

Thermal Performance of Nano-Enhanced PCM for Improving Melting Rate in Semi-Circular Shell and Tube Heat Exchanger

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Abstract: Phase Change Materials (PCM) are widely used in thermal energy storage systems due to their high latent heat storage capacity. However, the low thermal conductivity of PCM reduces melting rate and adversely affects the thermal performance of latent heat thermal energy storage systems. To enhance thermal conductivity, nanoparticles can be dispersed into PCM, forming Nano-Enhanced Phase Change Material (NePCM). The present study addresses the research gap by investigating the effect of nanoparticle dispersion on melting rate enhancement in a semi-circular shell and tube heat exchanger configuration. The present work employs numerical analysis using ANSYS Fluent to examine the melting behavior of PCM and NePCM in a semi-circular shell and tube heat exchanger with dual-side heating. Aluminum oxide nanoparticles were incorporated into paraffin wax at volume concentrations of 2%, 4%, and 6% to analyze their effects on melting time, thermal energy storage capacity, and energy storage rate. The results indicate that 2% nanoparticle concentration provides better energy storage performance at lower cost compared to higher concentrations; therefore, 2% concentration was selected for detailed investigation.

Keywords: Nano-Enhanced Phase Change Material, Latent Heat Thermal Energy Storage, Semi-Circular Shell and Tube Heat Exchanger, Aluminium Oxide Nanoparticles, Melting Rate, ANSYS Fluent.

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I. INTRODUCTION

Energy plays a vital role in supporting daily human activities as well as industrial operations. It is required for powering residential buildings, transportation systems and technological developments. However, the current methods of energy production and consumption are associated with environmental challenges such as air pollution and climate change. Therefore, it is essential to shift towards cleaner and more sustainable energy sources.

Renewable energy sources, such as solar and wind energy, provide an environmentally friendly method of

electricity generation. These sources are naturally abundant and can be utilized for long-term energy production. The adoption of renewable energy can significantly reduce dependence on fossil fuels and minimize greenhouse gas emissions. However, the intermittent nature of renewable energy sources creates challenges in meeting continuous electricity demand, as wind energy is not always available and solar energy is limited during nighttime. Therefore, efficient energy storage systems are required to store excess energy during availability and utilize it during demand periods. This helps in maintaining a balance between energy supply and demand and ensures a reliable and continuous energy supply.

II. THERMAL ENERGY STORAGE

Thermal Energy Storage (TES) is a technology used to store thermal energy for later use. It can be considered as a thermal battery that stores excess heat when available and releases it when required. TES systems help in maintaining a stable and reliable heat supply by storing surplus thermal energy and utilizing it during peak demand periods.

Various renewable energy sources such as solar, geothermal and wind energy can be integrated with TES systems for efficient energy storage and utilization. Among these sources, solar energy is one of the most widely used renewable energy sources for thermal energy storage applications. Solar energy is obtained from solar radiation and can be converted into thermal energy using solar collectors or concentrated solar power systems.

PCM can be integrated into TES systems such as heat exchangers, storage tanks and modular storage units. During periods of excess heat availability, PCM absorbs and stores thermal energy within its structure. During periods of high demand or low heat availability, PCM releases the stored thermal energy, ensuring continuous and reliable heat supply.

III. NANOPARTICLES

Nanoparticles are extremely small particles that can only be observed using advanced microscopes. Their size typically ranges from 1 nm to 100 nm. Due to their very high surface area to volume ratio, nanoparticles are highly suitable for thermal energy storage applications.

The addition of nanoparticles significantly enhances the thermal conductivity of PCM. Nanoparticles facilitate faster heat transfer within the PCM, which improves the rate of heat distribution. As a result, the charging and discharging processes of the thermal energy storage system become faster and more efficient.

