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Simulation of Phase Change Material Solidification for High-Performance Aero-Thermal Energy Storage

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Abstract

Phase Change Materials (PCM) can be used in aerospace thermal management systems due to their ability to absorb and release large amounts of latent heat during phase transitions, making them effective for controlling temperature fluctuations in high-performance aero components. The research paper examines the solidification of paraffin wax PCM in a rectangular enclosure through the computational fluid approach provided by ANSYS Fluent. These three geometrical regions comprised Geometry 1, whose size was 150 mm x 100 mm; Geometry 2, of 200 mm x 150 mm; and Geometry 3, of 250 mm x 200 mm, and were examined under three sets of thermal boundaries, which were 363 K-294 K, 380 K-300 K, and 400 K-310 K. The transient simulation with the enthalpy-porosity approach was run to assess the temperature distribution, the pressure profiles, and the phase change advancement. The findings indicate that increased geometry sizes and greater thermal differences favor a stronger natural convection and a rapid solidification. The numerical model demonstrates the correlation between design parameters and PCM behavior, allowing for the optimization of TES systems' thermal performance.

1. Introduction

The aerospace sector has experienced rapidly growing energy demands driven by advanced propulsion systems, increased aircraft operations, and the integration of high-power electronic technologies. Conventional energy sources such as aviation fuels and ground-based fossil energy remain costly and limited and contribute significantly to environmental challenges, including greenhouse gas emissions and global warming [1], [2]. Consequently, the aerospace industry has shown strong interest in high-efficiency energy conservation and thermal energy storage technologies to enhance system performance, reduce environmental impact, and support long-term sustainability.

When it comes to the management of heat supply and demand, Thermal Energy Storage (TES) systems play a crucial role in the spheres of renewable energy, HVAC, and the recovery of industrial waste heat [3]. TES systems are able to store energy in three ways: sensible heat, latent heat, and thermochemical energy [4]. Latent Heat Storage (LHS) with Phase Change Materials (PCMs) is one of these due to the fact that PCMs can absorb or release substantial quantities of energy over relatively constant temperatures during phase change, providing high energy densities and temperature stability [5], [6], as shown in Fig. 1.

PCMs are divided into three groups: organic, inorganic, and eutectic materials. Organic PCMs are also widely used and include paraffin wax, with its advantages being its chemical stability, non-corrosiveness, and maintenance of uniform thermal properties [7]. Though, its low thermal conductivity has the potential to restrain heat transfer during phase transitions. Numerical simulations of melting and solidification of TES systems, e.g., by CFD, are also gaining importance to provide a better insight into the PCM behavior and its optimization.

The proposed study is based on the CFD simulation in ANSYS Fluent to evaluate PCM solidification in three different-sized enclosures (150 x 100 mm, 200 x 150 mm, and 250 x 200 mm) of different boundary temperatures (363/294 K, 380/300 K, and 400/310 K). The enthalpy-porosity approach is a method that describes phase change dynamics; it monitors the fraction of the liquid phase in the domain. The goal is to examine how geometry and thermal gradient will influence the distribution of temperature and pressure development as well as solidification rate, which are essential in optimizing the design of TES systems.

