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Performance Characterisation of Thermal Energy Storage containing a Phase Change Material (PCM) Sphere with Low Conductivity Fins: Simulation-Based Analysis

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ABSTRACT

This paper presents the outcomes of a simulation study aimed at investigating the thermal performance of modified phase change material (PCM) structures within a sphere with integrated fins. The escalating global warming crisis and its associated weather anomalies necessitate urgent measures to mitigate its impacts. Numerous research endeavours have been undertaken to address this issue, including the utilization of thermal energy storage systems (TES) augmented with PCM. PCM can be incorporated into building walls to counteract rising temperatures. However, inadequate heat transfer caused by poor thermal conductivity has been a persistent challenge in these systems. The addition of high conductivity fins has found to improve the overall performance of TES. Yet, this study proposes the addition of low conductivity fins to study for the effect of shape factor to its performance. The research evaluates the phase change of 2-fins and 4-fins with varying thicknesses within the PCM structure. A comprehensive simulation framework is employed to analyse the thermal behaviour of the PCM-enhanced sphere without considering ambient temperature nor PCM properties, but fin dimensions and configurations. The simulation results reveal that the inclusion of fins significantly improves heat transfer within the system by cutting a minimum of 20% in phase change time and could promote the phase change process to happen earlier by a maximum of 38% in starting time. By optimizing the fin configuration and thickness, the overall thermal conductivity of the PCM-based TES can be enhanced. These findings contribute to the development of efficient thermal energy storage systems, offering potential solutions to combat global warming and promote sustainable thermal management.

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1. Introduction

The effective utilization and recycling of unused heat and solar energy are crucial in achieving sustainable energy systems. The introduction of Phase Change Materials (PCMs) in thermal energy storage (TES) was driven by the ability to store and release heat energy during phase transitions of the material. PCM-based processes, especially for cooling applications, offer promising solutions for efficient energy management. PCM absorbs or releases thermal energy from the surroundings through the solidification and melting processes. During melting, PCM absorbs heat from the environment, meanwhile during the solidification process, PCM releases heat back into the surroundings [1].

Designing PCM systems with encapsulation in spheres presents several challenges, particularly in achieving high density ratios for maximised use of latent energy [2]. An encapsulation is essential to maintain the PCM in its phase and prevent the access for foreign substances into the PCM. Additionally, most PCM materials having poor thermal conductivity, limits it in achieving desired temperatures [3]. In order to address this issue, conducting fins are introduced into PCM encapsulation to enhance the overall thermal conductivity and heat transfer efficiency. The incorporation of pins in PCM systems may change the thermal resistances within [4-6], allowing for efficient heat transfer. This paper comprehensively investigates the utilization of conducting fins to overcome the challenges associated with PCM-based thermal energy storage. A novel approach to enhance the thermal conductivity of PCM systems has been explored, and the utilization of latent energy for improved energy management and sustainability has proven to be optimisable [7].

The Thermal Energy Storage (TES) is a device that reserves energy for later use. Latent Heat Storage (LHS), Sensible Heat Storage (SHS), or Thermochemical Reaction Storage systems are the possible settings for TES. Considerable research literature has been reviewed on using encapsulated PCM in indirect air conditioning and refrigeration applications. According to the thermal mechanism used to store energy perspective, LHS is always preferred due to its usable large amount of latent energy, absorbed, or released when the PCM is changing its phase without a change in temperature [8].

Experimental validation for a computational fluid dynamic (CFD) and ε-NTU model for PCM encapsulated in spheres within a large tank has been conducted successfully proving that the basic of the ε-NTU method can promisingly be further use to evaluate other types of LHS configuration. The approach to optimise the configuration of the LHS system through numerical modelling and simulation is discovered to be more cost effective rather than the intricate experimental works. The ε-NTU method was used by Aziz *et al.,* [9] for the numerical analysis of a LHS system with PCM contained within spheres.

Spherical shaped container has been verified to be better in thermal performance area than any other configurations via the increment of available heat exchange area hence translated to higher heat transfer rate [10].

Optimization of the spherical shaped container especially its size and thickness are very important as over design of the container resulting the number of spheres can be filled into the tank will be decreased when large sphere size is used which could lead to significant increase in cost and a smaller usable amount energy density per unit of volume [11].

