Thermal analysis of a triplex-tube heat exchanger system incorporating multiple phase change materials

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Abstract. This study investigates the thermal storage performance of a heat exchanger system consisting of three concentric tubes, where the inner and outer tubes carry a heat transfer fluid (HTF), and the middle tube is filled with three types of phase change materials (PCMs) arranged in both radial and circumferential cascades. Due to their ability to absorb and release heat during phase transitions, PCMs make latent heat storage one of the most effective methods for charging and discharging thermal energy. In this study, three commercially available PCMs with distinct melting points are utilized: RT55 (PCM-1), RT60 (PCM-2), and RT65 (PCM-3). A two-dimensional numerical model using the finite volume method is developed to analyze the thermal behavior and storage performance of the triplex-tube heat storage system. The numerical model is validated by comparison with previously published numerical and experimental results from the literature. The influence of arranging cascaded PCMs in radial and circumferential directions is examined to identify the optimal configuration that improves both melting behavior and storage performance.

1 Introduction

Energy demand worldwide is experiencing continuous growth across key consumption sectors, notably in buildings, industry, and transportation. At the same time, the environmental concerns tied to fossil fuel dependence have encouraged researchers to focus on advancing the utilization of renewable energy sources. From these, solar energy offers particularly promising solutions; however, its intermittent and irregular availability underscores the importance of developing efficient thermal energy storage (TES) systems. Latent heat storage (LHS) devices using phase change materials (PCMs) are considered more efficient than sensible or chemical storages, as they enable the storage and release of significant amounts of energy at a nearly constant temperature. Nevertheless, their performance is limited by the inherently low thermal conductivity of PCMs. To address this limitation, several strategies have been proposed to enhance LHS and accelerate the melting process, such as incorporating fins [1], employing multiple PCMs [2], and dispersing

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nanoparticles [3] or embedding metal foam [4] within the PCM. Another effective enhancement approach involves employing innovative geometries for LHS systems [5]. Triplex-tube configurations, in particular, provide a larger contact area between the HTF and PCMs, which strengthens heat transfer and shortens the charging duration.

In recent years, the triplex-tube heat exchanger—where the PCM is contained in the middle tube and the HTF circulates through the inner and outer tubes—has attracted considerable attention. Its main advantage lies in offering a larger heat exchange surface between the HTF and PCM compared to the widely used double-tube storage system. Zaib et al. [6] studied the simultaneous melting and solidification processes of finned triplex-tube and finned double-tube LHS incorporating a single PCM. The findings revealed that the melting and solidification times reduced by 75.26% and 90.12%, respectively, when the triplex-tube LHS system is employed instead of the double tube system. Khatibi et al. [7] investigated the solidification behavior of RT82 enhanced with nanoparticles in both triplex-tube and double-tube LHS configurations. The results showed that the triplex-tube system enhances the discharging rate and shortens solidification time across all tested HTF temperatures and tube diameters. Elbahjaoui et al. [8] evaluated the thermal response of double-tube and triplex-tube LHS configurations co-operating with a flat plate solar collector during the charging of the collected solar thermal energy. The findings showed that using a triplex-tube LHS system leads to faster melting and improved storage efficiency compared to the conventional double-tube design.

The adoption of multiple PCMs in LHS systems is recently considered an efficient technique to improve the thermal performance [9, 10]. The current work investigates the combination of the triplex-tube geometry and the multiple PCMs during the charging process. The impact of arranging multiple PCMs in radial and circumferential directions on the melting behavior and thermal performance are examined. The results are expected to provide valuable insights, identifying the optimal PCM arrangement for enhanced melting rate and storage performance, and serving as a reference for researchers implementing multiple PCMs in similar LHS systems.

2 Methodology

2.1 System description

The triplex-tube LHS system considered in the present work is composed of three concentric tubes with inner diameters of 50 mm, 150 mm, and 200 mm. The tubes are of copper with a uniform thickness of 1 mm (e = 1 mm). Water, serving as the HTF, circulates through the inner and outer tubes, transferring heat to the PCMs in the middle tube, where it is stored as latent heat. Two configurations of PCM placement are considered in the LHS system: a radial distribution (Case 1) and a circumferential distribution (Case 2). As illustrated in Figure 1, the storage medium is divided into three equal volumes, each occupied by a different PCM. As the LHS system studied is intended to store solar thermal energy to provide domestic hot water, the three PCMs selected for this study are RT55 (PCM-1), RT60 (PCM-2) and RT65 (PCM-3).

