

Numerical Study Of Paraffin Wax Melting Enhancement Using Copper Metal Foam With Variable PPI And Porosity

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Abstract

This study presents a three-dimensional numerical analysis of melting enhancement in paraffin wax using copper metal foam. Given the naturally low thermal conductivity of paraffin wax, a copper metal foam structure is introduced to improve heat transfer within the phase change material domain. A constant heat flux of 9 kW/m^2 is applied to a copper wall, while all other boundaries are thermally insulated. The melting process is modeled using the enthalpy-porosity method in ANSYS Fluent with a time step of 2.5 seconds. The study investigates the effects of various pore densities (10, 20, 30, 40) PPI with porosity 90%, followed by the effects of 30 PPI at different porosities (85, 90, 95%). The results indicate that variations in PPI have minimal impact, with 30 PPI yielding the best overall performance. In contrast, porosity has a significant effect on the melting time: the case F with 85% porosity results in the shortest melting time, while the Case G with 95% porosity experiences the longest.

Keywords: phase change material; metal foam, thermal energy storage, heat transfer enhancement.

1. Introduction

Phase Change Materials (PCMs) are widely recognized for their ability to efficiently store thermal energy, owing to their high latent heat and nearly isothermal phase transitions [1]. These materials undergo a phase change (from solid to liquid or vice versa) within a specific temperature range, which allows them to absorb and release substantial amounts of heat, making them an ideal choice for thermal energy storage applications. PCMs are commonly classified based on their phase transition behavior and chemical composition [2]; [3]. They have found widespread use in various engineering and energy-related fields, particularly in systems designed to reduce energy consumption and improve thermal management. In the construction industry, PCMs are integrated into both passive and active energy systems to enhance energy efficiency and reduce reliance on traditional HVAC systems. In passive systems [4], PCMs absorb heat during the day and release it at night, helping to stabilize indoor temperatures without the need for external energy input. Active systems, on the other hand, incorporate PCMs with mechanical devices [5], such as fans or heat exchangers, to accelerate heat transfer, leading to significant energy savings and improving the overall efficiency of the thermal storage [6]; [7]. The versatility of PCMs allows them to be employed across a wide range of applications, from residential buildings to large-scale industrial facilities, to optimize energy use and minimize thermal fluctuations. In addition to their use in buildings, PCMs play a crucial role in solar energy systems by storing excess heat during the day and releasing it when sunlight is unavailable, ensuring a reliable energy supply even during cloudy days or at night [8]; [9]; [10]. This consistent energy supply is critical for improving the reliability and efficiency of solar thermal energy systems. Furthermore, integrating PCMs with other renewable energy technologies, such as wind or geothermal systems, has shown promising potential for further improving the stability and sustainability of energy supplies. Among the various types of PCMs, paraffin wax has garnered considerable attention due to its chemical stability, non-corrosiveness, and favorable thermal storage properties [11]. Despite its relatively high latent heat capacity, the practical use of paraffin wax is limited

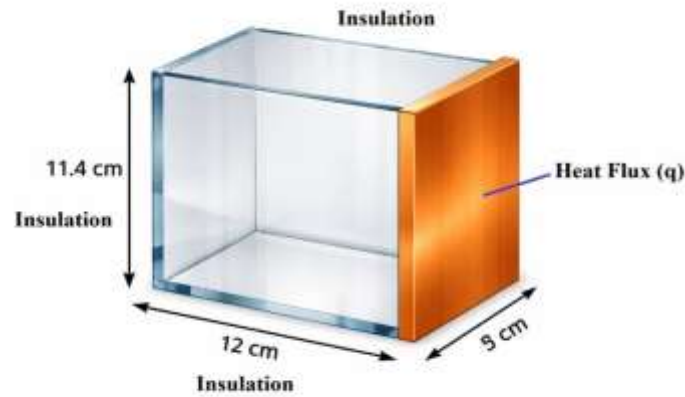
by its low thermal conductivity, leading to slow melting and solidification rates [4]. To address this limitation, several heat transfer enhancement techniques have been proposed, including the integration of high-conductivity porous structures [12], which improve heat transfer rates and response times in dynamic thermal management systems. Among the promising solutions, Metal foams (MFs), particularly copper MFs, have shown great potential for improving heat transfer in PCMs due to their high thermal conductivity, surface area, and interconnected pore networks. Studies have demonstrated that adding MF heat sinks significantly improves thermal performance by increasing surface area for heat transfer, reducing thermal resistance, and enhancing convective heat transfer [13];[14]; [15]. For instance, Model 3, with full MF, outperformed conventional aluminum heat sinks, showing a 16-27% increase in heat transfer efficiency, though with a slightly higher pressure drop. Overall, metal foam heat sinks are more effective for cooling in compact, high-performance electronics. These results suggest that MF heat sinks are more effective for cooling in compact, high-performance electronics. In addition, MF with gradient pore density has shown promising results in improving heat transfer. A study by [16] used MF with a gradually changing pore density, which optimizes the thermal performance within a rectangular channel. This configuration outperformed both the constant pore density foam and an empty channel by providing better heat transfer efficiency and reduced pressure drop. Another study by [17] examined staggered porous metal fins and found that they improved the electrical efficiency of the photovoltaic (PV) panels by 4.7% in Baghdad. Although these fins helped reduce the panel's temperature by 2-3°C, higher solar intensity still led to an increase in temperature, slightly reducing overall efficiency. Moreover, [18] investigated the effects of geometric modifications, such as the addition of fins, on thermal conductivity. And [19] investigated the impact of ten MF fins with a porosity of 0.93 distributed periodically along the axial direction between pipes, showing a significant improvement in heat transfer by increasing the mean heat transfer coefficient by 129%. Copper Foam Metal Finned Heat Sinks (FMFHS) were also studied by [20], where the fins themselves were made from copper foam. The study showed foam with 5 Pores Per Inch (PPI) provided the best heat dissipation, improving heat transfer efficiency by 21.6% and reducing thermal resistance by 16.9% compared to conventional heat sinks. While previous studies have demonstrated the effectiveness of MFs in enhancing thermal performance, there is limited research on the combined influence of structural parameters such as PPI and porosity on the melting behavior of PCM. These parameters are critical as they directly affect thermal conductivity, fluid flow resistance, and overall heat transfer characteristics of the system. Therefore, the current study aims to investigate the enhancement of the melting behavior in PCM (paraffin wax) embedded with copper MF using ANSYS software. The study will focus on analyzing the effects of varying PPI values (10, 20, 30, and 40) and different porosity levels (85%, 90%, and 95%) on the temperature distribution, melting rate, and thermal performance, to identify the optimal structural parameters for improving the efficiency of PCMs in thermal energy storage.

2. Physical Model description in ANSYS

A three-dimensional rectangular enclosure is used to represent the thermal storage domain. The dimensions of the enclosure are 12 × 11.4 × 5 cm (length × height × depth), made from acrylic except for the right vertical wall, as shown in Figure 1. The enclosure is filled with paraffin wax, like PCM. To enhance heat transfer during the melting process, a copper MF structure is uniformly embedded throughout the entire enclosure. The foam is treated as a homogeneous porous medium occupying the full volume of PCM. Heating is applied through the right vertical wall, which is modeled as a copper surface to simulate a realistic heat spreading boundary. The heated wall has dimensions of 5 × 11.4 cm, with

a uniform constant heat flux of 9 kW/m^2 applied across its entire surface. All other walls of the enclosure are assumed to be adiabatic, preventing heat losses and isolating the PCM–MF system.