An additional method to overcome the low heat transfer rate has been done by impregnating conductors which has proven effective. Hu *et al.,* [12] and Kamkari *et al.,* [13] found that by integrated the PCM with metal matrix and pin-fin able to enhance its thermal conductivity. Yang *et al.,* [14,15] used PCM to conduct numerical studies on the impact of metal foam on improving the thermal behaviour of the TES system. The results demonstrated that incorporating metal foam may substantially enhance the thermal behaviour of the TES unit and also enhance temperature uniformity. The emergence of fins within LHS systems is a compelling heat enhancement method to enhance heat transfer within the PCM [16]. Zheng *et al.,* [16] has successfully demonstrated that melting heat transfer performance of PCM in a thermal energy storage unit can be greatly improved via fractal net fins. Recently Jia *et al.,* [17] had conducted the studies of encapsulation of the PCM integrated with pin for cold storage and its enhancement. The results of this experiment show that adding more pin-fins does help to increase the charging rate of PCM capsules.

Thermal Energy Storage (TES) study involving the storage of thermal energy for later use in materials subjected to extreme temperatures is revised [18]. TES systems conserves energy through heating, which can be accessed during the reverse process [8]. TES has found to be able to prepare for more efficient utilization of energy resources by bridging the gap between resource extraction cycles and periods of high demand. The aim of this research is to optimize the thermal performance of TES systems by integrating fins within the PCM encapsulated sphere (Figure 1), thereby enhancing energy transfer rate, and improving overall system efficiency [19,20]. The findings of this study are meant to contribute to the advancement of TES technologies for sustainable and effective energy utilization.

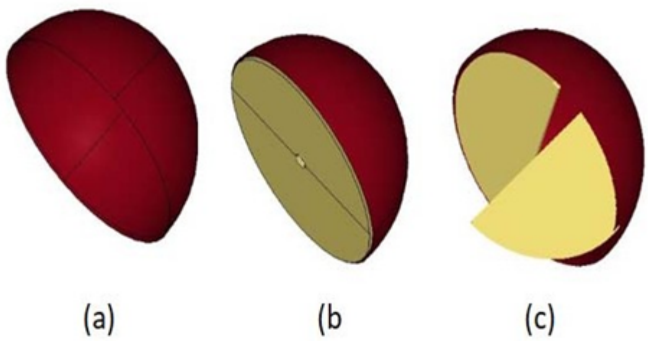


Fig. 1. Encapsulated sphere; (a) without fin, (b) with circumferentially finned, and (c) with orthogonally finned [10]

2. Methodology

Figure 2 shows the flow process of the entire study and the required processes involved within it. Initial conceptual designs were developed to have variations of fin configurations for the PCM sphere analysis. The elaborated analyses were done after the design parameters had been identified such that modelling of it was completed using the CAD software. The aid of Ansys CFX to simulate all fin configurations would provide the crucial data to analyse the thermal performance of PCM sphere variations.

