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Study of the application of PCM to thermal insulation of UUV hulls using Network Simulation Method

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Abstract The Unmanned Underwater Vehicles (UUV) designed for the detection and neutralization of naval mines are characterized by their high requirements regarding the reduction of the signatures of a vessel (thermal, acoustic, magnetic, etc.), all of them must be reduced in order not to be detected by the mines during the mission. This research work focuses on the reduction of the thermal signature transmitted by the UUV hull, where the use of phase change materials (PCM) is proposed as thermal insulation, placing it between the internal heat source of the UUV and the pressure hull, with the aim of drastically increasing the time in which the external face of the hull of the UUV is within a range of 3 °C and 5 °C temperature increase, allowing it to perform its mission without being detected by the thermal sensors of current naval mines. The simulation will be carried out using the Network Simulation Method for the resolution of the governing equations, which will allow the optimization of the necessary insulation thickness according to the required mission profile. In addition, it is proposed an expression that relates the PCM thickness and the time needed to reach a certain temperature increase.

1. Introduction

Nowadays, the applications of the Unmanned Underwater Vehicles, or UUVs, cover a wide range of missions, both in the civilian and military fields [17], using remotely controlled configurations, Remotely Operated Vehicles (ROVs), and

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autonomous vehicles, Autonomous Underwater Vehicles (AUVs) [7].

This type of craft must comply with the general design parameters, like any other type of ship, where all its design attributes must be optimized with its military use in mind [23]. For the UUV, the most recent research has focused on aspects such as the design of the pressure hull and the dimensional control of it [25], where the need for hull strength for both underwater and surface operations is identified, as well as for possible impacts and collisions, as required for any vessel operating in shipping areas. Although there are no publications on this subject for the UUV, studies on other types of vessels are applicable such as studies on structural damage caused by collisions between ships [30], or the optimization of the weight of the naval structures [14]. Other lines of research have focused their efforts on studies on their operations and deployment and recovery systems [20], as well as the system of control and fault detection [5], and path tracking control methodologies [22].

Within this broad spectrum of possible missions of this type of vessel, the military use for the identification and neutralization of naval mines is identified [31]. This type of mission is characterised by very strict requirements regarding the signatures issued by the unmanned vehicle [45], in terms of acoustic, magnetic, thermal and other signatures, [9,46]. In recent years some studies have been carried out on the firms issued by UUV, being studies focused on non-military uses, where the vehicles develop monitoring tasks of marine fauna, and aims to minimize the impact of operations on wildlife [44]. In the field of air drones for military use, a greater number of research projects have been carried out, an example is the work presented by Yaacoub et al. [47] where an analysis of the safety requirements for the operation of unmanned aerial vehicles (UAVs) is conducted.

Within the study of each of these firms (thermal, acoustic, magnetic, etc.), this research focuses on the thermal signature emitted by the UUV hull, where a significant increase in the external temperature of the hull of the submersible with respect to the temperature of the water in the area where the mine is buried will produce the activation of the mine by means of sensors that allow the capacity to generate thermal images in conditions of low luminosity [49].

In order to minimize the thermal signature of submersibles, some research has been carried out in recent years, focusing on the use of alternative materials for the hull, such as the use of composites [11], and analysing the infrared signature of combat ships [24]. The use of new energy generation systems, such as fuel cells [12], is a continuous line of progress in the UUV, although all these systems generate heat inside the boat hull and therefore an increase in the thermal signature of the UUV. This type of research aims to reduce the thermal signature on specific parts of the boat, although the complex reach very low values of temperature difference between the hull and the water surrounding the boat, while the new detection systems are increasingly powerful [32], being able to identify objects with a thermal variation between 3 and 5 °C [42].

The present research aims to present a thermal insulation system whose main objective is to temporarily reduce the thermal signature of the UUV, allowing to improve its operability during underwater mine detection and neutralization missions. For this purpose, the use of Phase Change Materials (PCM) is proposed. PCM are materials with a high latent heat, which allows them to maintain a constant temperature while the phase change from solid to liquid occurs [41]. This characteristic allows this type of material to be applied as an insulator of the submersible hull, providing it with a time interval in which the temperature of the external face of the boat hull will not increase, significantly reducing the thermal signature of the UUV. To this end, the use of these materials will be simulated in a construction proposal for the UUV hull, obtaining the time interval for which the external temperature does not increase by more than 3 and 5 °C, and verifying that this time interval is sufficient for the UUV to complete its mission of identifying and neutralizing submarine mines.

The methodology used for the resolution of the governing equations is the Network Simulation Method [18,36]. This method has been used in numerous problems of science and engineering such as heat transmission, corrosion, degradation of lubricants, etc. [16,33,34,35,38,39]. It is important to highlight the importance of these works since phase change processes similar to those in this study are presented [33,38].

2. Objectives

Analyzing the evidence found in the current literature, it is considered necessary to deepen the study of the signatures mitigation issued by the UUV, which are characterized, among other factors, by their low detectability, especially the vehicles destined to missions with special requirements in this aspect, as is the case of the UUV destined to the location and neutralization of naval mines.

The present research aims to explore in depth the reduction of the thermal signature emitted by the UUV, this signature is mainly due to the heat emitted by the internal components of the UUV, such as the propulsion generation system and the control hardware, being transmitted to the outside of the craft through the hull. In order to minimize the thermal signature, allowing to improve the mission profile for these submarine vehicles, this work focuses on the use of phase change materials (PCM) as insulation material between the internal zone of the craft and the external hull.