Commonly used nanomaterials include carbon-based materials such as carbon, graphene and graphite. Metallic nanoparticles such as copper (Cu) and silver (Ag), as well as metal oxide nanoparticles such as copper oxide (CuO), aluminum oxide (Al₂O₃), magnesium oxide (MgO), titanium dioxide (TiO₂) and zinc oxide (ZnO), are also widely used. These

nanomaterials possess excellent thermal conductivity and are available in different structural forms such as nanoparticles (0D), nanotubes, nanorods, nanofibers and nanowires (1D), and nanosheets, platelets and nanoflakes (2D).

A. Classification of Nanoparticles

Nanoparticles can be classified based on their composition and morphology. Based on composition, nanoparticles are generally categorized into three main groups: inorganic nanoparticles, organic nanoparticles and carbon-based nanoparticles. Inorganic nanoparticles include metals and metal oxides. Carbon-based nanoparticles include materials such as graphene and carbon nanotubes. Organic nanoparticles mainly include polymer-based and lipid-based nanomaterials.

B. Inorganic Nanoparticles

Inorganic nanoparticles are composed of inorganic materials such as metals (e.g., gold, silver and platinum) or metal oxides (e.g., titanium dioxide and iron oxide). These nanoparticles are widely known for their unique optical, electrical and catalytic properties, which make them suitable for various engineering and thermal applications.

C. Organic Nanoparticles

Organic nanoparticles are composed of carbon-based compounds such as polymers and organic molecules. These nanoparticles are widely used in drug delivery systems, nanomedicine and other applications that require biocompatible and biodegradable materials.

D. Carbon-Based Nanoparticles

Carbon-based nanoparticles include materials made entirely of carbon or carbon derivatives. Carbon nanotubes, graphene and fullerenes are common examples of carbon-based nanoparticles. These nanoparticles exhibit excellent mechanical strength, high thermal conductivity and superior electrical properties, making them highly useful in electronics, energy storage and nanocomposite applications.

IV. GEOMETRICAL CONFIGURATION AND DIMENSIONAL PARAMETERS

Figure 1 illustrates the semi-circular shell and tube geometry used in the LHTES system along with the triplex tube configuration. The geometry consists of

inner pipe, middle pipe, outer pipe and NePCM region. Figure 1(b) shows a semi-circular configuration where the inner tube is placed inside middle and outer semi-circular shells. Heat transfer fluid flows through inner tube and outer shell, while NePCM is filled in the middle shell. Figure 1(a) shows a circular triplex tube configuration where heat transfer fluid flows through inner and outer tubes and NePCM is placed in the middle tube.

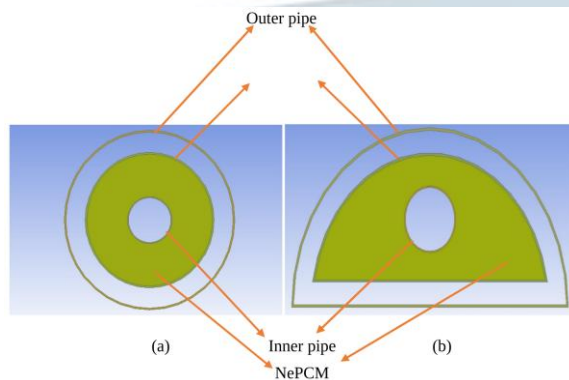


Figure 1: Representation of distinct zones for (a) Circular triplex tube and (b) Semi-circular shell and tube

A comparison between the circular triplex tube and semi-circular shell and tube arrangements has been carried out by maintaining the same volume of nano-enhanced phase change material (NePCM). Paraffin wax is used as the base phase change material (PCM), while aluminium oxide nanoparticles are used to enhance the thermal properties of the PCM. Figures 2 and 3 illustrate the dimensional parameters of both the semi-circular shell and tube and the triplex tube configurations. The semi-circular shell and tube LHTES system, as shown in Figure 2, consists of an inner tube having a diameter of 50.8 mm and a wall thickness of 1.2 mm. The middle shell and outer shell have inner diameters of 214 mm and 254 mm respectively, each having a thickness of 2 mm.