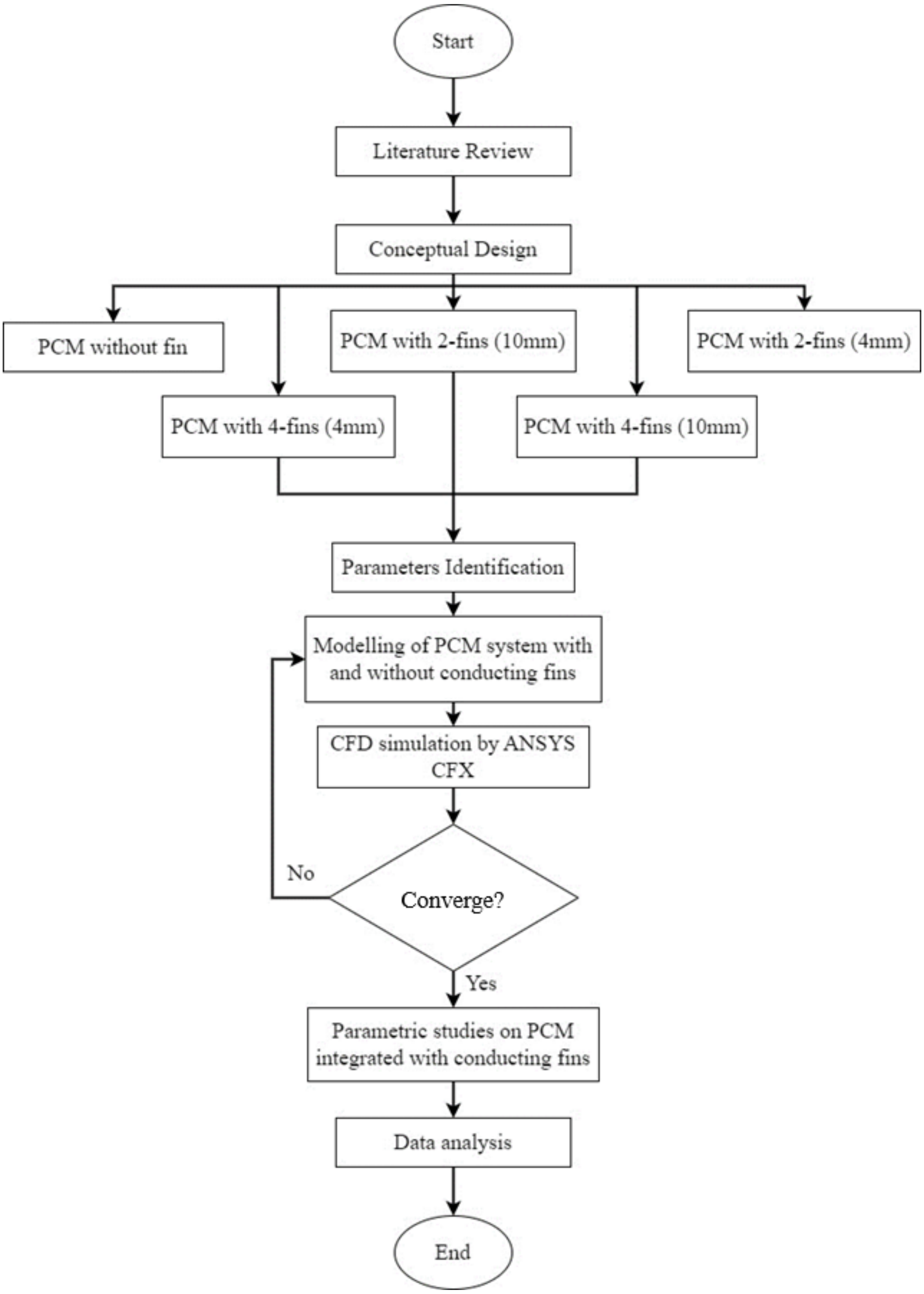


Fig. 2. Flowchart of the whole study

2.1 Design Parameters and Structures

A software namely CATIA V5 software was used to draw a three-dimensional (3D) model of a tank, measuring 300 mm in diameter and 403 mm in height. Figure 3 shows the tank comprises a heat transfer fluid surrounding a sphere (74 mm outer diameter with 2.5 mm thickness) encapsulating the PCM.

Fig. 3. Heat transfer fluid tank with PCM encapsulated sphere

The model was then imported into Ansys Fluid Flow CFX software for simulation analysis. The simulation utilized the .IGS file format to accurately represent the model.

2.2 CFX Simulation Setup

In this study, five different configurations of 3D models were developed and simulated in ANSYS CFX software, to evaluate their thermal efficiency. These models include a blunt phase change material (PCM) encapsulated in a sphere, a PCM encapsulated in a sphere with 2 integrated fins, a PCM encapsulated in a sphere with 4 integrated fins, and variations in fin thickness (10mm for 2 fins and 4mm for 4 fins).

Transient simulations were conducted with a total time of 60 minutes and a time step of 10 seconds. To ensure for convergence criteria of 1×10^{-4} , it is found that the use of Laminar model is best. The tank wall boundary condition was assigned as a no-slip wall boundary condition and adiabatic, with reasons are discussed elsewhere [1]. The encapsulated sphere was made of solid Medium Density Polyethylene with a thermal conductivity of 0.3 W/m-K, while the PCM material used was water-ice (PCM0). The global initial temperature of the system was set to -27 ℃, and the inlet temperature was set as 9 ℃. Figure 4 illustrates the four model of fin configurations in this study, providing insights into their thermal performance.

