

Thermal Investigation of PCM Capsule-Embedded Walls for Peak Heat Flux Reduction and Thermal Lag Enhancement

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Abstract: Reducing heat gain through building envelopes is important for improving indoor conditions and lowering cooling demand in hot climates. Phase change materials (PCMs) can provide passive thermal storage by absorbing and releasing heat over a narrow temperature range. This study numerically investigates the thermal performance of a wall embedded with aluminium PCM capsules under summer conditions in Islamabad, Pakistan, where relevant specific assessments remain limited. A transient three-dimensional CFD model was developed to compare a PCM-integrated wall with a reference wall without PCM. The effects of capsule diameter, capsule number and capsule wall thickness were examined. The results show that PCM integration effectively reduced heat transfer into the wall, with wall-side convective heat transfer decreasing from 26 W to 17 W. Increasing capsule diameter from 1.00 in (25.4 mm) to 1.15 in (29.2 mm) and 1.25 in (31.8 mm) reduced room-side convective heat transfer by 6.8% and 6.6%, respectively. Increasing capsule number also enhanced latent heat storage and delayed heat release. In contrast, changing capsule wall thickness between 20 gauge (0.914 mm) and 22 gauge (0.762 mm) had only a minor effect. The study identifies capsule diameter and capsule number as the dominant design parameters for improving the thermal performance of PCM-integrated walls in hot climate applications.

Keywords: Phase change materials; wall thermal performance; building envelope; numerical modelling; thermal lag

1. Introduction

The residential sector is accountable for 40% of energy utilization across the globe leading to severe environmental concerns (Lu et al., 2025). Factors related to the buildings have a substantial impact on HVAC efficiency (E. Cuce et al., 2023).

The pressing issue of climate change has compelled a re-evaluation of the methods buildings use for heating, cooling, ventilation, and dehumidification. As a result, the performance of HVAC systems has emerged as a crucial element in the energy profile throughout a building's life cycle. Enhancing these systems can boost energy efficiency, reduce operational expenses, and contribute to broader decarbonisation objectives (P. M. Cuce et al., 2025). To counter the menace of climate change and global warming, improvement of energy efficiency has become the priority of researchers and scientists. (The United Nations Framework Convention on Climate Change After 20 Years: Is There a Better Way Forward?, 2026.) According to a statement by the International Energy Agency (IEA), the residential



sector is a cause of huge potential in terms of energy efficiency. ([Global Status Report for Buildings and Construction 2019 – Analysis - IEA, 2026.](#)) Enhancing the energy saving potential of the residential sector using active and passive techniques is the primary goal of the agency. ([A Clean Planet for All: A European Long-Term Strategic Vision for a Prosperous, Modern, Competitive and Climate Neutral Economy - Sino-German Cooperation on Climate Change, 2026.](#)) Typical passive strategies aim to enhance the building envelope and take advantage of natural conditions. This includes employing advanced insulation materials such as EPS and aerogel ([Alvur et al., 2026; Cuce et al., 2024a; Brien et al., 2025](#)), utilizing low-emissivity (low-e) glazing ([Akram et al., 2023; Somasundaram et al., 2020](#)), incorporating shading devices ([Çelik et al., 2025](#)), and implementing constructions tailored to specific regions, like sunspaces ([E. Cuce et al., 2024](#)). Researchers have prioritized utilizing natural and recyclable materials as thermal insulation in buildings. [Cuce et al., \(2023\)](#) sought to explore methods for enhancing the thermal resistance of briquettes, which are commonly utilized in Anatolia. They achieved this by applying an advanced insulation plaster, free of carcinogenic substances, to the briquettes in varying thicknesses. Their findings indicated that the plaster significantly improved the thermal resistance of the briquettes; for instance, when a 20 mm layer was applied to both sides, the U-value was reduced from 5.5 W/m²K to 2.86 W/m²K. [Cuce et al., \(2024\)](#) employed a similar approach in their study of bamboo. In this research, a briquette sample was created using varying amounts of bamboo. To evaluate the outcomes, their approach involved conducting the coheating test. However, the comprehensive results revealed that the briquette containing the highest bamboo percentage (6%) exhibited the greatest resistance to heat transfer ([MERT et al., 2024](#)). Moreover, Advanced technologies, including vacuum glazing with U values reaching as low as 0.2 W/(m²K) and frame cavities filled with aerogel that decrease thermal permeability by 45%, exhibit significant potential for energy conservation ([View of Thermal Bridging in Windows: A Critical Review on Mitigation Strategies for Enhanced Building Energy Efficiency, 2026.](#)). Similarly, [Bendaikha et al., \(2025\)](#) contributed to the expanding body of evidence by demonstrating that insulation blocks made from raw and milled pine needles exhibit highly competitive thermal conductivity values (0.0228–0.0238 W/mK) and notably low densities (28.57–32.72 kg/m³), comparable to commercial sandwich panels. Among the tested variants, dried raw pine needles oriented perpendicular to the heat flow demonstrated superior performance in terms of temperature gradient and thermal resistance. Major research findings endorse the integration of PCMs in the construction or building supplies as a reliable solution to energy efficiency. ([Smart Buildings: Advanced Materials and Nanotechnology to Improve Energy-Efficiency and Environmental Performance - 384 Pages, 2026.](#)) PCMs are an appropriate and reliable passive cooling technique that can improve a building's thermal behaviour in an efficient manner ([Akeiber et al., 2016; Baetens et al., 2010; Madessa, 2014; Vik et al., 2017](#)). Furthermore, Ventilated Facades offer a flexible, passive-plus foundation for constructing low-carbon buildings, improving energy efficiency, longevity, and indoor comfort simultaneously. Anticipated developments in intelligent controls, bio-based materials, and integrated energy-recovery systems are expected to drive further performance improvements and hasten the industry's shift towards net-zero ([Cuce & Cuce., 2025](#)). Additionally, Various studies on employing PCMs in the building envelopes have been reported ([Pasupathy et al., 2008; Srinivasan & Ravikumar, 2014](#)). PCM are mainly categorized into two main types: organic PCM(OPCM) and inorganic PCM(IPCM) ([Lawag & Ali., 2022](#)). Organic PCM are suitable for low-temperature applications and has advantages like thermal and chemical stability, recyclability, and non-corrosiveness ([Paloma et al., 2016](#)). Inorganic PCM, in contrast, are suitable for high temperature applications and include salt hydrates, pure salt and metals ([Sun et al., 2023](#)). [Vicente & Silva., \(2014\)](#) tested hollow clay bricks and noticed delayed heat transfer and fewer temperature fluctuations. [Shi et al., \(2014\)](#) tested PCMs in a building in Hong Kong and concluded that PCMs laminated internally are the most efficient for the regulation of temperature. ([Bontemps et al., 2011](#)) evaluated PCMs filled in hollow glass bricks in passive solar buildings and observed a significant reduction in cooling demand. [Akeiber et al., \(2017\)](#) evaluated test rooms filled with macro-encapsulated PCM under the hot weather of Iraq and observed a reduction in energy consumption, improvement in temperature regulation, and enhancement of indoor stability. [Anter et al., \(2023\)](#) performed numerical and experimental studies in Aswan, a city in Egypt, to determine the effect of PCM type, thickness of capsules, and their position on the building's performance during the warm climate of summer. Obtained Results indicate that RT-35HC, placed 1.50cm from both ends of the wall reach the maximum efficiency, leading to reduction in heat gain by almost 66%. [Izadi et al., \(2023\)](#) assessed the behaviour of hollow bricks integrated with PCM for cold climates in Iran. Results showed that bricks filled with PCM RT18 markedly reduced heat flux, enhancing the thermal behaviour of the building as associated to conventional bricks. [Mahmoud et al., \(2024\)](#) considered the behaviour of PCMs placed in a commercial brick wall in UAE, considering various orientations. Results indicate that maximum stability, temperature regulation, and maximum

