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Air Bubble Position Effect on Phase Change Material Melting in a Semi-Cylindrical Container: A Thermal Analysis

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ABSTRACT

This study presents a thorough thermal analysis of the impact of air bubble position on the melting of a phase change material (PCM), specifically paraffin wax (RT58), within a semi-cylindrical container. The enthalpy-porosity technique and ANSYS/FLUENT 16 software were employed to conduct a numerical examination of the process. Three distinct air bubble positions were considered for their effects on the melting of paraffin; these positions included the bottom, center, and top of the container. The outcomes from these configurations were compared with a reference case devoid of air bubbles. It was observed that the presence of an air bubble naturally expedited the dissolution process, despite the increased volume of the PCM due to the inclusion of the air bubble. Notably, air bubbles located at the top or bottom of the container were found to reduce the time required for the dissolution process by 6%, compared to when the air bubble was situated at the center of the container. The findings from this study offer potential avenues for enhancing the heat transfer capabilities of PCMs, materials widely employed in diverse applications such as solar energy storage, electronic cooling systems, and building insulation.

1. INTRODUCTION

The advancement of modern society is deeply intertwined with energy, a catalyst for development that permeates diverse sectors and facets of daily life. In the quest for sustainable alternatives, renewable energy has emerged as a focal point of global research efforts. The appeal of renewable energy lies in its long-term cost-effectiveness, negligible environmental impact, and potential for ubiquitous implementation. However, a notable drawback is its intermittent availability, particularly from sources such as solar and wind energy [1, 2].

To address this intermittency inherent in renewable energy systems, researchers have turned to Thermal Energy Storage (TES) systems, with Phase Change Materials (PCMs) at the forefront [3, 4]. In periods of high renewable energy production, these PCMs-equipped TES systems are capable of storing surplus energy, which can be subsequently released during periods of low or no power generation. This ensures a consistent and reliable energy supply despite the cyclical nature of renewable sources. Intriguingly, the ability of PCMs to store and release considerable amounts of heat during phase transitions, a characteristic known as latent heat, renders them vital in the field of TES.

Different types of PCMs have been investigated by scientists to understand their respective impacts on heat storage and heat transfer. This involves probing into various categories, such as organic, inorganic, and eutectic PCMs, to identify the most effective materials for specific applications. Organic PCMs, exemplified by paraffin wax, are known for their high latent heat capacity and affordability. Inorganic PCMs, such as salt hydrates, exhibit excellent thermal conductivity and stability. Eutectic mixtures, which combine two or more materials that have a lower melting point than their individual constituents, enhance heat transfer and offer greater flexibility in temperature range selection. These attributes position PCMs as valuable tools for numerous applications, including thermal management in diverse industrial processes, solar energy storage, electronic cooling systems, and building insulation [5].

The significance of incorporating numerical predictions in experimental research has been underscored by Younsi et al. [6] and Shokouhm and Kamkari [7]. An empirical study investigating the melting process of PCMs in a rectangular container revealed an acceleration of the process with an increase in temperature [8, 9].

In a comprehensive study, Tan et al. [10] sought to elucidate the role of buoyancy-driven convection in the constrained melting of PCMs within a spherical capsule. The process of melting paraffin wax n-octadecane, confined within a transparent glass sphere, was monitored and analyzed juxtaposed with numerical results from the Computational Fluid Dynamics (CFD) code Fluent. The data indicated the formation of an unstable fluid layer at the bottom, triggering chaotic fluctuations and a wavy appearance. Upon comparison of measured and computed temperatures in the sphere's upper half, the stability of the molten liquid layer was confirmed.

A numerical examination on the unconstrained melting of nano-enhanced phase change materials (NePCM) within a spherical container was conducted by Hosseinizadeh et al. [11]. The analyses accounted for nanoparticles across three distinct Stefan numbers and volume fractions at a sub-cooling temperature of 6°C. The simulations suggested a boost in the thermal conductivity of NePCM due to nanoparticles, resulting in a quicker melting process than that of conventional PCM. This accelerated melting is attributed to an increase in thermal conductivity and a decrease in latent heat.

The longstanding exploration of unrestrained melting in a sphere has been revisited by Fan et al. [12], employing nano-enhanced phase change materials (NePCM). These NePCM samples were prepared using graphite nanosheets at various loadings up to 1 wt.%. An internal evaluation of the NePCMs' temperature and loading was conducted, alongside a comprehensive examination of key thermo-physical properties. The findings revealed that the enhanced thermal conductivity of NePCM, relative to pure PCM, led to a 10% reduction in total melting time for the 0.5 wt% sample at the minimum boundary temperature. A set of universal correlations were proposed for all NePCM samples, with an associated uncertainty of less than 15%.

Sun et al. [13] posited that elevating the air inlet temperature would intensify PCM melting and significantly augment the energy charge for both the latent and sensible heat of the PCM. The PCM melting process in a rectangular container was scrutinized numerically and experimentally by Yadav and Samir [14], and they illustrated an acceleration of the melting process with increasing temperature. Alshara and Kadhim [15] embarked on a numerical investigation of a Thermal Energy Storage (TES) system, utilizing a cylindrical cell. Their results suggested that the final cylinder in the column melted more slowly than the initial one, with the PCM's temperature presenting higher in the center and lower on the outer face of the cylinder.