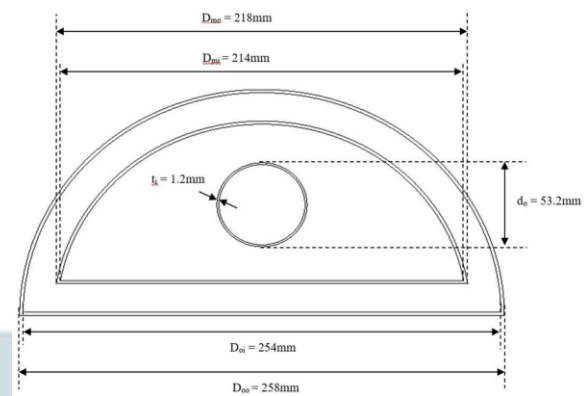


Figure 2: Dimensional parameters of semi-circular shell and tube configuration

Figure 3 represents the triplex tube heat exchanger configuration. In this setup, the inner tube has a diameter of 50.8 mm and a thickness of 1.2 mm, whereas the middle and outer tubes have diameters of 150 mm and 200 mm respectively, with a wall thickness of 2 mm.

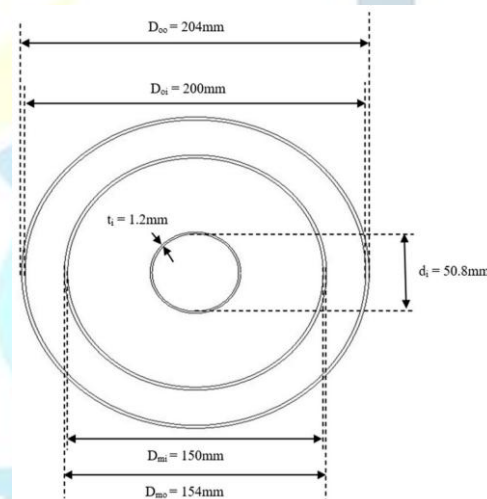


Figure 3: Dimensional parameters of circular triplex tube configuration

Further, Figures 4 and 5 present the three-dimensional (3-D) views of the triplex tube and semi-circular shell and tube LHTES systems, respectively.

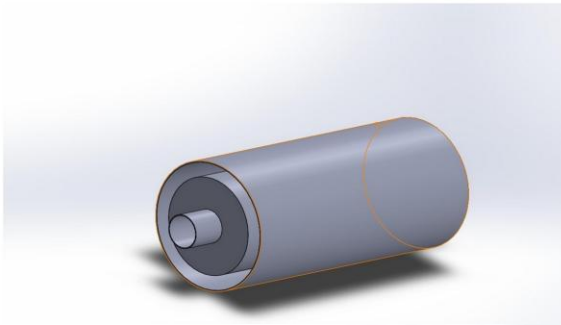


Figure 4: 3D view of a circular triplex tube

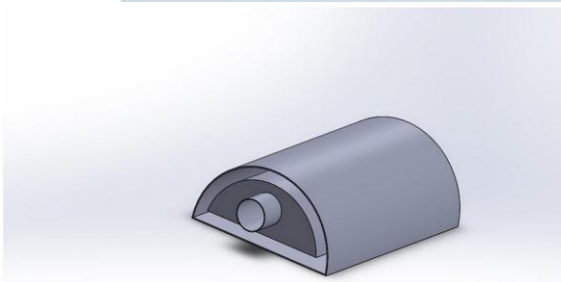


Figure 5: 3D view of a semi-circular shell and tube

V. MESHING (GRID GENERATION)

Meshing in ANSYS Fluent is the process of dividing the computational domain into a large number of smaller elements known as mesh cells. These cells collectively form a grid over the entire domain, enabling numerical calculations to be performed at discrete locations. The quality of the mesh plays an important role in achieving proper convergence and accurate simulation results.