energy savings are achieved when RT31 PCM is integrated in the roof or in the south wall. Hasan et al., (2016) studied the incorporation of PCM in blocks made of concrete in hot climates. The results showed lower heat transfer and delay in peak or apex temperature by almost 2.6 hour by the integration of PCMs. Jin et al., (2014) assessed PCM thermal shield incorporated in building walls in North America. The obtained results indicate that the PCM placed adjacent the inside wall face delayed peak or highest heat flux, although they show better performance at lower temperatures if placed between insulation layers. Therefore, the importance of advanced PCM in the improvement of thermodynamic aspect, thermal comfort and building energy conservation has proved their usefulness in ensuring building sustainability (Arumugam et al., 2024).

Although PCM integration in building envelopes has been studied extensively in hot-arid climates (Akeiber et al., 2017; Anter et al., 2023; Mahmoud et al., 2024) these studies were conducted under conditions of low ambient humidity and a single dry season. Islamabad's climate combines hot humid summers, a pronounced monsoon season, and cold winters, producing diurnal and seasonal temperature variations that differ from the hot-arid cases reported in the literature. Higher ambient humidity can lower the natural convection heat transfer coefficient at the room-side wall surface compared with arid climates, which affects how quickly the PCM charges and discharges heat. The diurnal swing in Islamabad also raises the question of whether the PCM fully resolidifies overnight, a condition not addressed in studies conducted for hot-arid climates. These climate-specific effects on PCM charging and discharging behaviour remain unquantified for Islamabad and for climates with a similar hot-humid, monsoon-affected profile. Figure 1 shows the monthly average ambient temperature of Islamabad. In addition, the combined effect of capsule diameter, capsule number, and capsule wall thickness on the thermal performance of PCM-integrated walls has not been systematically examined within a single study. To address these gaps, the present study employs numerical simulation to investigate the thermal performance of micro-encapsulated PCM integrated within a building wall under Islamabad's climate. Capsule diameter, number of capsules, and capsule wall thickness are evaluated for their effect on heat absorption, storage, and transmission delay, with the aim of quantifying reductions in room-side convective heat transfer and the resulting thermal lag.

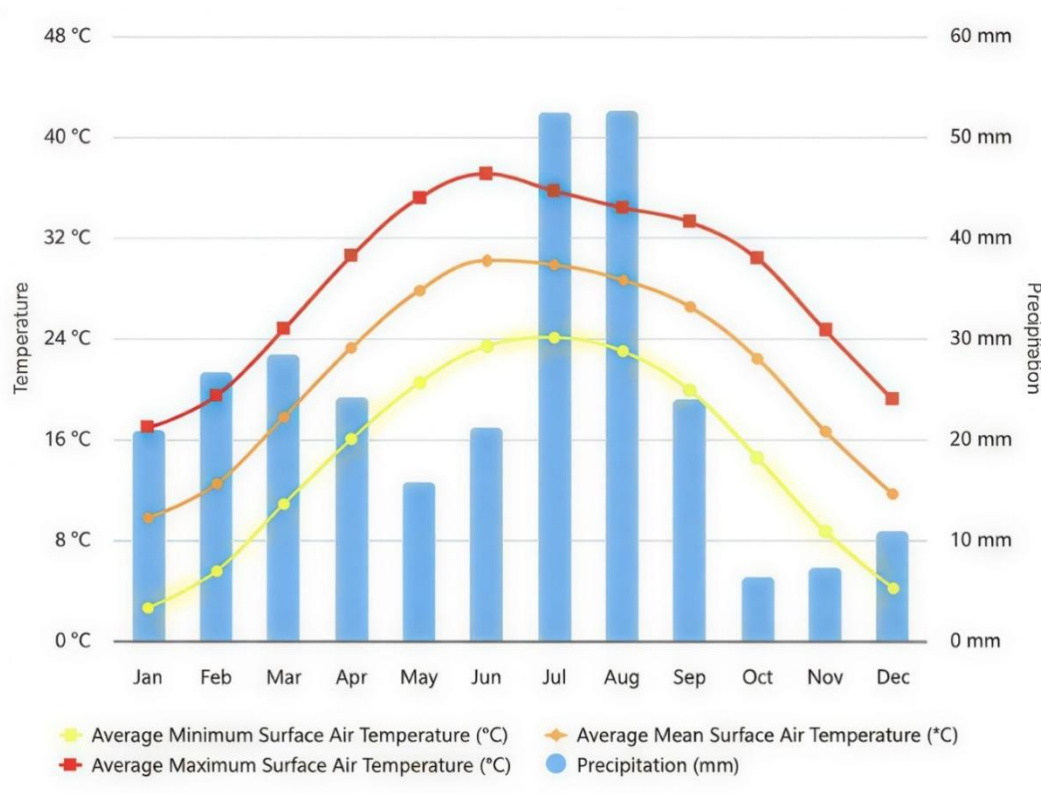


Figure 1. Monthly average ambient temperature of Islamabad

2. Numerical Model of PCM Integrated Wall

To govern the thermal response of a typically constructed wall integrating PCM and the optimum thickness of PCM capsule, it is essential to explain the model, take the essential assumptions, delineate

the fundamental equations, describe the boundary conditions and simulation, explain the properties of the materials utilized, and discuss the working methodology and solution method.

2.1. Computational Domain

Figure 2 shows the three-dimensional computational domain of a room's wall exposed to solar radiations from the sun. The wall is assumed to be south wall, and the peak summer day is selected for the simulation. The simulation of the outer or external environment was complicated in command to govern the rate of heat flow and the solar loading on the wall surfaces and so a simplified process is taken. For this purpose, the peak heat flux measured is given as the input to the exterior surface of the south wall. The dimensions of the wall taken is 1.2 m by 0.3 m. The wall is composed of 0.115 m thick bricks integrated with PCM capsules with the two 0.025 m thick plaster layers on both the inner side and outer side. The inner capsules are composed of aluminium filled with PCM. The length of aluminium capsules is 0.900m, while their inner diameter is 0.025m. The thickness of capsules is kept 20 gauge or 0.0009144m. The choice of aluminium for the capsules is due to its excellent thermal conductivity, high resistance to corrosion and high mechanical strength. The 1.2 m by 0.3 m wall section contains one full capsule unit. Since the capsules are arranged uniformly across the wall, this section reflects the behavior of the full wall throughout periodicity. At the same time the aluminum capsule has high thermal conductivity, and its bridging effect is fully included in the model. Symmetric boundary conditions were applied on the side faces, so the section behaves as if it is part of a continuous wall with no artificial edge influence. To minimize computational costs while preserving physical accuracy, symmetry boundary conditions were implemented at the mid-plane of the wall section. This effectively reduced the active computational domain to 0.6 m by 0.3 m. This method is valid under the assumption that the capsule arrangement exhibits a spatially periodic and uniform pattern, ensuring that the thermal behavior of the reduced domain accurately represents that of the entire wall. Three domains that are: impact of gauge thickness, distance between number of tubes and impact of number of tubes are studied. ANSYS Fluent 2024R1 is used for modelling and simulation.