Hlimi et al. [16] utilized a horizontal cylindrical capsule to probe the melting process. Their study underscored that conduction was the dominating mechanism in the initial stages of PCM melting. Thereafter, natural convection drove the melting process, thereby influencing the time required to complete the operation. A statistical examination of the partial melting of PCM in a vertical cylinder was conducted by Bechiri and Mansouri [17]. Their research highlighted the significant influence of tube dimensions, external wall temperature, thermophysical properties, and tube shell thickness on the melting process.

The melting of PCM in a spherical container was experimentally investigated by Rizan et al. [18], demonstrating that an increase in the heater wattage could expedite the melting process. Similarly, Ismail et al. [19] experimentally examined the melting process in a spherical PCM cell, determining that enlarging the cell width could diminish melting. Sattari et al. [20] provided a quantitative exploration of PCM melting in a spherical cell. They found that due to natural convection, the bottom half of the sphere melted more slowly than the top half.

PCMs were employed in a study on shell and tube latent heat storage for solar dryers [21, 22], where heat transport was primarily affected by natural convection, resulting in a faster melting rate near the top due to the buoyancy effect. Ebrahimi et al. [23] investigated the melting process of PCM in a multi-tube, finding that an increase in the number of tubes and temperature accelerated the process. Harikrishnan and Kalaiselvam [24] conducted experiments to ascertain whether the addition of nanoparticles would enhance heat transmission. Their results affirmed that incorporating nanoparticles into PCM improved heat transport, consequently reducing the time required to complete the melting operation.

In summary, it can be acknowledged that scientists are striving to address energy concerns and promote sustainable solutions by understanding and harnessing the properties of phase change materials (PCMs). By employing effective thermal energy storage (TES) systems that utilize PCMs, energy consumption can be reduced, the efficiency of renewable energy sources can be optimized, and the overall energy effectiveness of various applications can be enhanced. Additionally, by reducing greenhouse gas emissions and facilitating a transition towards cleaner, more sustainable energy sources, the development of advanced PCMs and related technologies can contribute to the fight against climate change.

Upon conducting a thorough review of existing literature, it is apparent that while numerous studies have investigated the melting process of paraffin wax in cylindrical cells, none have examined the influence of an air bubble and its position on the PCM melting process. To the best of our knowledge, it is essential to investigate the positioning of an air bubble within the paraffin wax in a half-cylinder container to better understand its effect on the phase change of PCMs. By examining the impact of air bubbles on heat transport and overall thermal performance, researchers can gain insights into their behavior within the PCM.

Moreover, we posit that understanding the influence of an air bubble on the melting process of PCMs can contribute to the enhancement of renewable energy storage. This understanding stems from the realization that trapped air bubbles in PCM act as thermal insulators, negatively affecting heat transfer efficiency throughout the melting process. To mitigate this thermal resistance and enhance the performance of energy storage devices, the impact of air bubbles on the melting process must be fully understood.

By being cognizant of the effects of air bubbles on melting, it becomes more efficient to construct PCM-based energy storage systems. Engineers can design systems that minimize the presence of air bubbles or account for their impact when assessing a system's performance. Furthermore, this knowledge can aid in optimizing the charging and discharging processes.

Therefore, the objective of this study is to investigate the positioning of an air bubble within the paraffin wax in a half-cylinder container and its influence on the PCM melting process. The underlying hypothesis of this research is that the position of an air bubble within the paraffin wax significantly affects the dissolution operation during the PCM melting process.

To simulate the PCM melting process with varying bubble positions, computational fluid dynamics simulations are being developed using computational modeling. The model developed can assist in predicting temperature profiles, heat transfer rates, and other relevant characteristics under various conditions. By adjusting the bubble's position within the model, we aim to assess its impact on the melting behavior.

2. NUMERICAL MODEL APPROACH

2.1 Physical model

Figure 1(a) reveals the physical model of the cavity (semi-cylinder), which presents that the 2-Dcavity is 6 cm in diameter, isolated from the side of the semi-cylinder cell, and passing hot water at the last side as a heat source with an existence of 3 cm diameter of an air bubble. The air bubble center was located 1.5 cm from the center of the cylinder. Figure 1(b) shows that the air bubble is positioned in the middle of the cell with the same dimensions. However, Figure 1(c) shows that the air bubble is at the top with the same dimensions. Figure 1(d) depicts the geometry without an air bubble as a basis for comparison with the case of the presence of the air bubble.

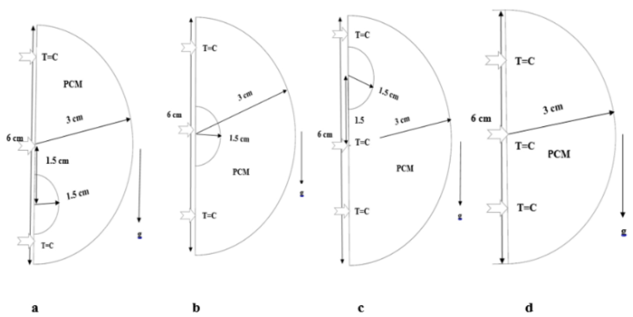

Figure 1. Arrangement of the physical mode

2.2 Computational mode

The CFD analysis allows for the prediction of melting process specifications inside the semi-cylindrical cell. Specifically, the two-dimensional flow was unstable, laminar and incompressible. It is assumed that each solid and liquid phase be isotropic, homogenous, and stay in equilibrium (thermal) at the mid-point (interface) to model the melting process. The enthalpy-porosity method was utilised to model the phase-change zone within the PCM. Because of its temporal behavior, continual and nonlinearity stir of the liquid-solid interface, PCM melting is a complicated phenomenon. The melting of PCM is modeled by considering the set of following correlations: energy, momentum, and continuity, which are presented in Eqs. (1) to (3) [25-28]:

