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High Power Lasers to Remove Paraffin in Offshore Pipelines

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Abstract. Paraffin residue deposition in offshore pipelines is a long-standing operational issue occurring in several basins around the world, due to the low temperatures and high pressures present on the seabed. This phenomenon can lead to an efficiency drop in fluid flow and an escalation in costs for the maintenance of subsea production equipment. This present research presents the technical feasibility of a safer, more efficient, and lower-cost tool using the radiation of a high-power laser attached to a Remotely Operated Vehicle (ROV) to melt the paraffin, thereby removing the layers attached to the inner walls of the pipelines and enabling the proper flow to be restored. The laser beam is aimed at the exterior of the pipeline, heating it enough to reach the required temperature to melt the paraffin inside the pipe. Numerical simulations and laboratory tests were carried out to optimize the parameters while ensuring the thermal efficiency of the process. In this work, a short pipe section to simulate an offshore pipe and industrial paraffin were used to carry out the laboratory experiments and multiphase simulations. This paper describes the results obtained in the laboratory and compares them with simulations, analyzing radiation time, distance, and power.

Keywords: Laser, Paraffin removal, Offshore pipelines, ROV, Numerical simulations.

1 Introduction

Paraffin buildup in oil production lines has been an issue for years in Brazil and worldwide. As oil production begins, the high temperature of the heavy oil flowing from the reservoir under external pressure and low temperatures in deep and ultra-deep waters leads to heat loss to the environment, thus facilitating the formation of paraffin crystals. The liquid fraction of the oil cannot dissolve the solid part of this material, which clumps together in certain areas inside the subsea pipelines, potentially reducing the flow rate, increasing equipment maintenance costs, and even causing production stoppages. The larger the paraffin clump, the greater the need to increase pumping power. Paraffins can occur under pressures ranging from 725 psi to 2175 psi in deep waters and up to 4350 psi in ultra-deep waters, with temperatures ranging from 2°C to 4°C depending on the operating field. Currently used hydrate removal methods (mechanical, chemical, and thermal removal using hot water or chemical methods) may be expensive, time-consuming, and cause damage to the equipment and environment.

This paper analyzes the technical feasibility of adapting a tool that can be attached to a Remotely Operated Vehicle (ROV) [1] to melt the paraffin through the radiation of a high-power 1800 W laser with a blue wavelength (445 nm). According to Gowida et al. [2], laser technology has great potential for use in the oil industry, including drilling operations, which reinforces its versatility and efficiency in challenging environments. Batarseh et al. [3] contextualize that the use of lasers in underwater environments has seen a lot of progress, overcoming the drawbacks of standard methods in extreme pressure and temperature conditions, like the ones described here.

The proposed technology utilizes a laser beam for a specific period, aimed at the equipment from a predetermined distance, heating it to temperatures above 57°C, sufficient to melt the paraffin without causing

damage, such that the paraffin will dissolve and flow with the oil. Several scenarios have been simulated and tested in the lab to analyze the power, radiation, and distance required to melt the paraffin. This paper discusses the main results obtained.

2 Paraffin Characteristics and Measurement Technologies

2.1 Paraffins

Paraffin deposits are primarily composed of heavy alkanes and naphthenes, which typically contain more than 18 carbon atoms. Their overall formula, whether straight-chain or branched, is CnH2n+2, where n stands for the number of carbon atoms. Based on their composition, paraffins occur in a solid state at high pressures and low temperatures. They are formed from the crystallization of n-alkanes that are found in the petroleum stream when cooled below a given temperature and under high pressure. Paraffin crystallization takes place in three stages inside offshore pipelines in deep and ultra-deep waters: nucleation, growth, and agglomeration. When these deposits accumulate in the equipment, they may block fluid flow, requiring rapid intervention protocols.