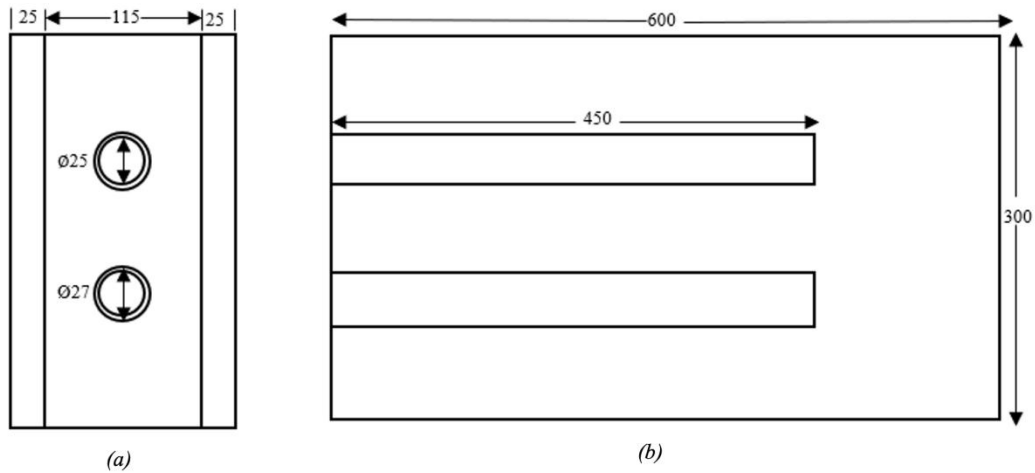


Figure 2. Geometric configuration of the wall containing PCM (a) side view (b) front view

2.2. Assumptions taken for the Numerical Model

To make the numerical simulation easier, the following suppositions are made:

1. The PCM enclosed within the aluminium capsules is pure, and there is no mass transfer between the PCM and the capsules.
2. All the materials used are isotropic and thermally homogeneous.
3. Latent heat, melting point and freezing point are assumed to be constant.
4. Thermal conductivity and specific heat capacity are given a constant condition.
5. Flow is supposed to be incompressible.

This method is employed in thermal modelling as evidenced from the literature. (Kong et al., 2014; Liu et al., 2021; Liu, Hou, Huang, et al., 2022; Liu, Hou, Wei, et al., 2022; Ye et al., 2017, 2020)

2.3. Thermophysical Properties

RT-28 is chosen as the PCM for the present work, which belongs to a family of paraffin-based organic phase change materials (PCMs). RT-28 is used due to its non-toxic and non-corrosive

properties, making it environmentally and structurally safe for building applications. Besides, it has a reasonably low melting temperature and exhibits phase change at about a steady temperature, which is ideal for thermal energy storage applications. Furthermore, RT-28 shows chemical and thermal stability during the phase transition process, guaranteeing consistent performance over repeated cycles. Figure 3 represents the Differential Scanning Calorimetry (DSC) curve of RT-28 obtained at a scanning rate of 1°C/min. The peak freezing temperature of RT-28 is 27.03°C and peak melting temperature is 28.9°C respectively. Table 1 depicts the thermophysical properties of the materials employed in the wall.

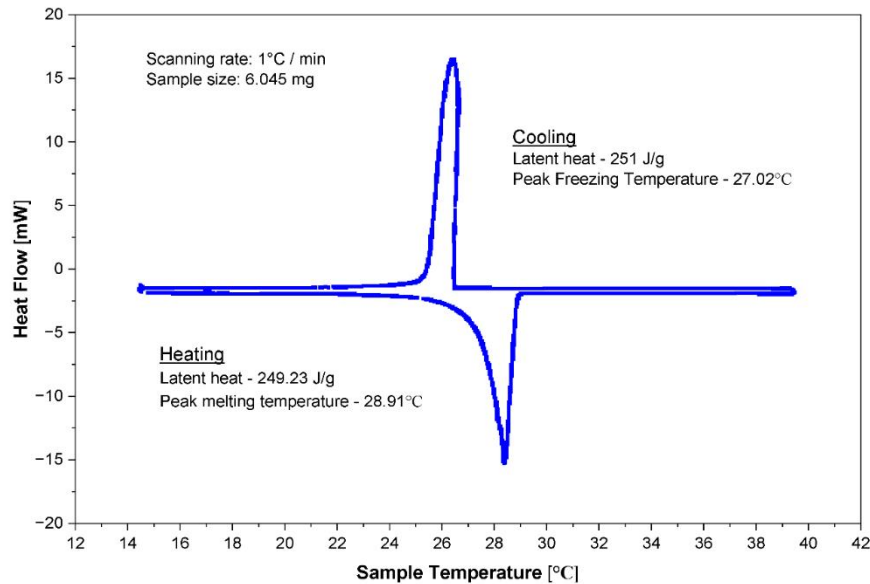


Figure 3. DSC Curve of RT-28

Table 1. Thermophysical properties of materials used

Property	Symbol	Units	Value
RT-28			
Density	ρ	kg/m ³	820
Specific heat	C _p	J/(kg·K)	2000
Thermal Conductivity	k	W/(m·K)	0.2
Viscosity	η	kg/(m·s)	0.0031
Thermal expansion coefficient	α	k ⁻¹	0.005
Pure solvent Melting heat	ΔH	J/kg	245000
Solidus temperature	T _s	K	300
Liquidus temperature	T _l	K	302
Plaster			
Density	ρ	kg/m ³	2320
Specific heat	C _p	J/(kg·K)	1138
Thermal Conductivity	k	W/(m·K)	0.5
Brick			
Density	ρ	kg/m ³	1800
Specific heat	C _p	J/(kg·K)	850
Thermal Conductivity	k	W/(m·K)	0.5

2.4. Governing Equations

The enthalpy-porosity technique was originally put forward by Voller et al., (1987) to simulate problems with phase change involving convective-diffusion heat transmission. This approach forms the foundation of the melting and solidification model explained in the ANSYS Fluent user guide (CFD Software: Fluid Dynamics Simulation Software, 2026.). The governing equations used for heat transfer are energy, momentum and continuity equations. The energy equations that are resolved in ANSYS (Fluent) can be written as:

$$\frac{\partial(\rho H)}{\partial t} + \nabla \cdot (\rho \vec{v} H) = \nabla \cdot (k \nabla T) + S \quad (1)$$

where ρ as the density of the fluid, H indicates the enthalpy, v as the velocity of fluid, S as the source term and ∇T as the spatial rate of change of temperature. The governing energy equation contains one enthalpy H that is the sum of latent and sensible heat.

$$H = h + \Delta H \quad (2)$$

where h shows the sensible heat of a point at a given point of time and ΔH represents the latent heat. The sensible enthalpy, h can be represented as the sum of the reference enthalpy, h_{ref} and the temperature integral of the heat capacity.

$$h = h_{ref} + \int_{T_{ref}}^T c_p T \quad (3)$$

The enthalpy difference, ΔH , is based on the liquid fraction f_L which ranges between 1 (complete fluid) to 0 (complete solid). In the enthalpy-porosity technique phase front is not explicitly followed as a distinct interface. Therefore, a mushy zone is assumed between the solid phase and liquid phase (Dutil et al., 2011). This range is defined by the solidus temperature T_{sol} and liquidus temperature T_{liq} , which represent the initiation and completion of the phase change.