Figure 1. Rectangular enclosure.



The copper metal foam (MF) was used to fill the enclosure in six different scenarios. In cases B, C, D, and E, the enclosure was filled with a copper MF block having 90% porosity and different PPI values of 10, 20, 30, and 40, respectively. In cases F and G, the enclosure was filled with a 30 PPI copper MF block, but with porosities of 85% and 95%, as shown in Table 1.

Table 1. Cases that study

NO.	Name	State	
		PPI	Porosity %
1	Case A	Without MF	
2	Case B	10	90
3	Case C	20	90
4	Case D	30	90
5	Case E	40	90
6	Case F	30	85
7	Case G	30	95

3. Thermophysical Properties of Materials

The physical properties of the materials used in the model are essential for accurately understanding the system's behavior. The key properties for PCM and copper (MF) are listed below:

3.1 Paraffin Wax (Phase Change Material):

- Density: 800 kg/m^3 (solid phase), 780 kg/m^3 (liquid phase)
- Specific Heat Capacity: $2.1 \text{ kJ/kg}\cdot\text{K}$
- Thermal Conductivity: $0.2 \text{ W/m}\cdot\text{K}$ (solid), $0.3 \text{ W/m}\cdot\text{K}$ (liquid)
- Latent Heat of Fusion: 200 kJ/kg , as shown in Table 2.

• Copper Metal Foam (MF)

- Density: 900 kg/m^3
- Thermal Conductivity: $400 \text{ W/m}\cdot\text{K}$

- Porosity: (85,90,95)%

In addition, copper MF with a porosity of 0.90 and a pore density of 30 PPI exhibits the properties shown in **Table 3**. Copper was selected as the base porous material due to its superior thermal conductivity, which significantly enhances heat transfer within the system. This results in faster melting and improved thermal energy storage (TES) efficiency. These properties are integrated into the energy and momentum equations to model heat transfer and fluid flow during the phase change of paraffin wax embedded with copper metal foam.

Table 2. Thermophysical properties of paraffin wax

Properties of Paraffin Wax	Value
Melting point	52- 54 °C
Density	760 kg/m ³ (58 °C liquid) 870 kg/m ³ (40 °C solid)
Specific Heat Capacity	5.90 kJ/kg.°C at 58 C° 5.16 kJ/kg.°C at 40 C°
Latent Heat of Fusion	240 kJ/kg
Thermal Conductivity (solid)	0.2705 W/m.°C
Dynamic viscosity	0.008 pa.s
Kinematic viscosity	1.0526 10 ⁻⁵ at 58 °C
Thermal expansion	5.8×10 ⁻³ K ⁻¹ .

Note: The thermophysical properties of the paraffin wax, including its specific heat volume, thermal diffusivity, and thermal conductivity, were measured using the Hot Disk Analyzer at the University of Technology, College of Materials Engineering.

Table 3. Properties of MFs according to equations 13 to 16

Pore per inch (PPI)	Pore size (d_p) (m)	ligament diameter (d_l)	Permeability (K)	inertial coefficient (C)	Porosity (%)
10	0.00254	0.00033642	7.43904E-03	0.077517	90
20	0.00127	0.000168169	1.86026E-08	0.077547	90
30	0.000846667	0.000112142	8.26547E-09	0.077515347	90
40	0.000635	0.000084084	4.6506E-09	0.077548	90
30	0.000846667	0.000129107	6.45519E-09	0.058400175	85
30	0.000846667	0.000102015	1.07232E-08	0.099111148	95

4. Mathematical Model

The melting behavior of paraffin wax within the copper MF matrix is governed by the conservation equations for mass, momentum, and energy. The MF region is treated as a porous medium, and the effects of flow resistance are incorporated via momentum source terms. Phase change is modeled using the enthalpy-porosity method, where latent heat effects are included directly in the energy equation. The mushy zone, which represents the region undergoing phase transition, is treated as a porous medium, with its permeability varying based on the local liquid fraction. The phase distribution is

described by the liquid fraction, which continuously changes from 0 in the solid state to 1 in the fully liquid state.

4.1 Initial Condition

Initially, the entire computational domain is maintained at a uniform temperature of 27°C, which is below the melting temperature of paraffin wax. This condition ensures that the PCM begins in a fully solid state. The transient simulation then captures the temperature rise and phase transition induced by the applied heat flux.

$$T(x,y,z,0) = T_0 = 27^\circ\text{C} \quad (1)$$

4.2 Boundary Conditions

- Right copper wall: constant heat flux 9 kW/m², as shown in **Figure 1**.

$$-k \frac{\partial T}{\partial N} = q \quad (2)$$

- Other walls: adiabatic.

$$\frac{\partial T}{\partial N} = 0 \quad (3)$$

4.3 Governing Equations

The conservation equations solved in the present study are as follows [21];[22]; [23]

The continuity equation is expressed as:

$$\frac{\partial \rho_{PCM}}{\partial t} + \nabla \cdot \rho_{PCM} \vec{V} = 0 \quad (4)$$

Momentum equation (Darcy -Brrinkman- Forchheimer model):

$$\frac{\rho_{PCM}}{\varepsilon} \frac{\partial \vec{V}}{\partial t} + \frac{\rho_{PCM}}{\varepsilon^2} (\vec{V} \cdot \nabla) \vec{V} = -\nabla P + \frac{\mu_{PCM}}{\varepsilon} (\nabla^2 \vec{V}) - \rho_{PCM} \beta_{PCM} \varepsilon (T_{PCM} - T_{ref}) \vec{g} + \vec{S} + \vec{F} \quad (5)$$

$$\vec{S} = -A_m \frac{(1-\lambda)^2}{\lambda^3 + 0.001} \vec{V} \quad (6)$$

$$\vec{F} = -\left(\frac{\mu_{PCM}}{K} + \frac{\rho_{PCM} C |\vec{V}|}{\sqrt{K}}\right) \vec{V} \quad (7)$$

For natural convection, the buoyancy force is modeled using the Boussinesq approximation by $(\rho_{PCM} \beta_{PCM} \varepsilon (T_{PCM} - T_{ref}) \vec{g})$

For the pure PCM case, the porosity equals unity and the porous resistance terms vanish, reducing the equation to the conventional Navier-Stokes formulation

Energy equation (local thermal equilibrium):

$$(\rho c_p)_e \frac{\partial T}{\partial t} + ((\rho c_p)_{PCM} \vec{V} \cdot \nabla T) = k_e \nabla^2 T - S_L \quad (8)$$

$$S_L = \frac{\varepsilon \rho_{PCM} H_{PCM} \partial \lambda}{\partial t} \quad (9)$$

4.3.1 Phase Change Model (Enthalpy-Porosity)

The total enthalpy is expressed as

$$H_{PCM} = h + \lambda L_{PCM} \quad (10)$$

Where the sensible enthalpy is

$$h = h_{ref} + \int_{T_{ref}}^T c_p dT \quad (11)$$

The liquid fraction (λ) is defined as

$$\lambda = \begin{cases} 0 & \text{if } T < T_s \\ \frac{T - T_s}{T_l - T_s} & \text{if } T_s < T < T_l \\ 1 & \text{if } T_l > T_l \end{cases} \quad (12)$$

4.3.2 Porous medium formulation

In MF cases, the flow resistance is modeled using the Darcy–Brinkman model. The permeability (K) and inertial coefficient (C) are used to account for the pressure drop within the porous structure.

$$K=0.00073d_p^2(1-\varepsilon)^{-0.224}\left(\frac{d_l}{d_p}\right)^{-1.11} \dots\dots\dots (13)$$

$$C=0.00212(1-\varepsilon)^{-0.132}\left(\frac{d_l}{d_p}\right)^{-1.63} \dots\dots\dots (14)$$

$$d_l = 1.18d_p\sqrt{\frac{1-\varepsilon}{3\pi}\left(\frac{1}{1-e^{-(1-\varepsilon)/0.04}}\right)} \dots\dots\dots (15)$$

$$d_p = \frac{0.0254}{\omega(PPI)} \dots\dots\dots (16)$$

The specific surface area of the metallic foams

$$A_{sf} = \frac{3\pi d_l\left(1-e^{-\left(\frac{1-\varepsilon}{0.04}\right)}\right)}{(0.59d_p)^2} \dots\dots\dots (17)$$

4.3.3 Effective Thermophysical Properties

To account for the presence of MF and steel balls, effective thermal conductivity and heat capacity are evaluated based on the volume fractions of each material. These effective properties are incorporated into the energy equation to accurately represent heat-transfer enhancement in composite systems.