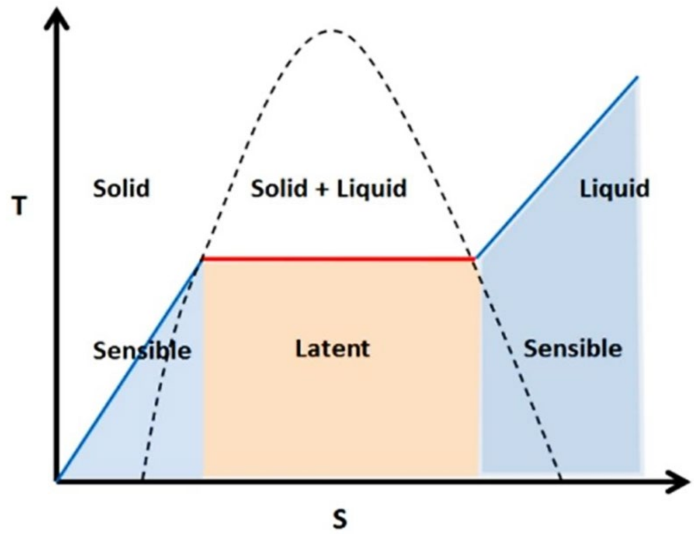


Fig. 1 *Heat stored during phase change of material*

Thermal Energy Storing (TES) technologies have become key players in energy management. Specifically, latent heat storage with phase change materials (PCMs) has been identified as having high energy density and being capable of near-isothermal phase change operation [1], [2]. There exist research studies on PCM use in thermal building [3], solar heating [4], electronic cooling [5], and waste heat recovery systems [6]. Solid organic PCMs such as paraffin wax are also commonly chosen due to a lack of stability, availability, and compatibility with containment materials [7]. Nevertheless, their low thermal conductivity interferes with the quick transfer of heat that occurs during melting and solidification. Researchers have tried to find a way to surpass this limitation with composite PCMs, nano-enhancements, and structural changes [8], [9].

The technique of computational fluid dynamics (CFD) has been a hot favorite for modeling PCM behavior. With the enthalpy-porosity method, ANSYS Fluent can extensively simulate the phase change by considering the balance of energy and fluid flow, as well as the dynamics of the phase boundary [10], [11]. In this approach, a source term is added that attenuates velocity at solid volume, which is associated with mimicking the transition to solid.

Theoretical frameworks of PCM-based TES are introduced by Sharma *et al.* [1] and Zalba *et al.* [3], and the design of storage systems itself is addressed by Mehling *et al.* [12]. Hassab *et al.* [13] and Al-Jethelah *et al.* [14] explored phase change in nano-enhanced enclosures and porous enclosures, respectively. Numerical predictions were confirmed by the experiment conducted by Ambarita et al. [15], which demonstrated close correspondence to experimental trends observed in real-world solidification over time. Computational results and emphasize the practical utility of PCM-based thermal storage.

The geometrical design of the storage unit significantly influences the heat transfer rates. Dhaidan and Khodadadi [16] and Faghri *et al.* [17] confirmed that larger enclosures have a positive effect on natural convection, whereas sharper temperature gradients have a positive effect on the movement of the phase front. The more recent studies indicate the importance of the CFD in relation to the optimization of the geometry of TES systems, the boundary conditions, and PCM choice [18]-[20]. The research complements previous reports that assume different treatment and geometric settings for paraffin solidification. It also seeks to optimize design parameters through precise modelling of CFD on how to manage efficient and reliable operation of thermal energy storage.

