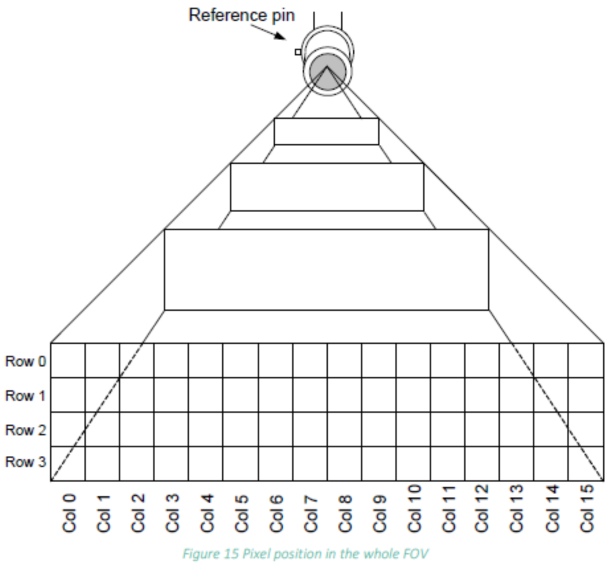


Figure 32



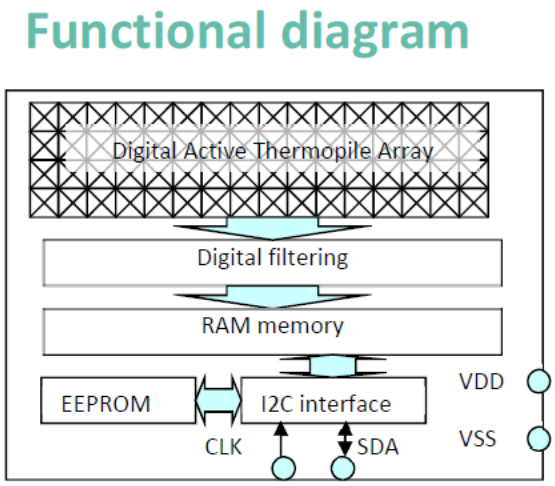


Figure 33

Figure 34

The library we used for the camera in the Arduino is which is available on https://github.com/Leenix/MLX90621-Lite
MLX90621.cpp and MLX90621.h, both are important to operate the camera.

5.1.7Arduino

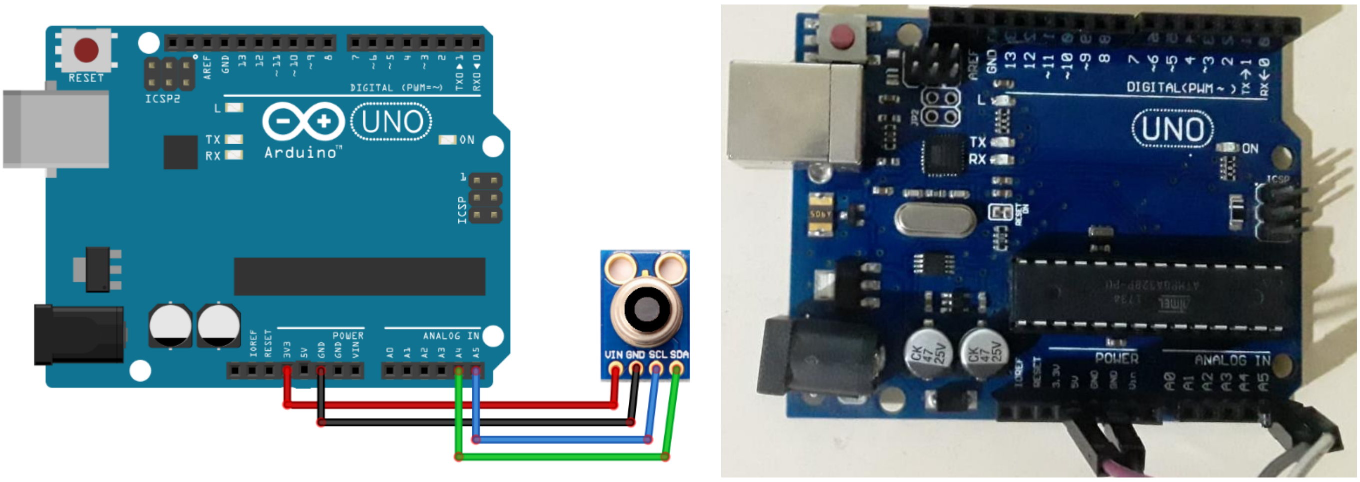


Figure 35

The Arduino is like a mini computer. It is connected to a Laptop via a “print” cable. It’s camera - Arduino connection is an I2C type.

