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Investigation of the Effect of Nanoparticles in Phase Change Materials on Heat Transfer in Building Wall

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Abstract

Phase change materials (PCMs) offer a viable approach for improving energy storage and thermal regulation in the construction industry. Despite their integration ease with building materials, PCMs face challenges with thermal conductivity. This study explores the effectiveness of different PCMs in reducing building energy consumption and investigates the role of nanoparticles in enhancing PCM conductivity. Specifically, the research evaluates three PCMs— N-octadecane, N-eicosane, and N-hexadecane—and examines the impact of two additives, Al_2O_3 and CuO, on thermal performance. Detailed analysis of temperature and heat flow parameters demonstrates that nanoparticle additives significantly enhance thermal conductivity and improve PCM absorption. Notably, higher nanoparticle concentrations result in delayed peak amplitudes by up to 1.5 hours and influence viscosity. Among the PCMs tested, N-hexadecane emerges as the most effective for improving winter thermal comfort in buildings, while N-octadecane is preferable for its melting point characteristics.

Keywords

phase change material (PCM), nanoparticles, heat flux, thermal conductivity

1 Introduction

Energy is essential to modern life, powering everything from transportation to industry. With global population growth and economic expansion, energy consumption has risen dramatically, especially in developing countries where industrialization and urbanization drive demand. In 2019, global primary energy consumption increased by 2.9%, the highest level since 2010, and this trend is expected to continue. One major area of focus is energy conservation in buildings, where phase change materials (PCMs) can play a significant role in heating and cooling. Phase-change materials are classified by chemical composition and melting points. However, PCMs can be used in buildings in two ways: passively in building walls or components and actively in thermal or cold storage units [1–5]. Researchers have focused on the applications of PCMs in building energy efficiency. Yoon et al. designed a floor heating system based on phase change materials and found that PCMs can reduce heating energy use by 8% to 43% [6]. Research [7] explores the thermal and energy benefits of incorporating phase change materials into building walls. Simulations using Ansys Fluent analyzed different types of phase change materials and layer configurations. Key findings include a 50% reduction in internal heat flux with the placement of internal phase change materials and an optimal layer thickness of 10 to 15 cm. Energy consumption was significantly reduced, demonstrating the potential of PCMs for sustainable building practices by improving thermal performance and energy efficiency. Nguyen et al. developed a phase change composite (PCC) using N-octadecane and fumed silica, which reduced maximum internal temperatures and delayed heat flux [8]. Mert et al. studied a PCM composite of N-hexadecane/zinc borate, noting its excellent shape stability and energy storage capacity of 123 J/g [9]. Kessock et al. simulated the effect of adding 10% K18 concrete to walls, which reduced cooling loads

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by 19% [10]. Arce et al. tested concrete cabins coated with PCM, which performed well in a Mediterranean climate [11]. Cabeza et al. observed a two-hour delay in temperature fluctuation in a concrete cabin with 5% PCM [12]. Lee et al. compared heat transfer in triple-pane windows with paraffin-based PCM and found reduced indoor temperature fluctuations [13]. Silva et al. proposed a PCM-glazed window shutter, which resulted in a 90% reduction in room temperature during winter [14]. Vicente et al. compared wall samples with different PCM coatings and found a 50% to 80% reduction in thermal capacity and a three-hour delay in reaching maximum temperature [15]. Kong et al. tested PCM-laminated perforated brick, which showed the greatest reduction in maximum temperature [16]. Other studies have explored PCM in graphite composites [17] and pavement designs for thermal conditioning [18]. A study [4] investigates the development of a phase-change composite material (CPCM) with two phase-change temperatures, aimed at enhancing thermal energy storage in building walls. The CPCM showed significant improvements in thermal performance, achieving higher latent heat storage (224.53 J/g) and maintaining stability after 300 thermal cycles. When incorporated into walls, it reduced temperature fluctuations by up to 54.51% in summer and 31.91% in winter, enhancing energy efficiency. The study proposes the CPCM as an effective solution for seasonal thermal storage in buildings. In the most common application with gypsum, Volker et al. conducted a pilot study where they created gypsum panels with added materials to improve the functional properties of the panel. Open PCM panels were tested in special lightweight rooms. Two identical test chambers were built next to each other, and in the first, the walls were covered with PCM and gypsum board, while in the second, the walls were covered with plain gypsum board. They found that during hot days, there was a decrease in peak temperature—about 3 K compared to a room without it [19]. Koschenz et al. created panels made of gypsum and PCM encapsulated in a microcapsule, designed to handle heat gains of up to 40 W/m^2 due to latent heat incorporation.

Despite significant advancements in integrating phase change materials (PCMs) into building materials, several challenges remain, including the poor thermal conductivity of PCMs, leakage issues, and the transformation of PCMs into insulators rather than utilizing their thermal properties. One study developed nanocapsules of silicon oxide coated with a layer of silicon oxide using the sol-gel method, resulting in enhanced stability and prevention of leakage [20]. These nanocapsules exhibited a heat content of 181.5 J/g and maintained strong thermal reliability after 200 phase change cycles. When incorporated into cement-based materials, the nanocapsules accelerated hydration but slightly reduced compressive strength at a 10% weight content. Cement samples containing nanocapsules achieved a significant reduction of 3.9 °C in peak temperatures under constant heat sources, demonstrating their effective thermal energy storage capabilities. Additionally, capillary tubes were integrated into gypsum boards to dissipate absorbed heat, yielding promising results under real temperature variations. However, the addition of PCMs significantly decreased the thermal conductivity of gypsum, necessitating the inclusion of aluminum fins to counteract this issue. Unfortunately, most studies have overlooked the problem of reduced thermal conductivity in PCMs, causing them to function more as insulators than as materials enhancing thermal comfort [21]. A recent study explored the development of bionano/organic phase change materials (bionano/PCMs) [22] to improve the energy efficiency and thermal comfort of buildings. Using paraffin wax as the base PCM and eggshell-derived nanoparticles as the impregnating agent, researchers fabricated bio-nano/organic PCMs (BCMs) with varying nanoparticle contents (0–2%). The results demonstrated that 1.0% impregnation significantly enhanced thermal conductivity by 53.33% and reduced supercooling while maintaining latent heat over 500 cycles. However, higher nanoparticle content reduced thermal storage capacity, emphasizing the need for optimized impregnation levels for construction applications. Another study [23] reviewed approaches and challenges in integrating PCMs with building materials, highlighting issues such as decreased mechanical properties in cement and increased porosity. The study underscored the potential of PCMs to enhance thermal comfort and sustainability in building design while also calling for innovative solutions to address these challenges. To overcome these limitations, a study investigated the effect of zinc oxide (ZnO), copper oxide (CuO), and aluminum oxide (AlO_3) nanoparticles on the thermal properties of nano-enhanced PCMs (NEPCMs) [24] using numerical simulations in ANSYS Fluent. The results revealed an inverse relationship between nanoparticle concentration (0.1–0.5%) and the PCM mass fraction, with CuO outperforming the other nanoparticles in improving melting properties due to its high thermal conductivity. Nanoparticles also enhanced the uniformity of temperature distribution in paraffin wax, providing insights for improving NEPCMs in energy-efficient applications such as buildings and solar systems. A recent study addressed the challenge of low thermal conductivity in PCMs [25] by proposing the incorporation of small-sized conductive fillers, such as metals, carbon-based materials, and ceramics. These fillers improved both thermal conductivity and mechanical strength, increasing the potential of PCMs for energy-efficient building applications. Preliminary results indicated reduced indoor temperature fluctuations and energy demand, particularly in winter. The study emphasized optimizing filler types and concentrations for long-term stability, demonstrating their potential for developing thermal energy storage systems and contributing to sustainable building designs.