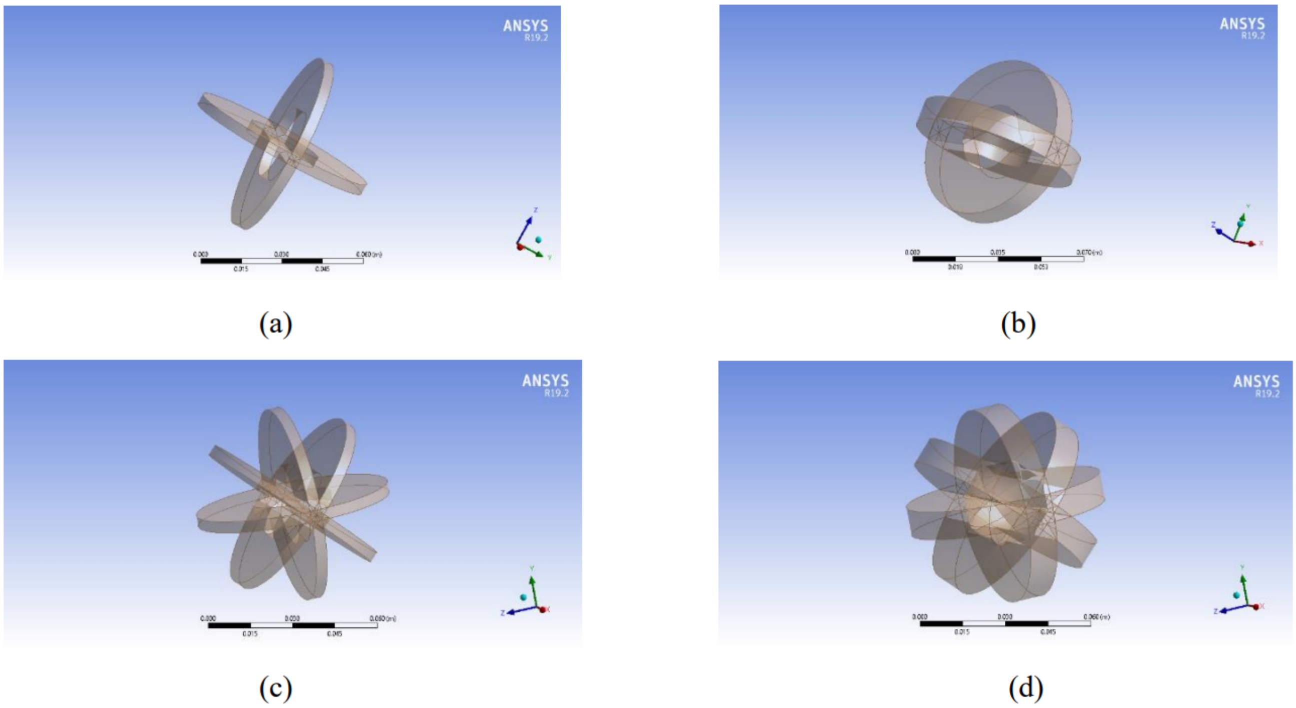


Fig. 4. Type of fin; (a) 2-fin-4mm, (b) 2-fin-10mm, (c) 4-fin-4mm and (d) 4-fin-10mm

3. Results

The primary focus of this study was to investigate the impact of fins structure on the heat transfer rate of the phase change material (PCM). A total of five simulations were conducted to explore how different fins' structure influenced the heat transfer rate of the PCM, in comparison to a plain sphere.

Figure 5 depicts the temperature against time step for each simulation, representing the relationship between the fins structure and PCM temperature. The insights into the trend exhibited by the PCM temperature under different fins configurations are shown in these graphs; all configurations albeit following a similar pattern. Furthermore, the contour plots were also generated for all the five designs. To compare them better, the data obtained from the solver were re-plotted in Figure 5. Analysing Figure 5, it can be observed that the PCM without any fin structure exhibits the slowest temperature increase, while the PCM with a 2-fin-4mm structure shows the fastest temperature increase. This suggests that the phase change occurs first in the PCM with the presence of a 2-fin-4mm structure. Comparatively, the PCM without fins reaches 0°C later than the PCM with fins. Among the tested configurations, the PCM with a 2-fin-4mm structure demonstrates the fastest achievement of 0°C, indicating that the integration of fins enhances the heat transfer rate within the system. The simulation results reveal that the inclusion of fins significantly improves the heat transfer within the system by enhancing the phase change process resulting to an earlier manifestation of phase change process by a maximum of 38%. The data suggests that the presence of the fins structure facilitates the heating process.