$$\frac{\partial}{\partial t}(\rho H) + \nabla.(\rho V H) = \nabla.(K\nabla T) \tag{1}$$

$$\frac{\partial(\rho v)}{\partial \mathrm{t}} + \nabla.(\rho V) = -\nabla P + \mu\nabla^2 V + \rho g + S \tag{2}$$

$$\frac{\partial \rho}{\partial t} + \nabla.(\rho V) = 0 \tag{3}$$

Both the sensible heat (h) and sum of latent heat (ΔH) generate the specific enthalpy (H):

$$H = h + \Delta \mathrm{H} \tag{4}$$

$$h = h_{ref} + \int_{T_{ref}}^{T} C_p dT \tag{5}$$

$$\Delta H = \beta L_f \tag{6}$$

The latent heat content varies between zero to one (one for a liquid and solid), and the fraction of liquid (β) is presented as follows:

$$\beta = \begin{cases} 0 \text{ solidus; if } T < T_s \\ 1 \text{ liquidus; if } T > T_l \\ \dfrac{T - T_s}{T_l - T_s}; \text{ if } T_s \le T \le T_l \end{cases} \tag{7}$$

Foe the momentum correlation, the damping term of Darcy's law that is added as a result to the change in phase change is the source term (S) in the momentum correlation. The source term in the momentum correlation is as follows:

$$S = \frac{C(1-\beta)^2}{\beta^3} V \tag{8}$$

C is the mushy zone coefficient, which reflects the melting front morphology. The mushy zone coefficient is an associated term with phase change or solidification processes in materials, notably in the context of PCMs. A zone where both the solid and liquid phases coexist frequently exists when a substance goes through a phase shift, such as solidification (freezing) or melting. The "interfacial region" or "mushy zone" are typical names for this area. As temperature or some external factor changes within this area, where there is a gradual transition from solid to liquid. This coefficient ranges between 10^4 to 10^7. In the current investigation, the value of coefficient C is taken as 10^5.

The selected above model reflects the energy, momentum, and continuity equations required. This is an important to evaluate the progression of the melting process and temperature and velocity patterns when an air bubble is existing at different positions of the semi-cylinder.

Table 1. Physical proprieties of paraffin wax [27]

Thermal Features	Paraffin RT58	Units
Density	840	kg/m^3
Specific heat	2100	J/kg K
Thermal conductivity	0.21	W/m K
Dynamic viscosity	2.69×10^{-2}	kg/m s
Thermal expansion coefficient	1.1×10^{-4}	1/K
Heat of fusion	180000	J/kg
Solidus temp.	48	℃
Liquidus temp.	62	℃

2.3 Boundary conditions

In order to supply heat, the wall is circulated with hot water flowing at a velocity of 0.3 m/s and a temperature of 77°C. The cell is isolated on the semi-cylindrical cavity to avoid heat transmission and the current statement that heat is transmitted from the wall to the whole PCM without losses. In the present study, the PCM is aparaffin wax (RT58). Table 1 shows the physical properties of the used paraffin wax [27].

2.4 Assumptions

When simulating the process of PCM melting inside a semi-cylinder, a number of assumptions have been considered as follows;

·The melting is depicted as a two-dimensional model;

·The cavity is primarily full with a solid PCM;

·Unsteady flow, laminar, incompressible fluid;

·The PCM thermo-physical properties are constant in both phases of liquid and solid;

·The viscous-dissipation is neglected;

·There is no heat gain or loss (the system is perfectly insulated and isolated from its surrounding);

·Volume changes associated with the liquid-solid phase transition are disregarded.

Please note that these above limitations are often deployed to simplify the mathematical modeling and computational analysis of the process. For example, a simplification that lowers computational complexity is to model melting as a two-dimensional process. Despite the fact that this assumption ignores fluctuations along the third dimension, it can nonetheless shed light on how the system behaves in its most basic forms. Also, assuming that solid PCM is largely filling the cavity gives the simulation an obvious initial state. By first ignoring the difficulties of mixed-phase zones, it simplifies the issue. Because the melting process involves ongoing changes over time, unstable flow is taken into account. The assumption of fixed tehrmo-ohysical properties is reasonable especially when the variation is minimal within the temperature range of interest. Neglecting the viscous-dissipation is acceptable to simplify the energy balance equation and fits low fluid velocities. Lastly, the negligible volume change of PCM during the phase transition allows to suppose the last assumption.

3. RESULTS AND DISCUSSION

The importance of PCMs in heat storage and the influence of an air bubble on the melting process have been considered across four diverse scenarios. These scenarios encompass the incidence of an air bubble at the bottom, middle, and top of the cylinder, as well as a scenario without any air bubble. The aim of this investigation is to analyse and understand the impact of these scenarios on the melting process. To conduct this, the progression of the melting process and temperature and velocity patterns when an air bubble is existing at different positions of the semi-cylinder will be studied thoroughly.

The amount of PCM was taken with the same volume of the cylinder, which was not decreased, and the air bubble volume was not also condensed to clarify the air bubble effect on the melting process. The associated results and corresponding discussion are presented in the next sections.

