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Thermal Management and Efficiency Improvements in PCM-based Energy Storage Systems

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***Abstract*—This work studies the performance of thermal energy storage (TES) with phase change materials (PCMs) and the effect of different heat transfer fluid (HTF) - PCM configurations on melt behaviour and overall storage system efficiency. The analysis is based on a 2D numerical model of herringbone-arranged PCM-filled pipe along which is horizontally installed, and HTF is passing through an external tube that is separated by a copper partition. The PCM, which is used to improve the thermal conductivity of the matrix, is composed of Palmitic acid, 1% graphene nanoparticles. Results indicate impressive enhancements of melting time and energy storage rate. For the baseline setup, with PCM and HTF being neighbouring, the melting time amounted to 19,179 sec. The melting time was 6,661 sec when a layer of HTF was introduced (case 1), which was respectively 65.26% lower. Even better solution was found in the case 2 (three-layer concentric), according to which the ruggedness time was 1,140 s and the time decrease was 94.05%. The most effective case, Case 3 (alternating PCM and HTF layers of 4 layers constitute the configuration) provides a minimum melting time of 586 seconds, which is a considerable 96.94% reduction from the reference case. These results highlight the significance of increasing the contact between HTF and PCM for improved heat transfer, but also points out that excessive further increases of the contact area will result in diminishing returns. The results of the study are useful for the design and optimization of PCM-based TES systems, especially at industrial scales.**

Keywords— Energy storage, Phase change material (PCM), Nanoparticles, Enhancement, Thermal management, Heat transfer fluid (HTF).

I. INTRODUCTION

This has greatly raised the demand for advanced energy storage technologies that are available on a large scale, efficient and reliable. With an increase in usage of renewable energy sources like solar and wind power, the need for effective thermal energy storage (TES) systems has increased in order to mitigate intermittency and guarantee energy availability [6]. Of different TES strategies, phase change materials (PCMs) show potential as promising candidates for TES, as they can absorb and yield considerable amounts of thermal energy during phase transitions. This feature allows the PCMs to control temperature changes and transfer heat between the pairs of molecules making them well-suited for this task; hence they find their use in space heating, cooling applications, and thermal management in professional and domestic sectors. PCM-based TES systems play a vital role in promoting energy efficiency, leading to a considerable decrease in the use of traditional fossil-fuel-based cooling and heating systems and subsequently alleviating the environmental impact and reducing carbon emissions.

In the last decade, several studies have been performed to enhance the performance of the PCM-based TES systems, with respect to its heat transfer features and applicability. A wide array of experimental and numerical studies have focused on different configurations and designs of these PCMs and systems to enhance their thermal performance. Aadmi et al. [1] investigated melting characteristics of PCM in a horizontal tube configuration, providing a foundation of melting characteristics for heat distribution in PCM system. Tay et al. [2] proposed a dynamic melting model for tube-in-tank systems, establishing a basis for improved thermal management protocols. (Liquid flowing) PCM windows by Chow and Lyu [3] revealed the benefits of PCM heat exchangers, where thermal regulation and energy savings can be enhanced. Additionally, Pahamli et al. [4], showed that achievement of heat transfer improvement by utilizing coupled inner pipe movement in double-pipe heat exchangers could reach due to phase change dynamics growth. Recent innovations in structural modifications have also contributed to the advances in PCM-based TES designs. Shinde et al. [5] which proposed the usage of a PCM pipe bank for space heating with significant improvements in energetic and thermal performance. Further, Boudjemline et al. [6] and Said et al. [7] studied wavy wall structures for heat recovery enhancement and latent heat storage improvement and found that the configuration was successful in shortening melting time and increasing the overall heat exchange rate. The melting characteristics of PCMs inside vertical tubes were investigated by Bechiri and Mansouri [8], highlighting the impact of the geometry and orientation on the thermal performance. Kurnia et al. [9] proposed an optimized PCM system with improved heat transfer surfaces, while Zhang et al. [10] enhanced these PCM-based systems by embedding heat pipe technology in them. Other studies, including those of Mellouli et al. [11] and Delgado et al. However, hybrid PCM solutions, such as metal hydride-PCM tanks [12], and microencapsulated PCM slurries [13] showed improved thermal conductivity and improved TES performance due to their enhanced heat transfer property compared to pure PCM.