MF saturated with PCM

$$k_e = (1-\varepsilon)k_{MF} + \varepsilon k_{PCM} \dots\dots\dots (18)$$

$$(\rho c_p)_e = (1-\varepsilon)(\rho c_p)_{MF} + \varepsilon(\rho c_p)_{PCM} \dots\dots\dots (19)$$

5. Numerical Simulation and Computational Setup

The numerical simulations are conducted using ANSYS Fluent under transient conditions. The enthalpy-porosity method is used to model the solid–liquid phase change of paraffin wax. Heat transfer and fluid flow are solved simultaneously to capture the combined thermal and hydrodynamic behavior during melting. A three-dimensional computational mesh is created for the entire enclosure. Mesh quality and solution accuracy are verified through a grid independence study by comparing key thermal indicators, such as temperature evolution and melting time, across increasingly refined meshes. A constant time step of 2.5 seconds is maintained throughout the simulation. This time step ensures numerical stability while providing sufficient temporal resolution to track the development of the melting front. To ensure numerical consistency and computational feasibility, the following assumptions are made:

- The flow is laminar, incompressible, and Newtonian.
- The thermophysical properties are assumed to be constant.
- The porous medium is assumed homogeneous and isotropic
- The Boussinesq approximation is used to model buoyancy-driven natural convection.
- Local thermal equilibrium between PCM and MF is assumed.
- Viscous dissipation and radiation heat transfer are neglected.

5.1 Mesh Generation

The computational domain was discretized into multiple control volumes, and the governing equations were solved numerically for each control volume. This approach ensures that the temperature, velocity, and pressure distributions within the system are accurately computed over time. While increasing the number of cells generally enhances accuracy, it also increases computational time. Therefore, a balanced mesh was selected to optimize both accuracy and efficiency. To ensure the results are independent of mesh

size, a grid independence test was conducted in similar studies, such as the one presented in [24]. The study performed the grid independence test using coarse, medium, and fine meshes. The results showed that the differences in melting time between the medium and fine grids were minimal, justifying the use of the medium mesh for all simulations. According to the study, higher grid resolutions (around 24) were optimal for larger buildings, where flow complexity increases. The study also evaluated the performance of each grid resolution using the Coefficient of Variation of Root Mean Square Error (CV(RMSE)) and the Coefficient of Determination (R^2) as accuracy indicators. As the grid resolution increased, the CV(RMSE) values decreased, indicating improved accuracy, as shown in Figure 2. For instance, at a grid resolution of 24, the CV(RMSE) values ranged from 4.25 for the A type to 9.23 for the E type, demonstrating significant improvement compared to lower resolutions (e.g., at resolution 4, where the CV(RMSE) values were up to 38.65 for the E type). Furthermore, the R^2 values improved with higher grid resolutions, as shown in Figure 3. At resolution 24, R^2 values were very close to 1 for most models, with the A type reaching 1.00 and the E type 0.98, indicating a strong correlation between the predicted and actual results.

Figure 2. Impact of Grid Resolution on CV(RMSE) for different building type

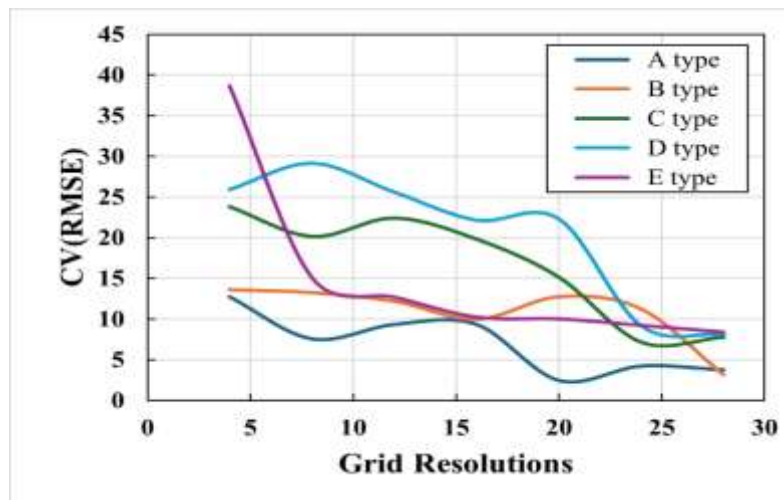
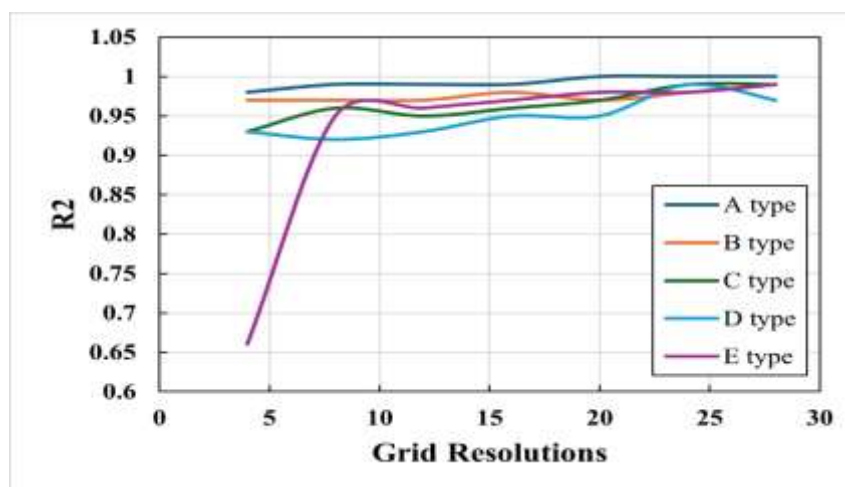


Figure 3. Grid Resolution vs R^2 for different building types.



6. Results & Discussion

The analysis focused on the impact of PPI and porosity on melting time, temperature distribution, and velocity. The key findings highlight how these factors influence the system's behavior.