3.1 Scenario one: Air bubble at the lower of the half-cylinder

In this particular case, the study shows that it takes 180 minutes for the PCM to fully dissolve. It has been observed that the presence of an air bubble impacts the dissolution process, as the melting of PCM initially relies on conduction and subsequently on natural convection. The melting process is illustrated in Figure 2, which demonstrates that heat transfer primarily occurs through conduction during the initial stages. Moreover, the presence of an air bubble at the lower part of the semi-cylinder facilitates the melting of PCM along the wall of the cylinder and enhances heat transfer. As the melting process progresses and moves far away from the semi-cylinder wall, heat is transported through natural convection, resulting in a slower melting rate. Over time, the melting process initiates from the top due to the influence of acceleration and the movement of hot PCM towards the top while solid PCM settles at the bottom. The occurrence of a lower air bubble impacts the completion of the melting process.

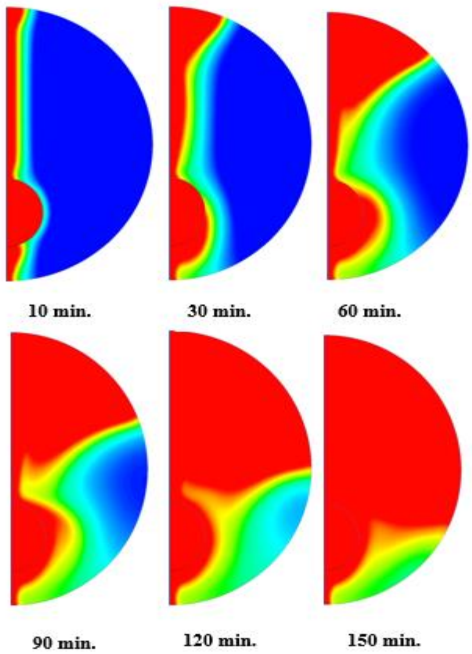

Figure 2. The progression of the melting process when an air bubble is existing at the bottom of the semi-cylinder

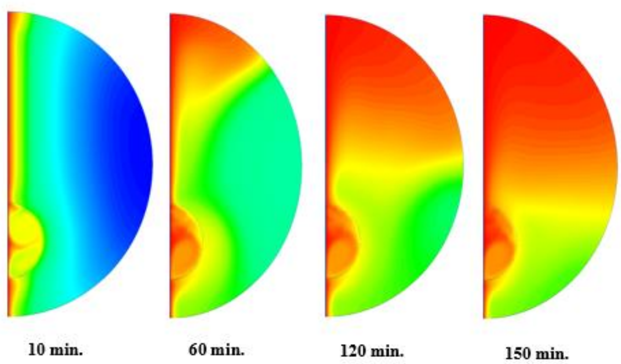

Figure 3. Temperature patterns observed when an air bubble exists at the lower section of the semi-cylinder

Figure 3 provides a detailed illustration of the temperature distribution when an air bubble exists at the lower portion of the semi-cylinder. Figure 3 demonstrates that heat transfer initially occurs primarily along the cylinder wall during the early stages of the melting process. However, as the process advances, heat transmission becomes reliant on natural convection, which consumes an extended time due to the melting rate decelerates as we move away from the half-cylinder wall. Notably, the incidence of an air bubble influences the heat transfer. Figure 4 portrays the velocity distributions and the rate of the melting process when an air bubble exists at the lower section of the half-cylinder. It has been deduced that the presence of an air bubble has enhanced the melting process, which consequently has an impact on the dissolution process.

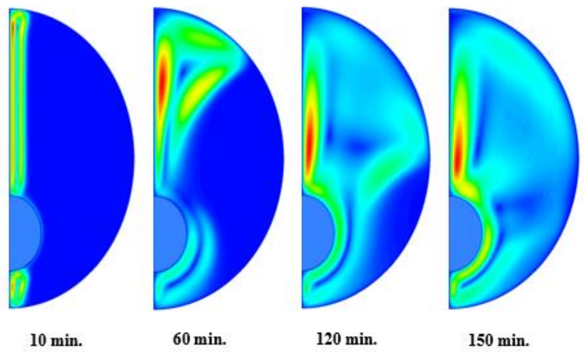

Figure 4. Velocity patterns with the existence of the air bubble at the lower of the half-cylinder

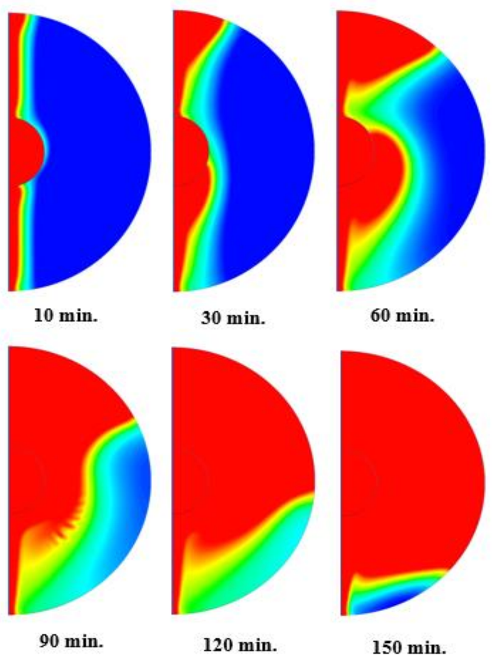

Figure 5. The progression of the melting process when an air bubble is existed in the middle of the semi-cylinder