This analysis is a part of our study to evaluate the thermal storage of PCM in 2D pipe configuration in the presence of water as the heat transfer fluid (HTF) flowing in the horizontal direction separated from PCM by a copper wall. The study follows a superficial if sectional analysis, albeit with replicated surface area engagements between PCMs and HTFs, to determine the heat transfer performance between the two types of materials at different conditions. Until now, the most recent studies on PCM-TES systems have concluded by evaluating how various design approaches and material choices affect system performance. The main aims of this study are:

- Mid-term project horizon: Design optimization of a compact and efficient thermal energy storage system using phase change materials.
- Evaluate multiple PCM-HTF systems to improve heat transfer performance to enhance energy storage efficiencies and decrease melting time.
- Develop numerical simulations and models to analyze the scalability and feasibility of PCM-based TES systems for large-scale industrial applications.
- Construct high energy storage industrial thermal management applications by optimizing design strategy and material selection for sustainable and affordable solutions

Thus, this study is focused on these aims, intends to add knowledge to next-generation PCM-based TES technologies, and ultimately contribute to the broader field of sustainable energy and optimal thermal storage.

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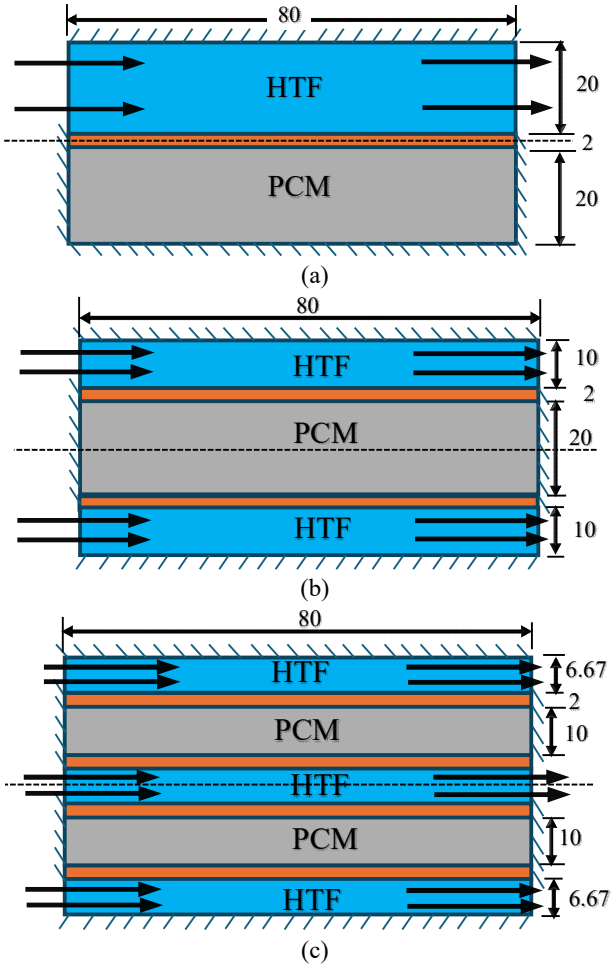
2. PROBLEM DESCRIPTIONS AND MODELLING

This work studies in detail the numerical characterization of one thermal energy storage (TES) system, where phase change material (PCM) is filled into a circular pipe. Under diverse geometric configurations, the system is utilized to evaluate heat transfer efficiency and latent heat storage performance. The main physical model is a horizontal phase change material (PCM) domain placed inside a circular pipe with dimensions: L = 80 mm (horizontal) and B = 20 mm (vertical). This is illustrated in the scheme in Fig. 1.

Water (T_w = 343 K) as a constant-temperature heat transfer fluid (HTF) flows horizontally across the adjacently located vertical pipe (B = 20 mm and L = 80 mm). A copper barrier of 2 mm thick is established between the PCM and HTF regions for thermal insulation and to limit conduction heat transfer through the structural integrity of the material. HTF flows through the tubes in the laminar region (Re = 1000), to control the convective heat transfer. This lower melting temperature (T_m) of the PCM compared to the inlet HTF temperature allows for a phase transition to occur during heat exchange. All system external walls are adiabatic except the inlet and outlet of the HTF pipe, minimizing heat loss to surroundings.