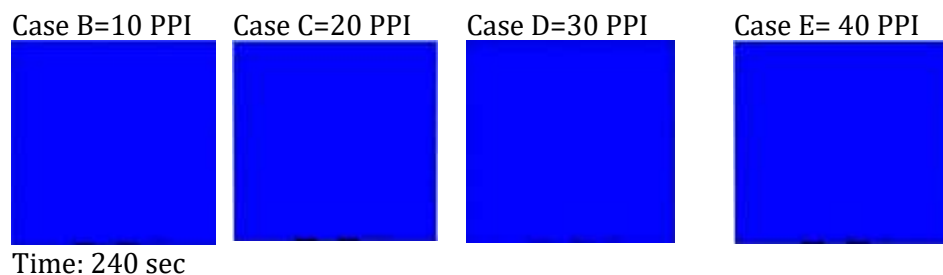
6.1 General Melting Behavior

The melting process starts near the right copper wall, where the constant heat flux of 9 kW/m^2 is applied. At early times, heat transfer is dominated by conduction, and the melting front advances gradually from the heated wall into the PCM volume. As the liquid region grows, buoyancy-driven flow becomes more pronounced within the molten paraffin, accelerating heat transport away from the heated side. The presence of copper MF creates additional conductive pathways, leading to a more uniform temperature distribution and a smoother advancement of the melting front compared to paraffin alone.

6.2 Effect of PPI

The influence of pore density (PPI) on melting time was found to be relatively limited within the investigated range (10–40 PPI). In general, the melting times across different PPI cases were close, indicating that changing pore density alone did not produce a substantial performance shift under the same heating conditions. This behavior can be attributed to the significantly higher thermal conductivity of copper foam compared with paraffin wax, leading to greater overall heat transfer enhancement even at lower PPI values, as shown in Figure 4. The melting process contour exhibits a similar pattern across all PPI cases. Melting begins near the heated wall and gradually spreads into the PCM domain. At later stages, the liquid fraction approaches uniformity, indicating that the paraffin wax is almost completely melted. The contour distributions are quite similar across 10–40 PPI, suggesting that pore density has a limited impact. Although the differences were small, the 30 PPI case provided the best overall melting performance among the examined values, as shown in Figure 5. This finding agrees with [22]. Figure 6 shows that the temperature field develops nearly identically across all cases (10–40 PPI). Heating begins near the right wall, and the hot region gradually spreads throughout the enclosure, eventually becoming almost uniform. Overall, the contour patterns are very similar, indicating a limited effect of PPI under these conditions. Based on the melting-time comparison, 30 PPI was chosen because it resulted in the shortest melting time.

Figure 4. Melting process contour of PCM with Copper MF at 90% porosity across various PPI at 9 kW/m^2



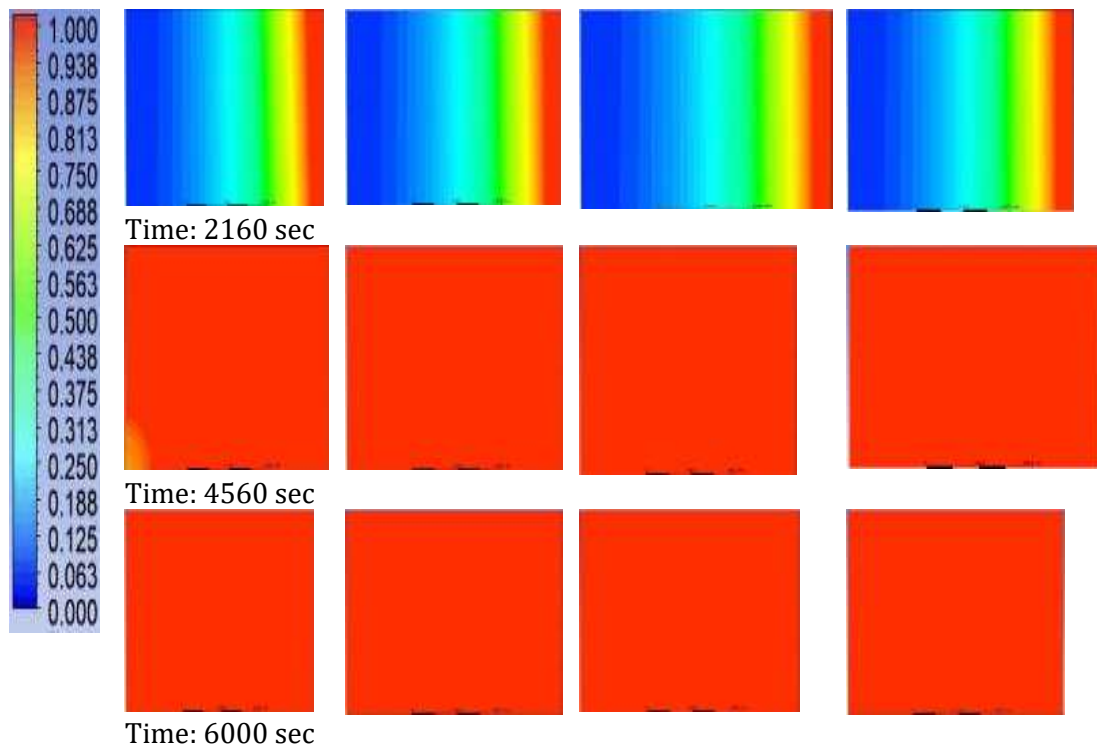


Figure 5. Liquid fraction for PCM at 90% porosity across different PPI levels at 9 kW/m^2 .