As a baseline hypothesis, in order to demonstrate that the use of PCM as an insulation material is a feasible technical solution, it is considered that the use of these materials should ensure that the increase in temperature on the outer face of the ships' hull does not activate the thermal detection system of conventional submarine mines, within the typical average operating time interval of the missions carried out by these ships. Fulfilling this hypothesis will ensure, in terms of thermal signature, that the UUV can successfully execute the missions for which it is designed.

In order to achieve these objectives, a simulation of the temperature increase on the outer face of the hull of a UUV will be carried out as a function of time and the thickness of the insulation layers used. This will make it possible to identify the optimum configuration according to the mission profile, which will facilitate technical decision-making for the design and installation of the UUV insulation.

3. Methodology and case of study

In order to pursue a rigorous process for obtaining consolidated conclusions, the subsequent procedure for obtaining results and analysing them will be followed:

- Choose a naval operation type scenario for the identification and possible neutralization of naval mines. Assigning the necessary contour conditions, in terms of geometry and main dimensions of the vessel, initial hull temperature, seawater temperature, vessel interior temperature and equation modelling its variation with respect to time, as well as the value of the temperature increase that will activate the naval mine (ΔT).
- Different insulation configurations will be simulated using phase change materials, using the above contour conditions. For each configuration the maximum operating time will be obtained to exceed the temperature increase of the outer face of the hull, setting as a target values of 3 °C and 5 °C thermal variation.
- Finally, a comparison will be made of all the simulations carried out in order to find out the optimum characteristics for the configuration of the insulation in order to meet the operating times required for the typical naval operations of this type of vessel.

3.1. Description of the typical scenario and boundary conditions.

The first step is to set up a model scenario in which the UUV operate, aimed at identifying and neutralizing naval mines. In this aspect, a mission profile can be used in which a military vessel approaches the vicinity of a field where naval mines are known to exist. Once located in a safe area, the vessel will deploy the UUV, will be lowered overboard until it enters the sea, leaving the UUV operational. Therefore, following this type pattern, the UUV systems will begin to generate heat when they are activated and begin to self-propelled, and this will involve increasing the temperature of its outer hull.

Analyzing the main types of UUV available in the system, an external hull thickness of 20 mm, made of 316 stainless steel, can be taken as an example for the present study, which is sufficient to withstand the immersion pressure required to navigate to the vicinity of submarine mines.

Fig. 1 represents a construction scheme of the hull of the UUV, where seawater is in contact with the pressure hull, and on the inner face of this has been placed the insulation conformed by Phase Change Material (PCM) that will be studied to reduce the thermal signature. In order to be able to attach the insulation to the hull, and if the hull changes phase and liquefies and does not spill, a thin sheet will be placed on the inner side of the insulation, as it is not structurally necessary, for example 2 mm thick. Inside you will find all the machinery and systems that are the source of heat that increase the thermal signature of the boat.

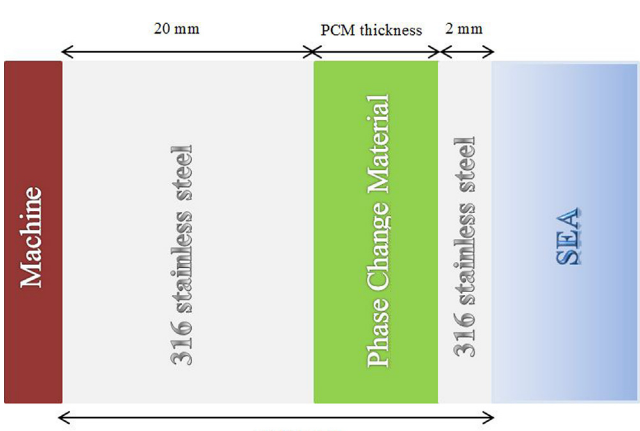

Fig. 1 Distribution of UUV hull layers.

As indicated above, two thermal profiles will be studied, one in which the outer face varies in 3 °C its temperature and the other in which it varies in 5 °C, taking these two data as representative for the activation range of modern naval mines [42]. This research will seek to define the necessary thickness according to the time it will take the external face of the pressure hull to increase by 3 °C or 5 °C, providing a viable technical solution depending on the desired duration of the missions. As a guideline, mission durations are expected to be between 60 and 120 min of UUV operation, with other variables such as battery autonomy and the need to return to the main vessel to carry out a UUV inspection for damage caused by the controlled detonation of a mine during its neutralization being already limiting.

3.2. Phase change material (PCM)

Phase change material (PCM) has numerous applications such as insulation in households, in vehicles, in refrigerators, etc. Its main feature is that it provides a practically constant temperature while the phase change occurs [27], and once the state change occurs, its properties as conductors are less than those of its solid state. The main difficulties presented by these materials are: i) choosing the right material for our range of working temperatures and ii) keeping the material watertight when it is in a liquid state. The first of the difficulties is the most complex to save, since if the temperature ranges in which the operation is to be carried out are not well known there is a risk that the use of PCM will not be useful [19,21]. To solve the second difficulty, the PCM will be encapsulated using a 2 mm thick plate.

3.3. The governing equations

The system of coupled differential equations for heat transmission for each material is given by Bejan and Kraus [6]:

$$D_l\left(\frac{\partial^2 T_l}{\partial x^2}+\frac{\partial^2 T_l}{\partial y^2}\right)=\frac{\partial T_l}{\partial t} \tag{1}$$

$$D_s\left(\frac{\partial^2 T_s}{\partial x^2}+\frac{\partial^2 T_s}{\partial y^2}\right)=\frac{\partial T_s}{\partial t} \tag{2}$$

where the thermal diffusivity takes the expression $D_i = k_i/(\rho_i\, c_{p,i})$ and where i refers to liquid (l) or solid (s), T is the temperature in kelvin degrees, ρ, the density, c_p, the specific heat capacity at constant pressure, k, thermal conductivity and finally, x and y refers to the dimensions of the space.