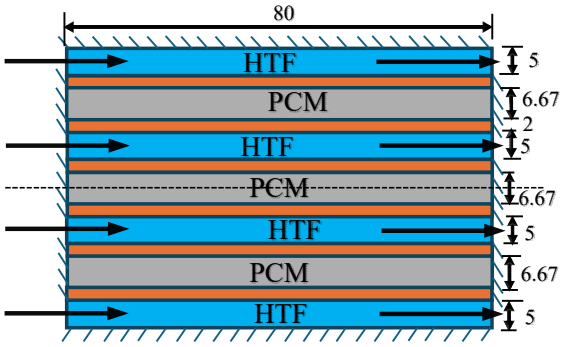


Figure 1. Schematic diagram of the set-up comprising (a) Base Case, (b) Case 1, (c) Case 2, and (d) Case 3 (all dimensions are in millimetre)

For the base Case configuration, the PCM and HTF domains are positioned adjacently, each having a height of 40 mm and a length of 80 mm, separated by the copper barrier. The study further explores three additional physical configurations to analyse the impact of geometrical modifications on heat transfer performance and latent heat storage efficiency.

- The first configuration (Case 1) is that the HTF passes through a rectangular pipe (80 mm × 20 mm), wrapped around with a 20 mm thick PCM layer and a 2 mm copper barrier to protect thermal conduction. This arrangement promotes heat transfer since it provides maximum contact area of the PCM with heat source.
- A concentric configuration (Case 2) with multiple pipes, where Heat Transfer Fluid (HTF) passes through each the central and outer pipes (6.67 mm thick each) and phase-change material is only housed inside an annular region of 10 mm. This design, featuring two 2 mm copper barriers that are separated from each other, promotes bi-directional heat absorption, enhancing energy storage and uniform melting.
- In the third configuration (Case 3), a four-layer concentric pipe system is used, which may contain alternating PCM (6.67 mm) and HTF (5 mm) layers. PCM-HTF-CCRs promote contact with a large overall surface area and improve thermal response and phase transition by virtue of the increased PCM-HTF interaction area.

The total PCM and HTF volumes are constant for all cases with an initial system temperature of 300 K. Palmitic acid ($CH_3(CH_2)_{14}COOH$) modified with 1% graphene nanoparticles is the PCM and copper (Cu) acts as the barrier due to its high thermal conductivity characteristics. The thermophysical properties of these materials are listed in Table 1.

Using numerical simulations, this study evaluates latent heat energy storage time, heat transfer characteristics, and energy efficiency per configuration. The enthalpy-porosity approach is followed to simulate the melting process, which allows for accurate characterization of the melting process as well as the heat transfer properties in PCM TES systems. The governing equations [14] are as follows:

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$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0 \tag{1}$$

$$\rho\left(\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}\right)=\mu\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right)-\frac{\partial p}{\partial x} -\frac{\mu}{k}u-A_{mush}\frac{(1-f)^2}{f^3+\delta}u \tag{2}$$

$$\rho\left(\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}\right)=\mu\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}\right)-\frac{\partial p}{\partial y}-\frac{\mu}{k}v -A_{mush}\frac{(1-f)^2}{f^3+\delta}v+\rho_{ref}g\beta(T-T_{ref}) \tag{3}$$

$$\left(\rho C_p\right)_{PCM}\left[\frac{\partial T}{\partial t}+u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}\right]=K_{PCM}\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}\right) -\left[\frac{\partial}{\partial t}(\rho\Delta h)+u\frac{\partial}{\partial x}(\rho u\Delta h)+v\frac{\partial}{\partial y}(\rho v\Delta h)\right] \tag{4}$$

$$f=\begin{cases} f=1, & T>T_m \\ \dfrac{T-T_s}{T_m-T_s}, & T_s<T<T_m \\ f=0, & T<T_s \end{cases} \tag{5}$$