Despite the extensive literature, there remains a lack of comprehensive studies examining the effect of nanoparticles on various PCMs, their suitability for real-world environments, and the influence of weather factors. This article presents a numerical analysis investigating the effectiveness of several PCMs in reducing building energy consumption and identifies the most suitable options for the climate of Oum El Bouaghi, Algeria. The research also explored the potential of nanoparticles to enhance PCM conductivity and address thermal conductivity issues. Three PCMs - N-octadecane, N-eicosane, and N-hexadecane - were evaluated to determine the best option for the study area. Furthermore, the study examined the effects of adding nanoparticles (AlO_3 and CuO) in varying proportions to assess their impact on PCM properties and their performance under atmospheric conditions, aiming to improve PCM functionality.

2 Material and method

2.1 Material

In this section, Table 1 presents the physical properties of the brick material and the physical properties of the nanoparticles [26, 27] and Table 2 presents the thermophysical properties of the transition materials used in the study [28–30].

2.2 Physical model

The current study uses the geometries shown in Fig. 1 (Protocols p_1, p_2), addition the proportion of nanoparticles (Al_2O_3 and CuO) of phase change materials is variants as follows: 5%, 4%, 3%, 2%, 1%, and 0%.

Where the red hollow parallelepiped brick has two sizes:

- p_1: The first type has eight inner hollow holes with a thickness of 100 mm, a width of 200 mm, and a length of 300 mm.
- p_2: The second type contains twelve inner hollow holes with a thickness of 150 mm, a width of 200 mm, and a length of 300 mm.

Inside each hole, both species have parallelepiped chambers of 35 × 35 mm^2 and 300 mm in length. Moreover, due to its compatibility with the container, non-corrosive nature, and chemical inertness, the use

Table 1 Main thermo physical parameters of the used materials [26, 27]

Materials	Diameter ($\times 10^{-6}$ mm)	Material density (kg/m^3)	Thermal conductivity (W/mK)	Specific heat capacity (J/kg K)
Unfilled Brick	N.R.	1600	0.7	840
Nanopart Al_2O_3	59	3600	36	765
Nanopart CuO	59	6500	18	540

Table 2 Properties of Hexadecane, N-eicosane, N-hexadecane and N-octadecane [28–30]

Properties of the PCM	N-hexadecane	N-eicosane	N-octadecane
Density, (kg/m^3)	−0.6854T +787.2	−0.549T +945.72	−0.65T +971.52
Thermal Conductivity, (W/(mK)	0.341 at 5 °C < T <17 °C 0.24 at 17 °C < T < 20 °C 0.150 at 20 °C < T < 40 °C	variable in terms of temperature	variable in terms of temperature
Specific heat (kJ/kg K)	2.240 Solid 4 Liquid	variable in terms of temperature	variable in terms of temperature
Melting temperature, $T_{solidus}$; $T_{liouidus}$, (K)	288.65; 290.90	307.15	301.15
Viscosity, (Ns/m^2)	0.0033exp [−0.019 − 20)]	variable in terms of temperature	variable in terms of temperature
Latent heat, atm. (kJ/kg)	235.95	248.0	244.0

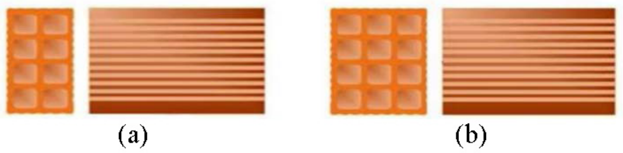


Fig. 1 Studied protocols (a) p_1, (b) p_2

of paraffin (particularly N-octadecane/ N-eicosane/ N-hexadecane) as a phase change material (PCM) within the cavities is proposed. The PCM is plastic covered to avoid liquid leakage. It has Newtonian solubility and incompressibility, as well as minimal viscous dissipation. Where the PCM's characteristics vary with temperature.

While Fig. 2 clearly illustrates the work done in this paper, the physical model is presented in more detail

Where the internal heat transfer coefficient and internal temperature remain constant, the external temperature and external heat transfer coefficient vary in response to weather changes.

2.3 Mathematical method

This study presents, unsteady heat conduction through a solid mass and heat transmission through exterior opaque boundaries. A division is made up of several isotropic, homogenous layers. The temperature field in any layer of a wall is given by the partial differential equation (Fourier equation for unsteady heat conduction) in the following form:

$$(\rho c)\frac{\partial \overline{T}}{\partial t} = K\nabla^2 T + \dot{q} \tag{1}$$

It can be assumed that there is no inner heat source, and the heat transfer through a wall is considered one-dimensional, so for every wall layer, the heat conduction equation takes the following form.

$$\frac{\partial T(x,t)}{\partial t} = a\frac{\partial^2 T(x,t)}{\partial x^2} \tag{2}$$

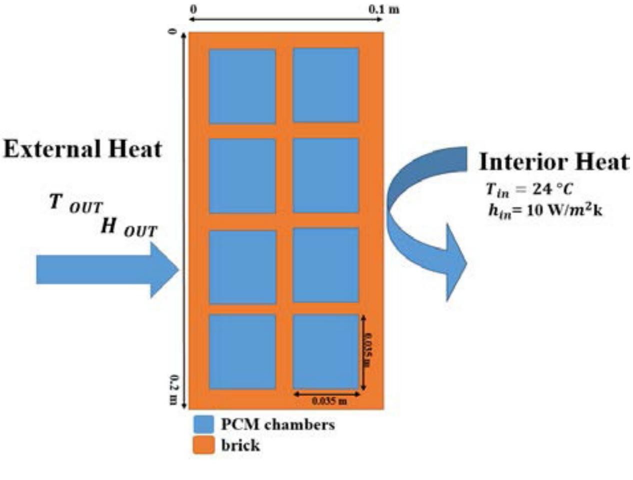


Fig. 2 Heat flow through the wall. Characteristic temperature boundary conditions (blue is chambers of PCM/ orange is bricks)

And the governing conservation equations are in the follows [31]. Continuity equation:

$$\frac{\partial \rho}{\partial t} + \nabla\left(\rho\vec{U}\right) = 0 \tag{3}$$

Momentum equation:

$$\frac{\partial}{\partial t}\left(\rho\vec{U}\right) + \nabla\left(\rho\vec{U}\vec{U}\right) = -\nabla P + \rho\vec{g} + \nabla\overline{\tau} + \vec{F} \tag{4}$$

Where P is the static pressure, $\overline{\tau}$ is the stress tensor, and $\rho\vec{g}$ and $\vec{F}$ are the gravitational body force and external body forces, respectively.

Energy equation:

$$\frac{\partial}{\partial t}(\rho H) + \nabla\left(\rho\vec{U}H\right) = \nabla(K\nabla T) + \dot{q} \tag{5}$$

Where H is the enthalpy of the nano-PCM, T is the temperature, ρ is the density of the nano-PCM, K is the thermal conductivity of the nano-PCM, $\vec{U}$ is the velocity, and $\dot{q}$ is the volumetric heat source term and is equal to zero in the present study. The total enthalpy H of PCM is calculated as the sum of sensible enthalpy h and latent heat ΔH. The latent heat content, expressed as the latent heat of PCM, L, is

$$\Delta H = \beta L\,, \tag{6}$$

where β is liquid fraction.