On the other hand, the advance of the position where PCM changes its state from solid to liquid is given by the Stefan equation:

$$k_s\cdot\frac{\partial T}{\partial n}-k_l\cdot\frac{\partial T}{\partial n}=\rho_s\cdot L\cdot\frac{\partial u_n}{\partial t} \tag{3}$$

where u_n is the interface displacement, n is the normal to surface and L is the latent heat of fusion.

The boundary conditions of the problem have been implemented taking into account that the machine in contact with the hull assumes a focus whose temperature changes with the time. By the other hand, the opposite hull face is in contact with the sea and the phenomena of convection and radiation occur.

3.4. The network model

The network model has been developed following the rules established by González-Fernández and Alhama [18] and Sánchez-Pérez et al. [36]. A simple synthesis of the procedure is as follows:

- First, the equivalence between the study variable, in this case the temperature, and the voltage at the network nodes is established.
- Secondly, the addends of the previous equations are implemented as electrical elements such as resistors, voltage sources, etc.
- Finally, the space is discretized in volume elements.

The final model is simulated using circuit analysis software such as NgSpice [29].

It is possible to find more information about the Network Simulation Method in González-Fernández and Alhama [18] and Sánchez-Pérez et al. [36], and more information about the resolution of phase change problems in the works developed by Sánchez-Pérez [33] and Sánchez-Pérez et al. [38]. It is worth noting the complexity of the resolution of these problems and that the process is temperature conduction in different materials where one of them changes its status and properties.

The development of the 1D network model of the governing equations shown above was carried out by Sánchez-Pérez et al. [38], where the procedure followed was explained in detail, as well as its validation. Furthermore, this work showed its usefulness for both corrosion and thermal processes. The change to 2D scenarios presented in the present work has been done by symmetry.

Finally, it should be noted that the Network Simulation Method has been applied to a large variety of strongly coupled and non-linear science and engineering problems that have been validated with analytical, semi-analytical or benchmark solutions. For example, in elastic Waves [8], in flow and (solute or heat) transport [1,2,3], microscopic tribology [26], soil consolidation [4], corrosion Sánchez-Pérez et al. [34] and Sánchez-Pérez et al. [35], and many others [38].

4. Simulation and results

In order to try to implement the Phase Change Materials (PCM) to the UUV, the heat transfer to the hull section that connects the machine to the seawater will be studied initially. Afterwards, different PCM thicknesses will be implemented and the necessary time will be studied to reach an increase of 3 °C and 5 °C in the hull face in contact with the sea.

The increase in the machine temperature, which is in contact with the hull face opposite the sea, has been implemented by the following expressions:

$$T = T_{ini} + (293 - T_{ini}) \cdot t \quad \text{for} \quad 0 \leq t \leq 1 \tag{4}$$

$$T = 293 + 6 \cdot \ln(t) \quad \text{for} \quad t > 1 \tag{5}$$

where t is the time and the subscript *ini* refers to initial parameters.

In this problem, the 316 stainless steel has been used as material of the UUV hull and as PCM, the acetic acid, since its melting point (T_M) is in the interval between the sea temperature (15 °C) and 3 °C or 5 °C increase of temperature over the sea that present the naval mines as the detection range. In Table 1 the properties of the selected materials are shown.

The hull that is in contact with the sea undergoes cooling processes by convection and radiation, the most important being the first one. The convection process is characterized by the convective heat transfer coefficient that for water takes values from 50 to 3000 (W/(m^{2}K)) for free convection and 50 to 10000 W/(m^{2}K) for forced convection [15].

In this work two studies have been carried out, one when the UUV is in motion and the other when it is motionless, since the convection coefficients are different. When the UUV is in motion it has a convection coefficient of 3057.4 W/m^{2}K for 2 m/s of velocity and a coefficient of 5474 W/m^{2}K for 4 m/s (these convection coefficient have been calculated using the thermal properties of seawater from [28,40]and experimental correlations from [48]. Obviously, when the coefficient is lower, there will be less cooling of the UUV hull. Fig. 2 shows the temperature evolution of the hull next to sea, without PCM and with 5 mm of PCM, for a velocity of 2 m/s. As can be seen, when the PCM is involved the hull temperature slightly changes while it is in motion, presenting a stable temperature of 15.5 °C. This temperature is lower when increasing the thickness of the PCM.

When the UUV is still, the convection coefficient depends on the dimensions of the UUV [28,40,48]. As it presents square plates of 1x5 m and assuming a maximum working depth of 400 m the following coefficients are obtained: lower horizontal plate, 153.44 W/m^{2}K, upper horizontal plate, 623.62 W/m^{2}K and finally, vertical plates, 579.75 W/m^{2}K (again, it has been calculated using data from [28,40]and experimental correlations from [48]. Since the lower the coefficient the less cooling occurs, the smaller of them has been selected for the study. In order to illustrate raised problem solution, Figs. 3 and 4 show the temperature distribution for a 0 mm and 5 mm of PCM thickness, respectively, using a 80x80 mesh.