3.2 Scenario two: Air bubble at the middle of the half-cylinder

In this scenario, the investigation indicates that the complete dissolution of the PCM requires approximately 170 minutes. Figure 5 introduces the melting process. Heat transfer primarily occurs through conduction at the beginning of the melting process, and the attendance of an air bubble in the center of the half-cylinder accelerates the melting of PCM and heat transfer along the wall. As the process advances, heat transmission shifts to natural convection since the melting rate decreases as we move further away from the wall. More importantly, it has been observed that the melting process initiates from the top due to the acceleration. The hot PCMs are transferred to the top while the solid portion settles at the bottom, and the existence of an intermediate air bubble impacts the completion of the melting process. However, the effect of the air bubble is less than the existence of the air bubble in the lower part. Figure 6 depicts the temperature distributions with the existence of an air bubble at the center of the semi-cylinder. It reveals that the transmission of heat at the beginning of the melting operation is over the wall, and then the transmission of heat becomes dependent on natural convection and has to be away from the wall for a longer period of time. In this regard, the presence of an air bubble has an effect on heat transfer. The speed of the melting process is presented in Figure 7. Accordingly, the dissolution process has been controlled by the occurrence of an air bubble which relatively impacted the melting movement.

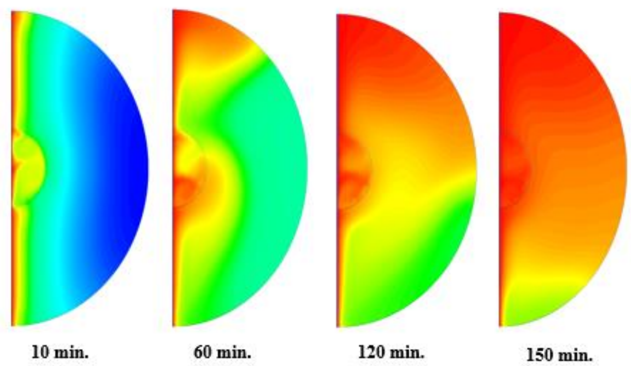

Figure 6. Temperature patterns observed when an air bubble exists at the center of the semi-cylinder

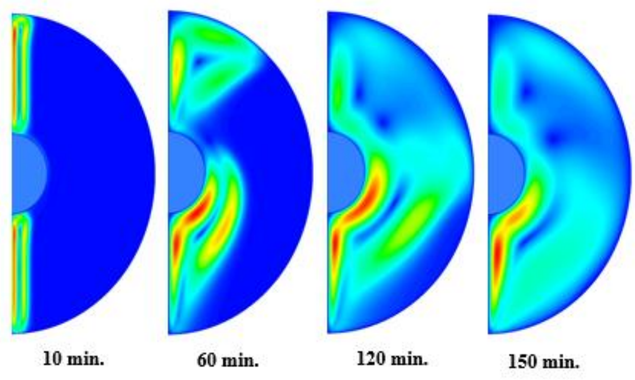

Figure 7. Velocity patterns observed when an air bubble exists at the center of the half-cylinder

3.3 Scenario three: Air bubble at the upper of semi cylinder

In this particular case, the study reveals that the complete dissolution of the PCM takes around 180 minutes. The melting process is illustrated in Figure 8.

Heat transfer primarily occurs through conduction during the early stages of melting. Particularly, the occurrence of an air bubble in the middle of the half-cylinder accelerates the PCM melting. As we move away from the wall, the melting process takes longer due to a shift in heat transfer to natural convection. Overall, it is observed that the melting process initiates from the top, where the hot PCMs move towards the top and the solid part settles at the bottom. Additionally, the occurrence of an upper air bubble influences the completion of the melting process, similar to the effect of the lower air bubble but more significant. Figure 9 displays the temperature distribution, indicating that heat transfer initially occurs along the cylinder wall during the melting process, followed by a dependence on natural convection, which requires a longer time away from the wall. The velocity patterns of the melting process at different operational time are depicted in Figure 10.

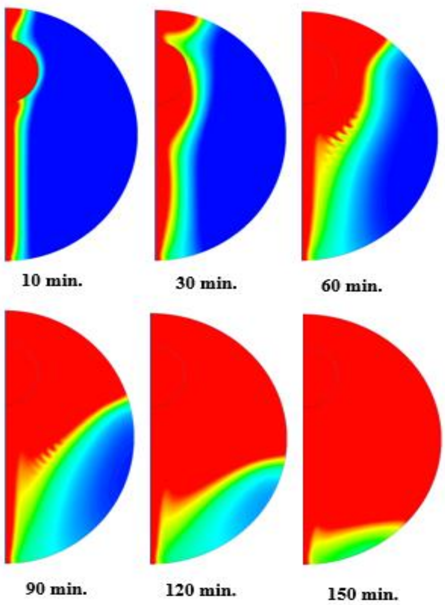

Figure 8. The progression of the melting process when an air bubble is existent at the top of the semi-cylinder

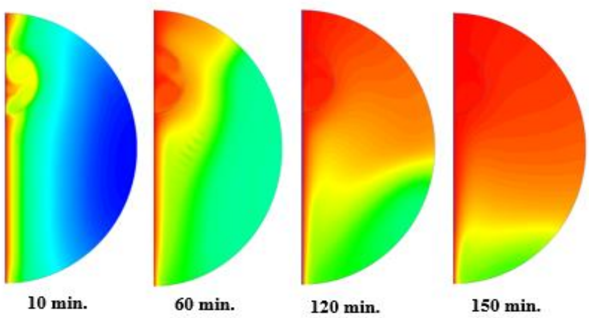

Figure 9. Temperature patterns observed when an air bubble exists at the upper portion of the semi-cylinder