2.4 Thermo-physical properties

In this section, the density, specific heat capacity and latent heat of the nanoPCM are defined as follows [32]:

The density of the nanoPCM defined by

$$\rho_{npcm} = \phi\rho_{np} + (1-\phi)\,\rho_{pcm} \tag{7}$$

And the specific heat of the nanoPCM:

$$C_{p,npcm} = \frac{\phi\left(\rho c_p\right)_{np} + (1-\phi)\left(\rho c_p\right)_{pcm}}{\rho_{npcm}} \tag{8}$$

The capacity of the nanoPCM:

$$L_{npcm} = \frac{(1-\phi)(\rho L)_{pcm}}{\rho_{npcm}} \tag{9}$$

The dynamic viscosity and thermal conductivity of the nano-PCM are given by the following [32]. To find the new viscosity of the nano PCM, we do the following:

$$\mu_{npcm} = 0.983e^{(12.959\phi)}\mu_{pcm} \tag{10}$$

Conductivity equation:

$$\begin{aligned} K_{npcm} &= \frac{K_{np}+2K_{pcm}-2\left(K_{pcm}-K_{np}\right)\phi}{K_{np}+2K_{pcm}+\left(K_{pcm}-K_{np}\right)\phi}K_{pcm} \\ &+5.10^{4}\beta_{k}\zeta\phi\rho_{pcm}C_{P,pcm}\sqrt{\frac{\dot{B}T}{\rho_{np}d_{np}}}f\left(T,\phi\right), \end{aligned} \tag{11}$$

where $\dot{B}$ is Boltzmann constant 1.381 × 10−23 J/K and $\beta_k = 8.4407(100\phi)^{-1.07304}$.

The provided Eq. (11) includes a temperature reference, written as T "ref," which is equal to 273 K. The Maxwell model is used to obtain the first section of the equation. The second component of the equation allows the temperature-dependent effect of Brownian motion on effective thermal conductivity. To account for the absence of Brownian motion in the solid phase, a correction factor, indicated as ζ, is given to the Brownian motion component. This factor has the same value as the liquid fraction.

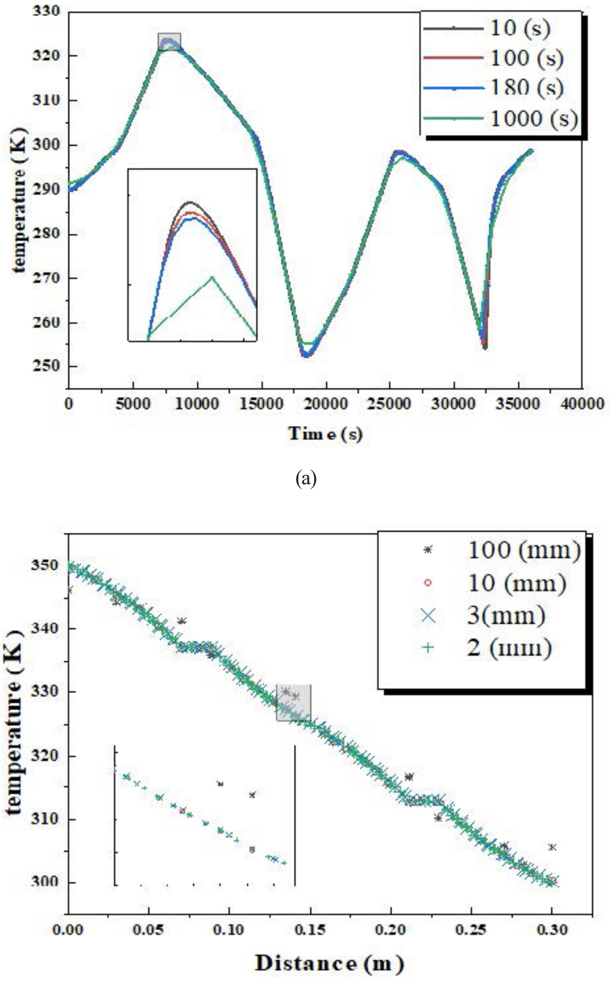
2.5 Time step and mesh sensitivity analysis

To ensure the accuracy of the simulation, both time step and mesh sensitivity were thoroughly examined. For the time step analysis, heat was applied to a brick wall with temperature limits based on the highest and lowest values of the year 2018. Various time steps were tested, revealing that a 180-second interval provided the best balance between precision and computational efficiency (Fig. 3 (a)), with larger time steps like 1000 seconds leading to noticeable deviations.

In the mesh sensitivity study (Fig. 3(b)), different mesh sizes 100 mm, 10 mm, 3 mm, and 2 mm were evaluated to optimize the accuracy of heat flow calculations through the wall. The 3 mm mesh was found to be the most effective, offering the same accuracy as the 2 mm mesh while minimizing computational resource usage and calculation time and Fig. 4 shows a close-up of the selected mesh.

2.6 Numerical validation

To validate the accuracy of the computational fluid dynamics (CFD) model, a numerical analysis was conducted to investigate the melting behavior of paraffin wax, serving as a phase change material (PCM) containing 5 wt% of Al_2O_3 nanoparticles within a square domain. The simulation results were systematically compared with the outcomes reported by Arasu and Mujumdar [33]. Fig. 5 depicts the comparison of the liquid fraction obtained through the current model and the liquid fraction derived from the study by Arasu and Mujumdar [33]. The visual representation in Fig. 4 demonstrates a satisfactory agreement



(a)

(b)

Fig. 3 Study the effect of time step and network sensitivity (a) time step, (b) network sensitivity

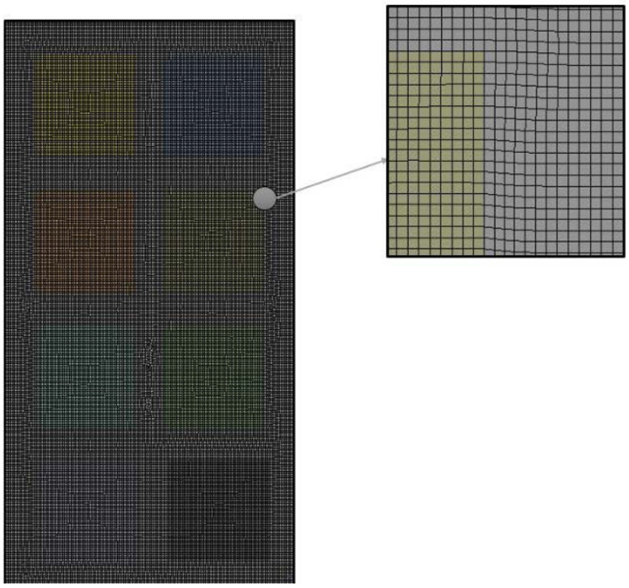


Fig. 4 Mesh used in the study

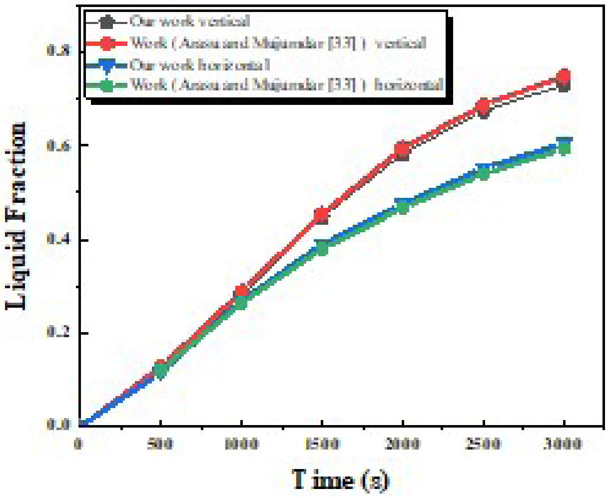


Fig. 5 Comparison of numerical model of liquid fraction

with the findings presented in [33]. Figs. 6 and 7 further illustrate the comparison of the present results concerning velocity vectors and isotherms with those obtained from the use of paraffin wax with 2 wt% of Al_2O_3 nanoparticles in the study by Arasu and Mujumdar [33]. Moreover, a comparison of the solid–liquid interface between the current work and that of Arasu and Mujumdar at t = 1000 s and t = 3000 s for paraffin wax with 2 wt% of Al_2O_3 [33] was performed. This detailed analysis showed a high level of agreement between the results of the two studies, with a small margin of error not exceeding 4 percent.