Figs. 3 and 4 show a decrease in the temperature of the external surface of the hull when using PCM, decreasing this from 39 °C to 21.9 °C when going from not using PCM to

Table 1 Properties of steel and PCM [19,21,43]

Phase	Properties	316 stainless steel	Acetic acid
Solid	k (W/mK)	13.79	0.20
	r (kg/m^3)	7950	1270
	c_p (J/kgK)	469.8	1960
Liquid	k (W/mK)	–	0.18
	r (kg/m^3)	–	1050
	c_p (J/kgK)	–	2004
Phase change properties	TM (°C)	–	16.7
	L (kJ/kg)	–	187

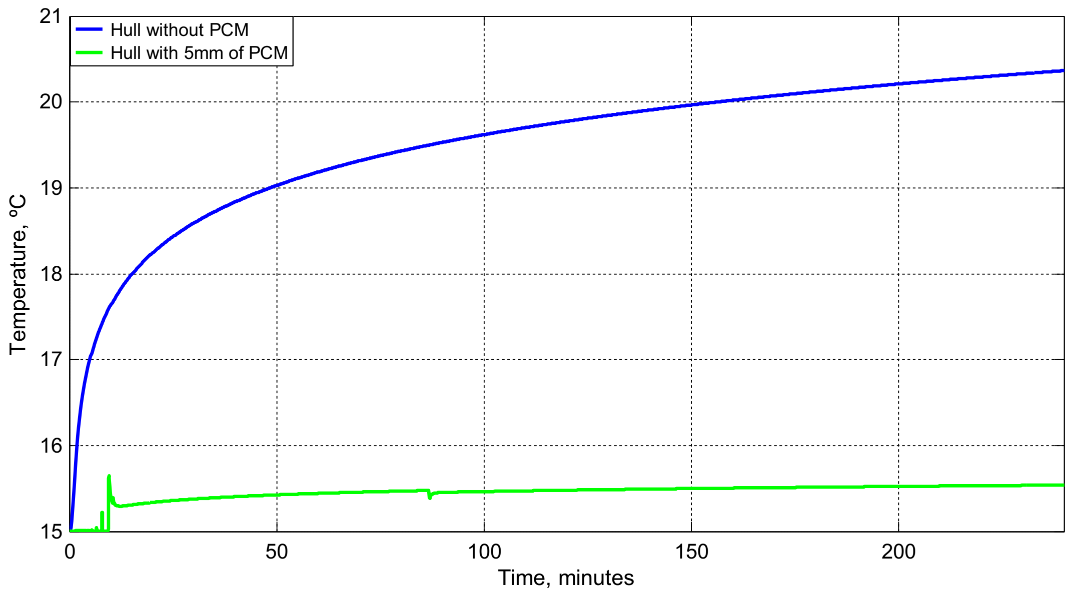

Fig. 2 Temperature evolutions for the hull side next to sea without PCM and with 5 mm of PCM with 3057.4 W/(m^2K) of convective heat transfer coefficient and a velocity of 2 m/s.

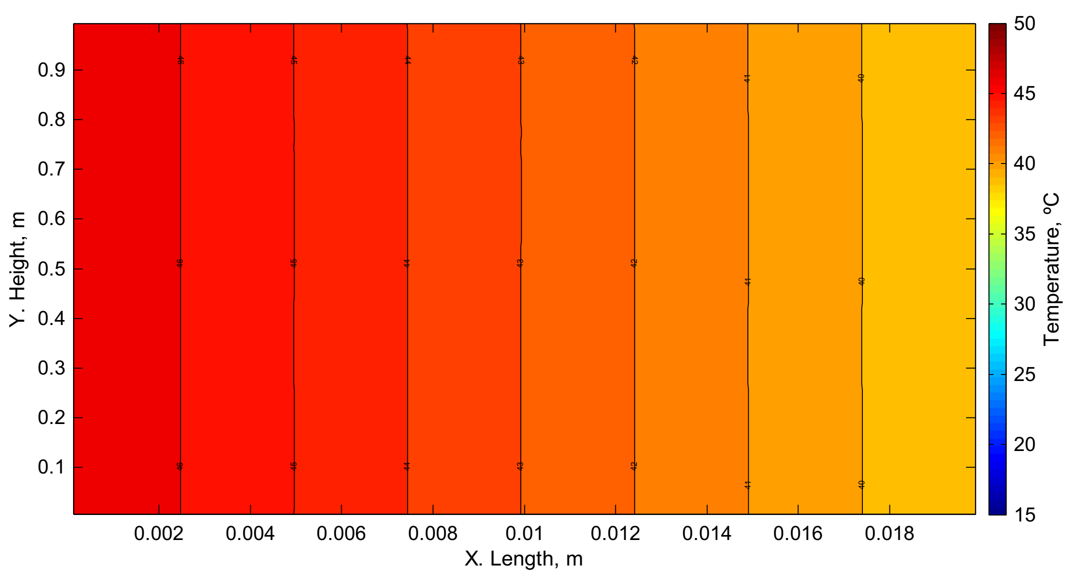

Fig. 3 Temperature distributions through the hull thickness without PCM and 20 mm of steel with 153.44 W/(m^2K) of convective heat transfer coefficient after an hour and a half of exposure to the heat source.

using 5 mm of this material. So, with PCM the external temperature is much similar to the sea temperature, decreasing the thermal signature. As can be seen in the figures, the temperature distribution without PCM is much regular than with it. This is mainly due to the phase change of the acetic acid. This process absorbs the energy that arrives to the PCM until the phase change is completed, so it stop during that time the heat transmission to the rest of the hull.