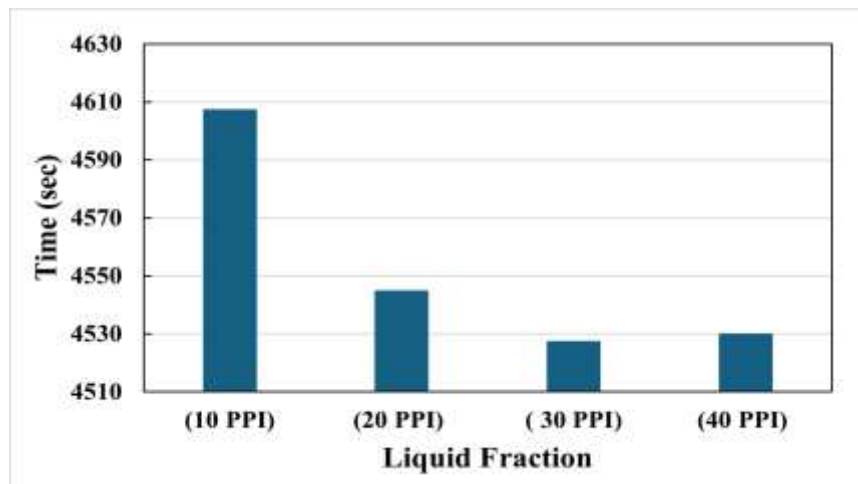
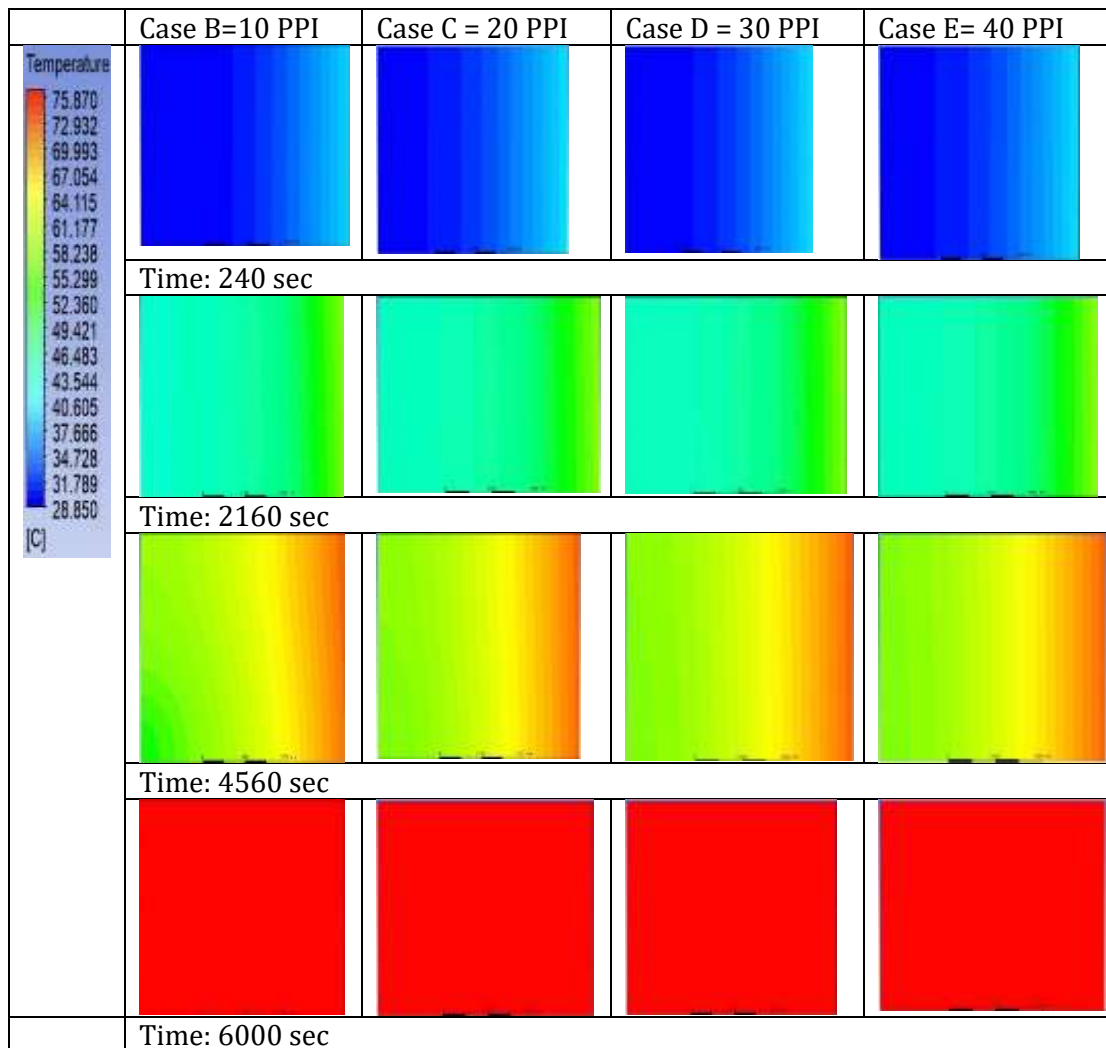


Figure 6. Temperature contour of PCM with Copper MF at 90% porosity across various PPI at 9



6.3 Effect of Porosity

Unlike PPI, porosity showed a clear impact on melting performance. As shown in Figure 7, reducing porosity significantly accelerates the melting process, while higher porosity results in longer melting times. Specifically, the Case F with 85% porosity achieved the fastest melting time, while the 95% porosity case G exhibited the longest, which agrees with the findings in references [13] and [25]. This behavior aligns with physical expectations. A lower porosity means a higher volume fraction of copper within the composite, which increases the effective thermal conductivity of the PCM-foam system and improves the rate of heat transfer from the heated wall to the interior. On the other hand, higher porosity (95%), leads to less solid copper within the foam, weakening the conductive network and slowing down the heat diffusion through the PCM. Additionally, the comparison with pure PCM shows that the presence of copper significantly improves the melting rate, even in the high porosity cases. Pure PCM, due to its lack of a solid conductive network, melts considerably more slowly than the composite materials. This further emphasizes the role of copper MF in enhancing heat conduction. It is also important to note that while higher porosity could potentially facilitate easier liquid flow through larger void spaces, the reduced presence of copper in these materials appears to

be the dominant factor influencing the slower melting times observed in the 95% porosity cases. Therefore, under constant-heat-flux conditions, the net effect is slower melting at higher porosity levels compared to pure PCM and lower porosity composites.

Figure 8 shows how heat spreads and how the material changes phase over time in copper foam with different porosities ($\varepsilon = 0.85, 0.90, 0.95$), as well as in pure PCM (without MF). The contour plots illustrate the heat flow and the melting process within the material. At the beginning ($t = 240$ seconds), we can see temperature differences across the material. In the lower porosity case ($\varepsilon = 0.85$), heat spreads more evenly because the higher copper content helps transfer heat more efficiently. On the other hand, in the higher porosity case ($\varepsilon = 0.95$), the temperature differences are more pronounced, indicating that heat transfer is slower. In the pure PCM case (without foam), the heat distribution is similar to the $\varepsilon = 0.85$ case, but heat transfer happens at a slower rate due to the lack of a metallic matrix. As time passes ($t = 2160$ seconds), the melting front progresses further. In the cases with $\varepsilon = 0.85$ and 0.90 , the material is almost completely melted, with a large high-temperature region. However, in the $\varepsilon = 0.95$ case, the material is still partially solid, with a clear transition zone. This shows that the higher porosity foam reduces heat conduction, delaying the melting process. In the pure PCM case, the melting process is slower compared to the foam cases because there is no metal to help transfer heat more quickly. Later ($t > 4560$ seconds), the temperature becomes nearly uniform across all cases, indicating that the system has reached thermal equilibrium. The disappearance of steep temperature gradients marks the end of the melting process, and the system stabilizes thermally. In summary, the plots show that lower porosity foams help heat transfer, and melting happens faster due to better heat conduction pathways. Higher porosity foams, while retaining more PCM material, slow down the thermal response. The pure PCM case, without MF, melts more slowly compared to the MF cases because it lacks the conductive support that the foam provides. This highlights the balance between heat transfer efficiency and energy storage capacity in these systems.

Figure 9 shows the velocity contours representing the flow behavior within the molten PCM region across different copper foam porosities ($\varepsilon = 0.85, 0.90$, and 0.95) at specific times. These images demonstrate how porosity affects natural convection during the melting process. At the beginning ($t = 240$ sec), the velocity magnitudes are very low for all porosities, indicating that heat transfer is mainly driven by conduction. The small amount of liquid in PCM limits the movement of the fluid, resulting in weak flow patterns. Although there are slight variations in flow between the different porosity cases, the overall velocities remain low across all cases. As melting progresses ($t = 2160$ sec), convection becomes more noticeable. The velocity field intensifies due to density differences in the molten PCM, driving buoyant flow. The higher porosity foam ($\varepsilon = 0.95$) shows higher velocities, as the reduced resistance to flow in the larger pores facilitates better circulation. On the other hand, the lower porosity foams ($\varepsilon = 0.85$) with denser structures limit fluid motion and suppress convection, despite the better heat conduction through the solid copper MF. When we consider pure PCM (without any foam), the velocity patterns are noticeably different. Without the metallic network, PCM shows even lower velocities compared to the foam cases. This is because there is no additional structure to facilitate fluid flow, and the heat transfer relies entirely on conduction, which is slower than convection. As melting nears completion ($t = 4560$ sec), the velocity patterns stabilize as the process approaches its final stages. The flow structure indicates a balance between buoyancy and viscous resistance within the porous medium. For pure PCM, the velocities remain lower and more uniform compared to the foam cases, confirming the absence of buoyant forces in the non-foam system. In summary, the results underline the dual role of foam porosity: lower porosity enhances conduction but limits convection, while higher porosity promotes convection but reduces thermal conductivity. For pure PCM, the system

relies solely on conduction for heat transfer, which results in slower melting. Together, these mechanisms—conduction and convection—play key roles in determining the melting efficiency of the PCM system.