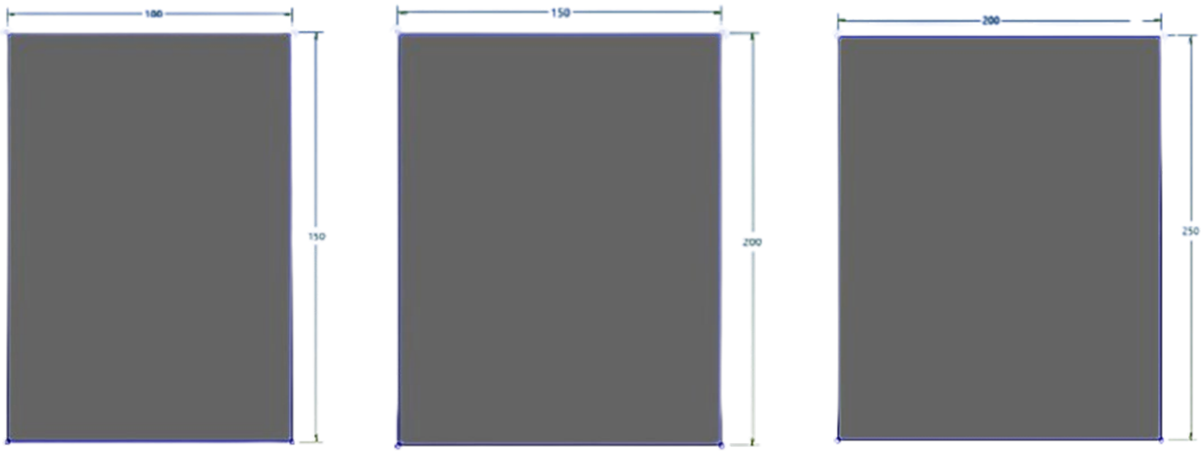
2. Methodology

In the simulation, a two-dimensional rectangular domain was used to represent the melting behavior of the phase change material. The boundary conditions are crucial in determining the thermal behaviors of the system. This work simulated a continuous thermal energy input source by applying a steady heat flux of 2500 W/m^2 to the left wall of the rectangular region. The top, right, and bottom walls were fully insulated, resulting in zero heat flux (q" = 0 W/m^2) on those surfaces. These settings ensure that heat is transferred only from the left boundary, giving a clear view of the melting process and phase front evolution caused by one-sided heating.

2.1 Geometry

Three different rectangular geometries were analyzed to observe the influence of domain size on the melting behavior of PCM (Fig. 2): (i) Geometry 1: Height = 150 mm, Width = 100 mm; (ii) Geometry 2: Height = 200 mm, Width = 150 mm; and (iii) Geometry 3: Height = 250 mm, Width = 200 mm.

Each configuration was designed to maintain the same aspect ratio between simulations for comparative purposes. These dimensions allow for the evaluation of how larger volumes of PCM influence melting duration, heat absorption, and thermal distribution within the cavity.



(a) **(b)** **(C)**

Fig. 2 *Geometry of thermal energy storage (a) Geometry 1; (b) Geometry 2; (c) Geometry 3*

2.2 Meshing

A well-structured mesh was used to discretize the computational domain of each geometry with the aim of delivering accurate values of simulations. The meshing process is a crucial factor that will influence the physical behavior of the Phase Change Material (PCM), particularly near the melting or solidification front where the temperature and velocity gradients are highest. In this research study, quadrilateral elements were used to mesh the true rectangular enclosures in ANSYS Fluent because these elements are suitable for approximating boundary layer characteristics and ensuring numerical stability in two-dimensional thermal investigations. The final simulation was done with a mesh comprising 9576 nodes and 9375 elements, which balances accuracy and the cost of computation (Fig. 3).

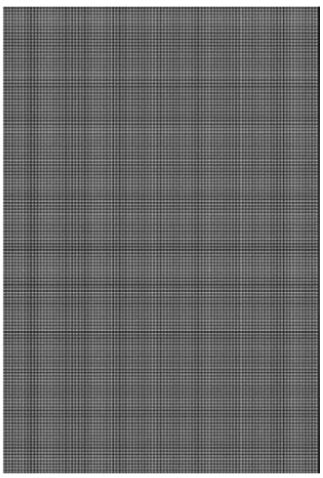


Fig. 3 *Meshing for geometry of the thermal energy storage*

2.3 Boundary Conditions

The simulation involved varying thermal boundary conditions to analyze their effect on the melting performance of the PCM. Specifically, three sets of temperature boundary conditions were imposed: (i) Condition 1: Left wall = 363 K, Right wall = 294 K; (ii) Condition 2: Left wall = 380 K, Right wall = 300 K; and (iii) Condition 3: Left wall = 400 K, Right wall = 310 K.

In all cases, the left wall served as the heating boundary while the right wall acted as a cooling surface. The top and bottom walls remained adiabatic (insulated) to ensure unidirectional heat flow. These setups replicate practical heating-cooling cycles and help to investigate the thermal response of PCM under different thermal gradients.