The mushy zone is modelled as a porous medium, while the porosity is represented by liquid fraction f_L . The difference in enthalpy can be found as:

$$\Delta H = f_L L \quad (4)$$

where L represents the latent heat of PCM and f_L represents the liquid fraction. The value of latent heat is taken as zero for solid form of material ($f_L = 0$) and ($f_L = 1$) for liquid form of material.

$$f_L = 0, \text{ if } T < T_{solidus} \quad (5)$$

$$f_L = 1, \text{ if } T > T_{liquidus} \quad (6)$$

$$f_L = \frac{T - T_{solidus}}{T_{liquidus} - T_{solidus}}, \text{ if } T_{solidus} < T < T_{liquidus} \quad (7)$$

where $T_{solidus}$ and $T_{liquidus}$ are the properties of the material.

The continuity equation is:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho U) = 0 \quad (8)$$

where ρ represents the density, and U represents the x component of velocity.

The momentum equation used is:

$$\frac{\partial(\rho U)}{\partial t} + \nabla \cdot (\rho U U) = -\nabla P + \nabla \cdot (\mu \nabla U) + \rho g + \left(\frac{1-\theta}{\theta^3+c}\right) U A_{mush} \quad (9)$$

where P indicates the Pressure, μ as the dynamic viscosity, g refers to gravitational acceleration, θ as liquid fraction, A as the mushy zone constant, c is a small number included to dodge division by zero.

2.5. Initialization and boundary conditions

When examining the boundary conditions for the wall assembly, specific thermal parameters are applied to simulate realistic environmental interactions. The simulations are conducted using climate data for a peak summer day in June, obtained from the Pakistan Meteorological Department. A heat flux of 500 W/m² is applied to the external surface of the wall, representing the peak solar-induced heat flux measured during summer peak hours in Islamabad using a calibrated heat flux measuring device. This value corresponds to the worst-case thermal loading scenario, which is particularly relevant for evaluating the effectiveness of PCM integration in reducing peak cooling loads. This heat flux represents the thermal energy per unit area being transferred to the wall's exterior surface, simulating the effect of external heat sources such as solar radiation or ambient heat. On the interior side of the wall, conditions are set to account for convective heat transfer. The inner surface is subject to convection, which is a mode of heat transfer involving the movement of fluid, in this case, air, over the wall surface. This convective boundary condition assumes an ambient indoor temperature of 298 K (approximately 25 °C), which is a standard room temperature. The convective heat transfer coefficient applied at this boundary is 2.134 W/m² K. This coefficient quantifies the efficiency of heat transfer between the wall surface and the adjacent air, indicating how effectively heat is being transferred from

the wall to the air or vice versa. The discharging cycle (i.e., re-solidification during night-time) was not simulated in this study which is a limitation and intended for future work.

2.6. Solver Settings

Viscous (K-Omega SST), three-dimensional, incompressible, buoyant, transient flow simulations are carried out. The energy, solidification and melting modes are used to simulate the model. The SIMPLE (Semi-Implicit Method for Pressure Linked Equations) scheme is employed for pressure-velocity coupling due to its robustness and broad applications in incompressible and weakly compressible flows. The least-squares cell-based method is cast-off for spatial discretization of gradients which ensures better accuracy in an unstructured mesh. Pressure interpolation is done with the Standard scheme, while the energy and momentum equations are discretized by second-order upwind scheme. The second-order upwind scheme maintains numerical stability and ensures better accuracy in capturing flows and thermal gradients. In contrast, the equations of turbulence are discretized by means of a first-order upwind scheme. For solving temporal discretization, an intrinsically stable second-order implicit scheme is used, and 10^{-6} is chosen as the residual's convergence criterion. These numerical settings are adopted to ensure a balance between stability, accuracy, and computational efficiency. To justify the flow regime the Rayleigh number for both regions was calculated to be 1.01×10^5 , which is well below the laminar threshold of 10^8 . This confirms that the flow inside the PCM capsule during melting is clearly laminar. It is acknowledged that the k-omega model was not strictly necessary for the PCM domain. But since it was the default model it was preferably applied. However, since the flow velocities are very small, the turbulence model has negligible influence on the phase change results.

3. Verification and Validation of the Numerical Model

3.1. Verification

To verify how accurate the CFD results are mesh independent, the liquid fraction of the PCM is determined at three diverse mesh sizes. The computational domain comprising of M1=256,546, M2=413,093, M3=775,907 cells having complete melting in almost 50,000 sec respectively, plotted with respect to melt fraction as represented in Figure 4. The mesh size, M2, comprising of 413,093 cells having complete melting in 50,000 sec is chosen as it is the most suitable mesh that offers best compromise between computational time and efficient results.

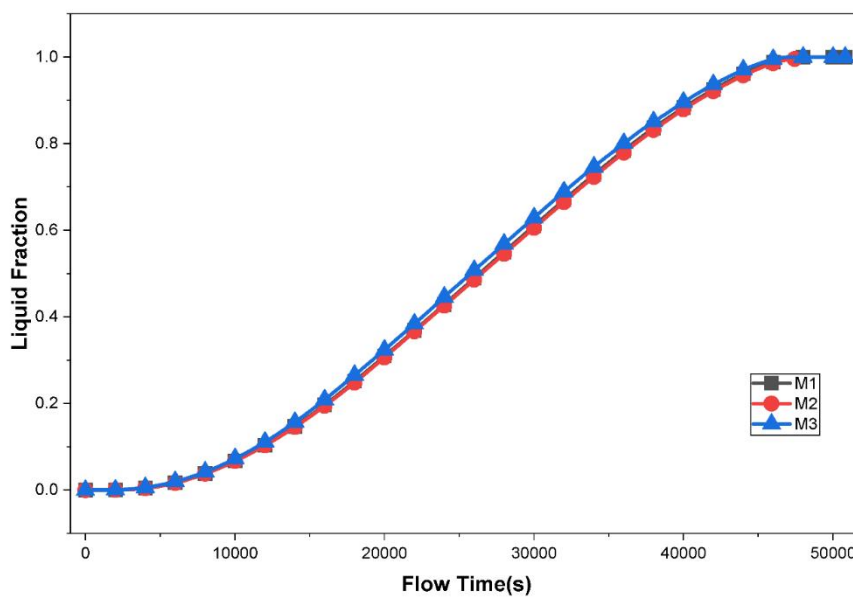
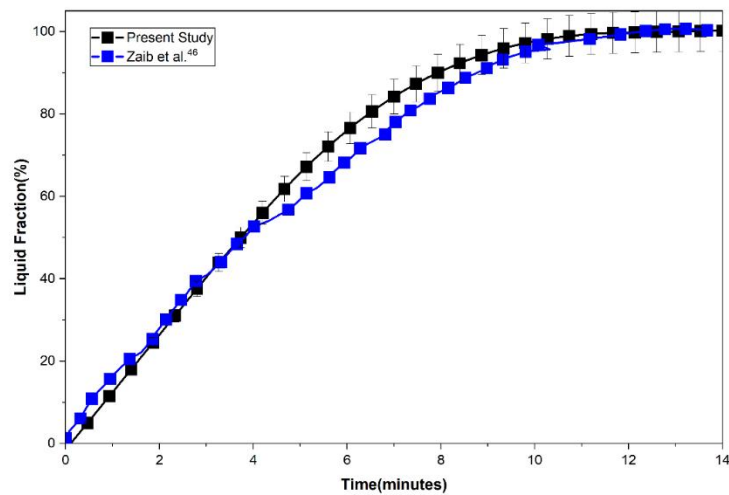