The total enthalpy is defined as the summation of sensible heat capacity and the latent heat of phase change, which is defined as: $\Delta h=h+L$ and the sensible enthalpy is as follows:

$h=h_{ref}+\int_{T_{ref}}^{T}C_p\,dT$; where h_{ref} is the sensible enthalpy of PCM (at T_{ref}). (6)

3. NUMERICAL TECHNIQUE

A 2D computational domain is developed using the finite volume-based Ansys FLUENT solver to run the numerical simulations. The PCM-filled cavity with dimensions of 80 mm × 40 mm is discretized using a quadrilateral cell mesh structure to guarantee the computational accuracy and stability. A mesh independence study is carried out using grid sizes of 160×80, 200×100, 240×120, 320×80, and 400×200, with the 400×200 grid (58,100 nodes, 56,320 elements) shown to be most appropriate, with an ideal and computationally ability balance.

Furthermore, a time independence analysis was performed with time step sizes equal to 2 s, 1 s, 0.5 s, 0.2 s, and 0.1 s, which showed that with a time step size equal to 1 s, not only guaranteeing a numerical stability but also accurate results. For density variation of PCM, the Boussinesq approximation is used, whereas the specific heat values are expressed as piecewise-linear functions to model the phase change correctly.

For pressure-velocity coupling, the SIMPLE scheme is used and for turbulence closure, PRESTO! scheme used for pressure correction equations to enhance the stability of low-speed convective flows. The initialization was standard, and 70 iterations per time step of 1 s were verified for converging and numerical accuracy in the simulation procedure [15].

Before executing an extensive simulation, the current computational approach undergoes a validation process to assess its accuracy. This is achieved by benchmarking against a previously published problem. As an initial verification of the developed model, the numerical framework proposed by Colla et al. [16] is simulated. The problem configuration consists of finned rectangular enclosures filled with pure RT-45 phase change material (PCM) and RT-55 PCM infused with 1% Al_2O_3 nanoparticles. The enclosure has a base length of 40 mm and a height of 50 mm. The base of this rectangular system is subjected to a constant heat input of 10 W, while the remaining boundaries are considered adiabatic, with the top surface exposed to ambient air. The cavity is initially filled with RT-45 PCM. The validation of the present computational methodology is carried out by comparing the temporal evolution of the liquid fraction with the published numerical results of Colla et al. [16] for 1% Al_2O_3 nanoparticle-enhanced RT-55 PCM 9as shown in Fig. 2). The comparison exhibiting strong concordance with the current numerical findings, with a deviation of less than 3% from the results of Colla et al. [16]. This comparative analysis affirms the high accuracy and reliability of the proposed computational technique.

Table 1 Thermo-physical properties of palmitic acid ($CH_3(CH_2)_{14}COOH$) enhanced with 1% graphene nanoparticles, water (at 343K), conducting wall material (copper) [14,15]

Properties	Palmitic Acid	Copper	Water	Graphene Nano-particles
Density (kg/m³)	Temperature (K): 332.84, 334.14. Density (kg/m³): 942, 862	8978	974.79 at 343K	2267
Heat Capacity (J/kg.K)	Temperature (K): 332.84, 334.14. Heat Capacity (J/kg.K): 2200, 2480	381	4190 at 343K	700
Thermal Conductivity (W/m.K)	0.16	387.6	0.671 at 343K	5300
Viscosity (Kg/m.s)	0.007998	-	0.000380 at 343K	-
Thermal Expansion Factor (J/K)	7.72×10^{-4}	-	-	1.25×10^{-5}
Latent Heat (J/kg)	2.03400×10^{6}	-	-	-
Solidus Temperature (°C)	332.84	-	-	-
Liquidus Temperature (°C)	334.14	-	-	-

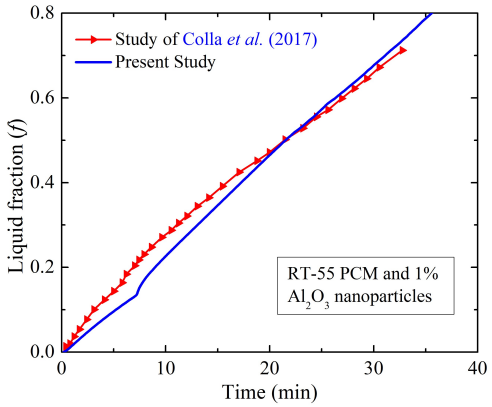

Figure 2. Comparison of the present computational methods with published numerical results of Colla et al. [16] for PCM (RT-55) mixed with 1% Al_2O_3 nanoparticles.