Figure 7. Liquid fraction for PCM with Copper MF at 30 PPI across various porosities at 9 kW/m^2 .

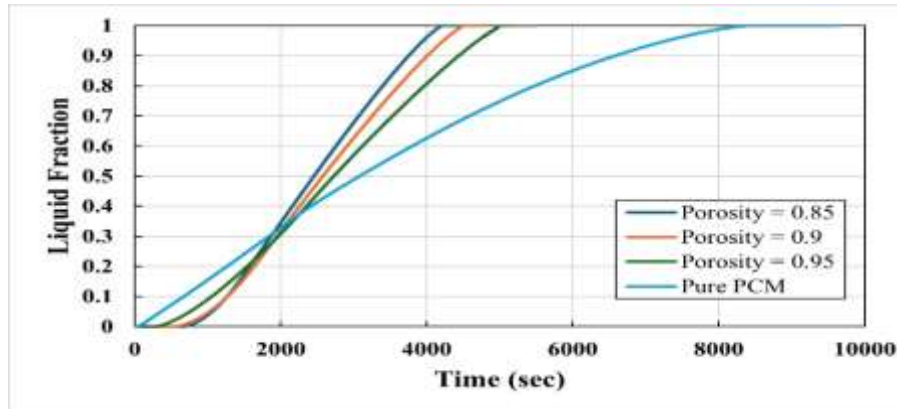
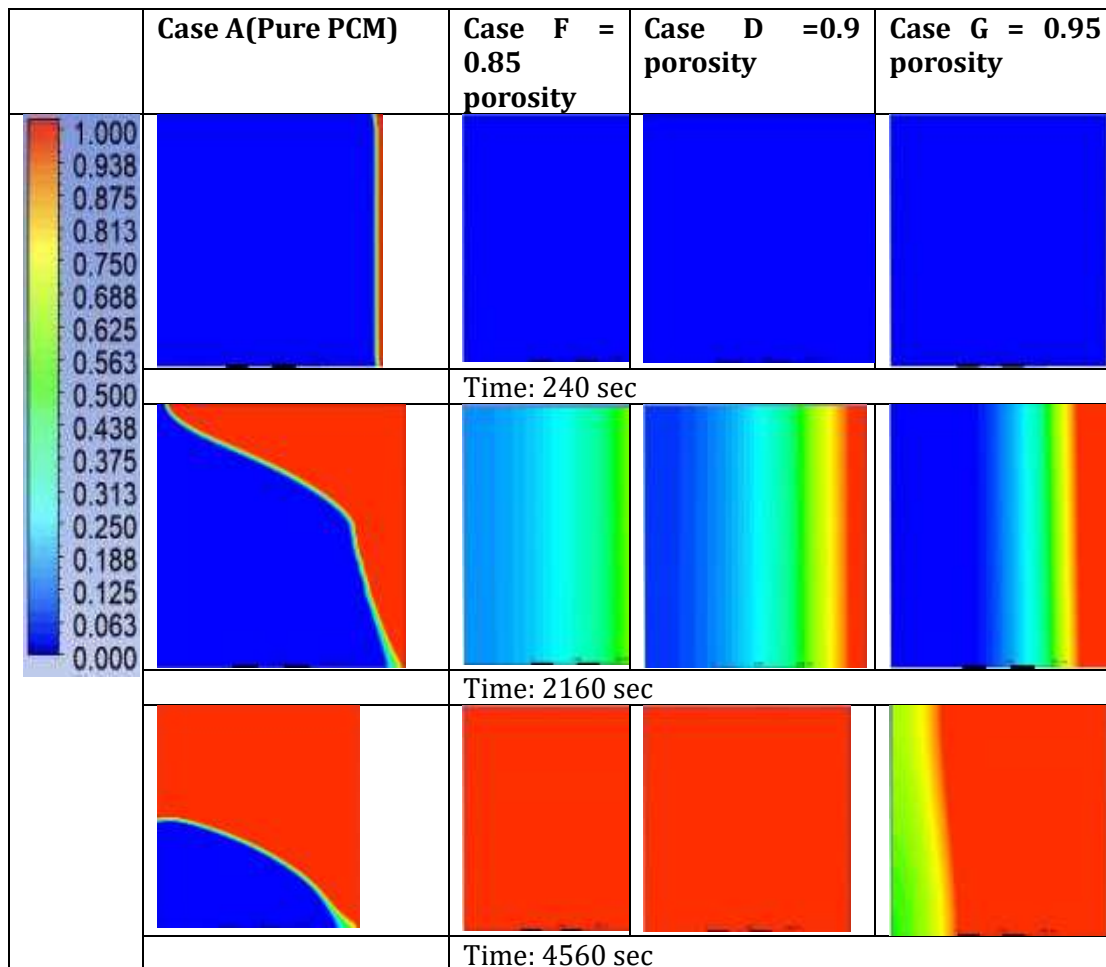


Figure 8. Melting process contour for PCM with Copper MF at 30 PPI across various porosities at 9 kW/m^2 .