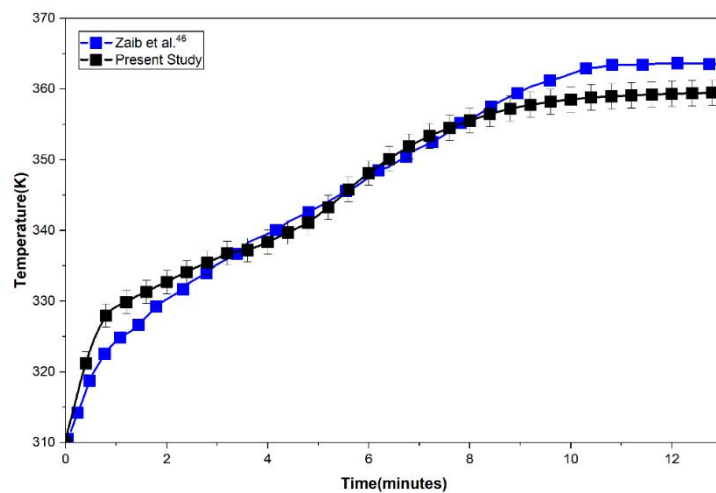
Figure 4. Mesh Independence

3.2. Validation

To authenticate the numerical model, it is necessary to compare the results obtained through simulation with the literature. Therefore, liquid fraction of a latent heat thermal energy storage unit (LTESU) with a Y-shaped configuration containing stearic acid as the PCM is compared. 30 The PCM is occupied in concentric tubes of spherical shape having an inner tube that has HTF at a constant temperature. Initially, PCM is kept at 300 K while the heated tube containing HTF has a temperature of 358 K. The simulation results are found to be consistent with the published results 30 as shown in Figure 5. The inclusion of fins considerably expedited the melting procedure leading to full melting in 14 minutes. Furthermore, the temperature variation of the spherical shaped concentric latent thermal energy storage unit is also compared. Stearic acid is used as the PCM having steel shell and the inner tube composed of copper. After an initial rise, the temperature growth slows down and gradually reaches a stable state by the end of the simulation. The temperature results are observed to agree with the results present in the literature with a numerical error of values being less than 5% while the trends observed to be almost similar (Zaib et al., 2023).



(a)



(b)

Figure 5. Numerical Validation: (a)Liquid Fraction (b)Temperature Profile (Zaib et al., 2023)

4. Results and Discussion

4.1. Comparison of Wall with and without PCM

Numerical analysis of a wall with and without PCM is performed under the boundary conditions described in Section 2.5, namely a constant heat flux of 500 W/m^2 on the exterior wall surface and a convective boundary on the interior surface with an ambient air temperature of 298 K and a heat transfer coefficient of $2.134 \text{ W/m}^2\text{K}$. The impact of PCM integration on room-side convection is studied as shown in Figure 6. At the initial stage (0 to 8000 sec), both curves remain nearly zero, showing a negligible difference in temperature between the indoor air and the wall surface showing a minimal amount of room-side convection. As the time progresses, the case without PCM indicates a swift increase in the magnitude of heat transfer, reaching at -26 W at about 50000 sec. This shows a faster rise in inner surface temperature and stronger transfer of heat from the wall to the room-side air. In contrast, the wall containing PCM exhibits a much gentler decline, with convection around -17 W at the same time. In relative terms, the PCM integration lowers the room-side heat transfer approximately 35 % during the later period of operation. Physically, this difference in heat transfer arises because the PCM capsules absorb the incoming heat as the latent heat during melting, which limits the temperature growth of the wall's inner surface. As a result, the wall integrated with PCM maintains a lower and more stable room-side surface temperature, delaying the indoor heat rise and improving thermal comfort. In contrast, the absence of PCM in the reference wall leads to a faster rise in temperature at the wall-room interface, leading to stronger convection and higher indoor thermal load.

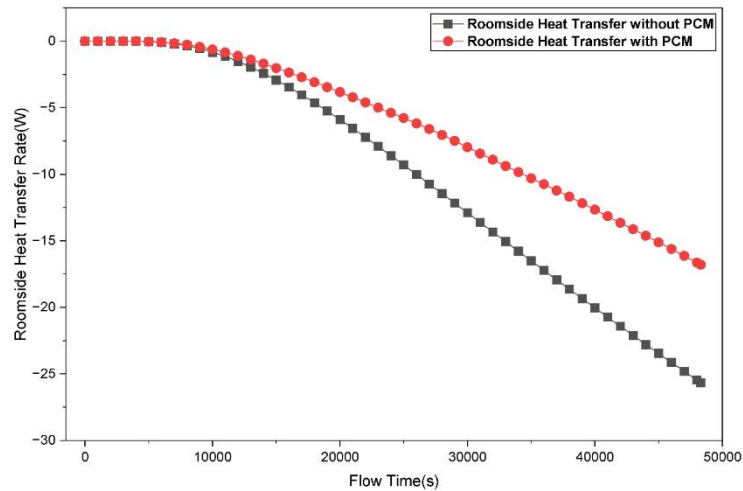


Figure 6. Room-side convection with and without PCM

4.2. Impact of Capsule Diameter

The behaviour of latent heat storage units (LHSUs) strongly relies on the geometry and size of the PCM encapsulation. By growing the diameter of the PCM tube from 1.00" (0.0254m) to 1.25" (0.03175m), the convective response on the room side is systematically reduced and delayed. Figure 7 shows the impact of increasing diameter of PCM capsule on room side convection. This trend agrees with earlier findings, where larger PCM diameters extended melting times and shifted heat release to later period (Hai et al., 2022; Punniakodi et al., 2024). Previous studies have reported that capsule diameter, shell thickness, and container shape significantly affect the charging/discharging rate and overall thermal efficiency (El Omari et al., 2011; Salunkhe & Shembekar, 2012). Numerical studies also confirm that larger PCM capsules exhibit longer melting times due to reduced surface-area-to-volume ratios (Hai et al., 2022). Similarly, Punniakodi et al., (2024) demonstrated experimentally that increasing tube diameter delays the onset of complete melting, though it improves thermal damping of temperature fluctuations. The peak convective heat flux consistently decreased as the diameter increased, with the 1.25" (0.03175m), configuration showing the smallest midday peak and the greatest phase lag compared to the external thermal driver. This behaviour is due to two factors: (1) larger capsules have a higher latent capacity, which keeps the temperature of surface near to the melting point and lowers the temperature difference that drives heat transfer, and (2) the natural-convection heat-transfer coefficient slightly decreases as the characteristic diameter increases.

As a result, the 1.25" (0.03175m), capsules are most effective in reducing peak loads and shifting heat release to the late afternoon or evening. However, the increased thermal mass also prolonged the charging and discharging period; in warm night-time conditions, the 1.25" (0.03175m), capsules are more likely not to fully solidify, reducing the benefits for the following day. The 1.15" (0.02921m) capsules provided a middle ground between peak reduction and overnight reset, while the 1.00" (0.0254m) capsules recharged most consistently overnight but offered the least peak reduction and time delay. Moreover, our observation that the intermediate size 1.15" (0.02921m) offers a balance between thermal lag and reset ability is in line with prior reports emphasizing trade-offs between storage capacity and responsiveness (El Omari et al., 2011).