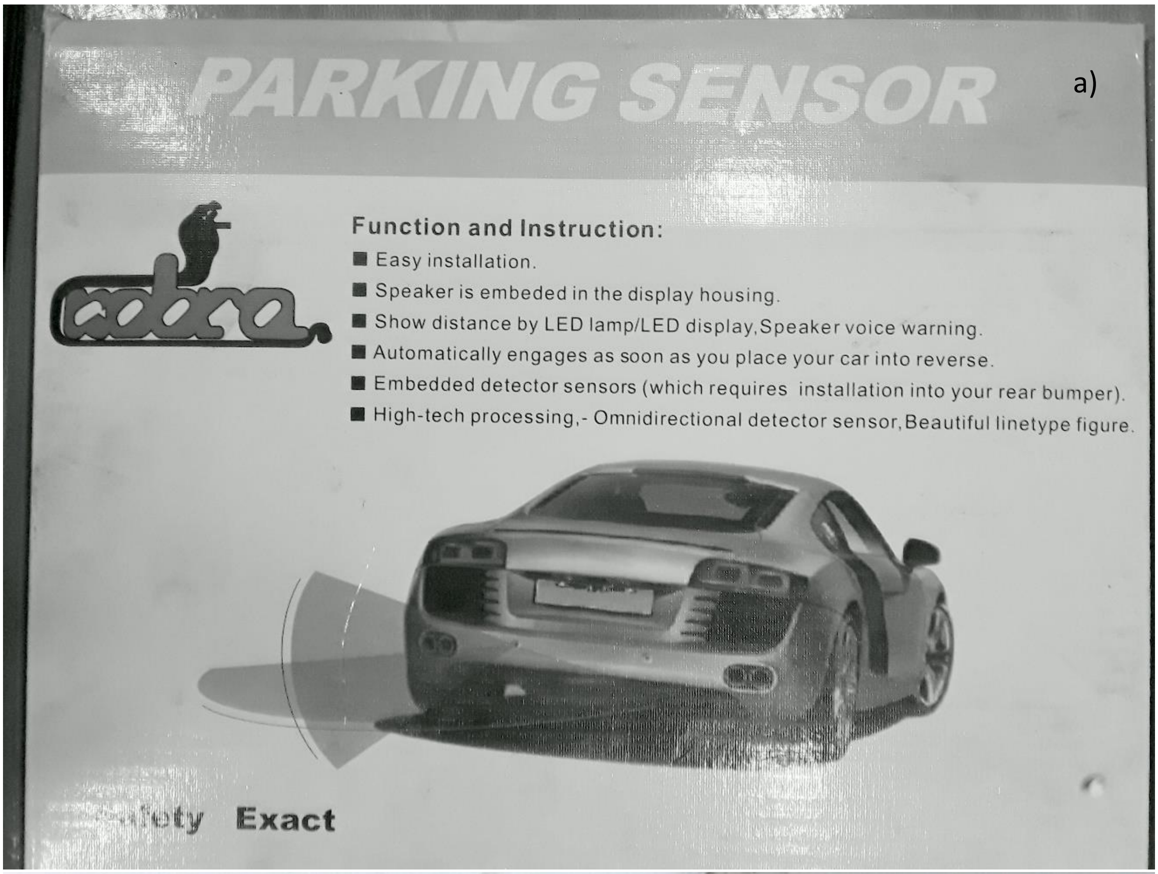
5.1.7.1Initial Program

The initial Program is titled “get temperature”. It only displays the temperatures and calculate the ambient temperature.

```
#include "Arduino.h"
#include <Wire.h>
#include "MLX90621.h"

int refresh_rate = 16;
MLX90621 sensor;

float temperatures[64];

void setup(){
  Serial.begin(115200);
  Serial.println("Starting MLX90621 thermopile sensor");
  pinMode(1, OUTPUT);
  digitalWrite(1, HIGH);

  Wire.begin();
  sensor.initialise(refresh_rate);
}

void loop(){
  Serial.println("\n\nReading sensor...");
```

```
    long start_time = millis();
    sensor.get_temperatures(temperatures);
    long time_taken = millis() - start_time;

    Serial.print("Time taken: ");
    Serial.println(time_taken);

    for(int y=0;y<64;y+=16){ //go through all the rows
        Serial.print('[');
        for(int x=0;x<16;x++){ //go through all the columns
            Serial.print(temperatures[y+x], 2);

            if (x < 15) {
                Serial.print(", ");