This effect can be best shown by representing the temperature evolution for the position of the hull near the heat source, for the PCM position and for the position close to the water of the sea. Thus, Figs. 5 to 8 show the temperature evolution for different PCM thicknesses.

Near the interior of the UUV and before the PCM (blue line), the temperature variation with time is similar with and without PCM. But in the outer part of the hull (green lines and red lines of Figs. 6 and 7), the temperature remains constants during some periods of time due to the thermal energy absorption of the phase change [27]. This effect and the lower thermal conductivity of the acetic acid makes that the external temperature of the hull (green line) increases very slowly with time.

As expected, an increase of the PCM thickness makes the time to reach a certain temperature in the outer part of the hull increases considerably. If we apply the non-dimensionalization technique to the governing equations, it can be seen that the

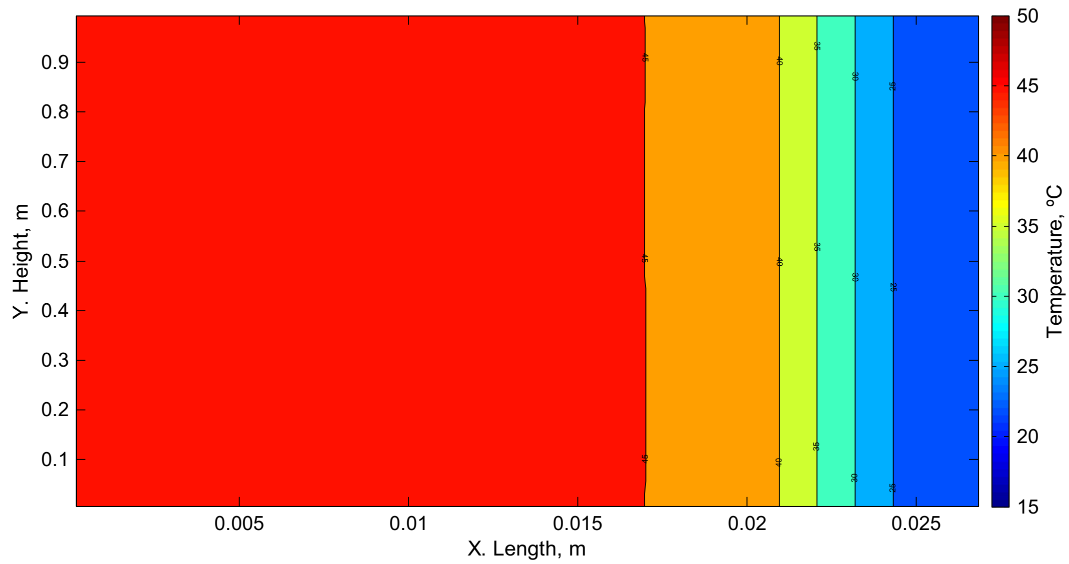

Fig. 4 Temperature distributions through the hull thickness for 5 mm of PCM thickness and 22 mm of steel with 153.44 W/(m^2K) of convective heat transfer coefficient after an hour and a half of exposure to the heat source.

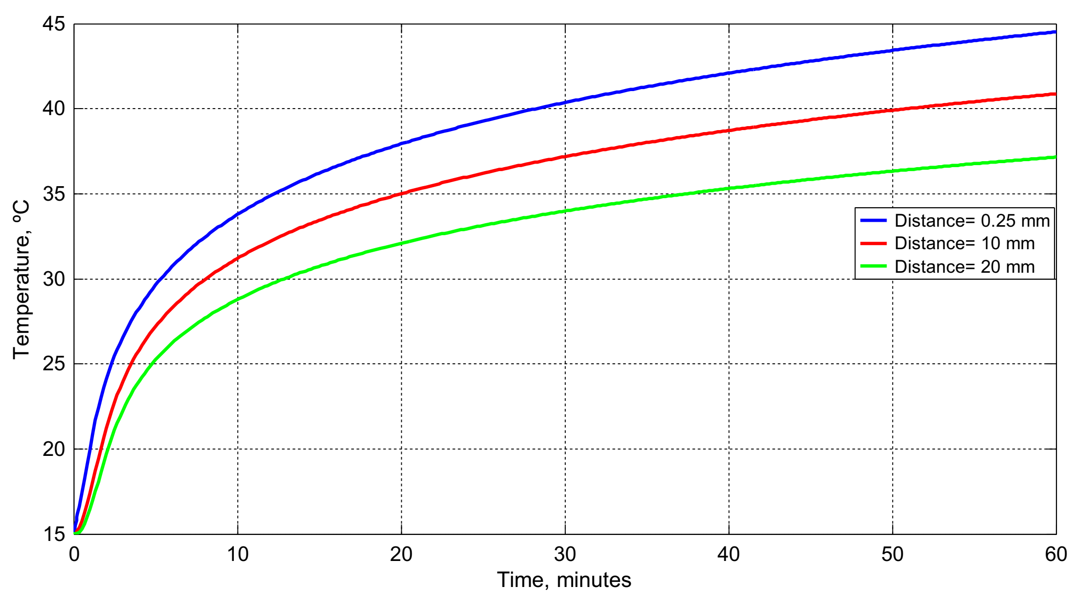

Fig. 5 Temperature evolutions for different position in a hull without PCM and 20 mm of steel with 153.44 W/(m^2K) of convective heat transfer coefficient.

time to reach a certain temperature is a function of the length of the materials, the latent heat of fusion, the specific heat capacity, thermal conductivity and density of the materials [10,37]. As in the study problem all the parameters remain constant except for the PCM thickness, a relationship between the time to reach a certain temperature and the mentioned PCM thickness can be obtained. Since the increase that interests us is 3 °C or 5 °C over the initial temperature of the seawater, depending on the sensitivity of the mine, Figs. 9 and 10 show the relationship between the time to reach these increments and the PCM thickness.