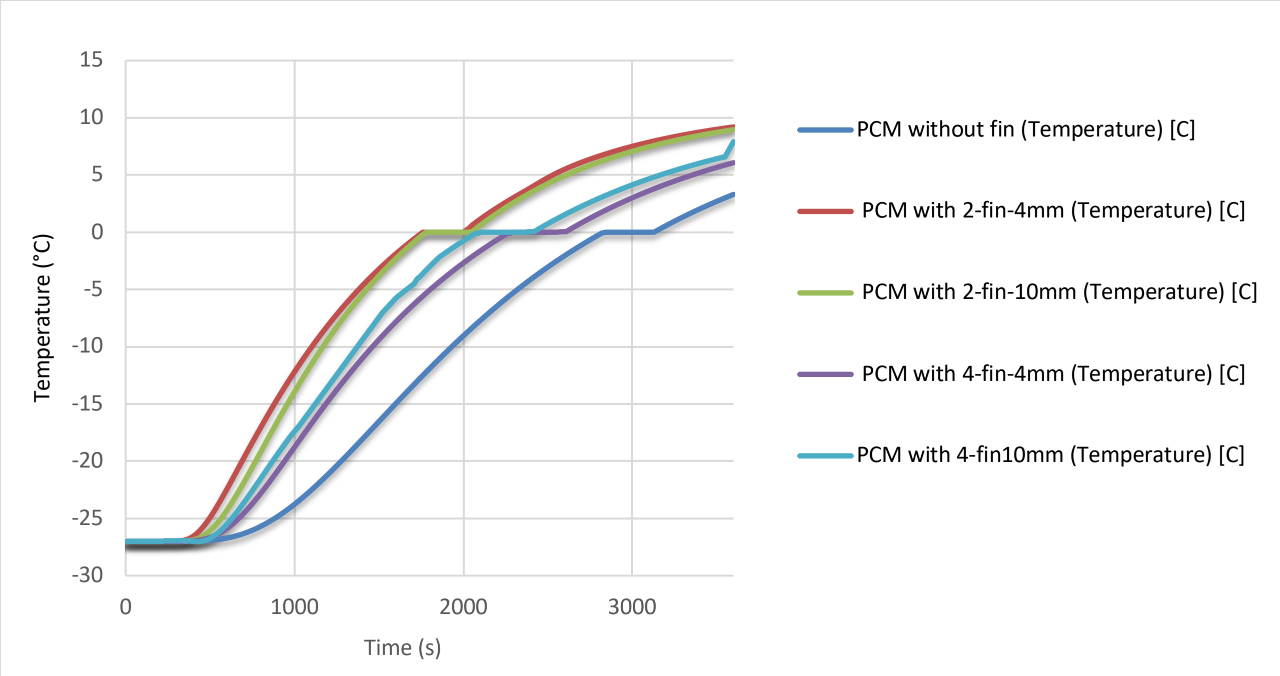


Fig. 5. PCM temperature profiles for different fin configurations

Referring to Figure 6, the heat transfer fluid (HTF) flow starts from the tank's bottom and moves vertically. The PCM, represented within a spherical compartment, is located at the middle of the tank, and the surrounding temperature is transferred to the PCM through convection and conduction. The heat transfer into the PCM occurs more rapidly with the presence of fins. The fins increase the heat exchange area, effectively increasing the contact surface between the PCM and the heat source. Consequently, the heat is dispersed more quickly throughout the PCM, resulting in enhanced heat transfer. Therefore, the overall heat transfer within the PCM is increased. The temperature contours at the end of the simulation, obtained through CFX-Post, for all the five configurations are presented in Figures 6 - 8. It can be concluded that after 60 minutes of simulation with 10 second timesteps, all the simulations have not reached steady state.

