PONTIFÍCIA UNIVERSIDADE CATÓLICA
DO RIO DE JANEIRO

Alexandre Lentz

Experimental results of a high-power laser for underwater paraffin removal

Graduation Project

Graduation Project presented to the Department of Mechanical Engineering at PUC-Rio

Advisor: Arthur M. B. Braga
Co-Advisor: Dario Prada Parra

Rio de Janeiro
November 2023

Acknowledgements

I would like to thank the LSFO laboratory and the GALP company for giving me the opportunity to work on this project.

I thank my guide Arthur Braga for his availability and the trust he placed in me.

I thank my co-advisor Dario Prada for all the help and advice he provided me throughout my project.

I would like to thank all the LSFO technicians for the help they gave me with the manufacturing of the prototypes and the tests with the laser.

I thank Paula Gouvêa for her help.

I would also like to thank the PUC-Rio University and the INSA CVL engineering school for providing me with the knowledge that was useful to me for this project.

ABSTRACT

Experimental results of a high-power laser for underwater paraffin removal

Paraffin, a complex mixture of hydrocarbons, plays a crucial role in the oil and gas industry, it presents challenges due to its complex nature, varying properties, and tendency to precipitate and adhere to production components, leading to decreased efficiency and increased operating costs. Paraffin deposition in oil wells is a long-standing problem, causing reduced production rates, blockages in flow conduits, and the need for costly removal processes. The troublesome paraffins, ranging from C18H38 to C38H78, can lead to severe inefficiencies in the oil recovery system, resulting in billions of dollars in losses within the petroleum industry annually.

This study focuses on the utilization of a high-power laser to help develop underwater paraffin removal technique, which utilizes a high-power laser to increase the temperature and melt the paraffin. The research aims to address the challenges posed by paraffin in the oil and gas industry by offering a potential solution for efficient paraffin removal. The technique has the potential to remove paraffin deposition, reduce downtime, and lower operating costs, thereby contributing to improved operational efficiency in the oil and gas sector.

Key words: High power laser. Paraffin removal. Fiber Bragg Sensor. Experimental. Finite element method.

RESUMO

Resultados experimentais de um laser de alta potência para remoção de parafina submarina

A parafina, uma mistura complexa de hidrocarbonetos, desempenha um papel crucial na indústria de petróleo e gás, apresenta desafios devido à sua natureza complexa, propriedades variadas e tendência a precipitar e aderir a componentes de produção, levando à diminuição da eficiência e aumento dos custos operacionais. A deposição de parafina em poços de petróleo é um problema de longa data, causando taxas de produção reduzidas, bloqueios em conduítes de fluxo e a necessidade de processos de remoção caros. As parafinas problemáticas, variando de $C_{18}H_{38}$ a $C_{38}H_{78}$, podem levar a graves ineficiências no sistema de recuperação de petróleo, resultando em bilhões de dólares em perdas na indústria do petróleo anualmente.

Este estudo centra-se na utilização de um laser de alta potência para ajudar a desenvolver a técnica subaquática da remoção da parafina, que utiliza um laser de alta potência para aumentar a temperatura e para derreter a parafina. A pesquisa visa enfrentar os desafios colocados pela parafina na indústria de petróleo e gás, oferecendo uma solução potencial para a remoção eficiente de parafina. A técnica tem o potencial de remover a deposição de parafina, reduzir o tempo de inatividade e reduzir os custos operacionais, contribuindo assim para a melhoria da eficiência operacional no setor de petróleo e gás.

Palavras chaves: Laser de alta potência. Remoção de parafina. Sensor de Bragg de Fibra. Experimental. Método dos elementos finitos.

Summary

Figure List

Table List

1. Introduction

1.1. Work Motivation

The two main problems in offshore oil production concern methane hydrates and paraffin plugs [1]. These problems make underwater operations difficult, often requiring their elimination using expensive and time-consuming methods that can damage equipment [2]. While there are solutions to reduce [3][4][5] paraffin deposits, it is impossible to completely prevent them [6].

During the last few decades, different types of methods have been developed to remove deposits from pipes. These methods can be mechanical like drilling pipes [7], they can be chemical methods [8], and finally thermal methods, or they can be simply thermal insulation [9] or removal by melting [10].

As the behavior of hydrates and paraffin is different, in our research we will focus on paraffin removal. For that, we will also have to understand what is paraffin [11], when how does it appear [12][13].

1.2. Objectives

In our case, we focused on removing paraffin with a thermal method. In fact, we want to analyze how it would be possible to remove paraffin by heating the tube from the outside using a high-power laser [14][1][2]. We found it interesting to remove the deposits with a laser coming to heat the tube, in order to melt the paraffin.

The objective of the work will therefore be to analyze the possibility and characteristics of such a machine. This, therefore, corresponds to determining the laser beam and finding the power that we are going to use.

The environment in which we will carry out the paraffin removal [2], will also be analyzed, as we will have to find out the convection coefficient under water at low temperature and high pressure.

In addition, it will be necessary to adapt the pipes that are already submerged.

2. Bibliographical review

2.1. Paraffin

2.1.1. Introduction on paraffin

Paraffin describes a group of hydrocarbons made from petroleum, coal, or oil shale. They are a mixture of hydrocarbon molecules that contain from 20 to 40 carbon atoms. A lot of different type of paraffin exist and some are key components for the development of the petroleum and natural gas industry. Depending on their carbon atoms number, they tend to different conditions at ambient temperature. Those with less than 5 tend to be gases; those with between 5 and 15 tend to be fluid in form. And finally, those with over 15 carbon atoms per molecule tend to be solid at ambient temperature [5][4].

Heavy oil is a type of crude oil that is more viscous and denser than conventional crude oil. There, we will find a higher concentration of paraffin wax, because of the type of oil it is, which can cause problems in oil production and refining. Paraffin wax is a component of crude oil that builds up and has drastic negative effects on oil transportation, production and refineries. The types of paraffins we can find in this environment have high molecular weight that have a choking effect on crude oil wells. Over time, the deposition of paraffin causes a decrease in production capacity and ability. These deposits vary in thickness and composition, from soft to hard [3][5][11].
Paraffin deposition is a process where paraffin wax, a normal hydrocarbon ranging from approximately $C_{18}H_{38}$ to $C_{38}H_{78}$ mixed with small amounts of branched paraffins, monocyclic paraffins, polycyclic paraffins and aromatics, precipitates and adheres to the liner, tubing, sucker rods, and surface equipment as the temperature of the producing stream decreases in the normal course of flowing, gas lifting, or pumping.

The buildup of paraffin deposits can lead to several issues:

- Decreased pipeline cross-sectional area
- Restricted operating capacities

- Additional strain on pumping equipment

Paraffin deposition is a significant concern for the oil and gas industry, as it can result in reduced crude oil flow, pressure abnormalities, and artificial blockages, ultimately leading to a reduction or interruption in production. Figure 1 shows an example of a pipe section with wax buildup [3][4][8][13].

Figure 1 – Wax deposit reducing the effective diameter in a retrieved pipeline (Singh et al., 2000).

Paraffin deposition, a prevalent issue in the oil and gas industry, is described by two primary mechanisms: shear dispersion and molecular dispersion. Shear dispersion focuses on the relationship between deposition rate and shear rate, while molecular dispersion deals with the overall dispersion of paraffin molecules in the fluid.

Shear dispersion occurs when the shearing of wax molecules takes place due to the hydrodynamic drag of the flowing fluid, which depends on the flow rate and viscosity of the fluid. Higher viscosity and low flow rates result in high wax deposition rates.
As paraffin wax accumulates on a surface, it is held in place by adsorption forces, which are influenced by the free surface energy of both the paraffin and the surface. The deposits do not adhere to the metals themselves but are held in place by surface roughness.

Molecular dispersion, on the other hand, involves the overall dispersion of paraffin molecules in the fluid. This process is influenced by factors such as the temperature gradient, which causes the wax and oil in the total deposit to separate, leaving more oil in the outer layers. This oil lowers the wax content of the deposit, making it harder.

In summary, the predominant mechanisms for paraffin deposition are shear dispersion and molecular dispersion. Shear dispersion describes the relationship between deposition rate and shear rate, while molecular dispersion deals with the overall dispersion of paraffin molecules in the fluid. These mechanisms play a significant role in the formation of paraffin deposits, which can restrict oil flow, cause pressure abnormalities, and lead to artificial blockages in pipelines as we can see in Figure 2 [3][4].