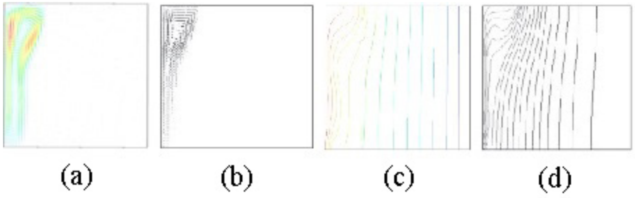


Fig. 6 Comparison of present results in terms of velocity vectors (left) and isotherms (right) with those that used paraffin wax with 2 wt% of Al_2O_3 nanoparticles [33], (a) Present work 500 s, (b) Arasu and Mujumdar [33] 500s, (c) Present work 500 s, (d) Arasu and Mujumdar [33] 500 s

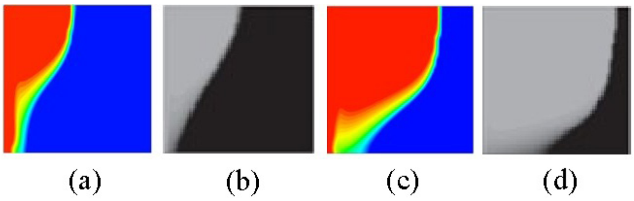


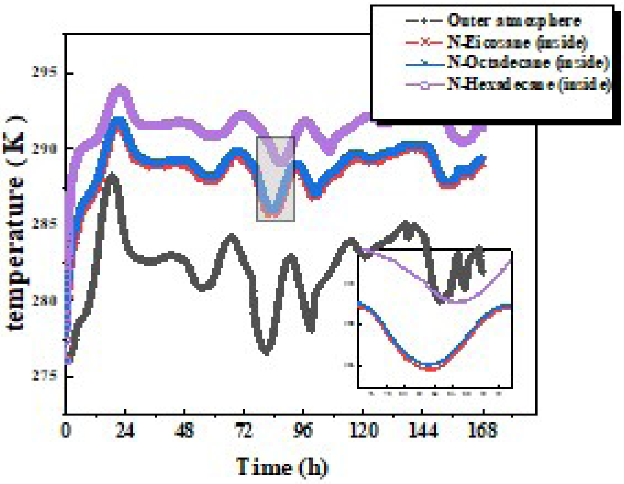
Fig. 7 Comparison of solid–liquid interface between present work and that of Arasuet al. at *t* = 1000 s and *t* = 3000 s for paraffin wax with 2 wt% of Al_2O_3 [33], (a) Present results 1000 s, (b) Arasu and Mujumdar [33] 1000 s, (c) Present results 3000 s, (d) Arasu and Mujumdar [33] 3000 s

3 Results and discussion

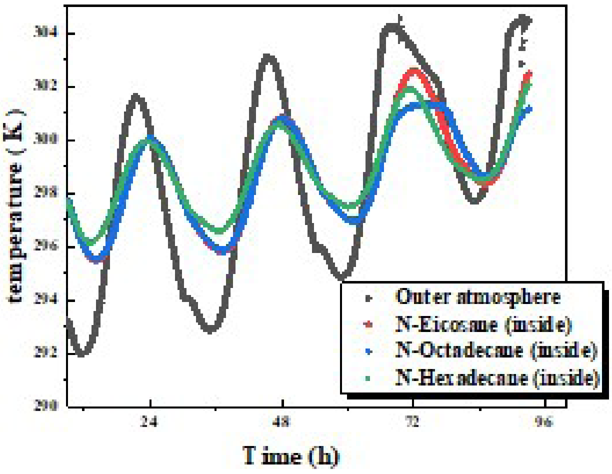
With the aim of selecting the best phase change materials for use in buildings to create thermal comfort in the Oum El Bouaghi region, Algeria, and trying to address the lack of thermal conductivity of phase change materials in order to obtain the best results, this work was completed and the following results were reached.

3.1 Distribution of temperature through time

Figs. 8(a) and 8(b) illustrate the temperature variation of the inner wall surface and ambient temperatures during January and July, based on real measurements from the study area. The wall, constructed with bricks containing cavities filled with phase change materials (PCMs) like N-octadecane, N-eicosane, and N-hexadecane (as shown in Table 2), demonstrated different behaviors depending



(a)



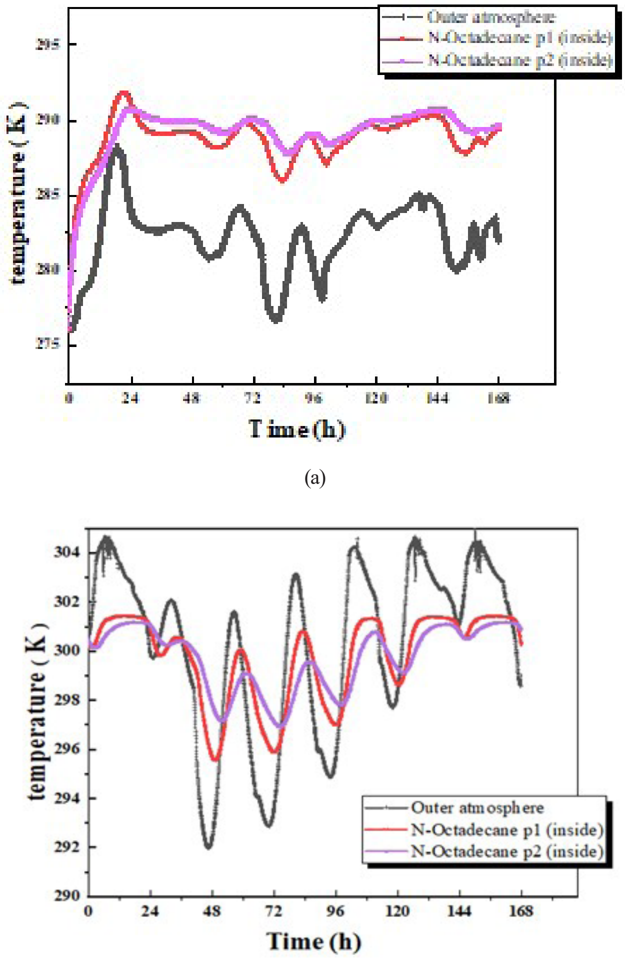
(b)

Fig. 8 Temperature distribution of interior and exterior walls; in protocol p_1 using different phase change materials, (a) 1–7 January 2018, (b) 2–6 July 2018 on the season. During January, N-hexadecane significantly outperformed N-octadecane and N-eicosane, maintaining a temperature closer to the optimal 24 °C and delaying peak amplitude at its melting point. However, in July, N-octadecane (Fig. 8(b)) outperformed the other materials, particularly near its melting point, where it stabilized temperatures more effectively and released heat in a manner closely aligned with indoor thermal comfort thresholds.

Figs. 9(a) and 9(b) display the temporal variation in interior wall surface temperatures and ambient temperatures throughout selected days in January and July. The investigation incorporates two distinct protocols, denoted as and, applied to a brick wall. Protocol features more cavities compared to, facilitating the integration of phase change materials like N-octadecane, N-eicosane, and N-hexadecane. Among these materials, the results pertaining to N-octadecane were selected for inter-protocol comparison due to their similarity to other materials, thereby avoiding redundancy. Analysis of the figures reveals that protocol exhibits superior insulation performance over by more than two degrees Celsius, and also demonstrates peak hour delay, exceeding that of during daytime hours, thereby impeding the outward flow of heat from the building.