2.4 Computational Grid

ANSYS Fluent's structured mesh was used to discretize the computational domain. A tiny mesh was designed to provide accurate resolution of temperature gradients and fluid flow, particularly near the melting front. The finished mesh has 9576 nodes and 9375 quadrilateral elements. This mesh density was chosen using a grid independence test to strike a compromise between accuracy and computational expense. The momentum equations were solved using second-order upwind schemes, but the energy equation was solved using a first-order upwind strategy. The SIMPLE algorithm was used for pressure and velocity coupling, and PRESTO for pressure interpolation. The simulation was time-dependent, with a 0.1-second time step and 10 iterations each time step to assure convergence. The simulation was run on a system with an Intel Core i3 processor and 4 GB RAM.

3. Results and Discussion

3.1 Grid Independence Test (GIT)

A Grid Independence Test (GIT) was carried out to have confidence that the size of the computational mesh did not affect the results of the simulation. The GIT results are forwarded in two figures (Fig. 4 and Fig. 5). The pressure field over the X-direction has been plotted in Fig. 4 with three mesh densities. As can be seen, pressure curves of the medium and fine meshes mostly coincide, which means that any additional dissection would not affect the outcomes greatly. Therefore, the medium mesh was adequate in terms of correct simulation.

Fig. 5 shows the temperature distribution of the X-direction in the same mesh schemes. Just like the pressure profile, the lines of the medium and fine mesh temperature demonstrate little variations, confirming the mesh independence. The choice of the mesh consisting of 9375 elements and 9576 nodes balances between computational time and accuracy. These plots confirm the non-dependence of the results on the mesh and justify the choice of a mesh configuration to be used in the rest of the simulation analysis.