3.4 Scenario four: Without air bubble in the half-cylinder cell

In this particular case, the study reveals that the complete dissolution of the PCM takes approximately 170 minutes. It is noteworthy that the absence of an air bubble has a considerable influence on the dissolution process, as the initial stage of PCM dissolution relies on conduction followed by natural convection. The melting process is depicted in Figure 11. Heat transfer primarily occurs through conduction during the early stages of melting. The absence of an air bubble in the half-cylinder cell notably hastens the heat transfer along the wall and PCM melting. Subsequently, heat transfer transitions to natural convection, resulting in a longer melting time and a bigger distance from the wall. It has also been observed that the melting process initiates from the top over time as a result to the acceleration, with the hot PCMs moving towards the top and the solid portion settling at the bottom. The dissolution process occurs more rapidly in the absence of an air bubble. Consequently, it can be inferred that the volume of PCMs increases as it encompasses the volume previously occupied by the air bubble. Figure 12 illustrates the temperature distribution without an air bubble in the semi-cylinder cavity. The study discloses that heat transfer primarily occurs along the cylinder wall during the initial stages of the melting process, followed by a dependence on natural convection, which requires a longer time away from the wall. Figure 13 demonstrates that the melting process is advanced in the absence of an air bubble, influencing the flow and dissolution of the process, as well as the overall time needed for completion.

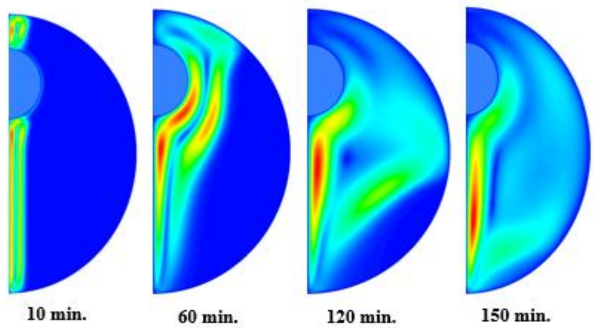

Figure 10. Velocity patterns observed when an air bubble exists at the upper section of the semi-cylinder