Heat transfer inside the wall in case of a 1-inch tube is -14.2269W (- sign shows the heat transfer inside) while in case of 1.15inch and 1.25inch capsules is -13.2651W and -13.2815W respectively. So, the percentage reduction in heat transfer in case of a 1.15-inch capsule compared to a 1-inch capsule is:

$$\frac{14.2269-13.2651}{14.2269} \times 100$$

$$= 6.8\%$$

Similarly, the percentage reduction in heat transfer in case of 1.25inch capsule compared to 1inch capsule is:

$$\frac{14.2269-13.2815}{14.2269} \times 100$$

$$= 6.6\%$$

Table 2 shows the room side convection at different tube diameter.

Table 2. Room side Convection at different tube diameter

Tube Diameter	Convection at 50000s (W)	Reduction (%) vs 1.00"
1.00"	-14.2269	
1.15"	-13.2651	6.8%
1.25"	-13.2815	6.6%

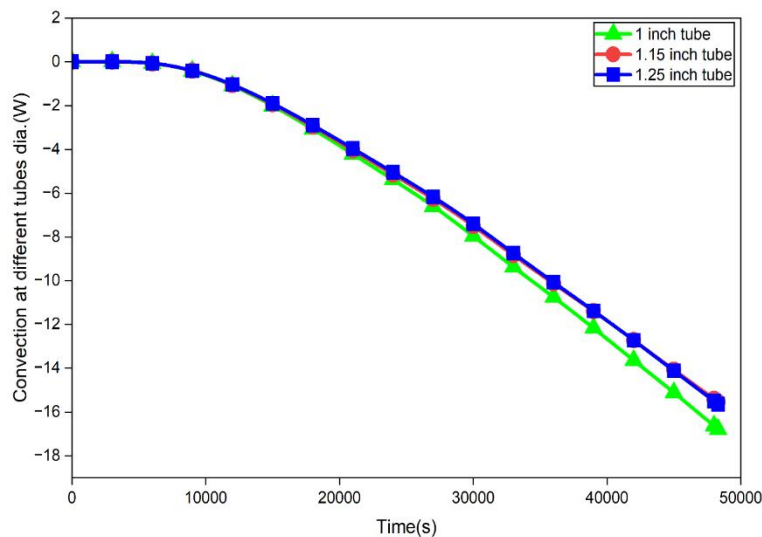


Figure 7. Room-side convection at different tube Diameter

4.3. Impact of Number of Capsules

Increasing the number of PCM capsules integrated in the wall markedly influences the room-side convection. As the tube count increases from 2 to 3 and 4, the total latent heat storage capability of wall increases proportionally with the volume of PCM. This permits a greater percentage of incoming heat to be absorbed at the PCM melting temperature, thereby diminishing the temperature gradient between the surface of inner wall and the ambient room air. This leads to the suppression of convective heat flux during peak hours and markedly delays the occurrence of peak flux. This phase lag is a direct outcome of the extended melting behaviour in the larger PCM inventory. Additionally, the cumulative convective energy transferred into the room over the entire simulation period is greater in the three- and

four-tube cases, as the system sustains heat absorption and release for longer. Thus, the primary benefit of increasing tube number lies in both attenuating the immediate midday heat flux and shifting the thermal load toward later hours, which is desirable for load levelling and peak-demand reduction in building applications. Moreover, the effect of number of tubes on heat transfer improvement observed in the present work is in line with the findings present in the literature. In the context of PCM systems, the earlier findings have incessantly shown that increasing the number of heat exchange tubes increases the overall heat transfer performance, which aligns with the trend observed in the present study. It is reported that increasing the number of PCM capsules from one to four markedly improves the melting rate (by approximately 29%) because of the combined effects of augmented heat transfer surface area and elevated natural convection (Esapour et al., 2016). Similarly, one study (Effect of Inclination Angle on the Performance of a Shell and Tube Heat Storage Unit - An Experimental Study, 2026) experimentally observed that increasing the number of inner tubes cause approximately 43% improvement in heat transfer throughout the process of melting, owing to the expansion of the thermal contact area between the heat transfer fluid and the PCM.

Heat transfer per unit area with two tubes is -17W (negative shows the heat transfer inside the room), while with three and four tubes is -21W and -25W.

So, percentage improvement in case of three capsules as compared to two capsules is:

$$= \frac{21-17}{17} \times 100$$

$$= 24\%$$

Similarly, percentage improvement in case of four capsules as compared to two capsules is:

$$= \frac{25-17}{17} \times 100$$

$$= 47\%$$

Table 3 shows the room side convection at different number of tubes.

Table 3. Room side Convection at different number of tubes

Configuration	Convection (W)	Improvement
2 tubes	≈ -17 W	—
3 tubes	≈ -21 W	$\sim 24\%$ $\uparrow$ vs 2 tubes
4 tubes	≈ -25 W	$\sim 47\%$ $\uparrow$ vs 2 tubes

Figure 8 depicts the temporal variation of room-side convective heat transfer for the wall incorporating 2, 3, and 4 PCM capsules. The negative sign indicates heat flow inside the room. In all setups, the amount of convective heat transfer grows over time, showing a progressive increase in buoyancy-driven natural convection as the PCM absorbs heat and establish a lower wall surface temperature. A distinct and consistent order is evident throughout the simulation:

$$Q_{conv,4} > Q_{conv,3} > Q_{conv,2}$$

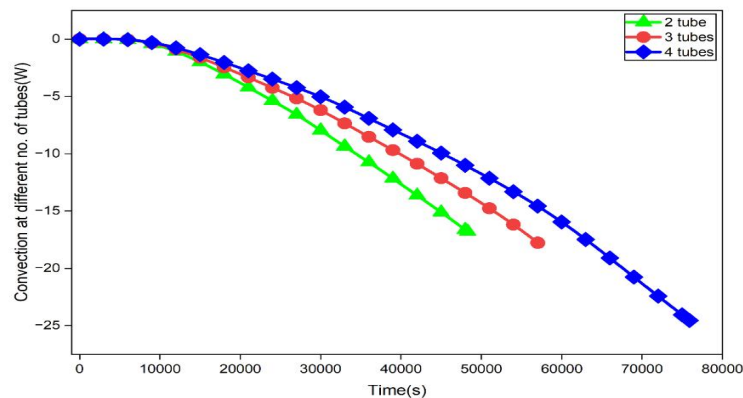


Figure 8. Room-side convection at different number of tubes

Figure 9 depicts the Liquid Fraction curves with 2,3, and 4 capsules. The liquid fraction curves show that in all three cases the PCM starts in a fully solid state and gradually melts over time as it absorbs heat from the external wall surface. In each case, there is an initial delay before melting begins, during which the PCM temperature rises to its melting point of 28°C. After melting starts, the liquid fraction increases progressively and reaches 1.0 (fully melted) within 50000s for 2 capsules, 58000s-60000s for 3 capsules and 60000s for 4 capsules confirming that the full charging cycle is captured. As the number of capsules increases from 2 to 4, the total time required to reach complete melting increases, which is expected since more PCM mass is present to absorb heat. The smooth and continuous rise in liquid fraction across all three cases confirms numerical stability and good convergence of the simulations.