2.2 Fiber Bragg Grating (FBG) Sensors and Samples

Optical fiber sensors are frequently used because they can be used to monitor light intensity, temperature, strain, pressure, radiation, and vibration. They suffer low electromagnetic interference and can be used in hazardous environments. An optical fiber cable can serve as the communication link between the test station and the external equipment that will receive the data. Specifically, in this application, Fiber Bragg Grating (FBG) sensors were employed to monitor temperature. Previously, PT1000 sensors had been tested, but the results showed they suffered interference and did not provide reliable measurements [1]. Despite being very small, sensitive, and jacketed as shown in Figure 1a, FBG sensors can maintain high data quality. To monitor temperature behavior inside the tubes, five FBG sensors were positioned at different points along the inner wall, which was then coated with paraffin (Figures 1b and 1c). As can be seen in Figure 1b and Figure 1b, the sensors were not equally spaced from each other.

The first sample (Figure 1b) was prepared with 22 mm of paraffin (used in Test 1), and the second sample (Figure 1b) with only 11 mm (used in Test 2), to simulate different thermal scenarios and their respective responses to heating. The FBG sensors inside the tubes, combined with different paraffin thicknesses, enable the analysis of the heat distribution generated by a high-power laser.

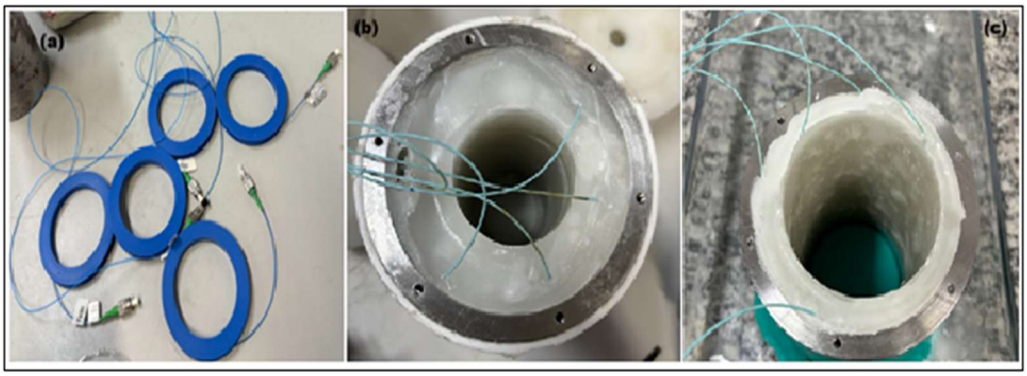


Figure 1a. Encapsulated fiber optic sensors. Figure 1b. Metal tube filled with 22 mm of paraffin with sensors installed. Figure 1c. Tube with 11 mm of paraffin and distributed sensors for thermal monitoring.

2.3 High Power Laser Tool to Melt the Paraffin

To fully understand the problem, the specifications of a laser tool were defined by researching the ideal operating conditions, taking into account all standards and interfaces with the ROV [1]. With a power of 1800 W, the results in this work indicate that this equipment will be capable of removing paraffin from subsea pipelines located in deep and ultra-deep waters. This power choice is supported by Batarseh & Alerigi [4], who reported successful milestones in drilling using high-power lasers, highlighting the effectiveness of systems above 1500 W for operations in complex underwater environments. This system, both efficient and compact, is being developed to withstand high pressures and low temperatures for extended periods. It also has cooling and power modules

designed to dissipate the heat produced by the laser diodes and convert the voltage supplied by the ROV to the voltage required by the tool, respectively. It is important for the tool to be as compact as possible, not exceeding the maximum weight supported by the ROV. For a more detailed analysis of the necessary energy supply and operational feasibility, see [1].

When it comes to eliminating paraffin deposits, this work investigates whether it is possible to achieve high operational efficiency using a high-power laser. As demonstrated by Batarseh et al. [5], the strategic deployment of lasers in underwater environments requires precise control of parameters such as power and distance to maximize thermal efficiency. Thus, the heating applied by the laser beam to the external face of the metal allows the paraffin deposited on the inner face to be melted indirectly through heat transfer by induction. When the paraffin reaches its melting temperature, around 57°C, these bonds are broken, turning the solid deposit into a liquid that mixes with the oil and can be transported by the normal pipeline flow. In this work, we investigated whether the amount of heat conducted in approximately 15 minutes of operation is enough to melt the paraffin accumulated inside offshore pipelines.