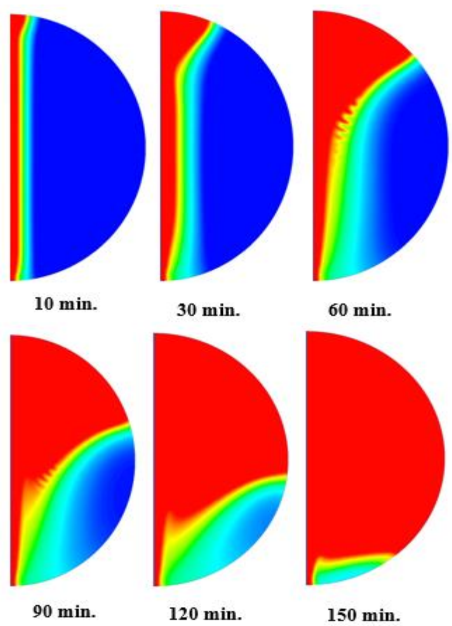

Figure 11. Melting process without air bubble in the semi-cylinder cavity

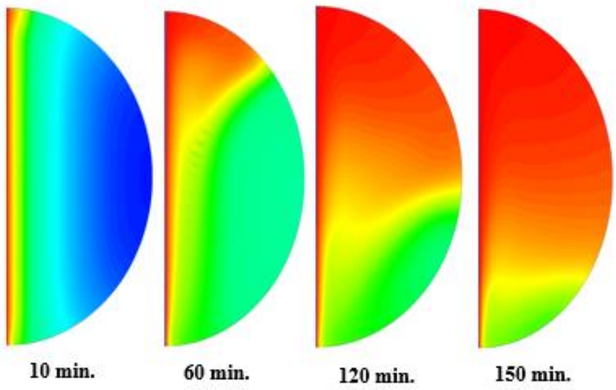

Figure 12. Temperature patterns without air bubble in the semi-cylinder cavity

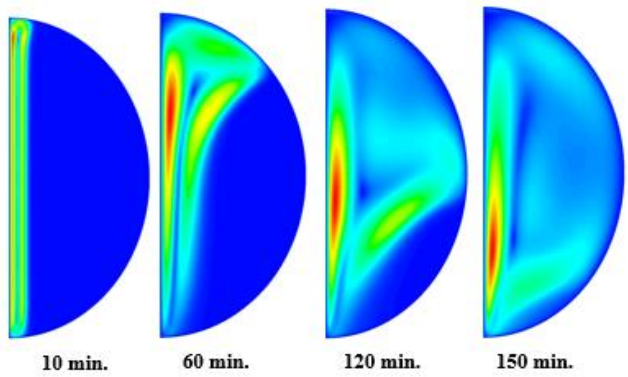

Figure 13. Velocity patterns without air bubble in the semi-cylinder cavity

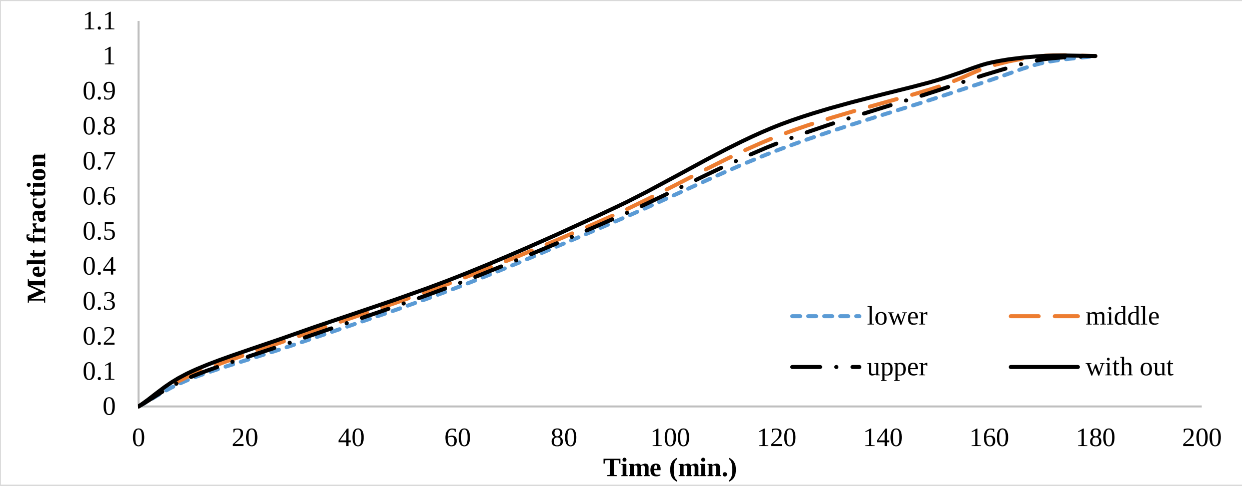

Figure 14. History of melt fraction for a volumetric flow rate of 25 l/min at $T_{in=}$90°C

3.5 A compromise of the four scenarios

Contrasting the four scenarios discussed above is essential to clarify the consequence of the existence of air bubble on the dissolution process. It is evident that the presence of an air bubble at both the top and bottom has occasioned in a 6% decrease in the time required to thoroughly finalise the dissolution process. However, the existence of an air bubble in the center of the half-cylinder has a lesser amount of effect than in the previous two scenarios. Moreover, the dissolution proceeds naturally, and the dissolution process is faster in the absence of an air bubble, meaning that the volume of PCMs is larger to calculate the volume of the air bubble. As illustrated in Figure 14, the process of fusion of PCMs in a semi-cylinder cavity without the incidence of an air bubble has required less operational time to accomplish the process of melting. This is attributed to the transfer of heat at the establishment of the melting process, which depends on conduction along the cylinder wall. Furthermore, the melting process relies on natural convection, and this requires further time because the transfer of heat is delayed besides the considerable impact of air bubbles on the melting process.

A comparison between the melting process in the four scenarios is depicted in Figure 15. The difference in the melting process between the absence of an air bubble in the cell with the presence of air and the location of the air bubble is observed in Figure 15 with its associated effect on the melting process.

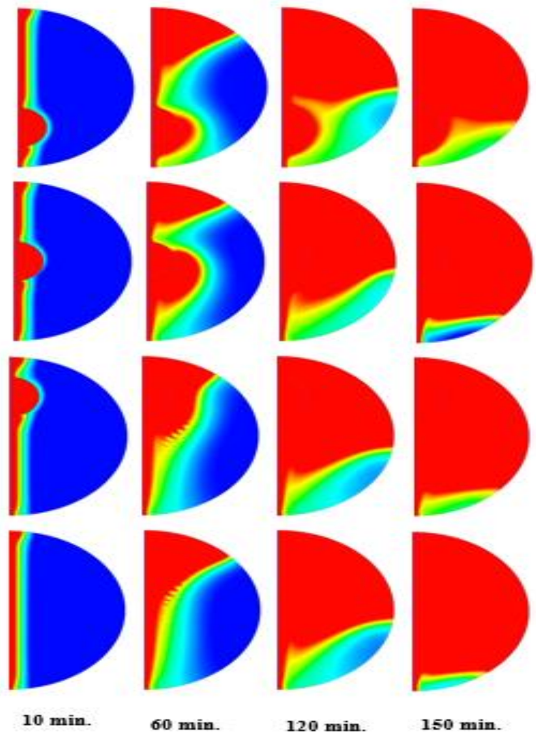

Figure 15. Assessment of the melting process between the four scenarios

An understanding of the temperature transfer inside the cavity is elaborated in Figure 16. Indeed, the presence of an air bubble has a clear effect on the heat transfer into the inside, which affects the melting process of PCM.