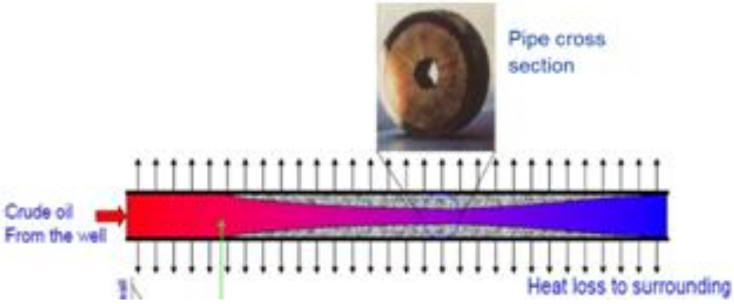


Figure 2 - Wax deposition occurs when the inner wall temperature is below the cloud point temperature [18].

2.1.2. Problem of paraffin deposition

Paraffin deposition is a common problem in the oil industry that can cause several issues, including plugging and increasing energy demand, both of which are costly to the operator. The following are some of the problems caused by paraffin deposition in the oil industry:

Reduced flow: Paraffin deposits can reduce the effective size of the flow conduits, which can restrict the production rate from the well.

Increased energy demand: Paraffin deposition can increase the energy demand required to transport the oil from the wellhead to storage through steel piping lines.

Formation damage: Paraffin deposition can cause formation damage by depositing on the pore walls or tubing surface, which can reduce the permeability of the formation and decrease the well's productivity.

Costly removal: Severe paraffin deposition requires removal of the deposits by mechanical, thermal, or other means, resulting in costly downtime and increased operating costs.

2.2. Paraffin removal

To remove paraffin wax build-ups in oil wells, there are several methods, including mechanical, thermal, and chemical treatments. Chemical removal of paraffin build-up from oil wells is a common method that involves using wax solvents or dispersants to dissolve the wax and disperse it into the oil. Before choosing a chemical to remove paraffin deposits, it is important to consider the nature of the wax build-ups. Oil wells that suffer from wax problems are usually experiencing other fouling as well [11].

There is already existing technology existing that uses those different methods:

- The Cold Flow: In the cold flow technique, foreign particles are added to decrease the tendency of the crystals of depositing (Figure 3).

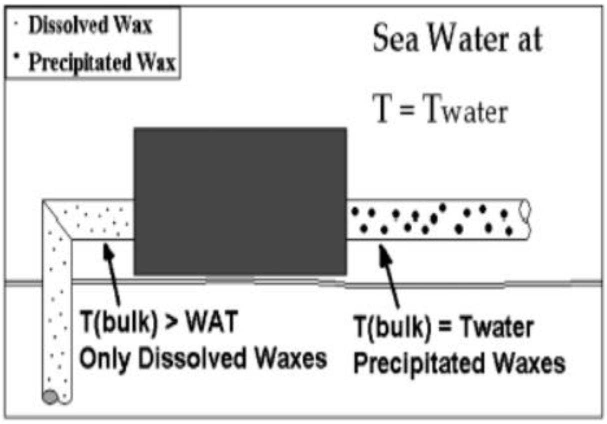


Figure 2 – Cold Flow Scheme [11].

- Chemicals reducing wax deposition: Wax crystal modifiers incorporate themselves with the growing wax. Surfactants are mainly used to sufficiently disperse the wax particles to affect aggregation and reduce their deposition.

- Wax removing chemical: Uses of solvents and dispersants. This technique is different from the previous one because here it is about removing the paraffin and not preventing it from depositing [8].

- Fused chemical reaction: The technique consists of using a fused chemical reaction with controlled heat emission to remove the wax deposit, as we can see in Figure 4. However, without good knowledge of the profile of the deposit, this solution damages the pipes.

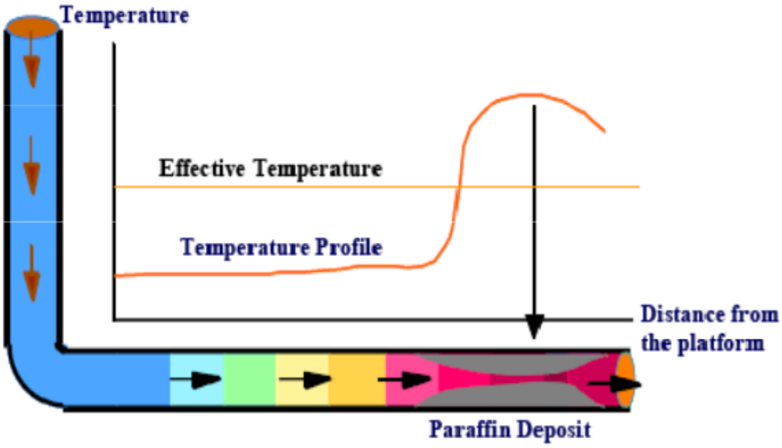


Figure 3 – Usage of a fused chemical reaction to remediate the paraffin plugging in subsea pipelines [11].

- Mechanical removal: On the surface pipeline, it is possible to wire line scrapper manually [7]. In the well tubing part of the production system, usually scrapers and cutters are used in order to effectively remove paraffin. Principles of operation of such devices is the same in all cases and consists of physical scraping of paraffin deposits from the tubing wall while the well is still producing. This operation is well described in Figure 5.

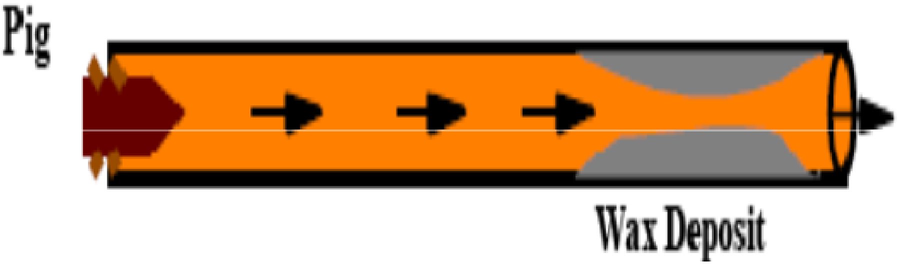


Figure 4 – Incrustação na válvula de controle de fluxo de fundo de poço [11].

- Heat application: Heat is applied by various techniques such as hot oil or hot water injection, steam injection and electric pipe heating [10].

- Magnetic Fluid Conditioning (MFC) technology: The MFC treatment alters the growth pattern of paraffins and scale crystals, which inhibits their clinging to pipeline walls. This technique uses powerful magnets to force the oil into a narrow passageway, helping to avoid the build-up of wax deposits and agglomeration by polarizing the wax molecules in a flow-direction orientation. As show in Figure 6.

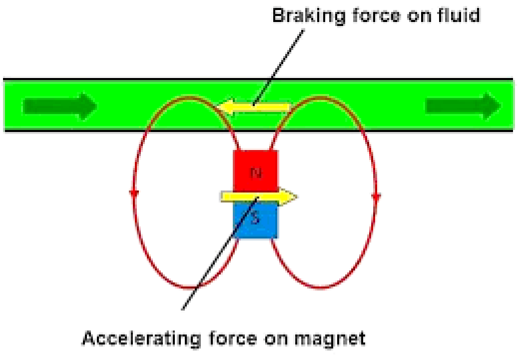


Figure 5 – MFC technical presentation.

- Use of Microbial Products: The method is based on the fact that there are natural marine microorganisms, which have the ability to absorb paraffin, and are able to effectively remove paraffin deposits or at least reduce the deposit over a certain period of time.

- Melting from the inside: Uses of a robot to melt paraffin from the inside [10].

2.3. High power lasers applied to the oil and gas industry

Laser technology is based on the phenomenon of light amplification by stimulated emission of radiation. It is widely used in almost every industry due to its unique features, such as precision, reliability, control, and accuracy. The oil and gas industry has capitalized on low-power laser applications such as sensing and measurements, but high-power laser applications remained beyond the realm of upstream until recently [1] [2].

2.3.1. Saudi Aranco Projects

This research was largely carried out by the company Saudi Aranco. They notably carried out research on:

The first pillar focused on developing a comprehensive experimental database of laser-rock interactions, which included tests on all types of rocks under different conditions.

The second and third pillars concentrated on tool development and energy transmission via optical fibers.

The last element analyzed how high-power laser applications enable sustainability in subsurface applications.

The success of the intensive research conducted over the past two decades led to the development of the first high-power laser system for field applications and unlocked several upcoming applications. The system's design is enclosed, providing a safe and risk-free operation. The system consists of a laser energy generator, nitrogen tank, vacuum truck, and tool.