Given the complexity of the problem presented, the research is conducted in two phases: lab experiments and computer simulations. Two laboratory prototypes were developed and submerged in a water tank for laser testing. A model in the COMSOL Multiphysics software to simulate thermal distribution inside the pipeline and evaluate the results obtained in both phases was also developed.

2.4 Experimental Setup

The experimental tests, carried out at the Fiber Optic Sensor Laboratory (LSFO) at PUC-Rio, involved laser irradiation on the two samples shown in Figures 1a and 1b. The aim was to monitor the temperature distribution obtained with the 1800 W laser to provide data for further simulations. The setup for these experiments is shown in Figure 2a. The tank was filled with tap water for the tests, carried out over two different days. The same water was used for each set of five experiments.

The laser power was 1800 W; however, the power actually received by the sample, located at 50 cm from the laser head, was 1460W due to attenuation occurring in the water and reflection at the tube. Figures 2b and 2c provide the superior and isometric views of the tube instrumented with temperature sensors identified as T1, T2, T3, T4, and T5. The fiber optic sensors were positioned inside the metal tube along with the paraffin with the purpose of monitoring the thermal variation over the irradiation period, considering the power of the incoming laser and the distance traveled by the radiation in the aqueous medium until reaching the sample surface. Figure 2b shows sensors T1, T2, T3, T4, and T5 mounted inside the tube. The sensors are positioned at the same height. Note that the sensors are not equally spaced and that there is a larger distance between T3 and T4.

The laser beam was targeted perpendicular to the outer wall, outside where each sensor was located, for a period of 15 minutes, with a cooling period in between. To analyze the influence of heat exchange and in the absence of a cooler, it was necessary to wait 15 minutes between each test until the water temperature stabilized at 22°C (room temperature). However, during the tests, the maximum water temperature reached was 28°C.

The rotation of the sample was adopted because the laser will have to be rotated around the pipe at the bottom of the ocean in order to heat the tube at different positions and release a section of the paraffin. The temperature measured by each of the sensors during the laser radiation was analyzed.

As a simplification, the tube was sealed at both ends such that the center was filled with air, and not with flowing oil. Additionally, the experiments were conducted under atmospheric pressure and room temperature instead of under the low temperatures and high pressures present on the seabed.

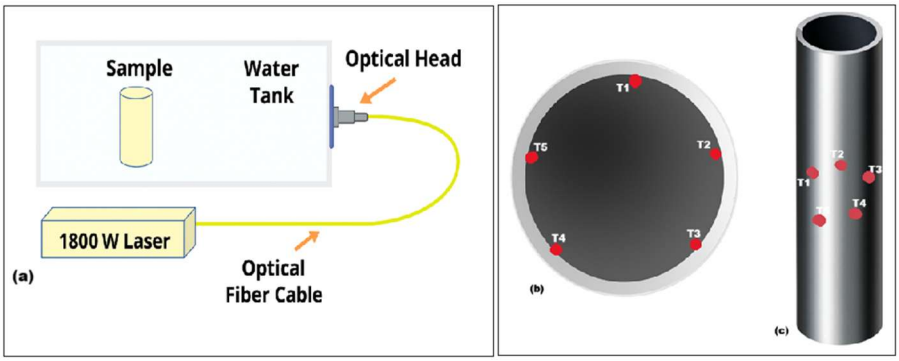


Figure 2a. Diagram of the irradiation system. 2b. Internal view of the tube containing fiber optic sensors. 2c. Side view of the tube with sensors.