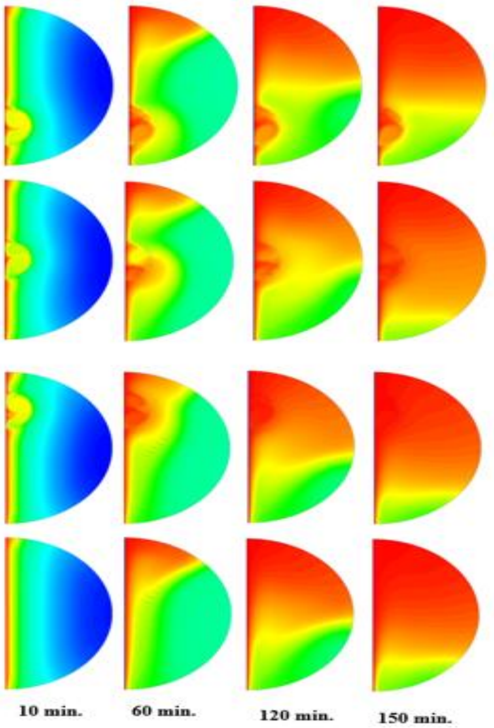

Figure 16. Comparison of the temperatures between the four scenarios

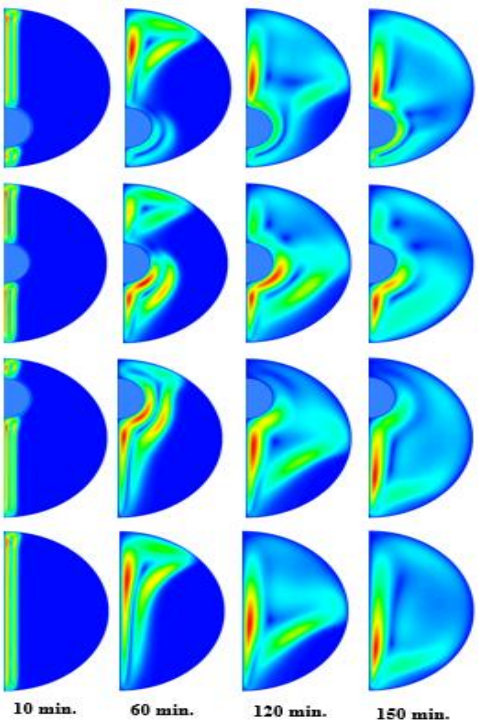

Figure 17. Comparison of the velocity between the four cases

A comparison of the speed of the dissolution process inside the cell is demonstrated in Figure 17. Here, it can be noticed that the presence of an air bubble has a significant effect on the melting movement.

In a summary, in order to maximise heat transfer and the melting process, the ideal placement for air bubbles inside a half-cylinder container must be determined. Air bubbles should ideally be kept to a minimum because they can impede heat transfer and interfere with the melting process. Air bubbles can still have an impact on melting and overall heat transfer even if they are present. The ideal placement for air bubbles would be away from the contact surface between the PCM and the container wall to enhance heat transfer and encourage effective melting. This is due to the fact that better heat conduction is made possible by direct contact between the substance and the container. Air bubbles that are present in this region act as insulators, decreasing the effectiveness of heat transfer and extending the melting process. Aside from that, it is advantageous to place air bubbles where they would not hinder the convection currents that naturally circulate and transmit heat. Warmer materials rise when cooler one's sink, causing natural convection to occur and circulate heat. The melting process can be hampered by adding air bubbles to regions where this flow is disrupted, which can reduce heat transfer.

4. CONCLUSIONS

While several studies have examined the melting of paraffin wax in cylindrical cells, it has been noted that no prior research has examined the impact of an air bubble and its location on the melting process of PCMs. Using a CFD analysis, this study intended to numerically investigate of the impact of air bubble and its position on the melting of the paraffin wax interior of a semi-cylinder cavity. In this regard, four scenarios were considered to evaluate the effect of air bubble on the dissolution process. The results indicated that the existence of an air bubble at the upper and bottom has a considerable influence on the reduction of the time required to end the dissolution operation by 6%. By forming a barrier, the air bubble's presence can obstruct this circulation. Natural convection may be boosted when the air bubble is at the bottom or top of a semi-cylinder that is horizontally orientated. On the other hand, the existence of an air bubble in the center has a smaller effect than in the previous two cases. Also, the dissolution has occurred naturally and at a higher rate with the absence of an air bubble, owing to the fact that the volume of PCM is larger than the volume of air. The findings of this research could be helpful to enhance the renewable energy storage as they represented how air bubbles impact the melting process inside a semi-cylindrical container besides offering the possible option to reduce the thermal resistance and increase the effectiveness of energy storage devices.

5. RECOMMENDATIONS FOR FURTHER RESEARCH

Run experimental tests to determine how the placement of the air bubble in the paraffin wax affects the results. Specifically, vary the position of bubble in equal increments along the length/width of the container. To evaluate the impact of the bubble's position, measure variables including temperature distribution, melting time, and heat transmission properties.

To observe and assess the heat distribution within the PCM throughout the melting process, it is recommended to use the thermal imaging technique. Thermal imaging technique or infrared imaging or thermography, are used to visualise and capture temperature variations in objects and scenes, such as Infrared Cameras or Infrared Thermometers. Researchers can track how the presence and position of the air bubble effect heat transport and melting behavior by periodically taking thermal photos. The effect of bubble position on overall thermal performance can be better understood using this method.

Use numerical optimisation algorithms, are commonly used to find the best solution to a mathematical problem within a defined set of constraints such as Particle Swarm Optimisation [29], is advantageous to determine where the air bubble should be placed in the PCM to maximise heat transfer and improve melting. Researchers can use numerical optimisation approaches to identify the best bubble position for enhanced thermal performance by setting objective functions and constraints.

Perform a thorough examination of the paraffin wax and its material characterisations besides the air bubble's characteristics, such as their thermal conductivity, density, and size are important. Understanding how these elements affect the dynamics of heat transmission inside the PCM and the entire melting process requires knowledge of this information.

·Investigate how the air bubble's location within PCMs will affect practical applications in the real world. Consider the effect on thermal energy storage technologies, such as solar thermal storage or building insulation. Examine how these systems' efficiency, dependability, and long-term performance are impacted by the bubble's location.

Last and not least, testing the influence of multiple air bubbles or different placements of a single bubble could be interesting directions for future studies.

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