There are also challenges faced during the lab-to-field transformation process. For example, attenuation is one of the critical factors limiting the reach and power that a fiber can transmit. Scattering is another physical phenomenon that deviates waves from their original trajectory into multiple paths due to localized defects or irregularities in the propagation medium. These interactions can severely disrupt light propagation to the target. However, several solutions have been advanced, and today there are different methods available to tackle them [1].

It discusses some of the challenges faced during the lab-to-field transformation process and the solutions that were developed to overcome them.

2.3.2. Ouronova, PUC-Rio and Galp Projects

A project from Ouronova, Galp and PUC-Rio university aims to develop a high-power laser tool to dissociate hydrate on subsea equipment in the oil and gas industry. The laser tool is designed to be carried, operated, and powered by an ROV, and it includes a cooling system capable of dissipating the heat produced by the laser diodes. The paper [2] presents simulations and experimental results that demonstrate the effectiveness of this technology. The laser tool has several advantages compared to other methods, such as high efficiency, precision, and safety, and it can be used for both direct and indirect dissociation of hydrate. The researchers suggest that further development and on-site experiments are needed to improve the technology and explore new commercial laser models.

2.3.3. Foro Energy projects

Another company researching high-potential lasers in the oil field is Foro Energy. Foro Energy's laser drilling technology offers several advantages compared to traditional drilling methods:

Economy: Foro Energy's laser-assisted drill bits have the potential to be up to 10 times more economical than conventional hard-rock drilling technologies, making them an effective way to access energy resources currently locked under hard rock formations.

- **Speed**: Laser cutting offers an exponentially faster approach to wellhead and casing removal compared to conventional excavation methods.

- **Safety**: Laser cutting provides a safer method for wellhead and casing removal, as well as plug and abandonment, decommissioning, and scale removal in well operations.

- **Customization**: Foro Energy's technology allows operators to create custom wellbore perforating geometries, thru tubing access to formation, single/dual string casing milling, or removal of hard scale interior to the production casings/tubulars.

- **Step change in performance**: The combination of high-power lasers and mechanical tools provides enhanced and potentially breakthrough performance and capabilities in drilling.

In summary, Foro Energy's laser drilling technology offers significant improvements in efficiency, speed, safety, and customization compared to traditional drilling methods, making it a promising solution for the oil, natural gas, geothermal, and mining industries.

2.4. Thermal property

2.4.1. Paraffin

Paraffin oil is a type of paraffin wax that is liquid at room temperature and is derived from petroleum, coal, or oil shale. It is a mixture of hydrocarbon molecules containing between 5 and 40 carbon atoms. Here are some of the thermal properties of paraffin oil:

- **Thermal conductivity**: Paraffin oil has a low thermal conductivity (0.4 W/m K), which is a major drawback as it decreases the rates of heat stored.

- **Heat capacity**: Paraffin oil is an excellent material for storing heat, with a specific heat capacity of 1.850-2.384 kJ.kg^(-1).K^(-1) (joules per gram kelvin) and a heat of fusion.

- **Melting point**: Paraffin oil begins to melt above approximately 60 °C.

- **Density**: The density of paraffin oil ranges from 775 to 856 kg/m^3, depending on the specific type and composition of the oil.

It is worth noting that the thermal properties of paraffin oil may vary depending on the specific type and composition of the oil (Table 1).

Table 1 – Table of the thermo-physical properties of paraffin wax

Property	Value
Latent heat of fusion	214 J/kg
Specific heat capacity (solid)	1.85kJ/(kg.K)
Specific heat capacity (liquid)	2.384kJ/(kg.K)

Thermal conductivity	0.4W/(m.K)
Density (solid)	856kg/(m^3)
Density (liquid)	775kg/(m^3)
Melting point	60°C

2.4.2. Water

It is necessary to know the thermal properties of water because, to put ourselves in the conditions which are closest to reality, we must carry out the test with the prototype and the submerged laser.

Water has several thermal properties that make it unique and important for many processes. Here are some of the thermal properties of water:

- **Specific heat capacity**: Water has a very high specific heat capacity, which means it can absorb a lot of heat with only a small temperature change. This is why coastal areas tend to have milder temperatures than inland areas, as the ocean absorbs and releases heat more slowly than land.

- **Boiling point**: The boiling point of water is 100°C at standard pressure.

- **Melting point**: The melting point of water is 0°C at standard pressure.

- **Latent heat of fusion**: Water has a high latent heat of fusion, which is the amount of heat required to change a substance from a solid to a liquid. In the case of water, it takes 80 calories of heat to melt 1 gram of ice.

- **Latent heat of vaporization**: Water also has a high latent heat of vaporization, which is the amount of heat required to change a substance from a liquid to a gas. In the case of water, it takes 540 calories of heat to vaporize 1 gram of liquid water.

- **Thermal conductivity**: Water has a relatively high thermal conductivity, which means it can transfer heat relatively well.

- **Heat capacity**: Water has a high heat capacity, which is the amount of heat required to raise its temperature. This means that water is difficult to heat or cool, as it can absorb or release large amounts of heat without changing temperature much.

In summary, water has several unique thermal properties that make it important for many processes, including its high specific heat capacity, boiling and melting points, and latent heats of fusion and vaporization.

2.4.3. Steel

Steel is a poor thermal conductor, which means it carries heat very slowly and is an ideal material to use as an insulator. The thermal conductivity of steel is measured at approximately 45 W/(m.K), which is extremely low compared to copper and aluminum, which exhibit thermal conductivity values of 398 W/(m.K) and 235 W/(m.K), respectively. Carbon steels represent the group with the highest thermal conductivity, averaging at 45 W/(m/K). Stainless steel exhibits a low thermal conductivity of 15 W/(m.K), which allows it to retain more energy, which stabilizes the surrounding temperature better. In summary, the thermal properties of steel are:

- Steel is a poor thermal conductor.
- The thermal conductivity of steel is approximately 45 W/(m.K).

- Carbon steels represent the group with the highest thermal conductivity averaging at 45 W/(m/K).
- Stainless steel exhibits a low thermal conductivity of 15 W/(m.K).

In our case we used steel AISI4340, which has a thermal conductivity of 44.5 W/(m.K).

3. Methodology

3.1. Heat transfer

3.1.1. Laser Heat transfer

The attenuation in air for the laser beam is very low and can be considered zero for this application. However, in water, the attenuation is higher mainly due to scattering of the beam caused by floating particles and absorption (depending on the wavelength).

The laser source used in all experiments and simulations discussed in this work is a 700 W blue diode laser from LaserLine.

The loss of power happens on all the movement inside the fluid, which means, further is the objective, the more loss there will be. Figure 7 shows the loss of power measured in water for the 700 W blue diode laser used in this project. This result shows that this laser loses 40% of his initial power after propagating 1 meter in water.

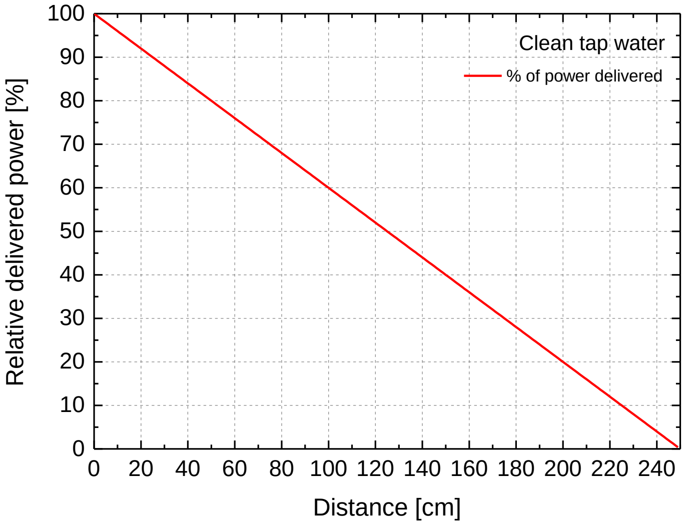


Figure 6 – Power of a laser depending on distance (Internal communication).

After propagating in water, the laser beam collides with the steel and heats it with thermal radiation. The steel absorbs the energy from the laser, causing its temperature to increase. Moreover, the temperature will be higher but more localized, the smaller the beam will be.

3.1.2. Thermal convection

As for the heat transfer with thermal convection, there are 2 types:

There is the thermal convection between a fluid and a solid material. It corresponds for us as the cooling of the steel surrounded by air and the cooling of the steel surrounded by water. To define it, there is a parameter and it is the heat transfer coefficient. For our studies, this coefficient was defined at 20W/(m^{2}K) for the air and 200W/(m^{2}K) for the water.

The other thermal convection that happens in this system is the thermal convection inside of the fluids, the water and the air.