4. RESULTS AND DISCUSSIONS

This study presents the thermal management and energy storage capability of a PCM-based TES system. The PCM material employed in this study is ($CH_3(CH_2)_{14}COOH$) with 1% graphene nanoparticles enhancement to enhance the thermal conductivity. The study focuses on the effects of variation of various HTF conduits and their relations with the melting behaviour of the PCM. Melting of PCM: Heat will transfer from the HTF into the PCM resulting the solid-liquid phase change during which the solid phase becomes liquid with buoyancy driven thermal convection. This model enhances the heat transfer from HTF to PCM dramatically.

The melting is simulated by liquid fraction contours which show the transition of PCM from the solid to the liquid phases with

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time. In the reference configuration, the melt time was measured at the 19,179 sec; this was attributed to the small surface area which allowed for the exchange of heat between the PCM and the flowing thermal oil. Case 1 where one more HTF layer of PCM was added showed a significant reduction in the melting time, which was 6,661 sec, indicating the enhanced professional value of 65.26%. This enhancement is due to the expanded contact area, facilitating a better convective heat transfer.

Case 2 further improves the efficiency of heat transfer by using a three-layer concentric arrangement which three HTF passes around the PCM. This configuration enables a good heat diffusion and the time for melting reduces to 1,140 sec (a 94.05 % reduction against the base case). These concentric layers facilitate the multi-directional heat absorption, leading to a more uniform PCM phase change.

The best option, Case 3, corresponds to a PCM-HTF system with a four-layered PCM-HTF structure. Such configuration improves the heat interaction, as the contact surface between the HTF and the PCM is maximized. The alternating configuration provides the minimum melting time of 586 sec, by facilitating the uniform flow pattern and thermal flux over the PCM volume. This is by no means a small improvement, with a value of 96.94% over the base case. However, it is demonstrated that although increasing the contact area of the HTF is effective in promoting heat transfer, there is an optimal value above which there is a significant diminishing return.

Temperature distribution contours further confirm these results, showing heat conduction through the PCM in different cases. In all simple cases, non-uniform heating slows down and weakens the phase transitions. It is clear that Case 1 has higher thermal penetration than Case 2, and Case 2 leads to more uniform heat spread with the concentric structure. Case 3 represents the best structure with the most uniform temperature gradient and better thermal conduction in the PCM.