3.2. Distribution of temperature through distance

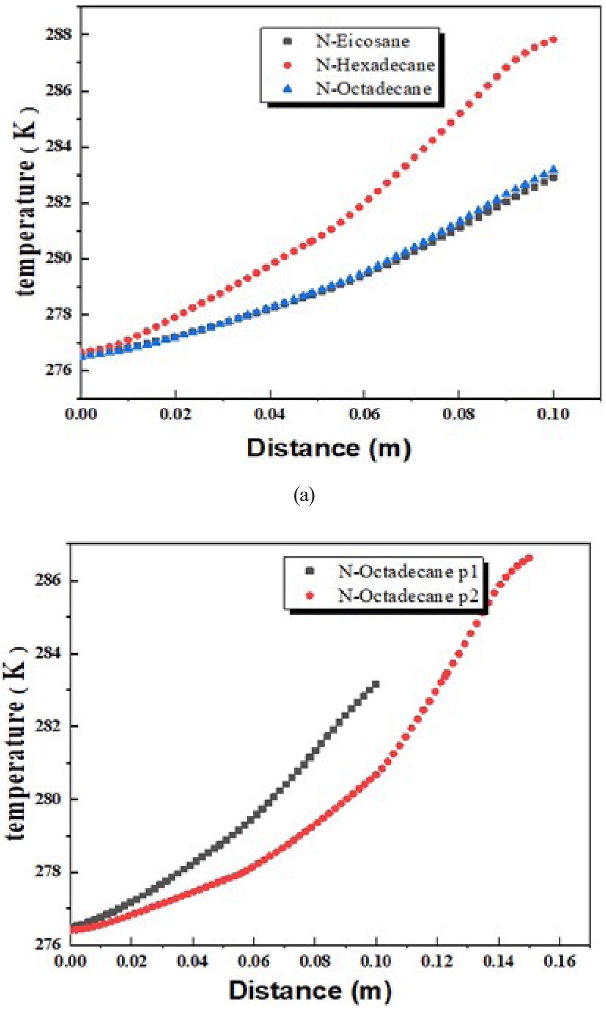
Fig. 10(a) Shows the range of average temperatures inside the wall to be investigated during a given hour of an average day (number results are extracted during the simulation, which initially explains the temperature difference), respectively. These numbers show that the brick wall and PCM combination N-hexadecane is more effective in reducing environmental impact (which has a lower ambient temperature) in January than N-octadecane and N-eicosane. Therefore, the PCM phase change temperature is a critical factor in determining the appropriate



(a)

(b)

Fig. 9 Distribution of indoor and outdoor temperatures over time; in protocols p_1 and p_2 (a) 1–7 January 2018, (b) 1–7 July 2018



(a)

(b)

Fig. 10 Temperature distribution over distance for bricks, (a) in protocol p_1, (b) in protocol p_1 and p_2

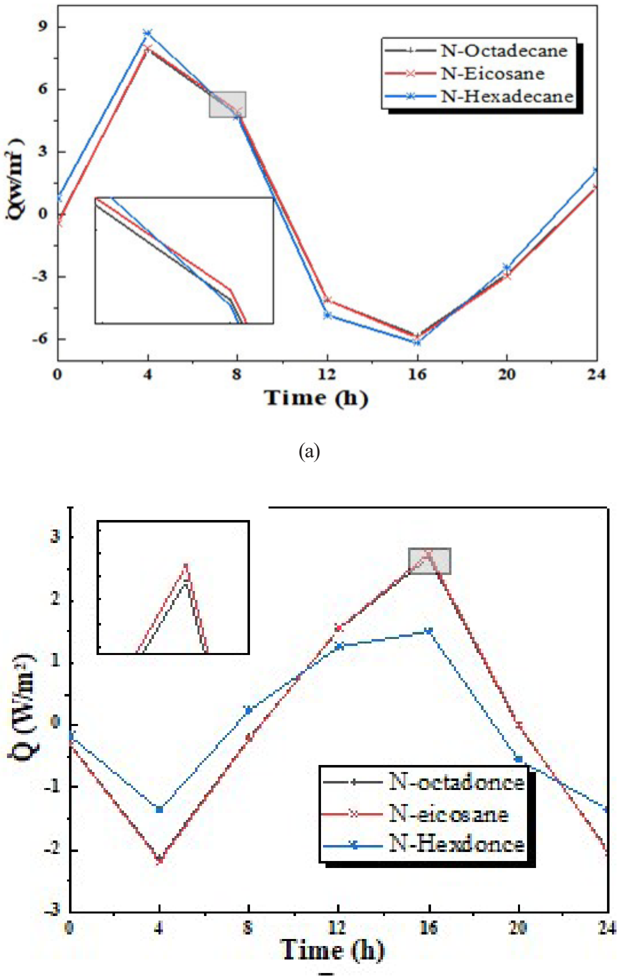
PCM for each region. In addition, this superiority is most likely due to the suitability of the phase change temperature of PCM N-hexadecan to the Oum El Bouaghi region in Algeria where the study was conducted. And (Fig. 10(b)) compares two protocols, and, and demonstrates that outperforms by up to 4 °C, particularly evident in the later onset of temperature change within the wall.

3.3 Distribution of heat flow

Fig. 11 illustrates the heat flow entering the room (positive values) or leaving the room (negative values) through the exterior walls. In Fig. 11(a (represents the heat flow during a July day for using a different phase change material. Similarly, Fig. 11(b) represents the heat flow during a January day for for each different phase change material. The heat flow is introduced into the wall every 4 hours. It is observed that the N-hexadecane phase change material outperforms N-octadecane and N-eicosane by reducing the heat flow, especially with positive flow (toward the chamber) in Figs. 11(a) and 11(b).

3.4 Study of nano-PCM effect

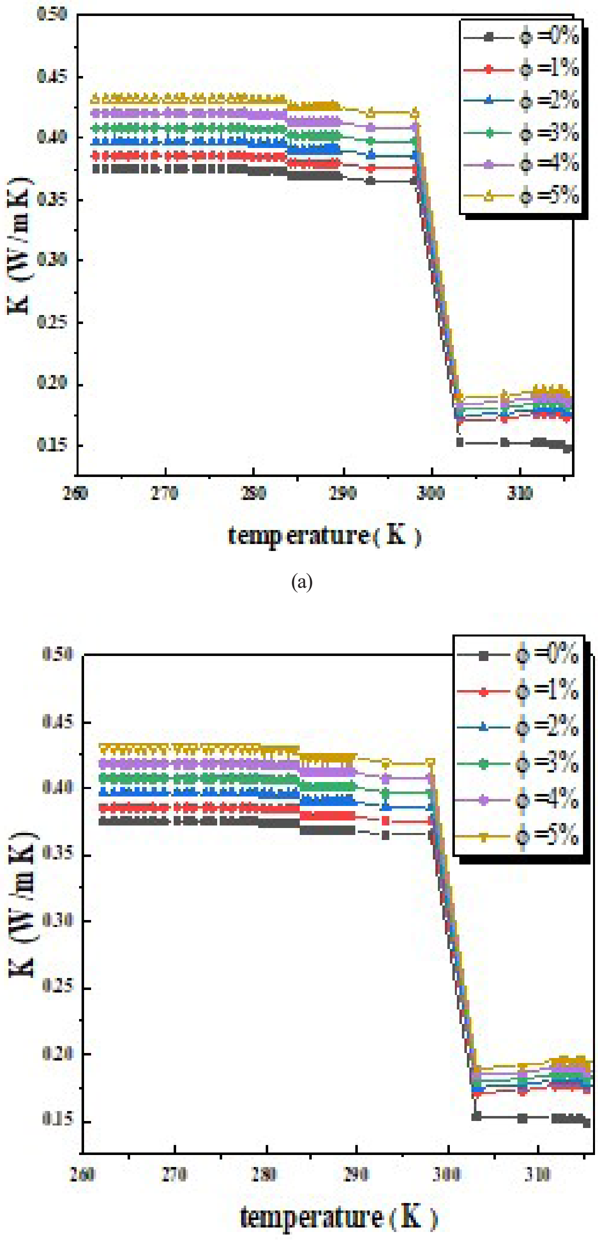
Fig. 12 shows the thermal conductivity figures of different phase change materials dispersed with nanoparticles, while Fig. 13 shows the dynamic viscosity figures of phase change materials dispersed with nanoparticles. The effective thermal conductivity and dynamic viscosity of selected phase change materials, namely N-octadecane,