3.1.3. Thermal conduction

And finally, the last one is the thermal conduction. The same as with thermal convection, there are 2 types of thermal conduction:

The thermal conduction between the materials, which for this case, is related to the heat transfer between the steel and the paraffin.

And the thermal conduction inside of each material, which is related to steel with a thermal conduction coefficient of 44.5[W/(m*K)] and the paraffin with 0.4[W/(m*K)].

3.2. Parts of the experimental setup

3.2.1. Tests specimen assembly

To build our test specimen, we used 2 parts, shown in Figure 8. First, a steel pipe which will be subjected to laser radiation and then 2 lids which will hermetically isolate the tube from the water when we carry out tests under water

Figure 7 – Parts of the test specimen.

We made acrylic caps so that we could see through them and observe the profile that the paraffin takes after it has melted through the action of the laser.

Figure 8 – Picture of the test specimen.

To assemble our test specimen, we used 3 threaded rods which hold the lids on each side using bolts, the test specimen final is shown in the Figure 9.

In addition, to install the specimen in the tank, we added a handle to hold it in place (Figure 10).

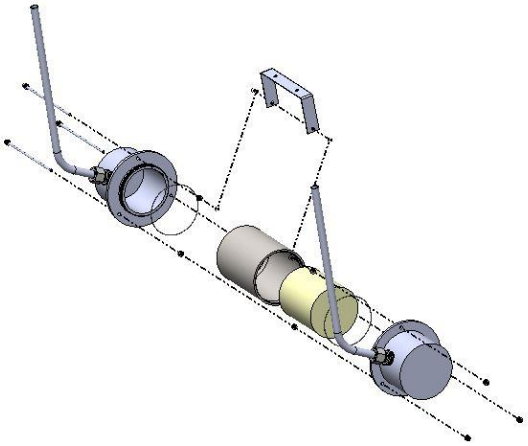


Figure 9 – Scheme of the specimen test

The final step of the assembly is to melt and put paraffin inside the tube before placing the lids, as can be seen in Figure 10. Finally, because the specimen test was placed underwater, we also had to put pipes on the sides to allow air exchange.

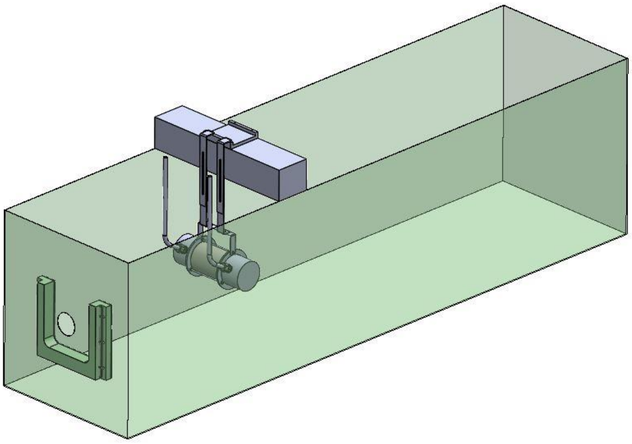


Figure 10 – Scheme of the tests.

Everything was placed in a tank perpendicular to the laser, as we can see in the Figure 11. So that you can add water when necessary.

For our tests, we decided to use commercial paraffin because it was easier in our approach. Indeed, it was already easier to obtain some to carry out our tests, but in addition. Our test consisted of melting paraffin and then letting it reform in our tube. Thus, commercial paraffin allowed us to have a more homogeneous material than with paraffin oil.

3.2.2. Operation of the temperature reading

With the idea of being able to see the overall evolution of the temperature within the tube, we placed sensors from under the point of impact of the laser to its end. In addition, to be able to observe the diffusion of temperature and the impact of cooling, we also added sensors to the sides of the point of impact, as show in the Figure 12.

The sensors used were sensors based on optical fiber. The advantage of the sensors with optical fiber are low interferences and a good accuracy. Moreover, they works well at our temperature.

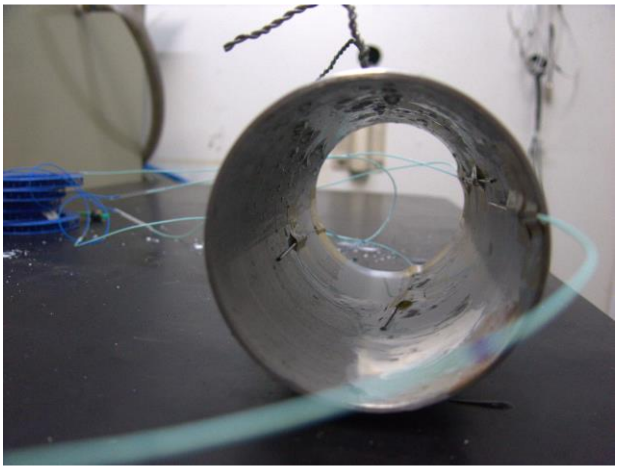
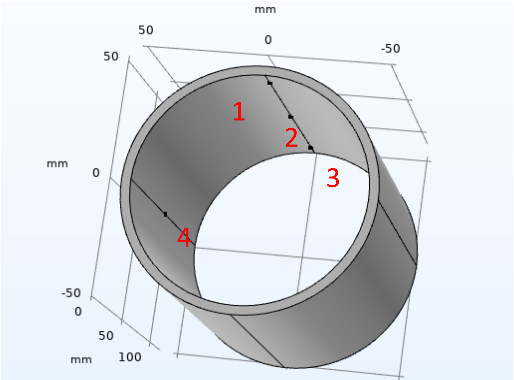


Figure 11 – Picture of the pipe with sensors.

In order to clearly see the heat transfers, we decided to place 5 temperature sensors inside our tube. A first just behind the point of impact of the laser, T2, where the temperature is the highest. Two others on the same line but on but 1 on each side to see the horizontal heat movement, T1 and T3. Another was placed in the tube at 90° to view the transfer along the tube wall, T4. And the last one at 180°, on the other side of the tube, to see the heat transfer inside the paraffin, T5. The placement of the different sensors can be seen of Figure 13 and 14.



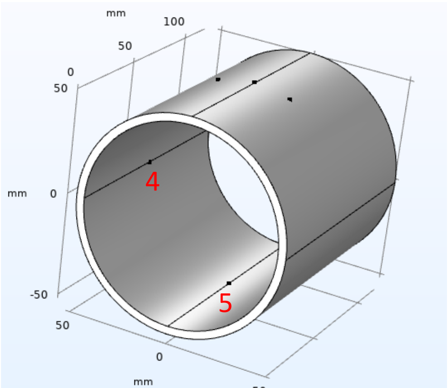


Figure 123 – Scheme of the sensor's placement

Figure 134 – Second scheme of the sensor's placement

3.2.3. Bragg's Law

Our temperature sensors utilize Fiber Bragg gratings (FBGs) based on Bragg's Law to measure temperature. FBGs are a type of distributed Bragg reflector constructed in a short segment of optical fiber that reflects specific wavelengths of light. The Bragg wavelength is responsive to both temperature and strain, enabling FBGs to serve as sensing elements in optical fiber sensors. A change in the temperature or strain around the grating results in a shift in the reflected wavelength, which is proportional to the change in temperature or strain. Thus, by monitoring the changes in the reflected wavelength, we can infer the changes in temperature or strain.

4. Results

4.1. Characterization of the beam diameter and power density

Initially, we performed tests to determine the spatial distribution of the beam, which was done by measuring its diameter at different distances from the laser head. The tests were performed with a thin layer of steel mesh exposed to the beam, while located at different distances from the laser head. The incident beam was allowed to burn a new hole on the mesh for each distance (Figure 15). Later, the diameter of the holes was measured (Table 2).

Figure 145 – Picture of one of the thin layers of steel after an experiment.