2.5 Numerical Model

For the second part of this research, COMSOL Multiphysics software was used, a tool based on the finite element method, employed to create computational models, perform numerical simulations, and analyze complex engineering problems involving multiple physical phenomena, enabling the visualization of results and preparation of diagnoses. Previous studies have also demonstrated the successful transition of high-power laser tools from the laboratory to the field, highlighting their practical feasibility under real operating conditions. We have chosen this software for this use because it is entirely feasible to perform a numerical simulation of an offshore pipeline heating process using a high-power laser, analyzing the temperature distribution and efficiency in terms of paraffin melting. Consideration is given to experimentally tested parameters, such as the power used, distance, and irradiation period. Similar studies, such as the one by Parra et al. [1], demonstrate the effectiveness of high-power laser tools in thermal dissociation processes in subsea production equipment, validating their suitability for deep-water use both experimentally and numerically. The present work aims to show that high-powered laser tools are effective in thermal melting of paraffin. The setup is an important step, where a bridge is built between the physical world (the experiment done in the lab) and the virtual world (the simulation).

In the development of this model, the coupled physics plays a key role in integrating the thermal phenomena involved in the paraffin removal process. The Heat Transfer module was used to model transient heat conduction in both steel and the paraffin layer, using the basic heat transfer equation, as shown below.

$$\rho C_p \frac{\partial T}{\partial t} = \nabla (k \nabla T) + Q_{laser} \tag{1}$$

Boundary conditions appropriate to the real problem were set. On the outer surface of the tube, in contact with the aqueous medium, a natural convection condition was applied to simulate heat dissipation to the water. The initial temperature of the system was uniformly set at 22°C. This initial uniformity ensures that the simulation starts from the same state observed in the experimental tests.

In the model, the boundary conditions were set to reflect the thermal behavior of the system during the paraffin removal process using the 1800 W laser. The natural convection condition on the outer surface of the tube is vital for simulating heat transfer between the metal and the surrounding water. The surface temperature (T) is 22°C.

Equalizing the flow by conduction:

$$-k \frac{\partial T}{\partial n} = 33000 \tag{2}$$

$$\frac{\partial T}{\partial n} = -\frac{33000}{k} = \frac{33000}{44.5} = -741.57\ °C/m \tag{3}$$

Calculation of radiation in the Laser–Tube system

$$P = P_o\ \mathrm{e}^{(-\mu.d)} \tag{4}$$

where: μ = 0.035m-1 (attenuation coefficient), d = 0.5m (distance from laser to tube), and P = 1800 W. Therefore, P = 1768.86W.

The attenuation coefficient (μ) for blue light in water is μ = 0.02 to 20. The calculations show that the power reaching the tube is about 1460W (23% loss of the original power), considering the water's attenuation and the reflection on the steel surface.

The greater the attenuated power, the less energy is lost in the water, resulting in higher temperatures in the tube and, therefore, faster melting of the paraffin. If the distance is too short, the beam may become too intense, possibly damaging the steel or generating hot spots. On the other hand, if the distance is too long, the thermal efficiency of the process is substantially reduced.

To calculate the laser irradiance (Power Density), the following applies:

$$E = \frac{P_{ffetive}}{A} \tag{4}$$

Finally, these boundary conditions are important because they enabled the computational model to reproduce the physical phenomena observed experimentally — from the initial heating by the laser action to the conduction processes through the pipe wall and the paraffin layer, as well as heat dissipation into the surrounding aqueous medium, as shown in Figure 3.

Figure 3a shows the paraffin inside the tube (pipeline). Figure 3b shows the laser incidence on the tube, and Figure 3c shows the finite element mesh used in the model. The finite element discretization of the model was designed to ensure accuracy in simulating thermal phenomena. Local mesh refinement was applied to critical regions of the system, specifically in the laser incidence area and at the interface between steel and paraffin. As shown in Figure 3c, the mesh was built with a total of 58,354 tetrahedrons and 21,610 triangles. The former was used to discretize the pipe volume and the 22 mm paraffin layer, while the latter was applied to the boundary surfaces, respectively.

The same simplifications used in the experimental setup were applied. In the implemented model, the inside of the pipe was filled with air to simplify the thermal boundary conditions. In real-world offshore operations, the interior of the pipeline is filled with flowing oil at high temperature, which actually favors the paraffin melting process through convective heat transfer. Also, the conditions used were atmospheric pressure and room temperature, instead of the low temperatures and high pressures present on the seabed. Additionally, in the simulations, the effect of the melting paraffin inside the tube was not considered because the model only took into account heat transfer from the laser radiation to the paraffin.