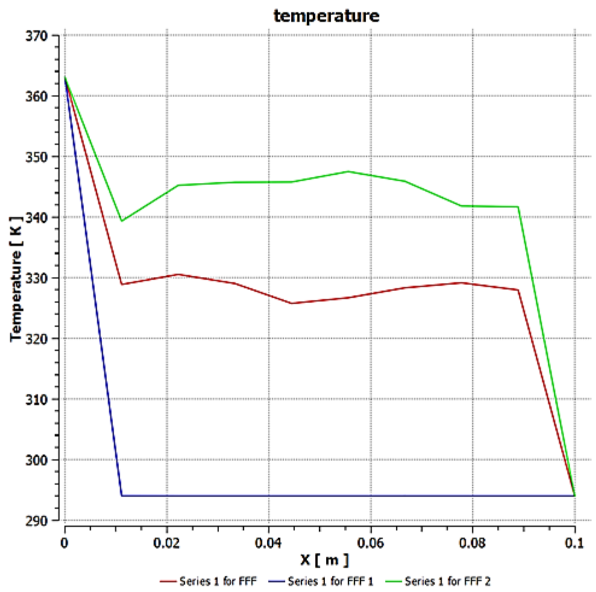


Fig. 4 *GIT for the pressure vs. x*

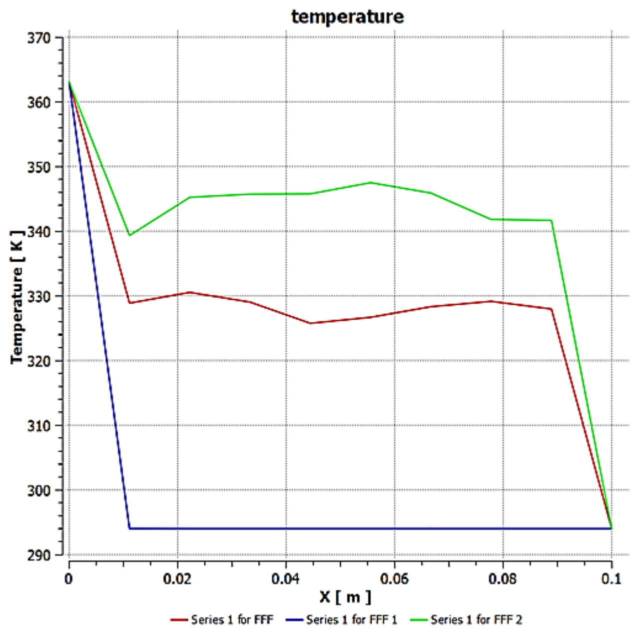


Fig. 5 *GIT for temperature vs. x*

3.2 Pressure Profile

Fig. 6 shows pressure profiles of Geometry 1 against three thermal boundary conditions. When Condition 1 (the left wall at 363 K and the right wall at 294 K) is placed, the pressure field is quite flat with minimal gradients, which implies low fluid motion and weak natural convection in PCM. In Condition 2 (380 K-300 K), a significant increase in the gradient of pressure is observed with the further elevation of the temperature difference, stimulating more active flow. In Condition 3 (400K/310K), the pressure contours are deeper and broader and reflect more robust internal circulation. This implies that greater thermal gradients produce stronger natural convection, which optimizes the performance of the heat transfer and aids in the solidification process by increasing the rate of liquid PCM movement.

Fig. 7 shows pressure contours for Geometry 2 using the same thermal boundary conditions. The height and width of the domain are a lot stronger, and the pressure is more noticeable due to its larger size in Geometry 2. In Condition 1, there are still changes in pressure, but they are narrow. When the thermal input is gradually raised to Condition 2 and Condition 3, the fluid motion becomes more active, getting wider and having many more pressure fields. This implies that a larger enclosure results in better circulation of PCM during solidification, which in turn leads to improved internal mixing and enhanced energy transfer.

Fig. 8 demonstrates the results of the pressure distribution for Geometry 3, the largest tested geometry. The differences in pressure are the most serious here, particularly under Condition 3 (400 K 310 K). The large area gives a greater surface area for fluid control, and the high temperature difference makes the effect of natural convection even stronger. Complicated flow patterns are observable in the pressure profile, which means that the PCM has good movement and is able to exchange heat within the cavity. This leads to a more effective process of solidification since the heat is distributed rapidly and evenly with the assistance of the internal movement.

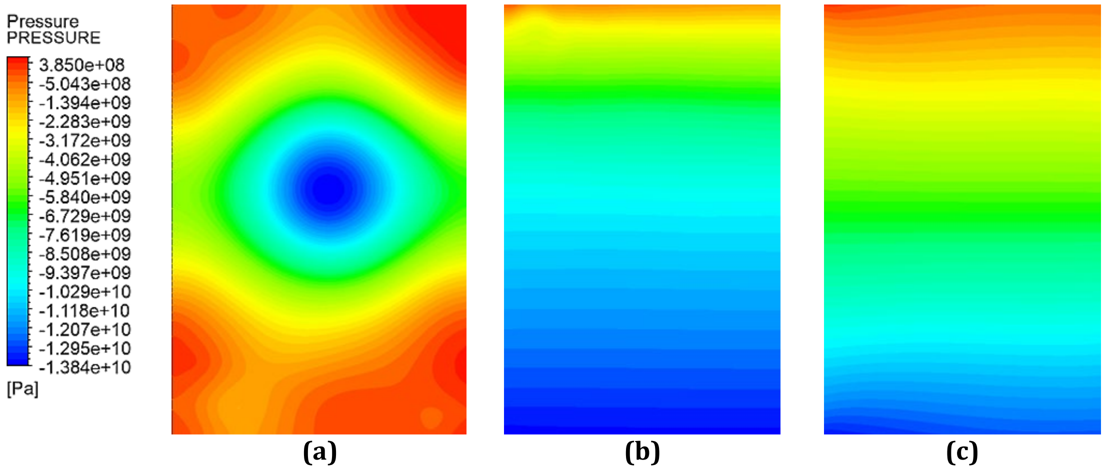


Fig. 6 *Pressure profiles for geometry 1 (a) Condition 1; (b) Condition 2; (c) Condition 3*