Table 2 – Results of the diameter size depending on distance

Distance (mm)	EXP1 Spot Size (mm)	EXP2 Spot Size (mm)	EXP3 Spot Size (mm)	Media Spot Size (mm)
750	36,1	35,7	35,67	35,8
1000	33,1	32,9	32,8	32,9
1250	35,3	35,3	34,8	35,1
1500	35,6	35,5	35,8	35,6

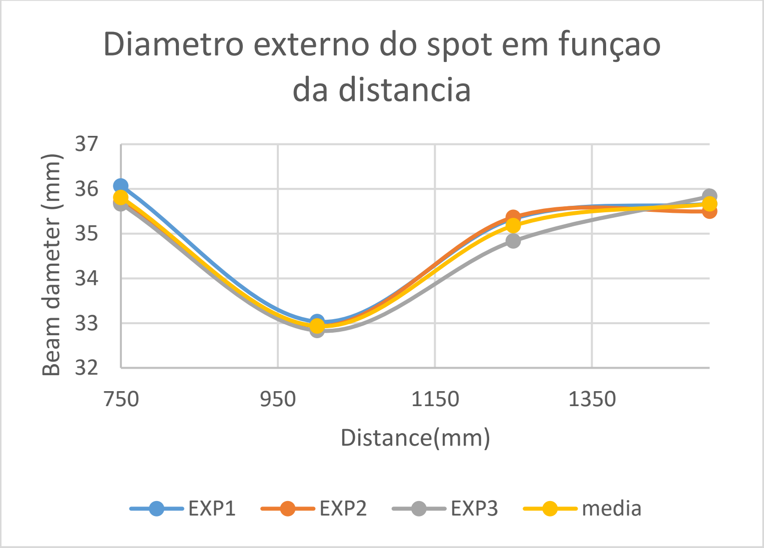


Figure 156 – Curve of the results on the estimation of the beam diameter.

Figure 16 shows the data in Table 2. As can be seen, in air, at 1 meter there is the diameter minimum and so the density of power maximum. Since the objective was to get the higher temperature possible, on the first experimental tests with paraffin, the sample holder (test specimen) was placed 1 meter away from the optical head. Because, as we can see on the Figure 16,

4.2. Verification of the feasibility (test in air)

4.2.1. Experimental setup:

This test was the first to be performed and it was carried out with paraffin in air. These are the conditions in which the temperature reached by aiming the laser beam at the test specimen is maximum. This test was done in order to know if the laser that we use, which has a power of 700W, was sufficient to melt paraffin. In fact, this test was carried out without temperature sensors because the aim was to verify the possibility of our future experiments.

This first test lasted 5 minutes and the specimen was 1 meter from the laser head

4.2.2. Objective:

The objective of this first experiment is to check if the laser is capable of melting paraffin. Therefore, it was carried out under the optimal conditions.

The other objective is also to obtain data to build a simulation model.

4.2.3. Results:

After the test, we see that after 5 minutes, a part of the paraffin has been well removed (Table 3). From the results in Table 3, we see that 22% of the paraffin has been removed (Figure 17).

Table 3 – Table of the evolution of paraffin quantity.

Before	After
444g of paraffin	348g of paraffin

Figure 167 – Picture of the pipe with paraffin after the test.

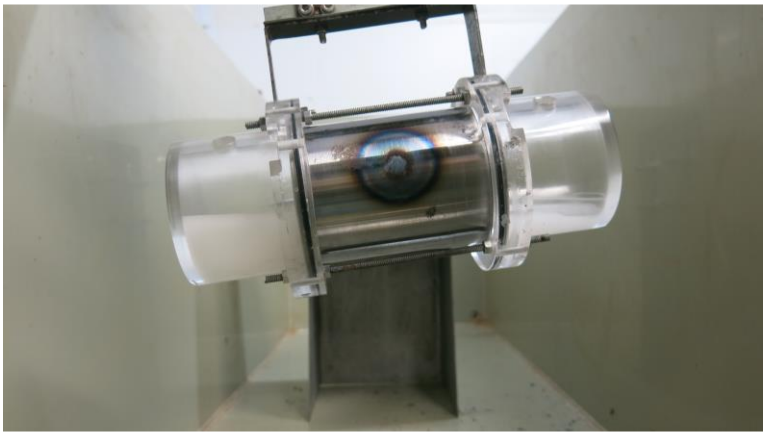


Figure 178 – Picture of test specimen after the test.

During the experiment, we tilted our system so that the paraffin could slide towards the plugs (Figure 18).

Figure 189 – View of the thermal camera during the test.

To obtain this thermal view, we used a FLIR thermal camera. However, since this cannot work underwater, it was only used in air (Figure 19).

4.3. First test in water (Heat transfer)

4.3.1. Experimental setup:

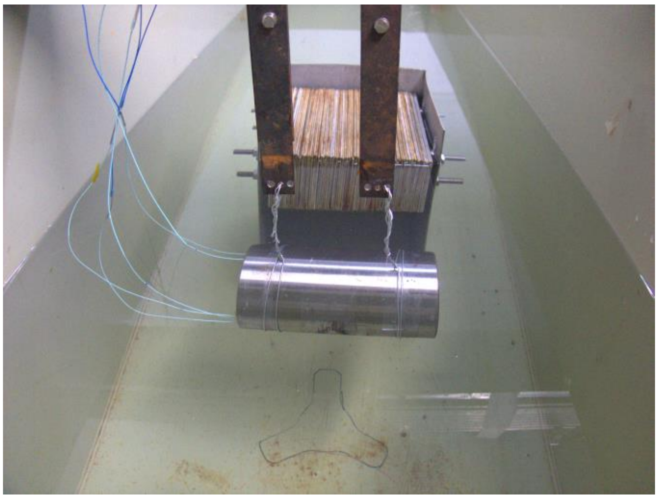


Figure 19 – Picture of the heat transfer test.

In this experiment, only the pipe will be tested. No paraffin was used. Sensors were placed as shown previously. This test was the first to be carried out underwater. Additionally, since there was no paraffin, the lids were not been mounted either (Figure 20).

4.3.2. Objective:

The aim of this test was to characterize the temperature distribution on the tube surface when it is subjected to heating caused by the incident laser beam, and also to be able to make a comparison with the simulated model. This test was performed using the temperature sensors.

This test was also carried out in order to validate the operation of the sensors in our temperature range.

4.3.3. Results:

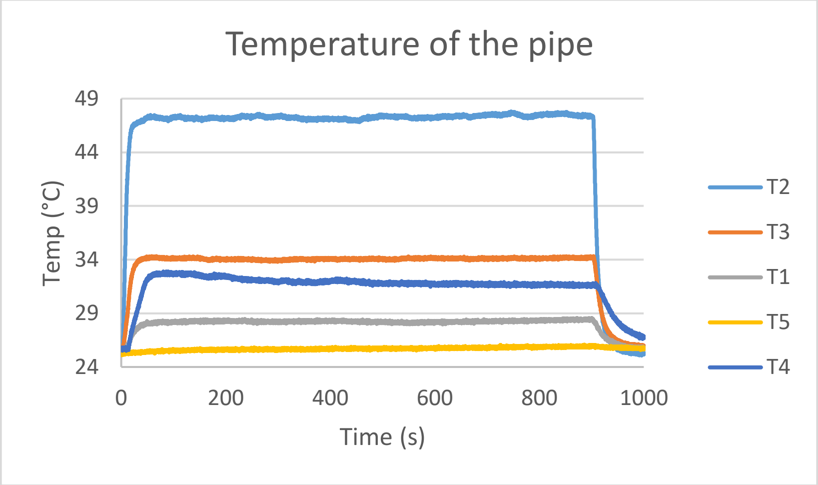


Figure 20 – Results of the pipe test.

As can be seen in Figure 21, the temperature rise is rapid and quickly reaches a constant temperature. However, only the temperature reached is not sufficient to melt paraffin.

4.4. Observation of the impact of the optical properties of the tube

4.4.1. Experimental setup

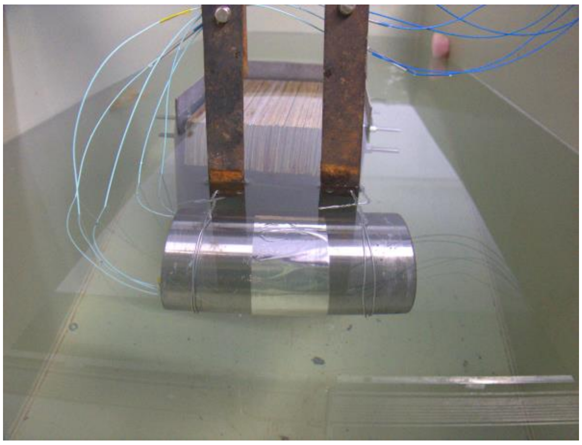


Figure 21 – Picture of the test with the aluminum sheet.

This test is the same as the previous one but with an additional aluminum foil around the tube (Figure 22)

4.4.2. Objective:

The maximum temperature of the previous test was lower than necessary to melt paraffin, which was not consistent with the results of the corresponding simulation. We added foil around it to try to understand how the surface of the pipe affects the temperatures reached because the surface of the foil reflects more and absorbs less energy from the laser beam. This will also allow us to analyze the impact of the optical properties of materials on our system.