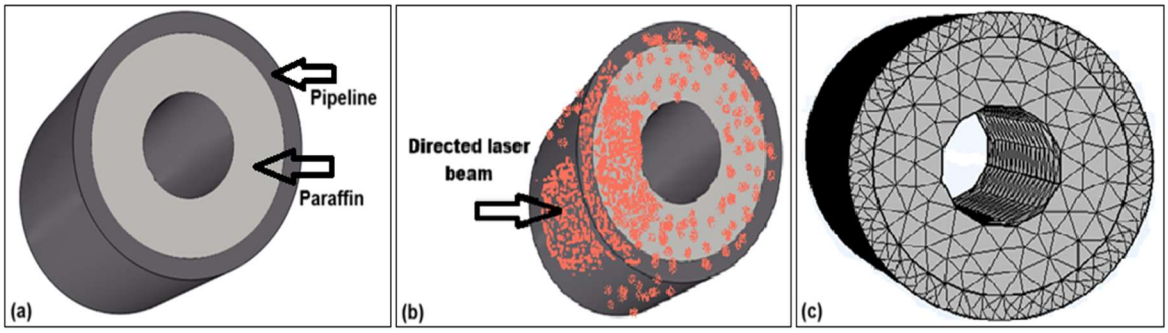


Figure 3a. Interface between the laser and paraffin. 3b. Laser incidence area. 3c. Finite element mesh.

2.6 Results and Discussion

Five experimental tests were performed on each of the two samples, totaling 10 experiments, each lasting 15 minutes of irradiation, with the main goal of analyzing the temperature distribution behavior across the entire surface of the tube to assess the heating caused by the incoming laser beam. Figures 4a to 4e show the experimental results for Test 1, with the sample (22 mm-thick paraffin wall) submerged in a tank with water at room temperature of 22°C. During the tests, the sample was placed 50 cm from the optical head of the laser beam. Likewise, Figures 5a to 5e show the outcomes obtained in Test 2, following the same principles applied to Test 1, except for a thinner paraffin wall (11 mm-thick paraffin wall).

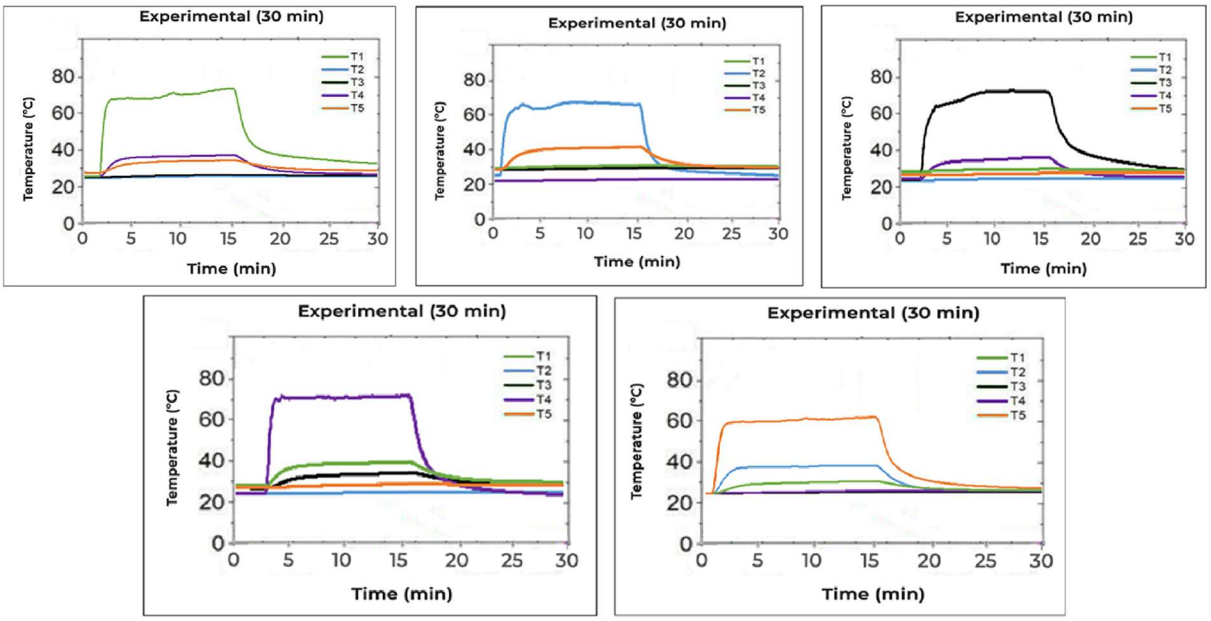
In the simulations, the heat distribution analysis was tested using thermal gradients within the tube, encompassing the laser parameters capable of returning results consistent with those obtained experimentally. Following the adopted methodology, the metal tube was exposed to the laser beam for 15 minutes. The simulated results for the sample with a paraffin wall of 22mm are in Figure 6, where only the results for T1 are shown. Note that the effect of the melted paraffin was not considered in the model.