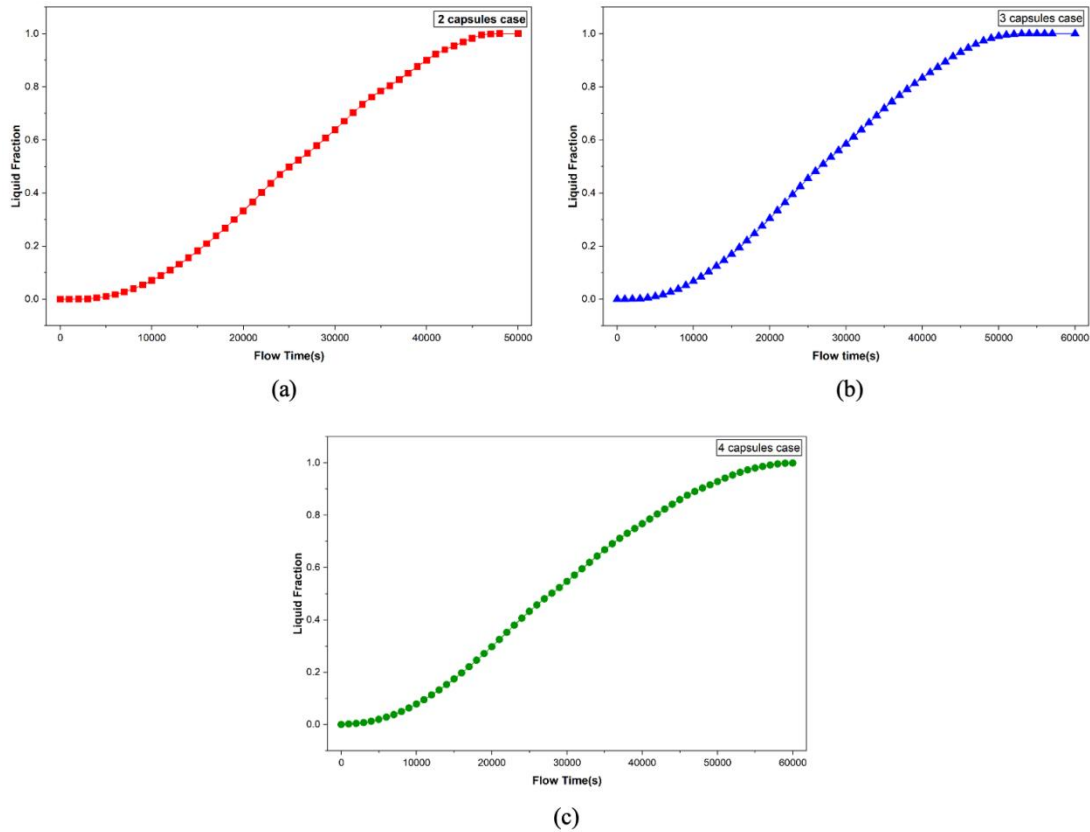


Figure 9. Liquid Fraction curves (a) 2 capsules (b) 3 capsules (c) 4 capsules

4.4. Impact of Capsule Thickness

Figure 10 illustrates the effect of the thickness of aluminium capsule on room-side natural convection. Two-gauge thicknesses: 20 gauge (0.0009144m) and 22 gauge (0.000762m) are considered. The results indicate that changes in gauge thickness have a minimal impact on both the magnitude and the temporal progression of convective heat transfer. This is evident from the nearly identical convection curves for all thicknesses. This pattern shows that the wall's surface temperature is the primary factor influencing room-side convection, rather than the wall's internal conductive resistance. The absorption of latent heat influences the thermal response, steadying the wall surface temperature and thus falling the sensitivity to moderate variations in wall thickness. Similar findings were reported (Zalba et al., 2003), which demonstrated that the effects of latent heat can surpass those of geometric conduction, resulting in minimal changes in surface heat flux for practical wall thickness ranges. Experimental studies by (Kuznik & Virgone, 2009) also showed that once PCM buffering is active, increasing wall thickness has a limited effect on indoor heat flux and convective heat exchange during the melting period. Similarly, Shi et al., (2024) found that within typical construction limits, variations in wall thickness have only a slight impact on indoor convective heat transfer when PCM controls the evolution of surface temperature. The current findings align with these studies, confirming that gauge thickness is a secondary factor in controlling room-side convection compared to the thermal buffering induced by PCM. Figure 11 displays the contours of liquid fraction of PCM capsules while Figure 12 demonstrate the temperature contours of wall with two, three and four capsules.