2.2 Governing equations

The enthalpy-porosity method was employed to model heat transfer and phase change phenomena in the triplex-tube LHS system, providing the mathematical formulation of the governing equations. Furthermore, the problem is modeled as two-dimensional, with the molten PCMs assumed to behave as laminar and Newtonian fluids. The variation in HTF temperature is neglected, and the thermophysical properties are considered temperature-independent. Under these assumptions, the governing equations are formulated as follows:

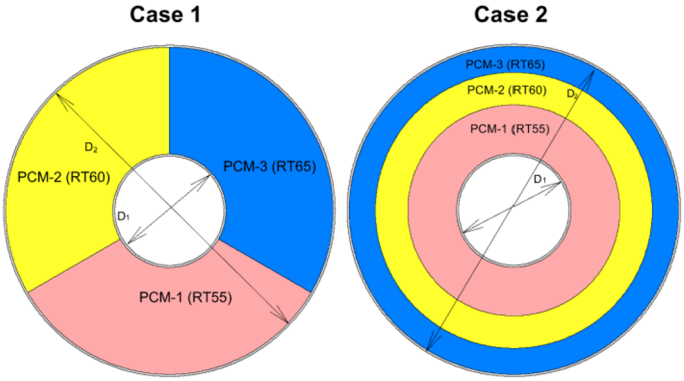

Fig. 1. Schematic representation of the triplex-tube heat exchanger with multiple PCMs arranged in circumferential (Case 1) and radial (Case 2) configurations.

- Continuity:

$$\nabla . \vec{U} = 0 \tag{1}$$

- Momentum equations in the r and θ directions:

$$\rho\left(\frac{\partial U_r}{\partial t} + U.\nabla U_r\right) = -\frac{\partial P}{\partial r} + \mu \nabla^2 U_r + \rho g \beta \sin(\theta)(T - T_{ref}) - A\frac{(1-f)^2}{f^3 + b}U_r \tag{2}$$

$$\rho\left(\frac{\partial U_\theta}{\partial t} + U.\nabla U_\theta\right) = -\frac{1}{r}\frac{\partial P}{\partial \theta} + \mu\nabla^2 U_\theta + \rho g \beta \cos(\theta)(T - T_{ref}) - A\frac{(1-f)^2}{f^3 + b}U_\theta \tag{3}$$

- Energy equation:

$$\frac{\partial(\rho h)}{\partial t} + \nabla\left(\rho U h\right) = \nabla\left(\frac{k}{c_p}\nabla h\right) - \rho L\frac{\partial f}{\partial t} \tag{4}$$

Here, U_r and U_θ denote the radial and circumferential components of the velocity vector U. The terms h, L, and f correspond to the volumetric sensible enthalpy, latent heat of fusion, and liquid fraction, respectively. The parameters A and b denote the mushy zone constant, set to 10^5, and a small constant of 0.001 introduced to prevent division by zero when the PCMs are in the solid state.

Initially, all PCMs are considered to be in the solid state, with their temperatures assumed constant as follows:

$$t = 0: \quad U_r = U_\theta = 0, \; T(r,\theta) = 303 \; K \tag{5}$$

At the inner surface of the inner tube and the outer surface of the middle tube, the temperature is assumed to be equal to that of the HTF, expressed as follows:

$$r = \frac{D_1}{2}: \quad U_r = U_\theta = 0, \; T(r,\theta) = 348 \; K \tag{6}$$

$$r = \frac{D_2}{2} + e: \quad U_r = U_\theta = 0, \; T(r,\theta) = 348 \; K \tag{7}$$

2.3 Validation

To validate the developed model, a comparison is performed with the experimental and numerical results reported by Al-Abidi et al. [11] for the melting of a single PCM (RT82) in a finned triplex-tube heat exchanger. The experimental conditions were replicated, with an initial temperature of 27 °C and an HTF temperature of 90 °C. The results were compared with experimental and numerical data based on the temporal evolution of the average temperature of the PCMs, as illustrated in Fig. 2. The findings demonstrate strong agreement between the predicted results and the experimental and numerical data reported by Al-Abidi et al. [11].