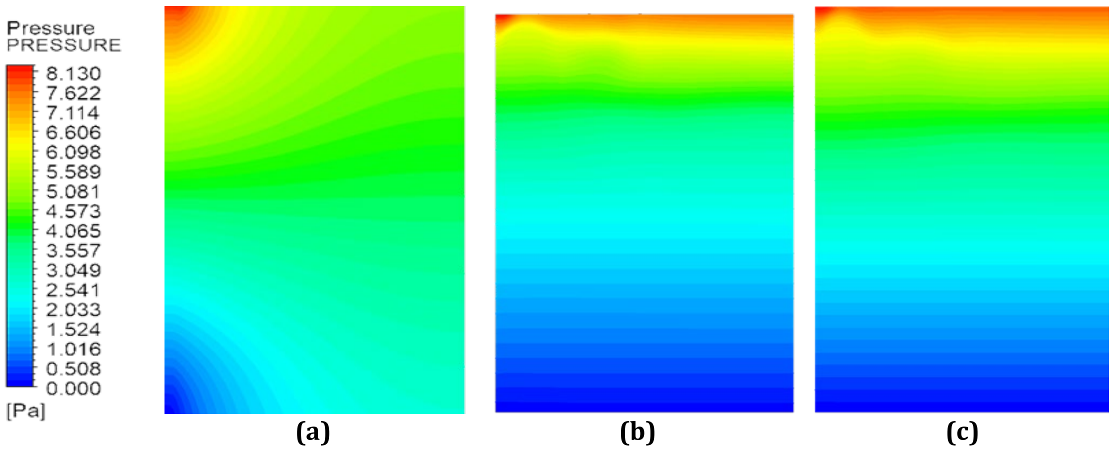


Fig. 7 *Pressure profiles for geometry 2 (a) Condition 1; (b) Condition 2; (c) Condition 3*

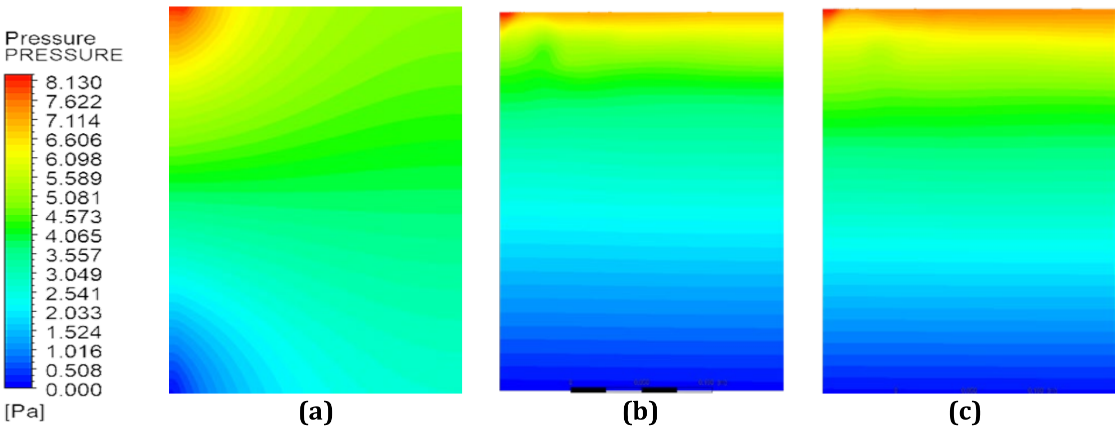


Fig. 8 *Pressure profiles for geometry 3 (a) Condition 1; (b) Condition 2; (c) Condition 3*

3.3 Pressure Profile

Fig. 9 shows temperature plots of Geometry 1 with the three boundary conditions. Under the least gradient (Condition 1), the leaking of the heat into the room occurs at a slow rate starting at the left wall, and most of the PCM is still in the initial cold condition. With Condition 2, the wall temperature is higher; consequently, the spread between the heat becomes larger, and also the melting front appears clearer. With Condition 3, the temperature field will expand in a more uniform manner throughout the cavity, and there is a much larger liquid fraction. This demonstrates that an increase in thermal input shifts the phase change and enhances the heat absorption of PCM.