(a)

(b)

Fig. 11 Distribution of heat flow versus time in the used protocols and the selected materials, (a) p_1 in July, (b) p_2 in January)



(a)

(b)

Fig. 12 PCM thermal conductivity, (a) N-octadonce with Al_2O_3, (b) N-octadoncewith CuO

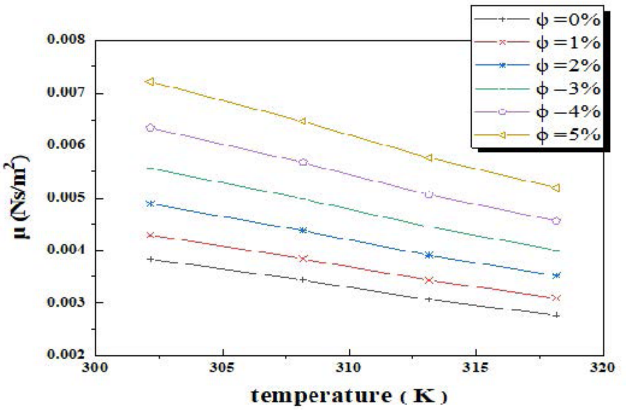
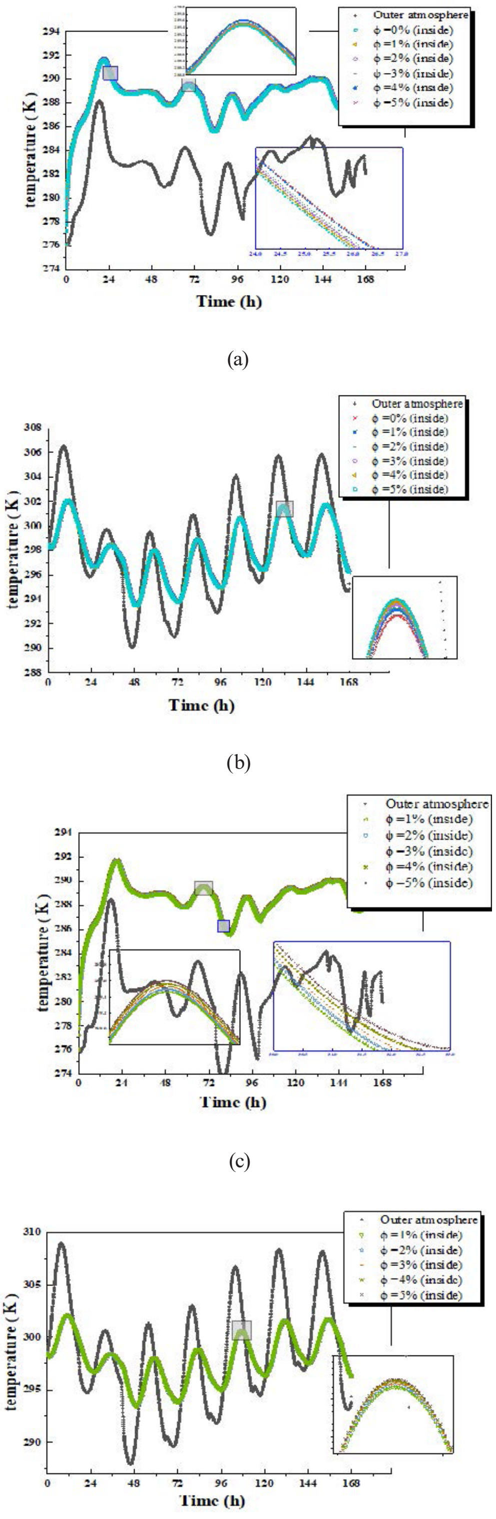


Fig. 13 N-octadecane PCM dynamic viscosity

N-eicosane, and N-hexadecane, dispersed with various volumes of Al_2O_3 and CuO nanoparticles (nanoPCM), ranging from 0% to 5%, were calculated using a specific equation. According to Fig. 12, the thermal conductivity of nanoPCM is greater than that of simple PCM, which results in a higher rate of thermal conductivity (the thermal conductivity of nanoPCM is increased to solve the problem of little absorption of PCM).

On the other hand, Fig. 13 reveals that the dynamic viscosity of nanoPCM increases as the nanoparticle concentration increases. This inc:rease in the dynamic viscosity of nanoPCM may affect the melting process in environments controlled by convection. Moreover, temperature and volume have an impact on the electrical conductivity and dynamic viscosity of nanoPCM, which is in agreement with the experimental findings reported in [33]. It is also worth noting that only the N-octadecane results were presented because all the results for the PCM materials are similar.

The research findings depicted in Fig. 14 illustrate the dynamic changes in interior wall surface temperatures alongside ambient temperatures over time for a brick wall employing Protocol p_1, integrated with varying proportions of phase change materials (PCM) — N-octadecane, N-eicosane, and N-hexadecan—dispersed at different nanoscale degrees (φ = 0%, 5%, 4%, 3%, 2%, and 1%) with the inclusion of Al_2O_3 and CuO. During the summer month of July, diurnal fluctuations indicate higher external wall surface temperatures compared to internal temperatures during daylight hours, whereas in winter, the internal temperature consistently tends towards an optimal range. Notably, an escalation in nanoparticle proportions correlates with heightened thermal conductivity, as evidenced by the augmented thermal transfer capacity of PCM compositions with increased nanoparticle content, as delineated in Figs. 14(a) and 14(c), aligning with prior



(a)

(b)

(c)

(d)

Fig. 14 Temperature distribution over time (January and July days); in protocol using different phase change materials and using nanoparticles; (a) A-Protocol p_1, N-eicosane with Al_2O_3 (January), (b) B-Protocol p_1, N-eicosane with Al_2O_3 (July), (c) C-Protocol p_1, N-eicosane with CuO (January), (d) D-Protocol p_1, N-eicosane with CuO (July) investigations [34, 35]. Although it is a slight superiority, it can be significant in other atmospheric conditions, as observed in the postponement of peak-hour occurrences with escalating nanoparticle ratios within PCM formulations. Specifically, the disparity between pure eicosane and dispersed eicosane becomes pronounced at a nanoparticle percentage of 5%, where temporal discrepancies, notably in heat dissipation, may extend to 1.5 h, consistent with earlier research endeavors such as study [36]. Furthermore, the augmented nanoparticle presence augments heat absorption capabilities, thereby enhancing PCM efficiency in harnessing and utilizing solar energy to prolong peak-hour occurrences. Despite comprehensive experimentation encompassing diverse seasonal conditions, the innate thermal conductivity limitations and viscosity effects of PCM warrant further exploration to optimally harness their potential. Additionally, it is pertinent to note that the presentation exclusively focuses on results pertaining to N-eicosane PCM, given the general similarity in outcomes across various PCM materials.

Fig. 15 depicts the introduction of heat flow into the wall every four hours during an average day in January, serving as a representative instance from numerous akin experiments to circumvent redundancy in reporting comparable findings. Observations indicate that the incorporation of nanoparticles into phase change materials (PCM) amplifies the magnitude of heat flux, thereby augmenting heat absorption capabilities. Conversely, PCM formulations devoid of nanoparticles exhibit comparatively lower heat flux levels. For instance, PCM lacking nanoparticles registers a heat flux of 103.61 W/m^2, whereas PCM containing 5% nanoparticles records a heat flux of 103.84 W/m^2. The adoption of nano-PCM technology evidently bolsters the thermal absorption attributes of phase-change materials.