4.4.3. Results

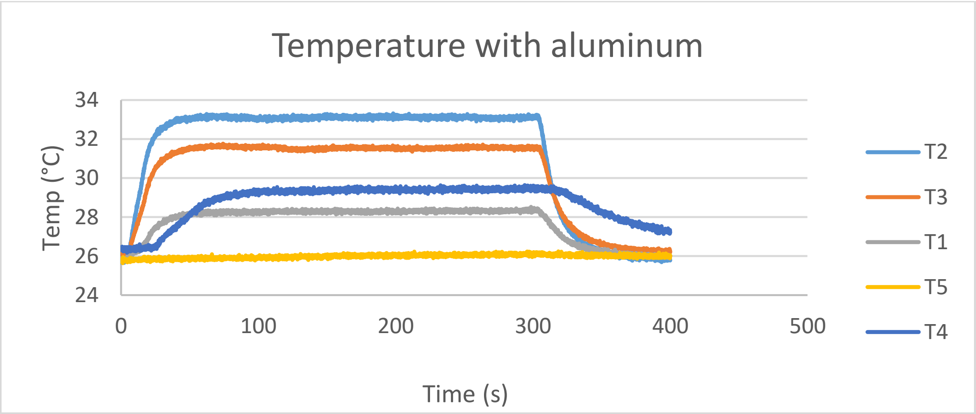


Figure 22 – Results of the test with aluminum.

As with the previous experiment, the temperature increase is rapid, until reaching a plateau temperature on Figure 23.

The results are even weaker. We therefore understand that the temperature is lower than expected because of the optical properties of the material. This is due to reflection which reduces the pfd.

4.5. Test of paraffin removal

4.5.1. Experimental setup:

The previous tests having served to calibrate and verify the best conditions for underwater tests, we therefore performed the first test with paraffin with the complete device (the tube, the lids and the sensors) at 1 meter distance from the laser head.

The test setup is shown in Figure 24. In addition, to give the paraffin time to melt, we have changed the duration of the tests to 15 minutes.

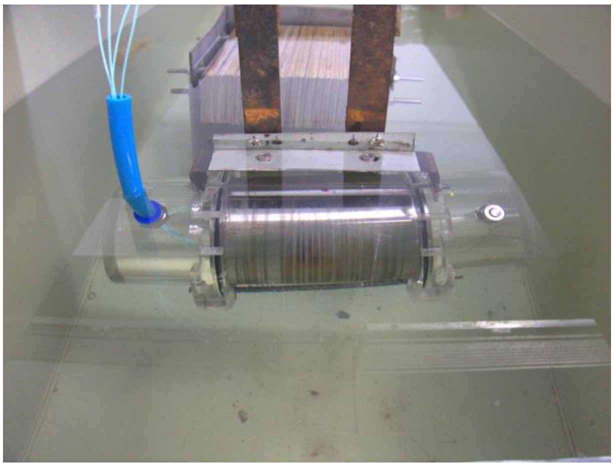


Figure 234 – Picture of the first paraffin test.

4.5.2. Objective:

As we currently know, the impact of thermal and optical properties on our models. We tested the model in its objective, to melt the paraffin despite the cooling of the thermal convection of the water.

4.5.3. Results:

Now that there is paraffin, we see on the Figure 25 that the temperature takes longer to stabilize. In addition, this time the temperature does not stabilize simultaneously.

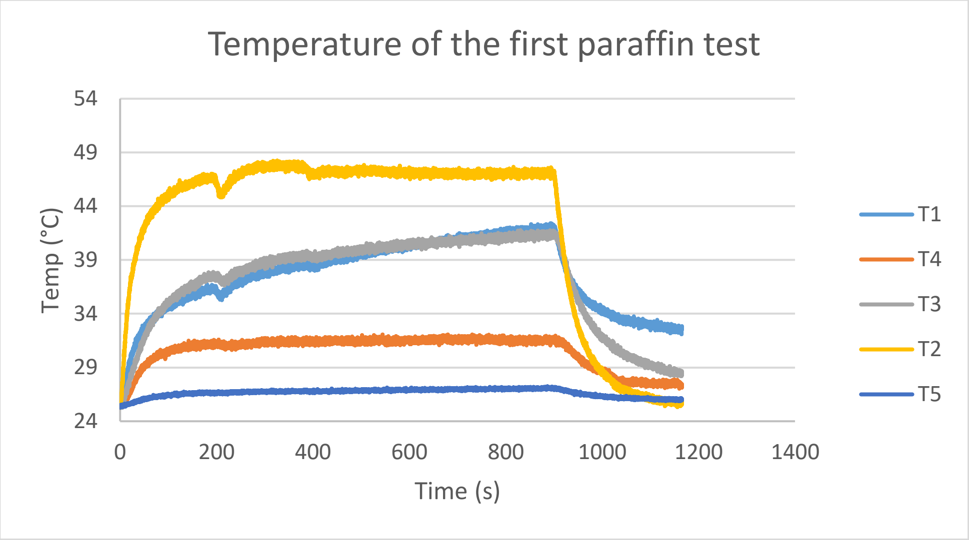


Figure 24 – Results of the first paraffin test.

During this test, there was no melting of the paraffin. And when we look at the temperature results, we see that the maximum temperature reached is not sufficient to melt paraffin.

4.6. Test of paraffin removal with a better power density

4.6.1. Experimental setup:

The situation is the same as in the previous test except that this time, we placed the test specimen 40 cm from the laser head to increase the power density because at 1 m there is too much attenuation (in water).

4.6.2. Objective:

Given that the temperatures reached with the sample located at 1 m (in water) from the laser head were too low to melt the paraffin, we reduced the distance that the laser travels in the water, thus reducing the power loss. The objective is to have a higher temperature, which could respect the principal objective of melting paraffin.

4.6.3. Results:

In the situation of Figure 26, the temperature increases rapidly at the laser impact point before decreasing slightly and stabilizing. Elsewhere, the temperature takes longer to stabilize and there is no decrease.

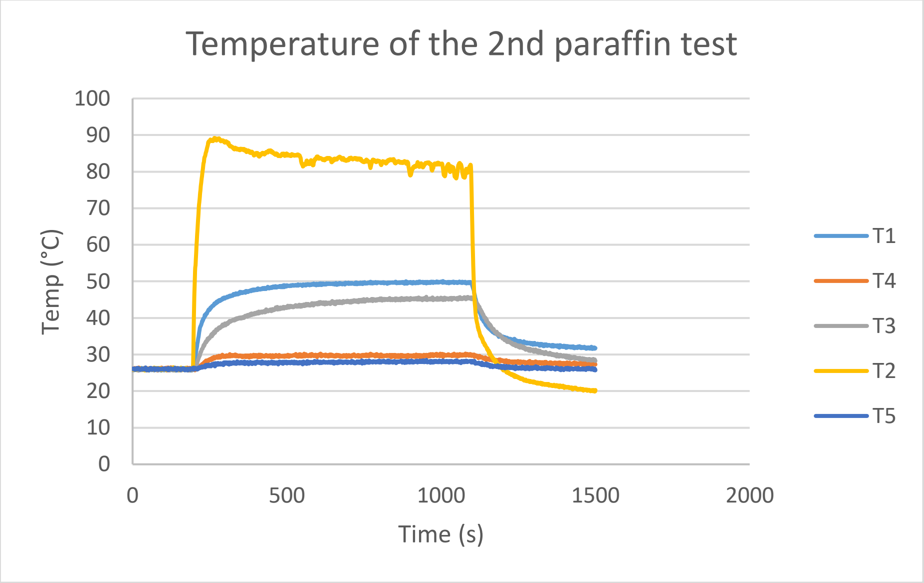


Figure 25 – Results of the 2nd paraffin test.

Moreover, this time, the temperature reached locally is sufficient to melt paraffin. However, because the amount that melts is too small, the paraffin cannot escape.

4.7. Cylindrical

4.7.1. Experimental setup:

For this test the only modification with the last one is that the is air inside of the tube, it is visible on the Figure 27.

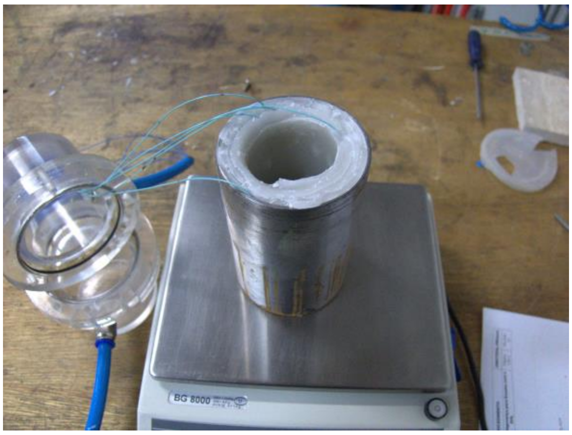


Figure 26 – Picture of the pipe with cylindrical paraffin.