            }
        }
         Serial.println(']');
    }
    Serial.print("Ambient temperature: ");
    Serial.print(sensor.get_ambient_temperature());
    Serial.println("°C");
    delay(500);
}
```

5.2 Appendix 2 Parking sensor



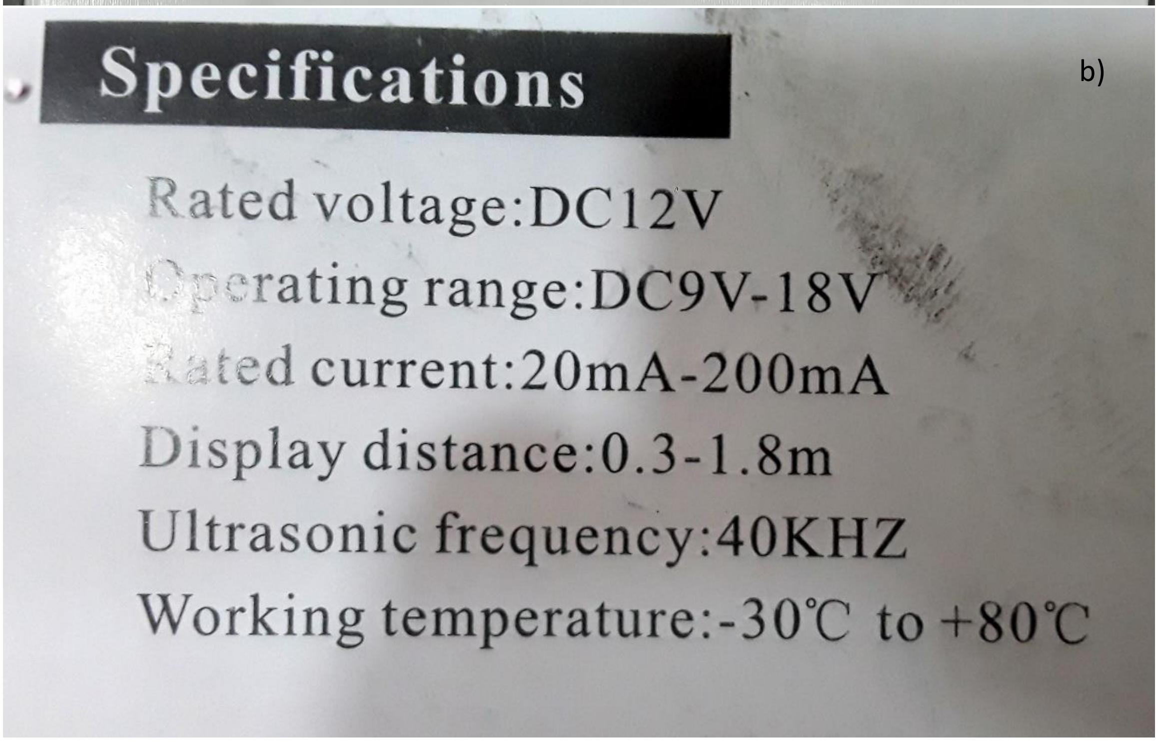


Figure 36 Ultrasonic sensor 200 000 LL. a) package b) properties c) d) device elements

5.3 Appendix 3 Python program

This python program, written by Abdurrahman Mourad, allow us to save the serial data from the Arduino:

```
import serial
import time
from datetime import date
from datetime import datetime

today = date.today()
dateTimeObj = datetime.now()
timestampStr = dateTimeObj.strftime("%d-%m-%Y-%H-%M-%S")

text_file = open(timestampStr+".txt", "w+")

ser = serial.Serial('COM3', 115200, timeout=0)




while 1:
 try:
  readed = ser.readline()
  print readed
  time.sleep(0.4)
  n = text_file.write(readed)
 except ser.SerialTimeoutException:
  print('Data could not be read')
  #time.sleep(1)


text_file.close()
```