Figures 4 and 5 show that the results for Test 1 and Test 2 are consistent with each other. The temperatures reached in both tests were more than sufficient to melt the paraffin, even with an incoming power of 1460W on the sample. The melting point of paraffin is around 57°C, and the data recorded by the sensors indicate that, in every test, the temperatures exceeded this level on the inner wall behind the point where the laser was focused. This proves that the experimental conditions were adequate for melting this material.

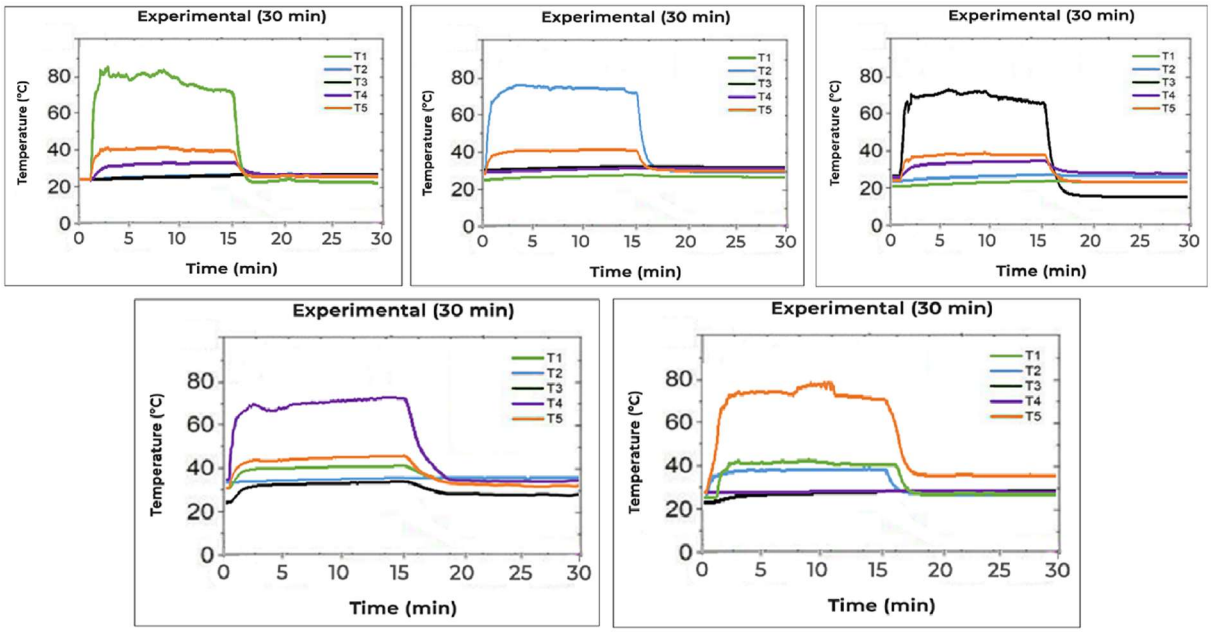
In addition, the average absolute error of the experimental results in the model (Figure 6) was lower in Test 2 (9.9°C) than in Test 1 (13.2°C), suggesting that Test 2 better reproduced the thermal profile, even though the simulated wall had a thickness equal to the same used in Test 1. Test 2 showed greater adherence to the simulated profile since its temperatures almost matched, with only a 1.7°C difference, even though some rare variations were identified. However, Test 1 showed a negative bias, suggesting unaccounted thermal dissipation because the temperatures were about 12°C to 20°C below the data obtained in the simulation, suggesting lower effective power.