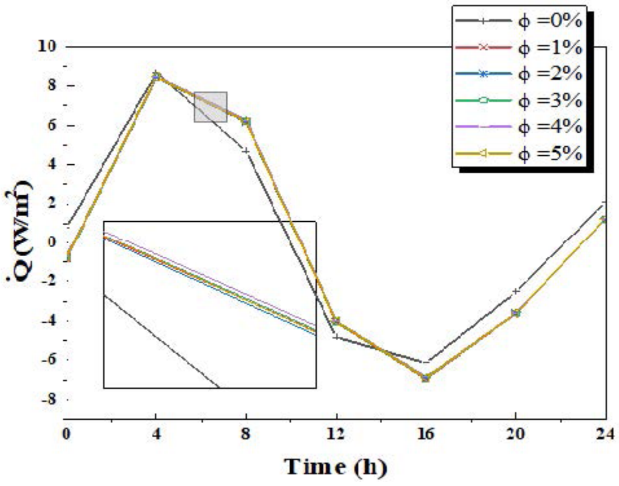


Fig. 15 Distribution of heat flow (days in January) in protocols p_1; using N-hexdonce and using Al_2O_3 nanoparticles

4 Conclusion

The primary objective of this study was to investigate the effects of organic phase change materials (PCMs) — N-n-octadecane, N-n-eicosane, and N-n-hexadecane — on maintaining temperatures close to thermal comfort and optimizing heat transfer in buildings during summer and winter. The PCMs were chosen based on the climatic conditions of the target region. Additionally, the study examined the impact of incorporating nanoparticles, specifically Al_2O_3 and CuO, at varying concentrations (0% to 5%), to enhance the performance of the PCMs.

Where this study found:

The protocol (p_1) outperforms its counterpart (p_1) by more than two degrees in terms of insulation, and (p_2) provides a delay for the peak hour during the day more than (p_1) and prevents the flow of heat amount outside the building.

Phase-change materials (PCMs) have demonstrated significant efficacy in energy conservation within buildings. However, it appears that N-hexadecane, with its variable phase, exhibits greater effectiveness than octadecane/ N-eicosane during the winter months. Conversely, during the summer, octadecane stands out due to its ability to reach its melting point, proving advantageous for both studied protocols.

The presence of nanoparticles in PCM improves and solves the problem of thermal conductivity. It also affects the viscosity and latent temperature, and also ensures greater heat absorption and delays the peak capacities, but it needs further research for use inside the walls of buildings. It may be appropriate to incorporate nanoparticles into gypsum boards that contain phase change materials to solve the problem. The issue of thermal conductivity.

The incorporation of nanoparticles into phase change materials improved thermal conductivity and thus increased the absorption rate of phase change materials. However, it requires further research to determine its suitability for direct incorporation into PCMs, and it may be a viable option to incorporate nanoparticles into gypsum boards containing PCM, as a means of solving the thermal conductivity problem. In addition, emulsification of PCMs resulted in a relative increase in dynamic viscosity compared to the previous viscosity, highlighting the importance of appropriate emulsifier selection to ensure optimal performance.

In previous studies, researchers encountered issues with the panel's thermal conductivity made of gypsum and PCM encapsulated in microcapsules. To address this problem, capillary tubes have been employed in gypsum boards to dissipate absorbed heat. However, incorporating nanoparticles into PCMs has been suggested in this study as a potential solution to enhance thermal conductivity. While further research is needed to determine its suitable use within building walls, integrating nanoparticles into gypsum boards containing phase change materials may offer a promising means to resolve the thermal conductivity issue.

Where these results may be useful to reduce the wall thickness in conventional buildings, thus decreasing its volume and consequently increasing the usable living area. It is beneficial for buildings residents, builders and real-estates.

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Nomenclature

a	thermal diffusivity coefficient [m^2/s]
$\dot{B}$	Boltzmann constant [J/K]
β	liquid fraction [l]
c	specific heat capacity of the material [J/kgK]
c_p	specific heat at constant pressure [J/kgK]
d_{np}	diameter of nanoparticles [10^{-6} mm]
$\overline{F}$	external body forces [N]
$\vec{g}$	gravitational [9.81 m/s^2]
h	specific enthalpy of the nanoPCM [J/kg]
K	thermal conductivity [W/mK]
L	latent heat [J/kg]
P	static pressure [N/m^2]
$\dot{q}$	volumetric heat source [W/m^3]
T	temperature [K]
$\overline{T}$	average temperature [K]
T_{liqu}	liquidus temperature [K]
$T_{solidus}$	solidus temperature [K]
T_{ref}	reference temperature [K]
t	time [s]
ΔH	latent heat [J/kg]
μ	Dynamic viscosity [Ns/m^2]
ρ	density [kg/m^3]
ϕ	volumetric fraction of nanoparticle [l]
$\overline{\tau}$	the stress tensor [l]
∇	nabla operator
ξ	correction factor [l]
pcm	base PCM
np	nanoparticle
$npcm$	nano PCM

References

[1] Zalba, B., Marín, J. M., Cabeza, L. F., Mehling, H. "Review on thermal energy storage with phase change: materials, heat transfer analysis and applications", Applied Thermal Engineering, 23(3), pp. 251–283, 2003. https://doi.org/10.1016/S1359-4311(02)00192-8

[2] Khudhair, A. M., Farid, M. M. "A review on energy conservation in building applications with thermal storage by latent heat using phase change materials", Energy Conversion and Management, 45(2), pp. 263–275, 2004. https://doi.org/10.1016/S0196-8904(03)00131-6

[3] Cabeza, L. F., Castell, A., Barreneche, C., De Gracia, A., Fernández, A. I. "Materials used as PCM in thermal energy storage in buildings: A review", Renewable and Sustainable Energy Reviews, 15(3), pp. 1675–1695, 2011. https://doi.org/10.1016/j.rser.2010.11.018

[4] Wu, W., Li, W., Han, H., Xu, M., Lu, E., Wang, Z. Zhai, C. "Advanced thermal energy storage made of a ternary CPCM with two phase change temperatures in building walls", Energy and Buildings, 318, 114445, 2024. https://doi.org/10.1016/j.enbuild.2024.114445

[5] Chihab, Y., Bouferra, R., Bouchehma, A. "Transient thermal behavior of clay walls integrated with phase change materials", Journal of Energy Storage, 73, 109246, 2023. https://doi.org/10.1016/j.est.2023.109246

[6] Yun, B. Y., Yang, S., Cho, H. M., Chang, S. J., Kim, S. "Design and analysis of phase change material-based floor heating system for thermal energy storage", Environmental Research, 173, pp. 480–488, 2019. https://doi.org/10.1016/j.envres.2019.03.049

[7] Aidi, M., Harnane, Y., Bouzid, S., Bordja, L. "Numerical Study on the Effect of Incorporating Phase Change Materials in a Wall", International Journal of Automotive and Mechanical Engineering, 21(2), pp. 11287–11301, 2024. https://doi.org/10.15282/ijame.21.2.2024.9.0872

[8] Hannig J. M. "Testing and simulation of phase change material wallboard for thermal storage in buildings", Thesis, University of Dayton, 1998. [online] Available at: https://ecommons.udayton.edu/graduate_theses/3133 [Accessed: 20 December 2024]

[9] Kissock, K., Limas, S. "Diurnal Load Reduction Through Phase-Change Building Components", ASHRAE Transactions, 112(1), pp. 509–517, 2006.