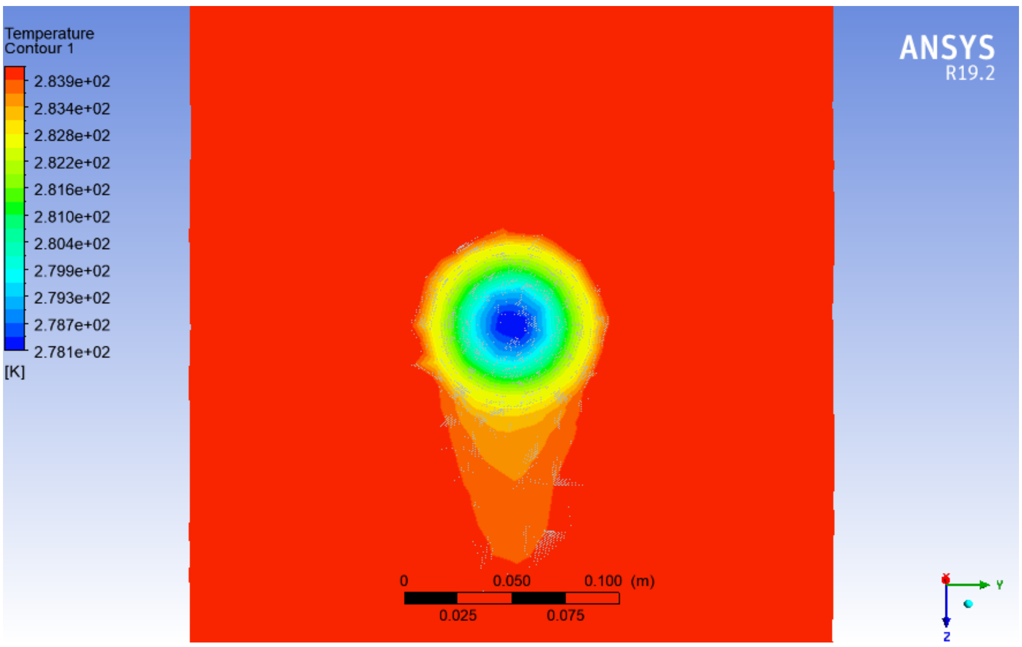
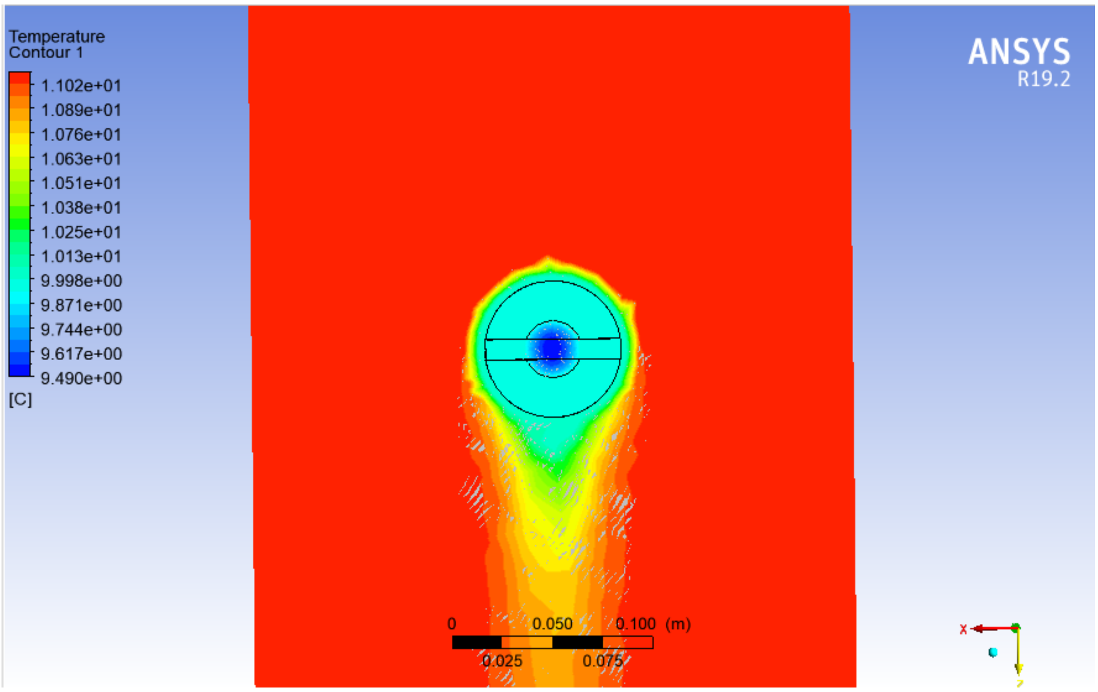
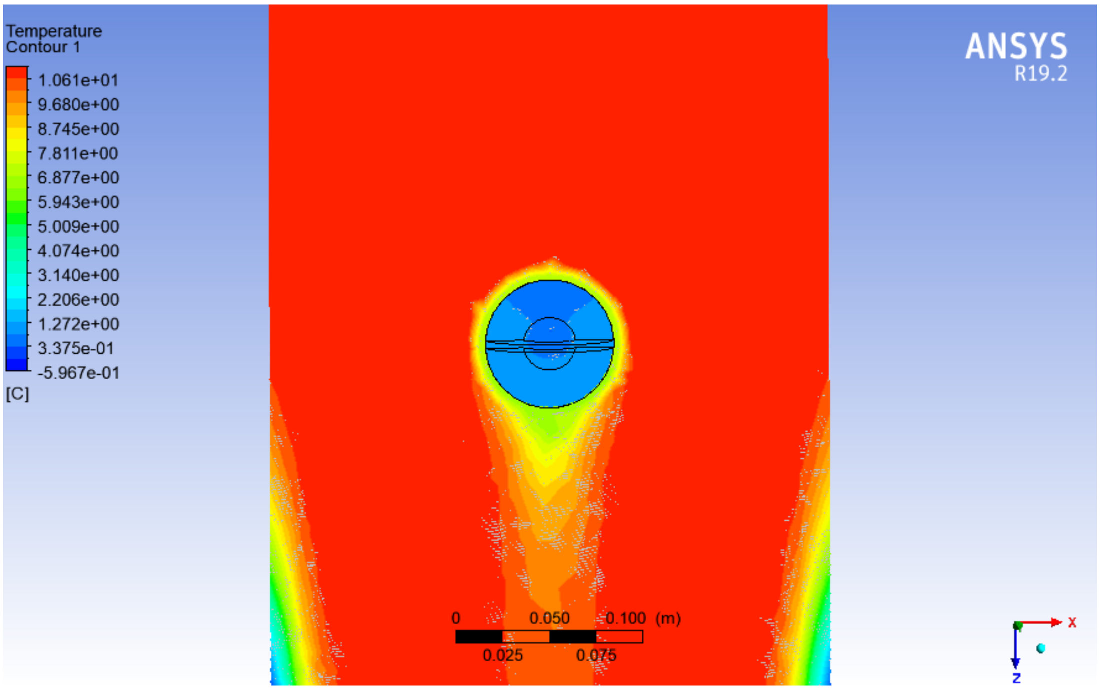