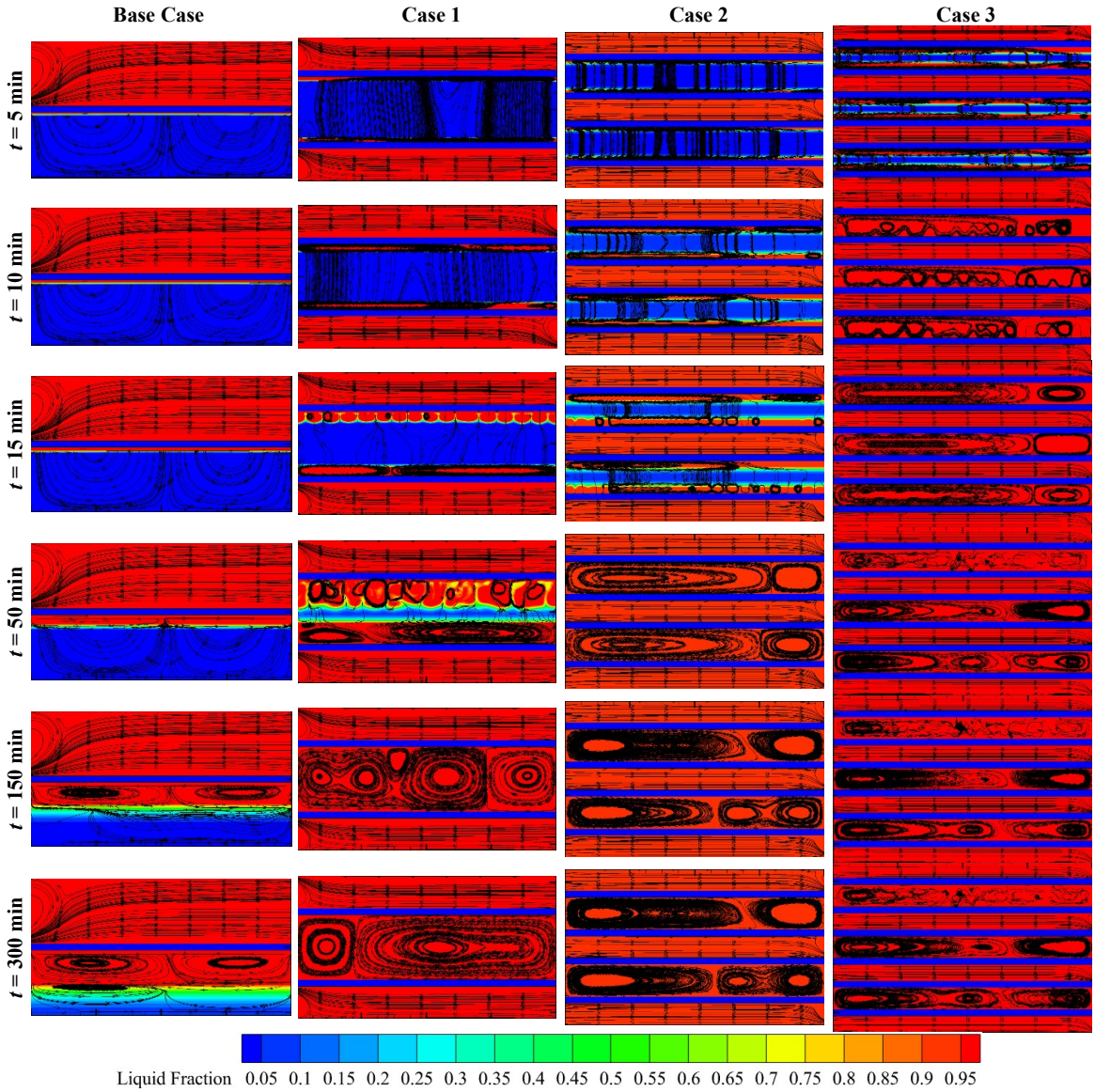

Figure 3. Liquid fraction contour with streamlines for the various time frames of three different cases with base case.