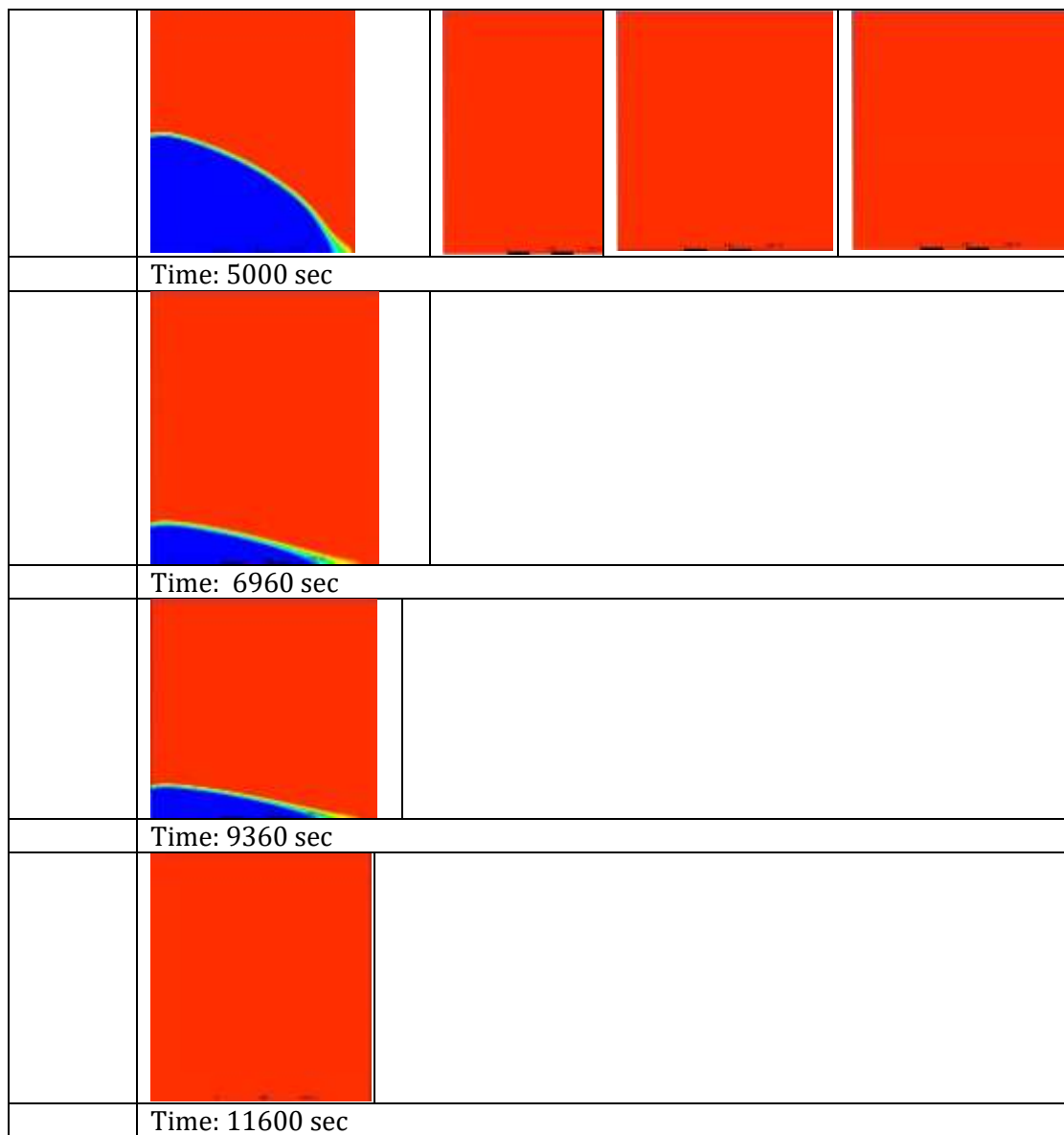
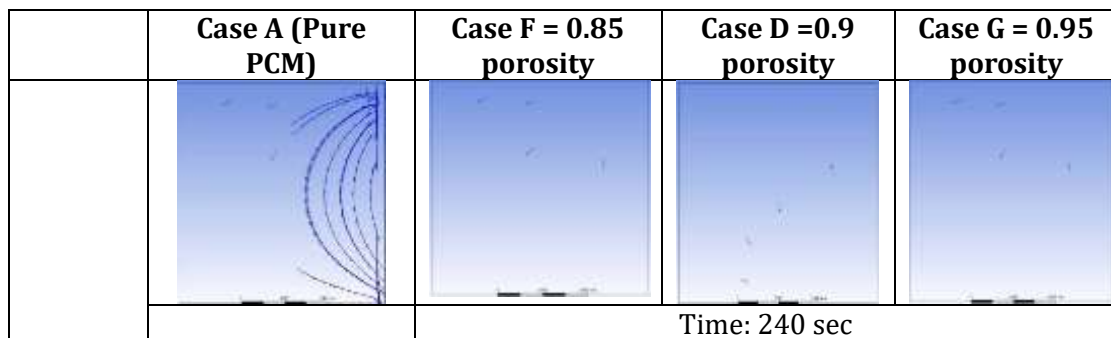
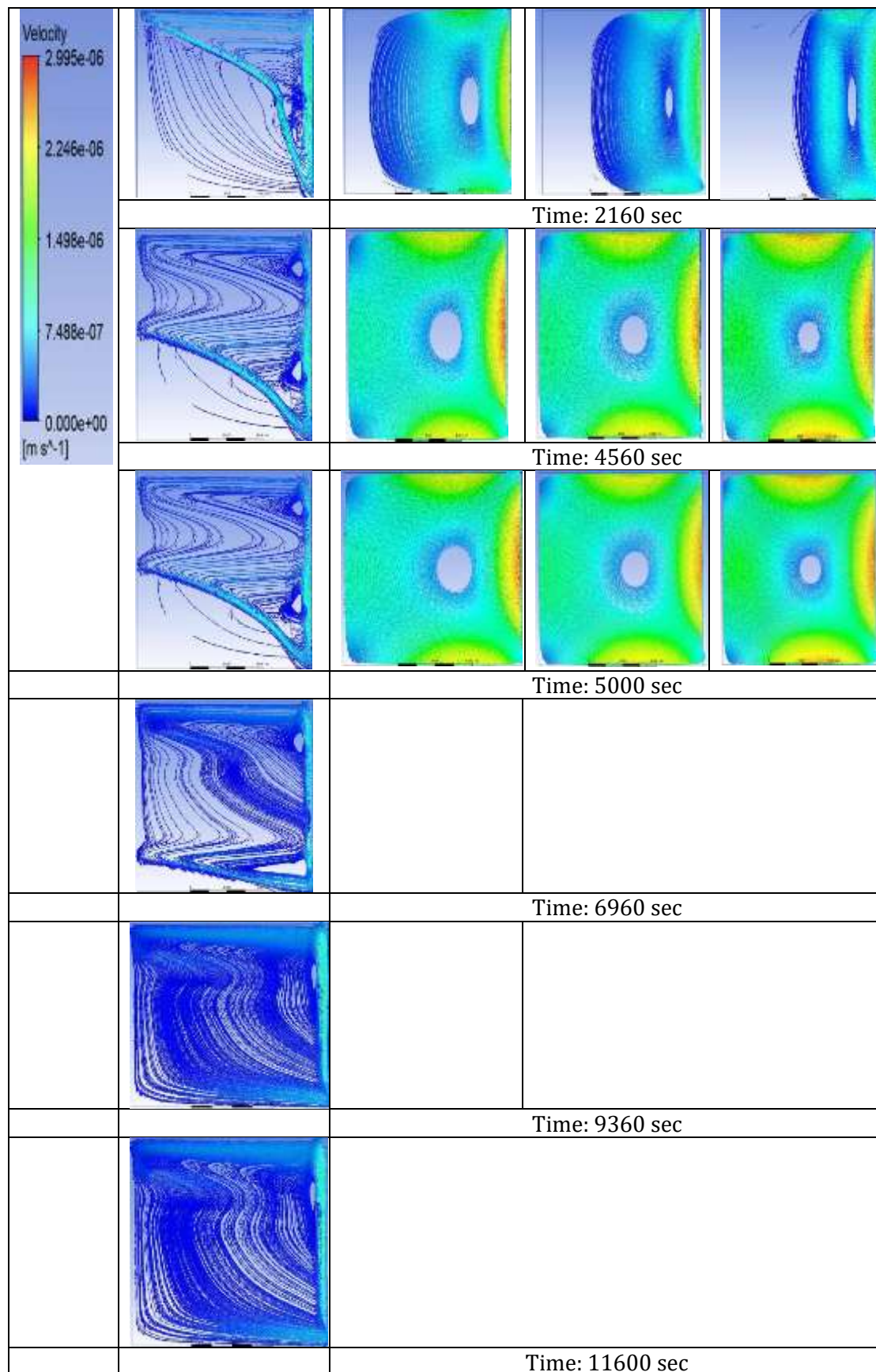


Figure 9. Velocity contour for PCM with Copper MF at 30 PPI across various porosities at 9 kW/m^2 .





6.4 Overall Comparison

The parametric comparisons reveal that porosity is the most influential structural parameter affecting melting time, while PPI causes only minor variations within the tested range. According to the current numerical results, the optimal configuration for enhancing melting under these operating conditions is copper foam with 30 PPI and 85% porosity. Conversely, 95% porosity consistently results in the slowest melting response. The melting process begins near the heated copper wall and gradually spreads into the enclosure. Embedded copper foam significantly enhances heat transfer within the paraffin wax, resulting in smoother temperature gradients and more uniform melting patterns.