Fig. 6. Temperature contour for the no fin case

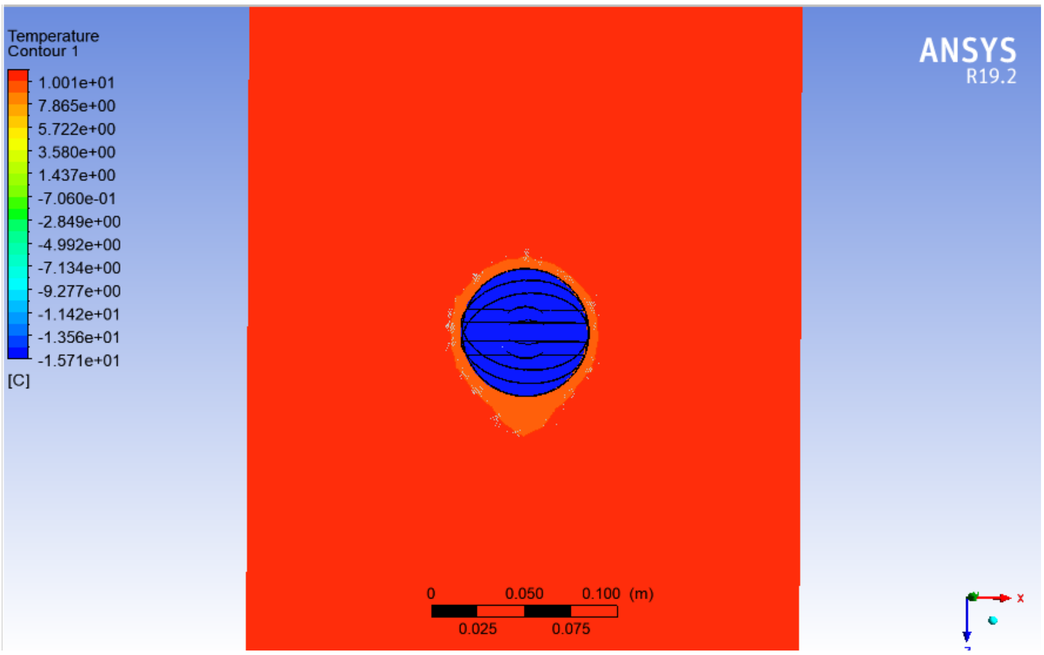


(a)

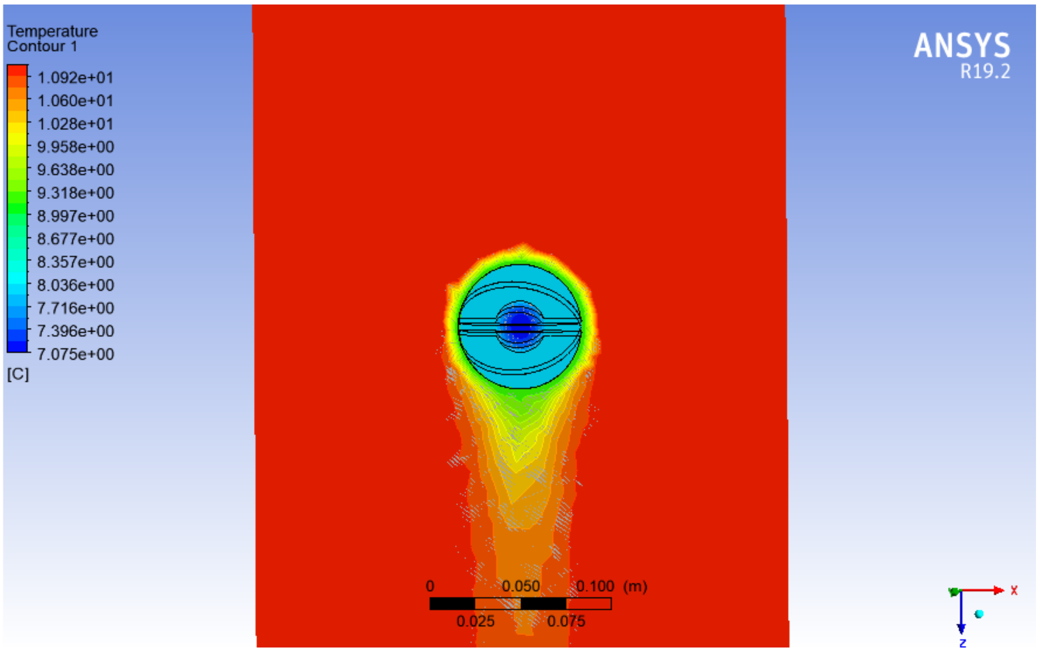


(b)