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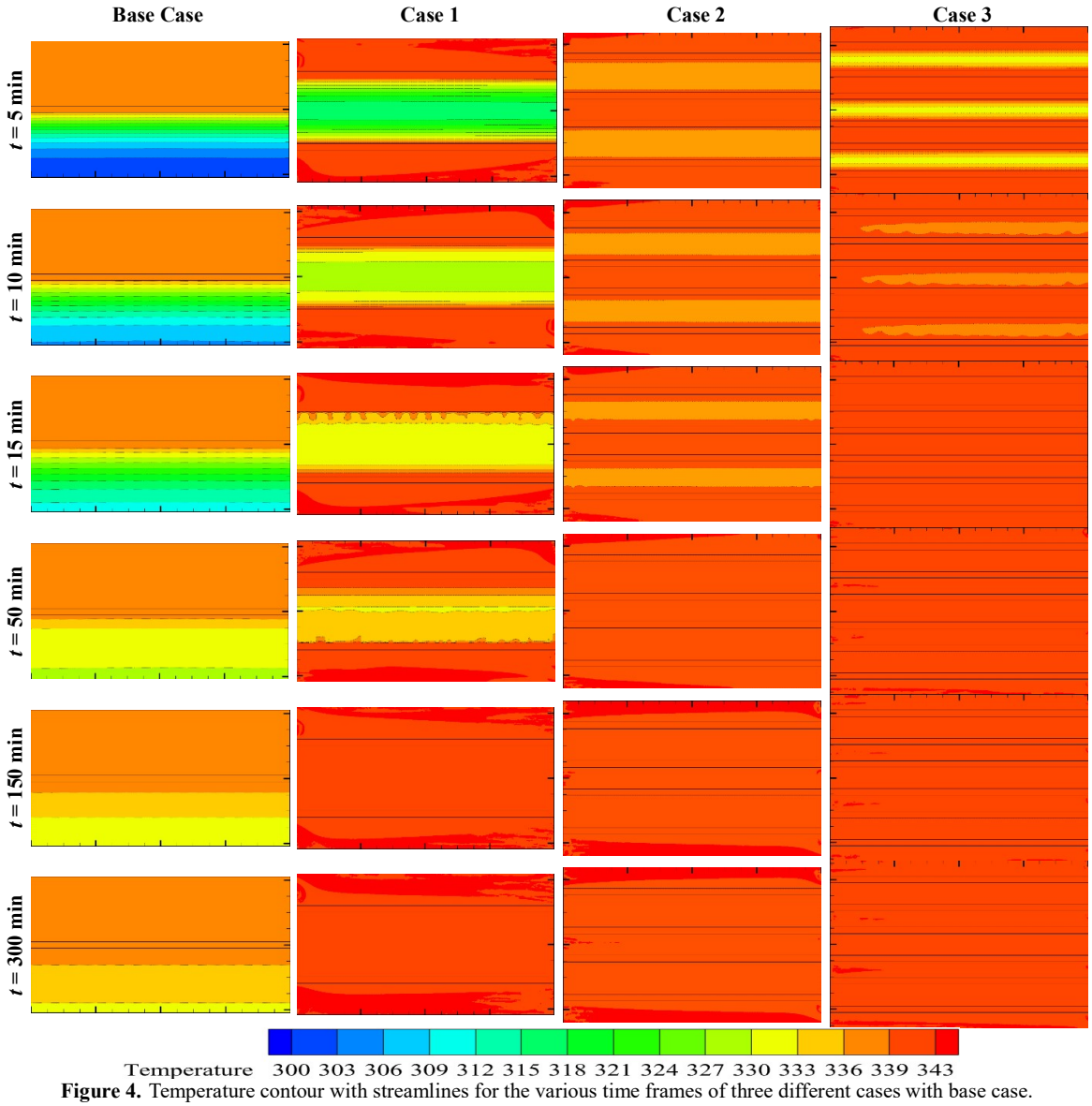

Figure 4. Temperature contour with streamlines for the various time frames of three different cases with base case.

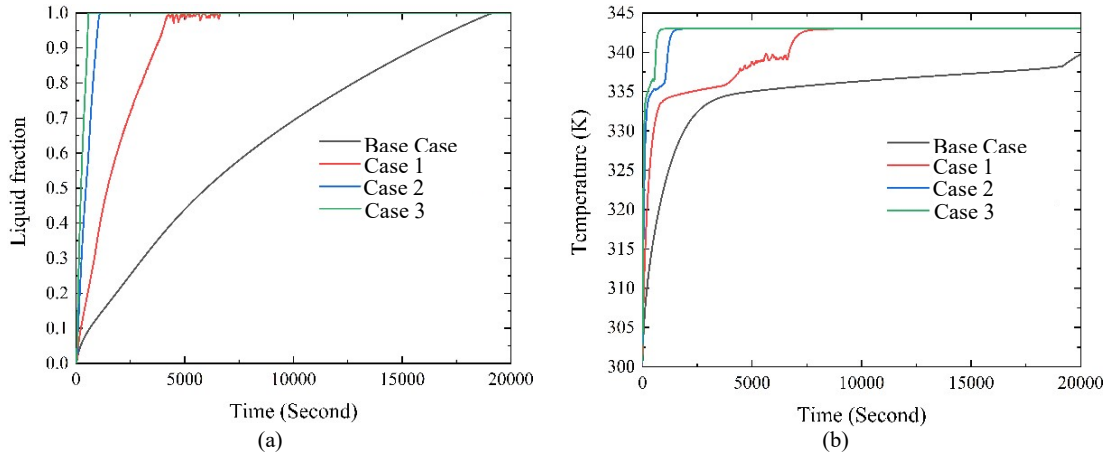

Figure 5. Comparison of (a) liquid fraction and (b) temperature with (s).