Convergence of a simulation refers to the condition in which the calculated solution does not change significantly with further iterations, indicating a stable and reliable solution. Several mesh quality parameters must be maintained within acceptable limits to ensure high-quality mesh generation.

A. Element Quality

Element quality represents the shape and distortion level of individual mesh elements. For a good quality mesh, the element quality value should be close to 1. The value ranges between 0 and 1, where a value close to 0 indicates poor mesh quality.

In a 2D domain, a perfect square mesh arrangement corresponds to an element quality value of 1. For 2D quad/tri elements, the element quality is given by:

$$Quality = C \times \frac{Area}{\sum(edge\ length)^2}$$

B. Aspect Ratio

Aspect ratio is defined as the ratio of the longest edge to the shortest edge of a mesh element. A lower aspect ratio indicates a well-shaped element, whereas a higher aspect ratio represents a distorted element. For good mesh quality, the aspect ratio should be close to 1.

C. Orthogonality

Orthogonality indicates the angular alignment between adjacent cell faces or edges. The value ranges between 0 and 1. For a high-quality mesh, orthogonality should be as close to 1 as possible. This ensures that adjacent faces or edges remain nearly perpendicular to each other, which improves numerical accuracy.

D. Skewness

Skewness represents the deviation of a mesh element from its ideal geometric shape. For a good quality mesh, the skewness value should be close to zero, indicating minimal distortion.

$$Skewness = \max \left[\frac{\theta_{\max} - \theta_e}{180 - \theta_e}, \frac{\theta_e - \theta_{\min}}{\theta_e} \right]$$

where $\theta_{\max}$ is the largest face angle of the cell, $\theta_{\min}$ is the smallest face angle of the cell and θ_e is the equiangular cell angle (90° for a quadrilateral and 60° for a triangular cell).

E. Grid (N) Independence Test

The grid independence test is an important procedure in computational fluid dynamics (CFD) used to determine the minimum number of mesh elements required to obtain accurate simulation results. This test is performed by running simulations with different mesh sizes and comparing the results. If the results approach a constant value with mesh refinement, the solution is considered grid independent.

This test ensures that simulation results are not affected by mesh size variation. Although a finer mesh generally improves accuracy, it also increases computational time. Therefore, an optimal mesh size must be selected to balance accuracy and computational cost.

The grid independence test was performed for the circular triplex tube LHTES unit using four different grid systems consisting of 12,345, 15,678, 18,785, and 21,980 nodes, as shown in Figure 6. The results indicate that the simulation is grid independent, and 12,345 nodes are sufficient to achieve the desired level of accuracy.

Similarly, for the semi-circular shell and tube heat exchanger, four grid systems consisting of 26,675, 30,654, 34,652, and 38,543 nodes were analyzed, as shown in Figure 7. The results show that 26,675 nodes are sufficient to achieve accurate results while maintaining the same initial and boundary conditions.

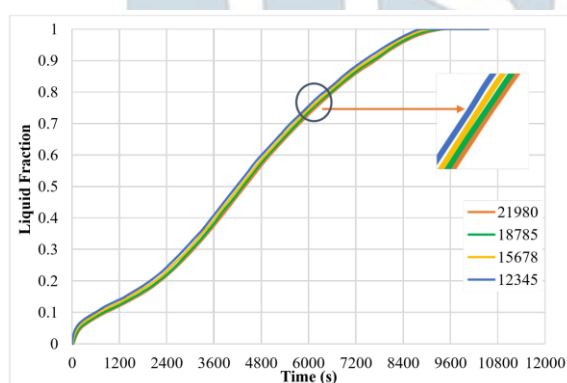


Figure 6: Liquid fraction v/s time plot for different grid sizes for circular triplex tube heat exchanger LHTES unit