[10] Arce, P., Castellón, C., Castell, A., Cabeza, L. F. "Use of microencapsulated PCM in buildings and the effect of adding awnings", Energy and Buildings, 44, pp. 88–93, 2012. https://doi.org/10.1016/j.enbuild.2011.10.028

[11] Cabeza, L. F., Castellon, C., Nogues, M., Medrano, M., Leppers, R., Zubillaga, O. "Use of microencapsulated PCM in concrete walls for energy savings", Energy and Buildings, 39(2), pp. 113–119, 2007. https://doi.org/10.1016/j.enbuild.2006.03.030

[12] Li, S., Sun, G., Zou, K., Zhang, X. "Experimental research on the dynamic thermal performance of a novel triple-pane building window filled with PCM", Sustainable Cities and Society, 27, pp. 15–22, 2016. https://doi.org/10.1016/j.scs.2016.08.014

[13] Silva, T., Vicente, R., Rodrigues, F., Samagaio, A., Cardoso, C. "Development of a window shutter with phase change materials: Full scale outdoor experimental approach", Energy and Buildings, 88, pp. 110–121, 2015. https://doi.org/10.1016/j.enbuild.2014.11.053

[14] Silva, T., Vicente, R., Rodrigues, F., Samagaio, A., Cardoso, C. "Performance of a window shutter with phase change material under summer Mediterranean climate conditions", Applied Thermal Engineering, 84, pp. 246–256, 2015. https://doi.org/10.1016/j.applthermaleng.2015.03.059

[15] Vicente, R., Silva, T. "Brick masonry walls with PCM macrocapsules: An experimental approach", Applied Thermal Engineering, 67(1–2), pp. 24–34, 2014. https://doi.org/10.1016/j.applthermaleng.2014.02.069

[16] Kong, X., Lu, S., Huang, J., Cai, Z., Wei, S. "Experimental research on the use of phase change materials in perforated brick rooms for cooling storage", Energy and Buildings, 62, pp. 597–604, 2013. https://doi.org/10.1016/j.enbuild.2013.03.048

[17] Marín, J. M., Zalba, B., Cabeza, L. F., Mehling, H. "Improvement of a thermal energy storage using plates with paraffin–graphite composite", International Journal of Heat and Mass Transfer, 48(12), pp. 2561–2570, 2005. https://doi.org/10.1016/j.ijheatmasstransfer.2004.11.027

[18] Cerón, I., Neila, J., Khayet, M. "Experimental tile with phase change materials (PCM) for building use", Energy and Buildings, 43(8), pp. 1869–1874, 2011. https://doi.org/10.1016/j.enbuild.2011.03.031

[19] Voelker, C., Kornadt, O., Ostry, M. "Temperature reduction due to the application of phase change materials", Energy and Buildings, 40(5), pp. 937–944, 2008. https://doi.org/10.1016/j.enbuild.2007.07.008

[20] Ju, S., Miao, Y., Wang, L., Shi, J., Wang, F., Liu, Z., Jiang, J. "Development of octadecane/silica phase change nanocapsules for enhancing the thermal storage capacity of cement-based materials", Journal of Energy Storage, 89, 111636, 2024. https://doi.org/10.1016/j.est.2023.111636

[21] Koschenz, M., Lehmann, B. "Development of a thermally activated ceiling panel with PCM for application in lightweight and retrofitted buildings", Energy and Buildings, 36(6), pp. 567–578, 2004. https://doi.org/10.1016/j.enbuild.2004.01.016

[22] Selvasofia, S. D. A., Shri, S. D., Kumar, P. M., Prakash, K. B. "Characterization of bio-nano doped phase change material (bio-nano/PCM) for building energy management", Energy Sources, Part A: Recovery, Utilization, and Environmental Effects, 46(1), pp. 3760–3778, 2024. https://doi.org/10.1080/15567036.2023.2205235

[23] Reddy, V. J., Ghazali, M. F., Kumarasamy, S. "Advancements in phase change materials for energy-efficient building construction: A comprehensive review", Journal of Energy Storage, 81, 110494, 2024. https://doi.org/10.1016/j.est.2023.110494

[24] Khazaal, M. A., Daneh-Dezfuli, A., Habeeb, L. J. "Influence of Nanoparticle Concentrations on Heat Transfer in Nano-enhanced Phase Change Materials", Power Engineering and Engineering Thermophysics, 2(4), pp. 228–237, 2023. https://doi.org/10.56578/peet020404

[25] Jacob, J., Paul, J., Selvaraj, J., Vaka, M. "Phase change materials integrated buildings: A short review", IOP Conference Series: Earth and Environmental Science, 1281(1), 012008, 2023. https://doi.org/10.1088/1755-1315/1281/1/012008

[26] Chwieduk, D. A. "Dynamics of external wall structures with a PCM (phase change materials) in high latitude countries", Energy, 59, pp. 301–313, 2013. https://doi.org/10.1016/j.energy.2013.06.066

[27] Sasmito, A. P., Kurnia, J. C., Mujumdar, A. S. "Numerical evaluation of laminar heat transfer enhancement in nanofluid flow in coiled square tubes", Nanoscale Research Letters, 6(1), 376, 2011. https://doi.org/10.1186/1556-276X-6-376

[28] Rossini, F. D., Li, K. "Selected values of physical and thermodynamic properties of hydrocarbons and related compounds: comprising the tables of the American Petroleum Institute Research Project 44 extant as of December 31, 1952", American Petroleum Institute, 1953.

[29] Vélez, C., Khayet, M., De Zárate, J. M. O. "Temperature-dependent thermal properties of solid/liquid phase change even-numbered n-alkanes: n-Hexadecane, n-octadecane and n-eicosane", Applied Energy, 143, pp. 383–394, 2015. https://doi.org/10.1016/j.apenergy.2015.01.054

[30] Motahar, S., Nikkam, N., Alemrajabi, A. A., Khodabandeh, R., Toprak, M. S., Muhammed, M. "A novel phase change material containing mesoporous silica nanoparticles for thermal storage: a study on thermal conductivity and viscosity", International Communications in Heat and Mass Transfer, 56, pp. 114–120, 2014. https://doi.org/10.1016/j.icheatmasstransfer.2014.06.005

[31] Ansys Inc. "ANSYS Fluent Theory Guide", [pdf] Ansys Inc., Canonsburg, PA, USA, 2024. Available at: https://dl.cfdexperts.net/cfd_resources/Ansys_Documentation/Fluent/Ansys_Fluent_Theory_Guide.pdf [Accessed: 19 December 2024]

[32] Chow, L. C., Zhong, J. K., Beam, J. E. "Thermal conductivity enhancement for phase change storage media", International Communications in Heat and Mass Transfer, 23(1), pp. 91–100, 1996. https://doi.org/10.1016/0735-1933(95)00087-9

[33] Arasu, A. V., Mujumdar, A. S. "Numerical study on melting of paraffin wax with Al_2O_3 in a square enclosure", International Communications in Heat and Mass Transfer, 39(1), pp. 8–16, 2012. https://doi.org/10.1016/j.icheatmasstransfer.2011.09.013

[34] Yang, R., Li, D., Salazar, S. L., Rao, Z., Arıcı, M., Wei, W. "Photothermal properties and photothermal conversion performance of nano-enhanced paraffin as a phase change thermal energy storage material", Solar Energy Materials and Solar Cells, 219, 110792, 2021. https://doi.org/10.1016/j.solmat.2020.110792

[35] Tong, X., Li, D., Yang, R., Arıcı, M., Wu, Y., Liu, C., Yıldız, Ç. "Experimental investigation on photothermal properties of Zn–ZnO/paraffin hybrid nanofluids", Journal of Thermal Analysis and Calorimetry, 148(20), pp. 11029–11040, 2023. https://doi.org/10.1007/s10973-023-12310-1

[36] Li, D., Wu, Y., Liu, C., Zhang, G., Arıcı, M. "Numerical investigation of thermal and optical performance of window units filled with nanoparticle-enhanced PCM", International Journal of Heat and Mass Transfer, 125, pp. 1321–1332, 2018. https://doi.org/10.1016/j.ijheatmasstransfer.2018.04.152