Fig. 10 presents the temperature contours of Geometry 2. The enlarged size creates increased space in which temperature gradients can develop. In Condition 1, the thermal field is not so big, whereas in Conditions 2 and 3, the melting front enters deeper into the field. With Condition 3, the temperature field is steady and extensive, which means its melting properties are better. The enlarged geometry improves convective heat transfer, resulting in lower thermal resistance and enhanced heat absorption by the PCM.

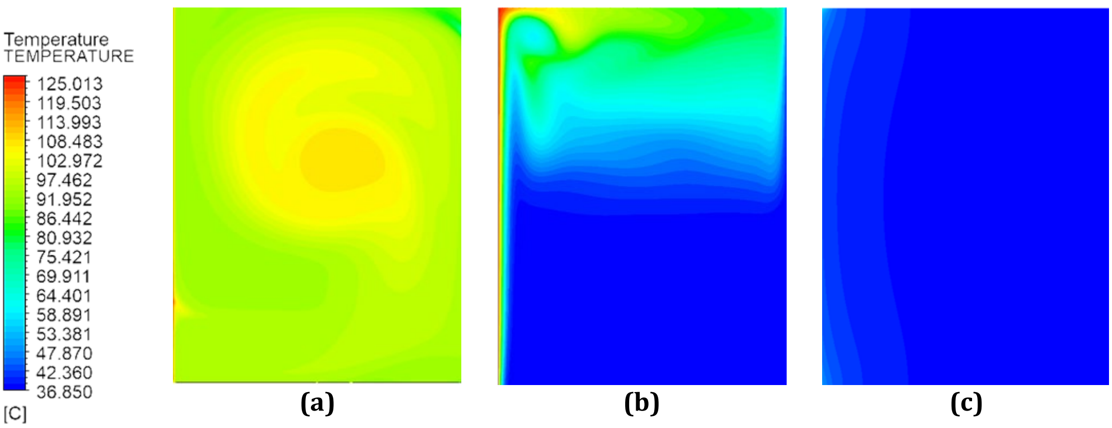


Fig. 9 *Temperature profiles for geometry 1 (a) Condition 1; (b) Condition 2; (c) Condition 3*

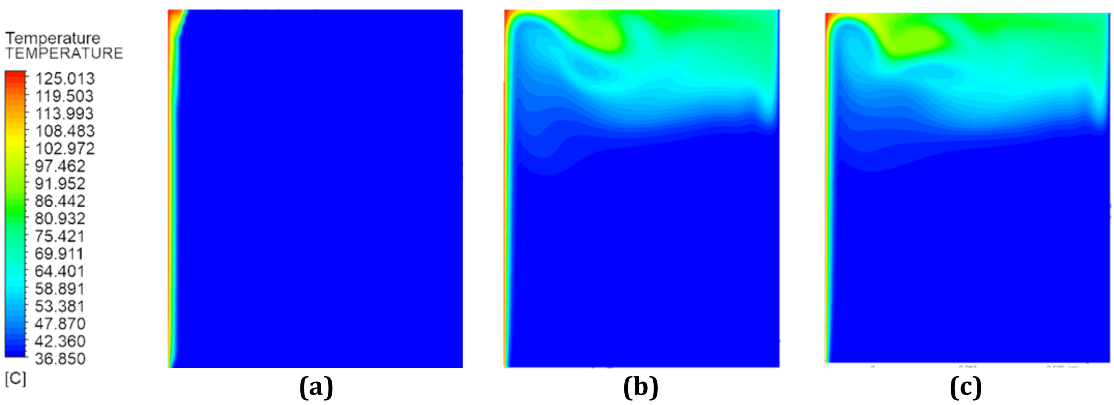


Fig. 10 *Temperature profiles for geometry 2 (a) Condition 1; (b) Condition 2; (c) Condition 3*