4.7.2. Objective:

The objective is to let the paraffin escape once it has melted and not let it stuck as it where on the last test. And therefore, to see if our system works.

4.7.3. Results:

This time, the temperature at the point of impact of the Figure 28 is similar to the previous test, but at other positions of the pipe, this is not the case. In fact, the temperature is lower.

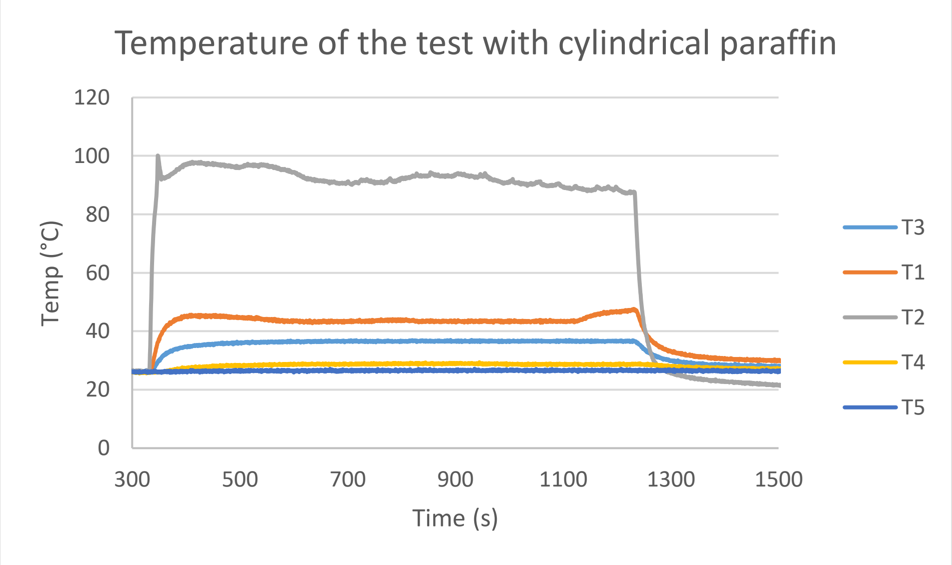


Figure 27 – Results of the test with cylindrical paraffin.

Finally in this test, the paraffin came away from the wall and was deformed but it did not melt. This deformation can explain the temperature profile that changed.

5. Conclusion

Unfortunately, we were unable to melt the paraffin in the pipes using the current laser setup. However, our results suggest that it is possible to achieve this goal with a more powerful laser and a laser that moves along the pipe. To improve the chances of success, consider the following:

- **Increase laser power**: The higher the heat flux, the higher the temperature of the heated side, and the shorter the time needed to completely melt the paraffin. By using a more powerful laser, we can increase the heat flux and potentially melt the paraffin more effectively.

- **Use a moving laser**: The high temperature able to melt is near the point of impact of the laser. By moving the laser along the pipe, we can ensure that the heat is distributed more evenly and increase the likelihood of melting the paraffin.

In conclusion, while we did not achieve our goal with the current setup, our results provide valuable insights into the potential benefits of using a more powerful laser and a laser that moves along the pipe. By exploring these possibilities, we can improve our chances of successfully melting the paraffin in the pipes in the future.

Bibliographic references

1. Sameeh Batarseh, Damian Pablo San Roman Alerigi, and Abdullah Al Harith, 2023 Saudi Aramco PE&D; **Key Success Factor for High Power Laser Deployment: Strategy and execution.**

2. Dario Prada Parra and Bruno Greco de Sousa, PUC-Rio; Giancarlo V. de Faria, Ouronova; Paula M. P. Gouvea, Luiz F. N. Moura, and Guilherme P. Temporão, PUC-Rio; Rulliane T. Gonçalves, Ouronova; Aldo B. Sola and Khrissy A. R. Medeiros, PUC-Rio; Pedro E.G. Panta, Ouronova; Mario L. P. Ribeiro, Natalia Ribeiro, and Arthur M. B. Braga, 2023, PUC-Rio; **Simulations and Experimental Results for a High –Power Laser Tool to Dissociate Hydrate on Oil and Gas Production Equipment in Deep Water.**

3. Carlos I. Gomez D. and Edgardo J. Medina F., SPE, Petrowayuu E&P, and Edgar Patiño, 2007, Baker Petrolite; **Monitoring and controlling paraffin depositation.**

4. María del Carmen García; 2001, SPE, PDVSA-Intevep,;**Paraffin deposition in oil production.**

5. K. M. Barker, SPE, J.M. Bigler, K. Hake, D.C. Sallee, 2003; **Paraffin problems in gas systems.**

6. Mark Embrey, SPE, and James Larke, SPE, BJ Services; 2010, **Paraffin plug remediation in deep water wells via capillary tubing.**

7. E. Moura, E. Cockeis, G. Lucas, Baker Hughes, M. Fontes, R. Pessanha, A. 2011, Aragão; **Paraffin based HPHT fluid technology applied successfully in exploration well.**

8. C.N. Khalil, L.F. Neumann, C.A. Linard, and I.G. Santos; 1994;, Petrobrds S.A; **Thermochemical Process To Remove Paraffin Deposits in Subsea Production Lines.**

9. O.L. Owodunni and J.A. Ajienka, 2007; Institute of Petroleum Studies, University of Port Harcourt, Rivers State, Nigeria; **Use of Thermal Insulation to Prevent Hydrate and Paraffin Wax Deposition.**

10. Hugo Francisco Lisboa Santos, Petrobras; Eduardo André Perondi, UFRGS; André Viegas Wentz, Senai-RS; Anselmo Luis Silva Júnior, Senai-SC; Dante Augusto Couto Barone, UFRGS; Maurício Galassi, Bruno Barbosa de Castro, André Manoel Goja Ferreira, Ney Robinson Salvi dos Reis, Hardy Leonardo da Cunha Pereira Pinto, and Lincoln Homero Thomé Ferreira, 2020, Petrobras; **Proposal and experimental trials on a robot for hydrate and paraffin removal in submarine flexible lines.**

11. Mohammed Al-Yaari, 2011; King Fahd University of Petroleum & Minerals; **Paraffin Wax Deposition: mitigation and removal techniques.**

12. T.S. Brown, V.G. Niesen, and D.D. Erickson, 1994; Conoco Inc.; **The Effects of Light Ends and High Pressure on Paraffin Formation.**

13. J.F. Keating and R.A. Wattenbarger, 1994, Texas A&M U; **The Simulation of Paraffin Deposition and Removal in Wellbores.**

14. Damian San Roman Alerigi, Sameeh Batarseh, and Wisam Assiri, 2021; Saudi Aramco PE&D; **The Effect of High Power Laser on Organic-Rich Shales.**

15. F P Bharadwaj Reddy, C Gunasekar, Atul Shalikrao Mhaske, Mr N Vijay Krishna; 2018; **Enhancement of thermal conductivity of PCM using filler graphite powder materials.**

16. 2018 https://www.crownoil.co.uk/guides/paraffin-guide-uses-history-more/

17. H. Sadiq, S.M.ASCE, J. Tashan, R. Al-Mahaidi, X.-L. Zhao ; 2018; **Determination of steel emissivity for the temperature prediction of structural steel members members in fire.**

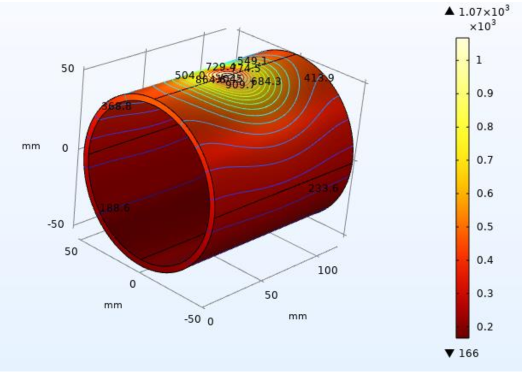
18. Muhammad Theyab; 2018; **Wax Deposition Process: Mechanisms, Affecting Factors and Mitigation Methods.**

Appendix

In parallel with my experiments, I also worked on a simulation allowing me to model the different experiments. However, as I mainly focused on the thermal characteristics, the results had the profile of the real results, but with lower values.

To obtain the data, most of them are experimental data, some others are additional data retrieved from different documents such as the convection coefficient and the remaining ones are data obtained through experiments such as the diameter of the laser for example.