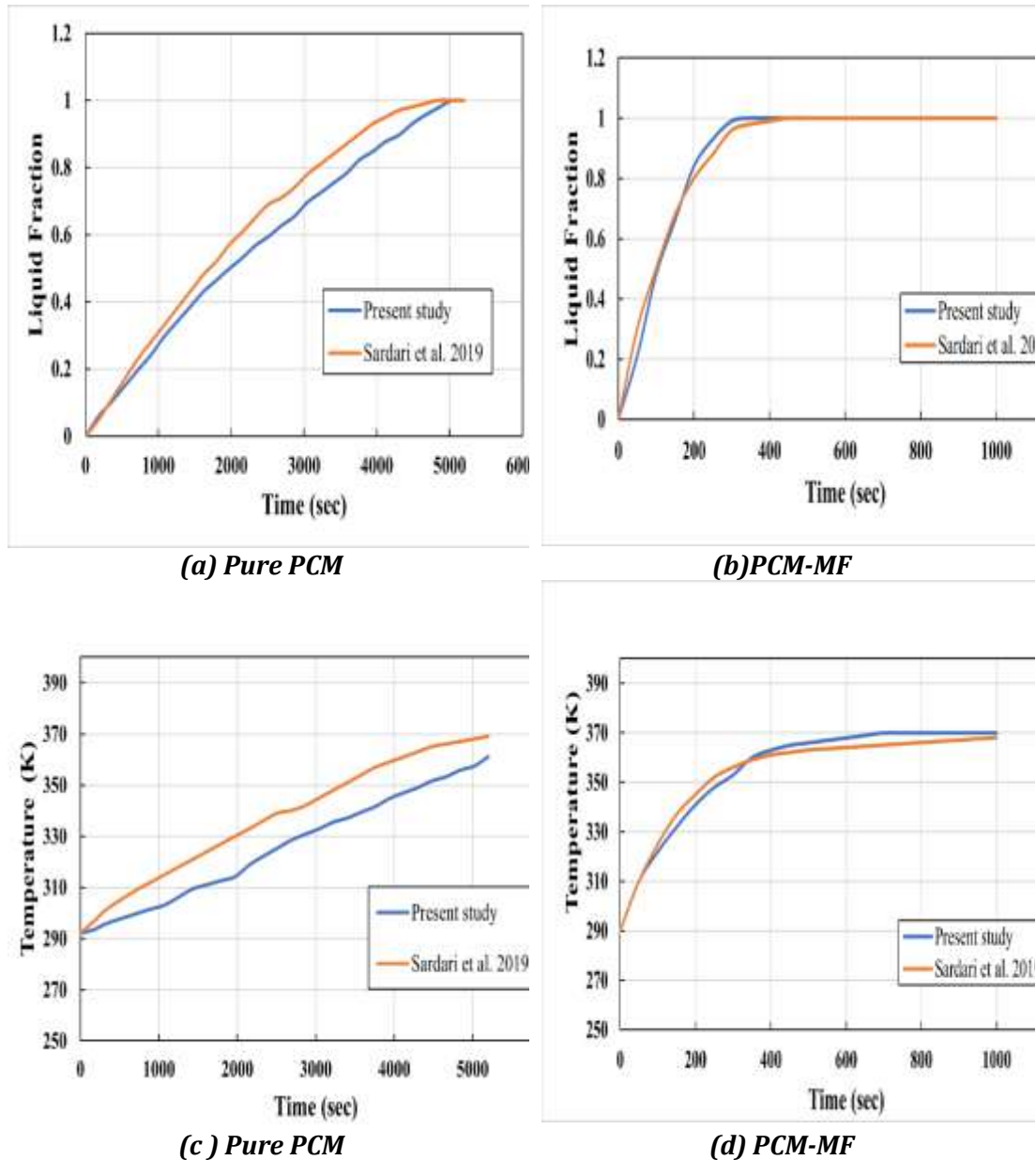
7. Conclusions

This study numerically investigated the more efficient enhancement of paraffin wax melts using a copper metal foam in a 3D enclosure, heated by a steady heat flux of 9 kW/m^2 applied to a copper wall, with all other boundaries insulated. The main conclusions are: (i) The limited variation in melting performance across different PPI values can be explained by the dominant role of the highly conductive copper matrix once the MF is introduced. In the investigated range (10–40 PPI), all foam structures show significantly higher thermal conductivity than paraffin wax. As a result, the copper foam itself greatly enhances heat diffusion, making the melting process less sensitive to further changes in pore density. Increasing the PPI results in smaller pores and denser ligaments, which can improve local heat distribution by increasing the contact area between the metal and the PCM. However, smaller pores also increase flow resistance within the porous structure, potentially limiting the movement of liquid PCM. These competing mechanisms tend to balance out, resulting in only minor differences in melting time across the tested PPI cases. Although the variations are limited, the 30 PPI setup provides the best overall melting response. This indicates that an intermediate pore density offers a practical balance between improved conductive heat transfer and hydrodynamic resistance within the porous network. (ii) Porosity has a stronger impact on melting time than PPI, with 85% porosity resulting in the fastest melting and 95% in the slowest. Porosity plays a more significant role in melting behavior because it directly determines the copper volume fraction within the enclosure, which, in turn, strongly influences the system's effective thermal conductivity. Lower porosity (85%) means a greater proportion of conductive copper, enhancing heat pathways and accelerating thermal energy transfer into the PCM. Consequently, the melting front advances more rapidly, resulting in shorter melting times. Conversely, higher porosity (95%) reduces the amount of solid copper in the foam, weakening the conductive network and slowing heat transfer. While larger voids might facilitate fluid movement, the reduction in conductive material remains the dominant factor under the current heating conditions. Therefore, the highest porosity consistently results in the slowest melting. Overall, the findings suggest that porosity has a greater impact on melting performance than PPI, since it directly controls the effective thermal conductivity of the PCM–foam system.

Validation and Verification

To verify the accuracy of the numerical model, the current results were validated against the numerical data reported by [22]. This comparison focused on the temperature distribution and the progression of the liquid fraction during melting. A strong agreement was observed between our simulation and the published data, confirming the reliability and accuracy of the numerical method. A detailed comparison between our results and those of Walker et al. is shown in **Figure 10**.

Figure 10. The validation results of PCM, porous-PCM in comparison with the Sardari et al. 2019 studies (a) the liquid fraction time for PCM only, (b) the liquid fraction time for Porous-PCM, (c) the temperature of PCM for case PCM only, (d) the temperature of PCM for case Porous-PCM



CRedit Authors' Contribution Statement

Sajida Lafta Ghashim: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization.

Bushra Sabah Younis: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Software, Funding acquisition, Formal analysis.

Conflicts of Interest

The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analysis, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results

Nomenclature

$\vec{V}$	velocity vector (m/s)
∇P	pressure drop (Pa)
g	gravitational acceleration (m/s ²)
$\vec{S}$	Mushy zone term in the momentum equation
A_m	Mushy zone constant (10 ⁵)
$\vec{F}$	Forces acting due to Darcy resistance and rchheimer inertia
S_L	latent heat source term
λ	liquid fraction
d_l	ligament diameter of the metal foam structure (m)
d_p	pore size (m)
ε	porosity
$\omega(PPI)$	pore density
k_e	effective thermal conductivity (W/m.K)
k	thermal conductivity
ρ	density

Abbreviations

PCMs	Phase Change Materials
MFs	Metal Foams
TES	Thermal Energy Storage
GCI	Grid Convergence Index
CFD	Computational Fluid Dynamics
CV(RMSE)	Coefficient of Variation of Root Mean Square Error
R2	Coefficient of Determination

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