If the previous figures are analysed, for both cases, about an hour is available until the temperature increase for a PCM of 12.5 mm thickness. It should be noted that once the time in which the complete fusion of the PCM is reached, there is a sudden increase in temperature (Figs. 6 to 8). This effect could affect the operation manoeuvrability so it should always work at times below the limit. If the effect of using 12.5 mm of PCM is analysed, it can be seen that there is an increase of 43 and 30 times of the operating time to increase the hull temperature in 3 °C and 5 °C, respectively. It should be noted that the previous figures are only valid for a maximum operating depth of 400 m.

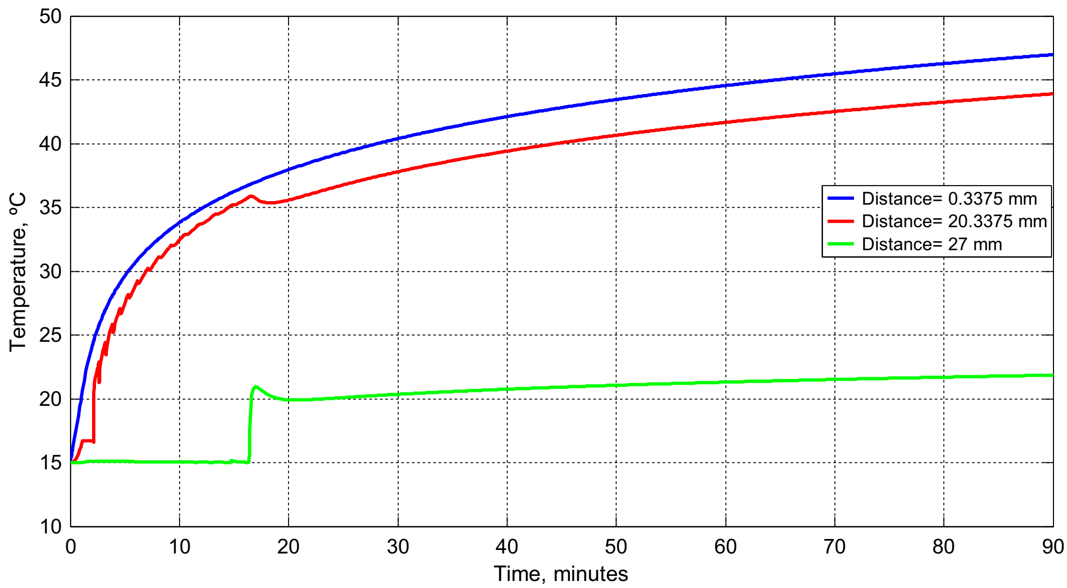

Fig. 6 Temperature distributions through the hull thickness Temperature distributions through the hull thickness for 5 mm of PCM thickness and 22 mm of steel with 153.44 W/(m^2K) of convective heat transfer coefficient.

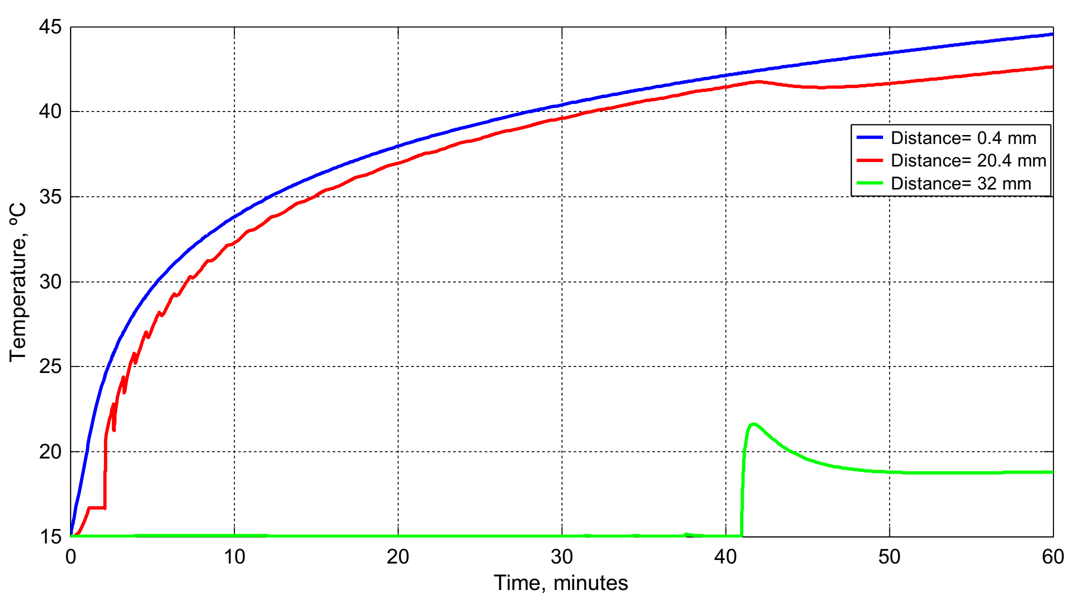

Fig. 7 Temperature distributions through the hull thickness for 10 mm of PCM thickness and 22 mm of steel with 153.44 W/(m^2K) of convective heat transfer coefficient.