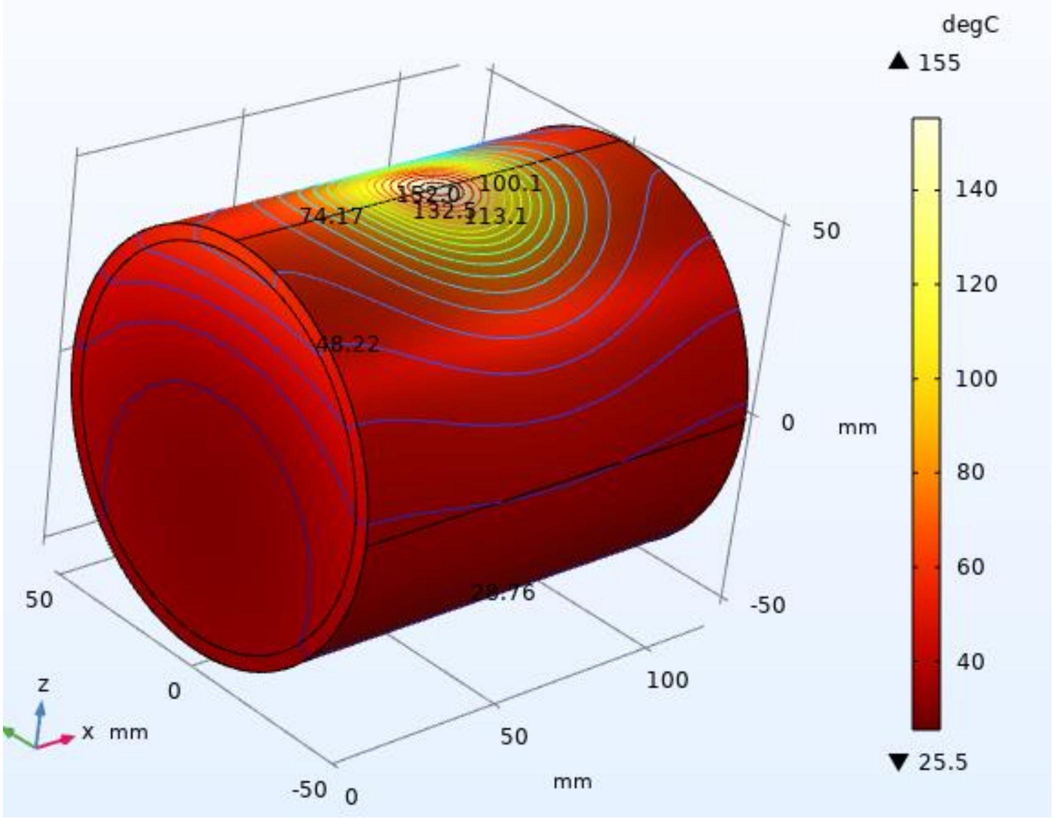
I carried out simulations along with my experiments, so I have them for many cases. Most of my experiments are done in 2D and represent the wall of the tube occasionally subjected to the laser. First of all, we just had to model the simple tube in the open air.



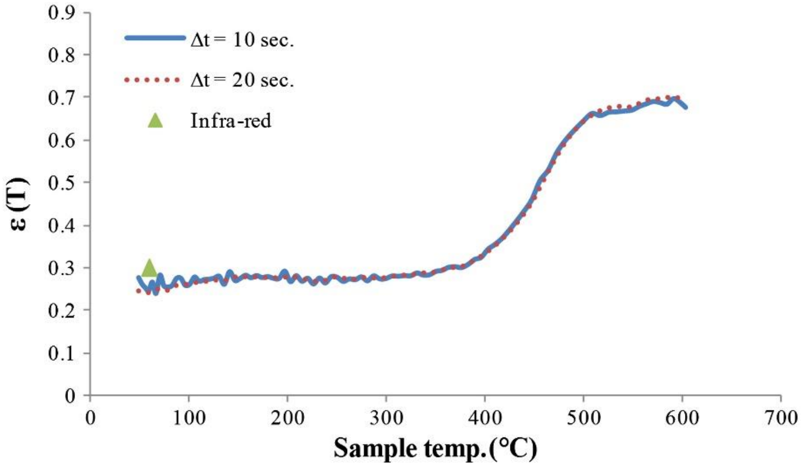
3D

On the simulation in 3D at the air, we observe a really high temperature, but it’s really centralized near the impact point. This can be explained because of the convection coefficient of the air which represent the cooling effect is very low and also because the emissivity of the steel here is high. In fact, due to a paper [17], we know that at a high temperature the emissivity increase.

In the end when we add the paraffin and consider that we are in the water and that we have a loss of power due to passing through the water, we obtain:

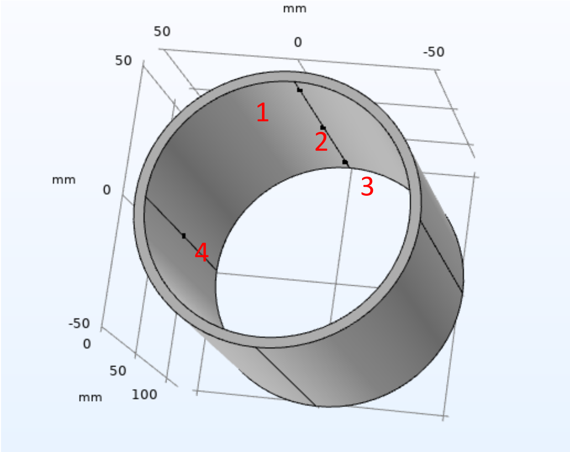


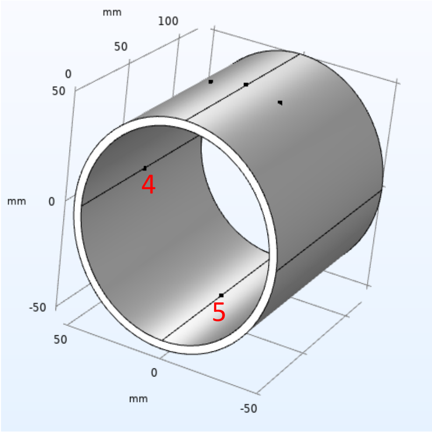
Here when we compare to the case at the air and with n paraffin, we see a big variation. To begin with the temperature is far lower and the temperature don't succeed to spread to all the paraffin. Moreover, there is not many places with temperature high enough to accomplish our objective.



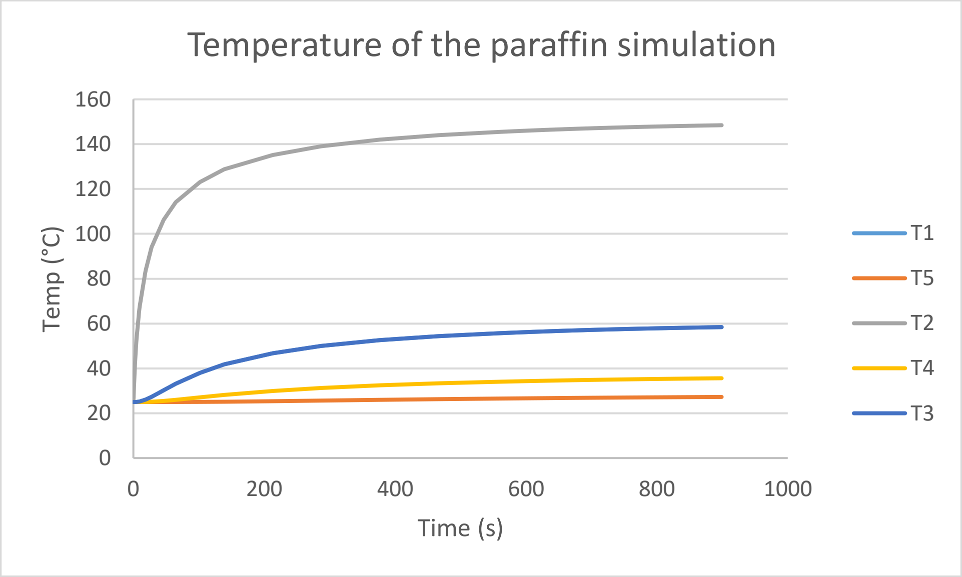
Graph from paper 17

With the aim of finding a model as close as possible to reality, I carried out numerous simulations by modifying the parameters to get as close as possible to the real case. However, as the model does not take everything into account, this was not functional.





With the sensors corresponding to the schemes above, here are the results for the simulation with paraffin inside water.



Here what we can observe is that close to impact of the laser, the temperature skyrocket but, on other places, it takes more time to reach their final temperature. Moreover, close to the impact point is the only places where temperature is high enough to melt paraffin.