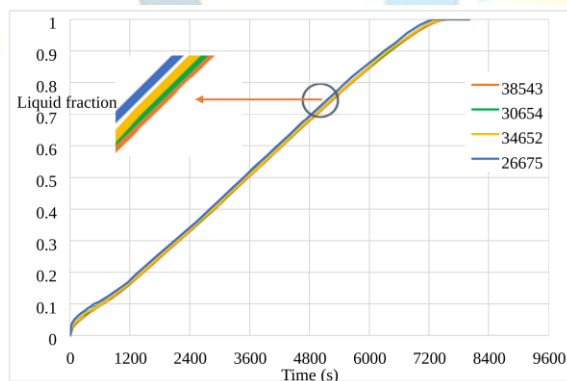


Figure 7: Liquid fraction v/s time plot for different grid sizes for semi-circular shell and tube heat exchanger LHTES unit

F. Time Independence Test

The time independence test in ANSYS Fluent is performed to evaluate the stability and convergence behaviour of the numerical simulation for different time step sizes. This test is essential to determine an

optimal time step that ensures accurate results while maintaining reasonable computational cost.

In the present study, the time independence test has been conducted to select a suitable time step size for the simulation. The test was performed by running simulations using different time step sizes of 0.07 s, 0.09 s, 0.2 s and 0.4 s for both circular triplex tube and semi-circular shell and tube configurations, as shown in Figures 8 and 9. From the analysis, it was observed that all selected time step sizes produced nearly similar results, which indicates the stability and convergence of the numerical solution. Therefore, a time step size of 0.3 s has been selected for the present study as it provides a balance between computational time and simulation accuracy.

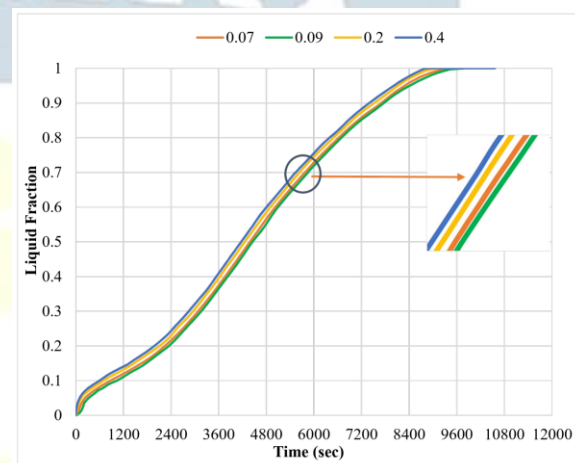


Figure 8: Liquid fraction v/s time plot for different time step sizes for circular triplex tube heat exchanger for LHTES unit

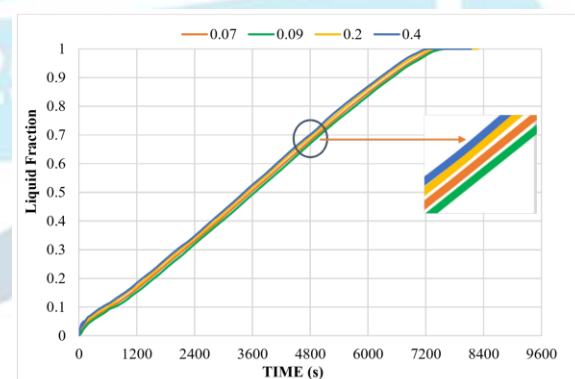


Figure 9: Liquid fraction v/s time plot for different time step sizes for semi-circular shell and tube heat exchanger for LHTES unit

Meshing of 2D circular triplex tube and semi-circular shell and tube LHTES system has been shown in Fig.

The quality parameters of the generated meshes are listed in Table 1.

Table 1: Quality parameters for meshing

Parameter	Circular triplex tube	Semi-circular shell and tube
Element Quality (Avg.)	0.93551	0.95712
Aspect Ratio (Avg.)	1.2482	1.1693
Skewness (Avg.)	0.004156	0.007859
Orthogonality (Avg.)	0.99995	0.99344

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