According to the mission profile that has been assessed in this research, these times are adequate for the UUV to successfully carry out its missions, without increasing its thermal signature by more than 3 °C during the period of time that the mission lasts. In addition, it is possible to provide the PCM insulation layer with a greater thickness, as long as the dimensions of the UUV allow it, adapting it to the mission profile on which the craft must operate. The handling of the UUV is not altered, so that the crew in charge of the use of the UUV does not need specific training for its use, simply know a basic guidelines that are limited to keeping the UUV away from a heat source during transport in the mothership, so that the PCM is in its solid state and with all the ability to absorb heat intact.

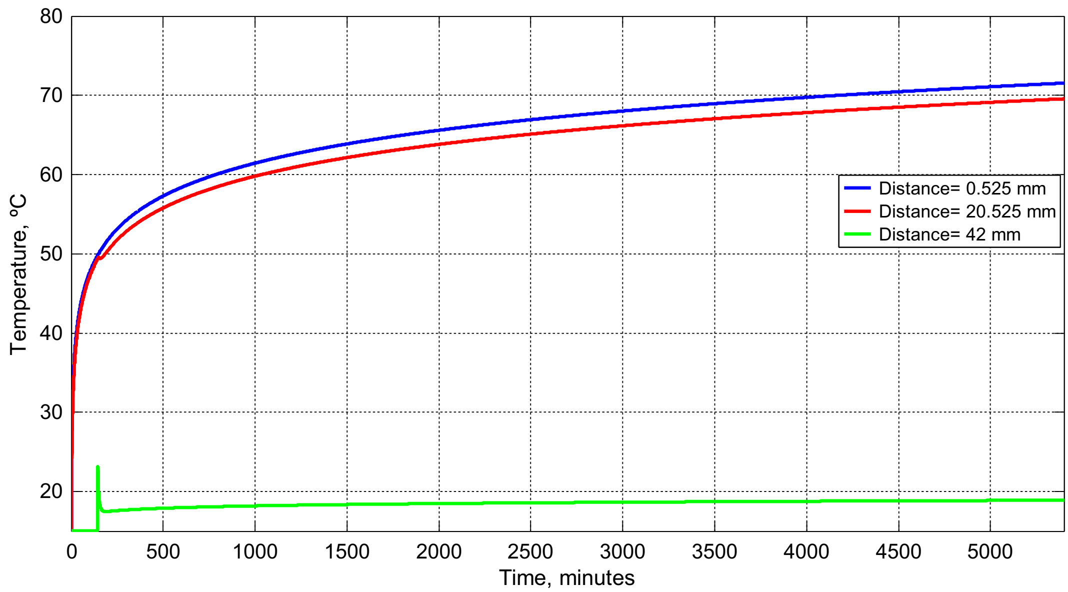

Fig. 8 Temperature distributions through the hull thickness for 20 mm of PCM thickness and 22 mm of steel with 153.44 W/(m^2K) of convective heat transfer coefficient.

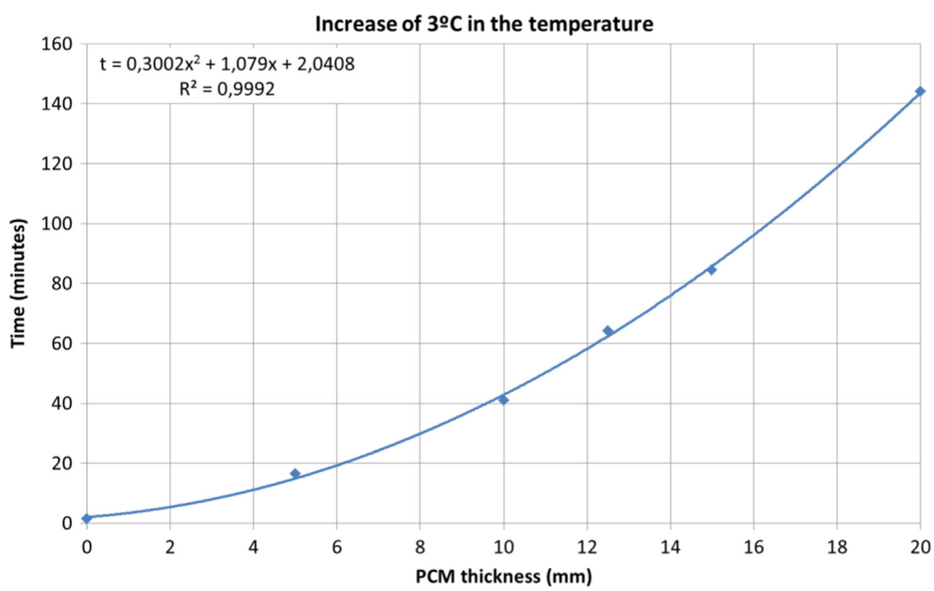

Fig. 9 Relationship between time to reach an increase of 3 °C in the temperature at the face hull close to the sea and PCM thickness with 153.44 W/(m^2K) of convective heat transfer coefficient.

5. Conclusions

It should be noted that Phase Change Materials (PCM) are widely used in numerous applications such as in automobiles, refrigerators, air conditioning, electrical devices and so on [21,13]. Therefore, in this work has proposed its use to increase the UUV operation time when it must work in a limited temperature range. To carry out this study, a heat transmission simulation model has been developed that includes phase change materials with the Network Simulation Method.

It has been established that the incorporation of PCM reduces the temperature increase of the part of the hull next to the sea and allows the UUV to operate without danger during more time. The relationship between the PCM thickness and the time to increase the outer temperature in 3 and 5 °C have been found.