BIBLIOGRAPHY

[1] https://core.ac.uk/download/pdf/35460262.pdf
[2] https://www.ieabioenergy.com/wp-content/uploads/2018/09/Gas_analysis_report_II-1.pdf
[3] http://www.iup.uni-bremen.de/doas/doas_tutorial.htm
[4] https://www.smart-piv.com/en/techniques/lif-plif/
[5] http://przyrbwn.icm.edu.pl/APP/PDF/116/a116z330.pdf
[6] file:///C:/Users/QSC/Downloads/Axetris_LGD%20BR_Laser-Gas-Detection%20EN.pdf
[7] https://www.seika-di.com/en/measurement/principle_of_lif.html

[8] Gas monitoring in the process industry using diode laser spectroscopy I. Linnerud, P. Kaspersen, T. Jæger
[9] http://www.chemistry.uoc.gr/lapkin/OrazioSvelto_PrinciplesOfLasers_5thEd.pdf
[10] Distributed-feedback laser/ Dr. Rüdiger Paschotta https://www.rpphotonics.com/distributed_feedback_lasers.html#:~:text=eagleyard%20Photonics,with%20an%20extremely%20narrow%20linewidth.&text=Find%20your%20suitable%20DFB%20laser,from%2010%20to%20150%20mW.

[11] https://application.wiley-vch.de/books/sample/3527327150_c01.pdf
[12] https://study.com/academy/lesson/what-is-carbon-monoxide-effects-lesson-quiz.html
[13] https://edinburghsensors.com/news-and-events/carbon-monoxide-detection-with-a-co-sensor/
[14]https://www.euro.who.int/__data/assets/pdf_file/0020/123059/AQG2ndEd_5_5carbonmonoxide.PDF
[15] https://socratic.org/questions/by-writing-molecular-orbital-configuration-for-no-co-o2-molecules-calculate-the-
[16] chemline_chemical_resistance_guide_2015 pdf https://everythinginsidethefence.com/wp-content/uploads/chemline_chemical_resistance_guide_2015.pdf
[17] https://www.britannica.com/science/Beers-law
[18] 030220_laser_gas_detection Siham Aisha & Maryam Abd AL Karim
[19] https://www.mouser.com/pdfdocs/ROHM-PO-WP.pdf
[20] https://automotive.hamamatsu.com/eu/en/safety/distance.html
[21] Kinetic Studies for Formic Acid Decomposition by Sulfuric Acid Using Differential Methods A. Seza Baştuğ Department of Basic Pharmaceutical Sciences, Faculty of Pharmacy, Marmara University, Haydarpaşa, 34668, İstanbul, Türkiye file:///C:/Users/QSC/Downloads/FABOZ.pdf

[22] Gas Sensors for Underground Mines and Hazardous Areas,
S.K. Chaulya, G.M. Prasad, in Sensing and Monitoring Technologies for Mines and Hazardous Areas, 2016
3.4.5.1.2 Working Procedure
https://www.sciencedirect.com/topics/earth-and-planetary-sciences/semiconductor-laser

[23] https://forum.arduino.cc/index.php?topic=447024.0
[24] https://htmlcolorcodes.com/
[25] https://www.colorhexa.com/009900
[26] MLX90621-Datasheet-Melexis
[27] https://pubchem.ncbi.nlm.nih.gov/compound/281#section=Vapor-Density
[28]https://bhs.banning.k12.ca.us/documents/Webmaster/AP%20Courses/Chem%20AP%20Formula%20Sheet.pdf
[29] http://www.depts.ttu.edu/chemistry/Faculty/jones/chapter_14.pdf
[30] https://chemequations.com/en/?s=CO+%2B+O2+%3D+CO2
[31] https://www.sciencedirect.com/topics/earth-and-planetary-sciences/incinerator
[32] https://www.sciencedirect.com/science/article/pii/S1996681416301729
[33]https://www.researchgate.net/publication/267304356_Thermal_processing_for_Heavy_Metal_Removal_of_Municipal_Solid_Waste_Fly_Ash
[34] https://www.unitconverters.net/typography/centimeter-to-pixel-x.htm

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