The experimental results and the presented simulation showed similar behavior in all tests performed. The temperatures obtained in the numerical simulation were slightly higher than those recorded in the experimental tests, particularly regarding Test 1. The average simulated temperature was approximately 80°C, which was higher than the average for Test 2 (76.3°C) and even higher than Test 1 (68.1°C). Upon reaching a peak temperature of 90°C, the results suggest that the numerical analysis of the system accurately reproduced the experimental behavior. It was not necessary to perform two tests in the simulation because we were only testing the thermal behavior.

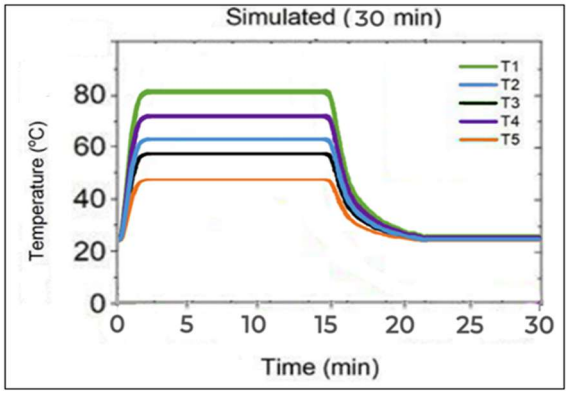
All records reached temperatures above 57°C during the 15-minute irradiation period, which corresponds to the paraffin melting point, thus proving the thermal effectiveness of the system in promoting the melting of the material. It became evident that in Test 2, the thermal intensity reached higher levels when compared to Test 1. This difference is accounted for by the variation in the thickness of the paraffin layer that was used inside the tube. Although both tests were carried out under the same time and laser beam power settings, Test 2 had exactly half the thickness of paraffin of the first sample, as shown, 11 mm and 22 mm, respectively.



Figures 4a, 4b, 4c, 4d e 4e: Test 1, temperatures measured by FBG sensors (22mm-thick paraffin wall) with the laser beam targeted at the point on the tube directly in front of sensors T1, T2, T3, T4, and T5, respectively.



Figures 5a, 5b, 5c, 5d, and 5e: Test 2, temperatures measured by FBG sensors (11mm-thick wall of paraffin) with the laser beam targeted at the point on the tube directly in front of sensors T1, T2, T3, T4, and T5, respectively.



Figures 6: Simulation results sensors (22mm-thick paraffin wall) with the laser beam targeted at the point on the tube directly in front of sensors T1.

3 Conclusions

This research discusses experimental tests carried out in the lab and the numerical simulations supporting the development of a high-power laser tool for underwater removal of paraffin deposited in offshore pipelines. The results showed good agreement, even though adjustments are necessary to better model situations with greater thermal loss. The purpose of the tests and simulations conducted was to generate data for the analysis of maximum and minimum temperatures reached during the process of paraffin removal over time, as well as to validate the numerical model developed. The results obtained reinforce the viability of the numerical model as a predictive tool in the process of thermal removal of paraffin. This validation contributes to the evolution of the laser tool, demonstrating that the proposed system has great potential for real applications in underwater environments. Future steps should adjust the model to represent operational variations and tests in larger controlled environments, and later, in real underwater conditions. Further development will require the effect of the melting paraffin inside the tube to be considered by the numerical simulations. Additionally, the model will have to consider flowing oil inside the tube and sea seabed conditions before field tests are performed.

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