If the results are analysed, the use of a minimum thickness such as 12.5 mm of PCM can mean an increase in operating time of 43 and 30 times for a temperature increase range of 3 °C and 5 °C, respectively. In addition, curves are presented to determine the optimal thickness of PCM based on the desired operating time for a maximum working depth of 400 m.

In the literature review carried out during the period covered by the present investigation, it has been possible to iden-

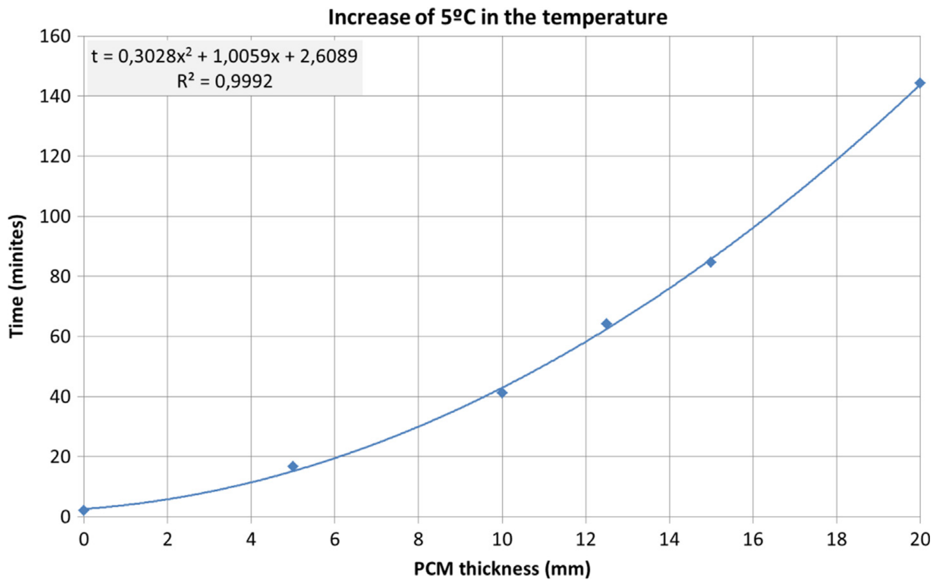

Fig. 10 Relationship between time to reach an increase of 5 °C in the temperature at the face hull close to the sea and PCM thickness with 153.44 W/(m^2K) of convective heat transfer coefficient.

tify the need existing in the naval industry to improve thermal insulation. This need is defined by the increasingly demanding requirements in terms of reducing the different signatures issued by the vessels, in this case the thermal signature, which has to be reduced in order to adapt the ships to the operational profiles for which they are designed. In this aspect, the specific case of the UUV for the identification and neutralization of naval mines has been identified. These mines are activated when an emission level is exceeded in some of the characteristic signatures of the vessel, such as electromagnetic, acoustic or thermal signatures. It has been possible to verify that there is recent research on the improvement of systems aimed at reducing radiated noise or electromagnetic fields, but it has been necessary to deepen and expose new solutions to the reduction of the temperature increase of the hull due to the internal heating sources of the UUV, it is at this point where the results of the work done are located.

The exposed results allow engineers to optimize the design of the UUV structure to considerably reduce the thermal signature, allowing operation times of between 1 and 2 h in which the external face of the UUV hull would not have an increase of more than 3 °C, which will allow a successful approach to naval mines, without fear of being detected by the thermal sensors of the mines, and thus facilitate the detection and neutralization of them. Of course, this type of insulation is effective in reducing the thermal signature, having to consider the other signatures present on the ship (magnetic, acoustic, etc.).

The analysis carried out throughout this research has a direct application to the current manufacturing industry of Military Unmanned Underwater Vehicles (UUV), although PCM can also be applied for the insulation of other types of vessels, as could be the case of oceanographic research UUV where it is not wanted to distort the data acquired seawater temperature by the thermal increase of the vehicle itself, in the study of marine fauna, minimizing the impact on the species thanks to thermal insulation, or in the use of firefighting bulkheads in any type of vessel, such as ships with hulls manufactured in composite materials.

The main limitations of the study presented are focused on the baseline parameters that have been assumed. In this aspect, it should be considered that the present work has been carried out using an external hull of 20 mm, made of 316 stainless steel, although the model is valid for other types of material used in the hull, such as conventional steel or other types of stainless steel, as well as other ranges of sheet thickness. Regarding the initial temperature range, the research has taken a sea water temperature of 15 °C, with a maximum increase of 3 °C or 5 °C as activation values of the naval mine detection systems. Depending on the operating conditions of the UUV, such as the temperature of the water in the area of operation, it would be advisable to recalculate the results. At the same time, it would be convenient to verify that the temperature increase due to the internal heat sources of the UUV correspond to expressions (4) and (5), if they were different, the current study would have to be adjusted and any new findings would have to be assessed, although the general method described above is applicable, even if these values are modified. As for PCM, acetic acid, was selected for its melting temperature since it was in the range of working temperatures. In case this range changes, a new PCM should be selected and its study carried out in the same way as that presented in this work.

6. Declarations section

Ethics approval and consent to participate
Not applicable

7. Availability of data and material

Not applicable

8. Competing interests

The authors declare that they have no competing interests.

Funding

Not applicable

10. Authors' contributions

J.F. Sánchez-Pérez and C. Mascaraque-Ramírez came up with the initial idea for the work. All authors performed the simulations and all the data analysis. All authors participated in the writing and revising of the manuscript.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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