Temperature profiles of Geometry 3 are plotted in Fig. 11. This geometry presents the greatest and most homogenous volume of temperature field, especially under Condition 3. Melting is further developed, and the isothermal lines are uniformly spaced, indicating an efficient and even phase change process. The bigger domain would have stronger natural convection, which would improve the flow of the liquid PCM and would lead to faster solidification and energy transfer processes within the enclosure.

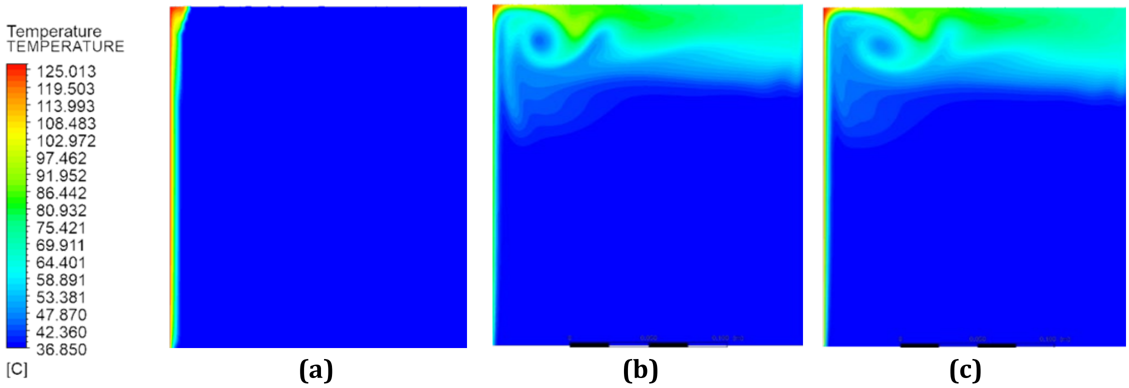


Fig. 11 *Temperature profiles for geometry 3 (a) Condition 1; (b) Condition 2; (c) Condition 3*

4. Conclusions

Finally, the current research endeavor showed how the enclosure contours and thermal limits impact the solidification of phase change materials in computer-assisted fluid-filled systems. The outcomes demonstrate that the size of such enclosures as Geometry 3 is more permissive to natural convection and accelerates and evenly distributes heat traction. In combination with a greater temperature gradient (Condition 3), the PCM activity of fluid motion was bigger, pressure differences became larger, and melting front areas were more expansive. The pressure profiles indicated an increase in circulation, while the temperature profiles demonstrated improved energy absorption and accelerated phase reactions.

In general, increased cavity and greater thermal gradient cause a more efficient solidification process. These results are indicative that optimizing the size of the PCM container and temperature of the boundaries on which it has contact is essential in enhancing the performance of the thermal energy storage system. It is possible that tests of various PCM materials, changes in insulation parameters, or simulation validation against experimental results could be carried out in the future to further enhance the design of the system.

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Conflict of Interest

There is no conflict of interest regarding the publication of the paper.

Author Contribution

The authors confirm their contribution to the paper, as follows: ***study conception and design:*** *Izzul Nisa' Muhamad Noor, Ishkrizat Taib, Mohammad Hasiff Mohamad Haniff, Norhasikin Ismail;* ***data collection:*** *Izzul Nisa' Muhamad Noor Mohd Syahir Abd Razak;* ***analysis and interpretation of results:*** *Izzul Nisa' Muhamad Noor Mohd Syahir Abd Razak;* ***draft manuscript preparation:*** *Izzul Nisa' Muhamad Noor, Ishkrizat Taib, Mohammad Hasiff Mohamad Haniff, Norhasikin Ismail. All authors reviewed the results and approved the final version of the manuscript.*

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