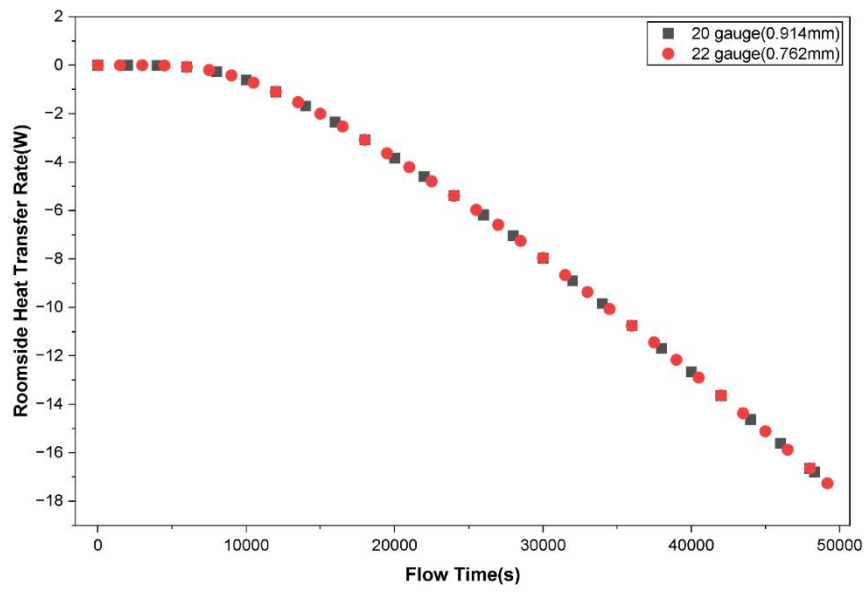


Figure 10. Room-side convection at different gauge thickness

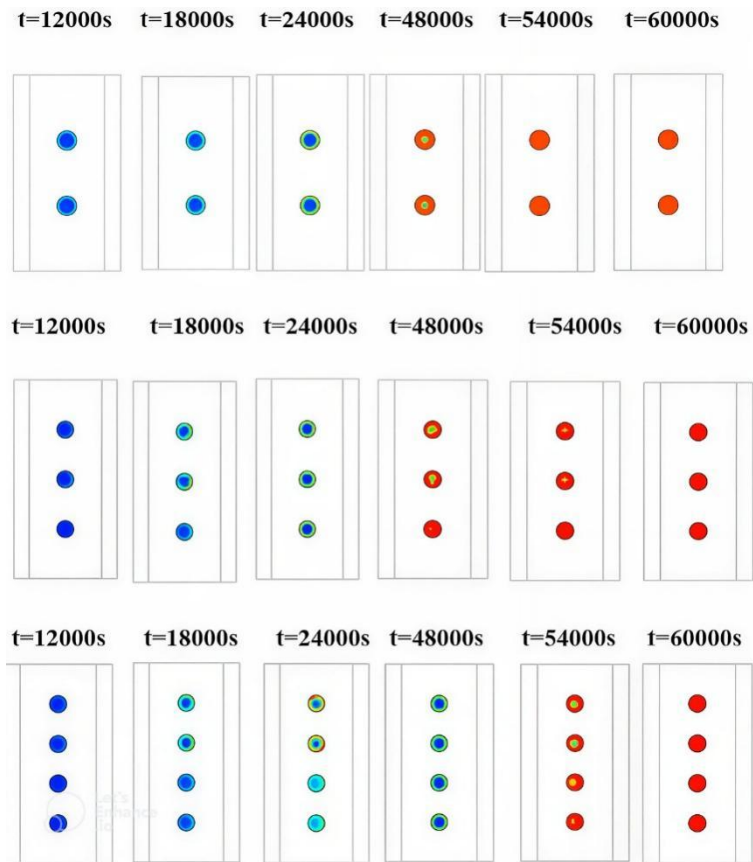


Figure 11. Contours of Liquid Fraction with two, three, and four capsules

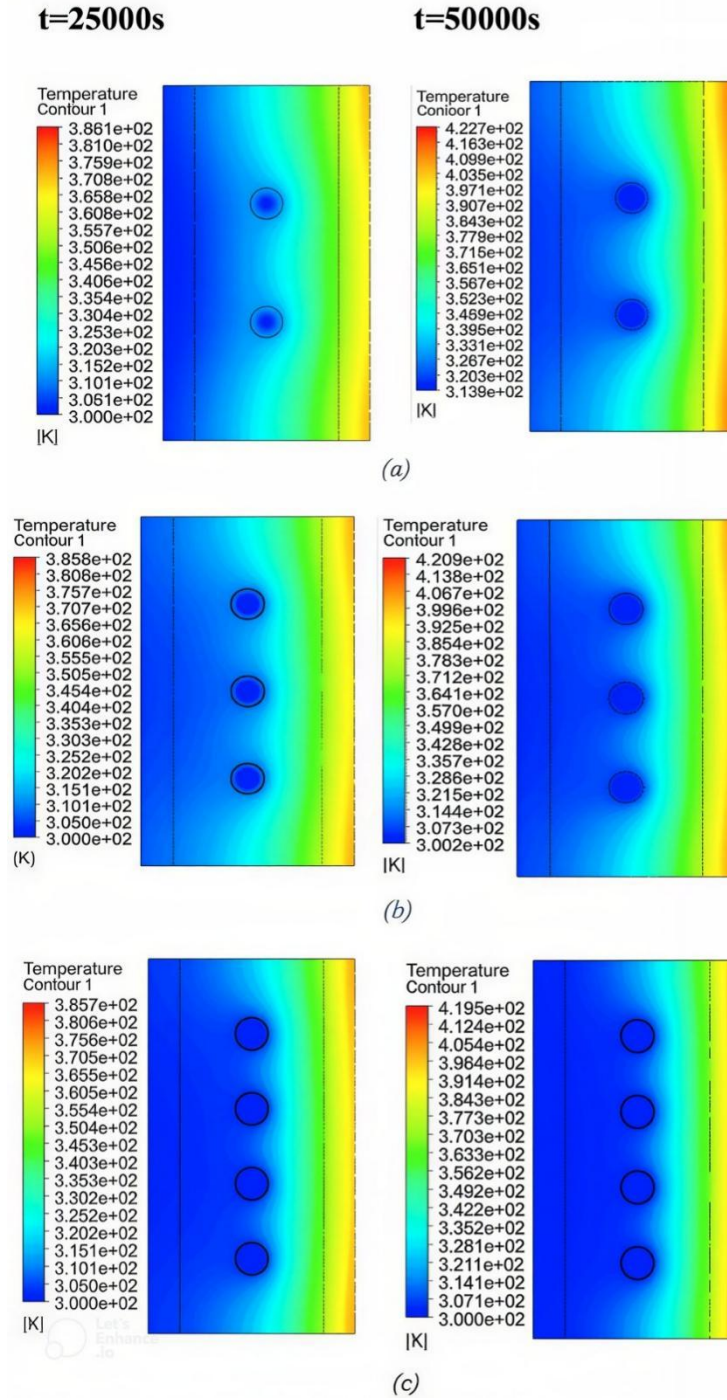


Figure 12. Temperature contours of wall with two, three and four capsule

4.5. Impact of capsule spacing on room-side convection

Although the spacing between the capsules differs across the configurations examined, it is not considered as an independent parameter in the present study. The variation in spacing naturally results from changes in the number of PCM tubes that fit within the wall. The findings show that the convection on the room side is mainly determined by the number of capsules and their diameter, which have a direct effect on the total latent heat storage, the progression of wall surface temperature, and the resulting Rayleigh number on the room side. On the other hand, capsule spacing influences the internal thermal interactions within the wall but does not directly affect the airflow dynamics on the room side. As a result, setups with fewer capsules and wider spacing (such as 2 tubes with 100 mm spacing) demonstrate weaker room-side convection compared to those with more capsules and narrower spacing (like 4 tubes with 60 mm spacing). This is not due to the spacing itself but rather because of the

reduced PCM content and delayed heat release. Therefore, the effect of capsule spacing on room-side convection is indirect and minimal when compared to the more significant impacts of the number of capsules and their diameter.

4.6. Disadvantages of PCMs

Although the advantages of using PCMs are promising, however, their large-scale usage in residential sector poses several challenges. Organic PCMs, like paraffin, shows low thermal conductivity, which limits the rate of heat transfer and diminishes overall efficiency of the system. Similarly, Inorganic PCMs, like salt hydrates, are prone to phase separation, leading to decreased thermal stability over time. Another challenge is leakage of PCMs during phase transition which can undermine the structural integrity of construction materials. Long term use of PCMs may results in degradation leading to reduced effectiveness over time. Some applications may face challenges in usability within specific climates or building types due to limitations in temperature range. Another disadvantage is material degradation due to extended usage involving multiple phase changes. The lack of universal standards for the selection and implementation of PCMs complicates their adoption. Another disadvantage of PCMs is thermal hysteresis. PCMs have distinct solidus and liquidus temperatures, which can lead to inefficiencies in storing and releasing heat. Another challenge is compatibility with existing materials. Incorporating PCMs into walls and ceilings requires meticulous design in order to ensure that they are compatible with current materials. Production cost associated with advanced encapsulated PCMs is also a big challenge thus limiting their penetration in the market. Similarly, the cost associated with maintenance and replacement are considerable due to the aging or decline in performance of PCMs over time (Pereira et al., 2025).

5. Conclusion

This study numerically investigated the thermal performance of a wall embedded with PCM-filled aluminium capsules under summer conditions in Islamabad, Pakistan. The results confirm that PCM integration can effectively moderate heat transfer from the wall to the indoor side. At around 50,000s, the room-side convective heat transfer was reduced from about 26 W for the reference wall to about 17 W for the PCM integrated wall. This demonstrates a clear reduction in indoor-side thermal load and a delay in heat transfer. The parametric analysis further showed that capsule geometry and quantity are the main design variables controlling the thermal response of the wall. Increasing the capsule diameter from 1.00" (25.4 mm) to 1.15" (29.2 mm) and 1.25" (31.8 mm) reduced the room-side convective response at 50,000s by about 6.8% and 6.6%, respectively. Larger capsules provided stronger damping of heat transfer. The intermediate diameter offered a better balance between thermal lag and overnight reset. In addition, increasing the number of capsules from 2 to 3 and 4 increased the total latent heat storage capacity and shifted the peak heat release to later hours. Changing the aluminium capsule wall thickness from 22 gauge (0.914 mm) and 22 gauge (0.762 mm) had a minor effect on the room-side thermal response, which shows that wall thickness is a secondary parameter within the range considered.

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