Table 2 Summary of the total melting time, stored energy rate.

Cases	Melting Time (s)	Melting Time (min)	ΔT (K)	Q Total (J)	Average energy storage rate (J/min)

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Base Case (P-H)	19179	319.65	38.26	300.47	0.94
Case 1 (H-P-H)	6661	111.02	39.59	303.37	2.73
Case 2 (H-P-H-P-H)	1140	19.00	39.29	302.67	15.93
Case 3 (H-P-H-P-H-P-H)	586	9.77	38.50	301.12	30.81

Simulation of the PCMs, in order to investigate energy storage performance, a 2D (millimetre-scale) model was utilized in Figs. 2 and 3, which represented the PCM volume of 1,600 mm^3 (1.6×10^{-6} m^3) with a mass of 0.0013874 kg, and a specific heat capacity of 2160.785 J/kg·K and the latent heat of fusion was 198,082.4 J/kg. Energy storage calculations has been performed based on the equation $Q = m.Cp.\Delta T + m.Lf$ having energy storage rates calculated as the total stored energy over the period of melting. We summarize the results with melting time and average energy storage rate:

Base Case: 19,179 sec, 0.94 J/min, Case 1: 6,661 sec, 2.73 J/min
Case 2: 1140 sec, 15.93J/min, Case 3: 586 sec, 30.81 J/min.

The interpretation of these results indicates that the HTF-PCM geometry shows significant effects on the heat transfer efficiency. The convective heat transfer is enhanced by Case 1 adding an extra HTF layer, and in Case 2 the more uniform temperature distribution is obtained in the concentric layers. The HTF-PCM configuration in Case 3 not only reduces the discharging time but also the distribution of heat. Consequently, this configuration is the most effective design for large-scale TES systems.

Finally, the four layers of PCM-HTF alternating configuration are the best in terms of melting time and energy storage rate. This research highlights the need for optimized HTF-PCM interface design for increased heat and energy storage performance in PCM based TES applications, thus offering more efficient thermal management solutions for industrial applications.

5. CONCLUSIONS

This work successfully shows the improvement of TES and performance optimization of PCM based TES system using palmitic acid ($CH_3(CH_2)_{14}COOH$) incorporated with 1% graphene nanoparticles. The study details the impact of different PCM-HTF conduit configurations on the thermal performance of the system with PCM and HTF volumes same for all the cases.

The results clearly identify that alteration of the PCM-HTF arrangement leads to enhanced thermal behaviour and energy storage effectiveness by enhancing the melting time. The melting duration was longer in the base configuration (Base Case) of 19,179 sec as the worst heat transfer is experienced. Nevertheless, the inclusion of an added HTF in Case 1 led to a large reduction of the melting time to 6,661 sec (corresponding to 65.26% reduction compared to the base case.). These two together promoted the thermal hydrodynamic interaction, which was beneficial to the heat exchange efficiency.

The duration of melting was also decreased to 960 seconds in Case 2, with the use of a central three-layer geometry that promoted heat penetration, 94.05% faster than the melting time recorded in Case 1. This arrangement was beneficial for a more uniform heat transfer through the PCM that helped to shorten the phase change time.

The highest enhancement was obtained in Case 3 by using a four-layer PCM-HTF alternating layers design. This novel configuration showed the minimum melting time of 586 sec that was 96.94% lower than the reference case. Between the PCM and HTF alternate layers helped to both maximize the contact area and to allow a uniform heat flux, which greatly increased heat transfer rate and reduced the thermal resistance. Therefore, the design of Case 3 is the best choice for large-scale TES, and with the best trade-off between fast phase change and energy storage efficiency.

In conclusion, the findings of the study demonstrated that the increase of HTF-PCM contact area would cause a rise in heat transfer performance, although the effect weakened after reaching a certain configuration. The newly proposed PCM-HTF alternating layer structure of case 3 provides new ideas to design the next-generation high-efficiency TES system, thus it is the best choice for the industrial scale.

ACKNOWLEDGMENT

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