Fig. 7. Temperature contour for; (a) 2-fin-10mm, (b) 2-fin-4mm



(a)



(b)

Fig. 8. Temperature contour for; (a) 4-fin-10mm, (b) 4-fin-4mm

Table 1 presents the phase change times recorded within the temperature range of -0.01°C to 0.01°C. The times were obtained by multiplying the time step by 10 seconds. Analysis of the data in Table 1 reveals that the integration of fins has significantly reduced the phase change time of the PCMs. A shorter phase change time indicates improved performance of the PCM.

Table 1
Phase change time for different fin configurations

Design configurations	Phase change time step	Phase change time (s)
PCM without fins	40	400
PCM with 2-Fin-4mm	24	240
PCM with 2-Fin-10mm	26	260
PCM with 4-Fin-4mm	32	320
PCM with 4-Fin-10mm	29	290

The heat transfer rate between solid surface of PCM encapsulated sphere and PCM fluid per unit surface area per unit temperature difference is calculated for comparison work by using the following Eq. (1).

$$Heat\ transfer\ rate = \frac{Q}{t} = \frac{mc\Delta T}{t} \quad (1)$$

The mass of PCM (m) is obtained by multiplying PCM density that is $1000\ kg/m^3$ (ice-water density) to the volume of PCM which was $0.00017198\ m^3$ acquired from the ANSYS Modelling. The specific heat capacity (c) for ice-water is $4220\ J/kg.K$ and the temperature difference (ΔT) is between -27°C to the final temperature the PCM reached at 360th time step. The rates of heat transfers are compared relative to the heat transfer rate of PCM without fins configuration which served as a benchmark. Performance increments are calculated in percentage relative to the benchmark of this study by using Eq. (2).

$$Performance\ (\%) = \frac{|Heat\ transfer\ rate\ no\ fin - Heat\ transfer\ rate\ with\ fin|}{Heat\ transfer\ rate\ no\ fin} \times 100 \quad (2)$$

Table 2 presents the final temperature at 360th time step for all five PCM sphere configurations as well as their respective heat transfer rates and performance increment percentages. Analysis of the data from the following table showcases that integration of fins has successfully increased the rate of heat transfer consequently speeding up the phase change process of PCM. It was concluded that from all of these fin configurations, PCM sphere with 2-fin-4mm structure is the best design in this work.

Table 2
Heat transfer rate calculation

Design configurations	Final temperature at TS 360 (°C)	Heat transfer rate (W)	Performance (%)
PCM without fins	3.30	6.11	
PCM with 2-Fin-4mm	9.20	7.30	+ 19.47%
PCM with 2-Fin-10mm	8.96	7.25	+ 18.65%
PCM with 4-Fin-4mm	6.07	6.67	+ 9.17%
PCM with 4-Fin-10mm	7.91	7.04	+ 15.22%

Overall, the simulation results reveal that the inclusion of fins significantly improves heat transfer within the system by cutting a minimum of 20% in phase change time and could promote the phase change process to happen earlier by a maximum of 38% in starting time.

4. Conclusions

In conclusion, this project aimed to investigate the performance of thermal energy storage materials with integrated fins. A spherical PCM encapsulation with fins was designed within a fabricated storage tank to facilitate heat transfer from the heat transfer fluid to the PCM during the charging process. CFD simulation using Ansys Fluid Flow CFX was employed to predict the thermal performance of the fins structure during the PCM melting process. The simulations successfully analysed TES systems with and without fins, demonstrating their beneficial impact on the overall heat transfer.

The study explored the effect of fin number and thickness on the TES performance. The introduction of the fin structure had a significant influence on the temperature difference within the PCM capsule. Both the number of fins and their thickness enhanced the thermal performance of the PCM. However, it is important to ensure a sufficient filling ratio of the PCM, thus the diameter of the fins should not be increased arbitrarily. In essence, the integration of fins increased the heat transfer rate of the PCM. Optimum results were obtained with 2 fins, as the use of 4 fins resulted in a decrease in heat transfer efficiency.

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