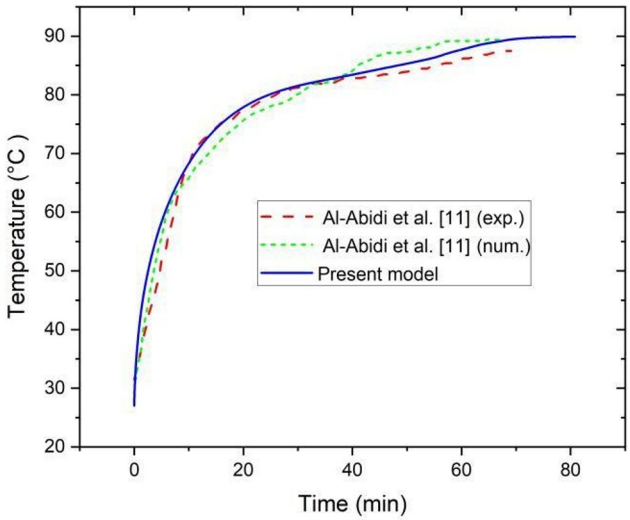

Fig. 2. Schematic representation of the triplex-tube heat exchanger with multiple PCMs arranged in radial (Case 1) and circumferential (Case 2) configurations.

3 Results

To analyze the impact of arranging multiple PCMs in radial and circumferential directions, numerical simulations were conducted to evaluate the temporal evolution of the liquid

fraction, the average temperature of PCMs, and the corresponding contours of liquid fraction and temperature.

Figure 3 illustrates the temporal evolution of the liquid fraction in triplex-tube LHS systems filled with multiple PCMs arranged in radial and circumferential configurations. In the initial minutes of the charging process, the liquid fraction exhibits a similar behavior in both configurations. As the charging process progresses, the system with circumferentially arranged PCMs shows a higher melting fraction, a trend that persists until complete melting is achieved. Notably, the complete melting time of the PCMs is approximately 103 min for the system with circumferentially arranged PCMs and 124.6 min for the system with radially arranged PCMs. The analysis indicates that, compared to the radially arranged configuration, the melting time is reduced by approximately 17.3% when the PCMs are arranged circumferentially.

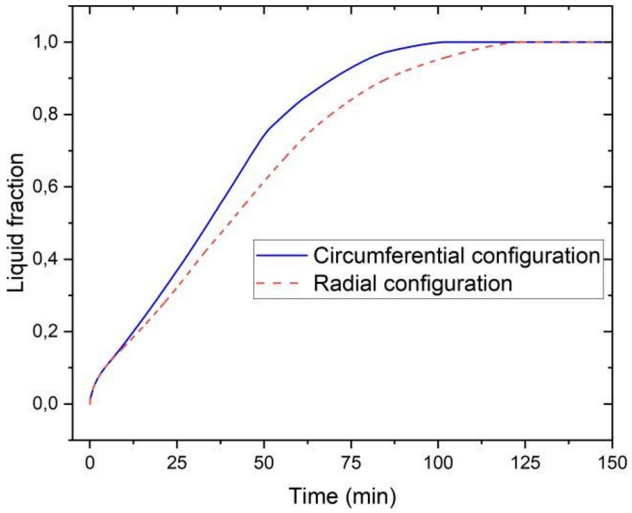

Fig. 3. Temporal evolution of the liquid fraction in the triplex-tube heat exchanger with PCMs arranged in radial and circumferential configurations.

Figure 4 presents the temporal evolution of the average temperature of the PCMs in triplex-tube LHS systems with multiple PCMs arranged radially and circumferentially. In the initial stage, the average temperature exhibits a similar trend for both radial and circumferential configurations. This behavior is mainly attributed to heat transfer being dominated by thermal conduction during the initial stage, along with the comparable density and specific heat of all PCMs. As time progresses, the average temperature curve in the circumferential configuration exhibits a steeper rise compared to the radial arrangement, until it approaches the HTF temperature at steady state. This behavior is primarily attributed to the stronger natural convection currents developed in the circumferential configuration, which enhance heat transfer within the liquid PCMs and thereby accelerate the rise in average temperature. It is noteworthy that, compared to the radial configuration, the charging time—defined as the duration required to reach steady state—is markedly reduced when the PCMs are arranged circumferentially.

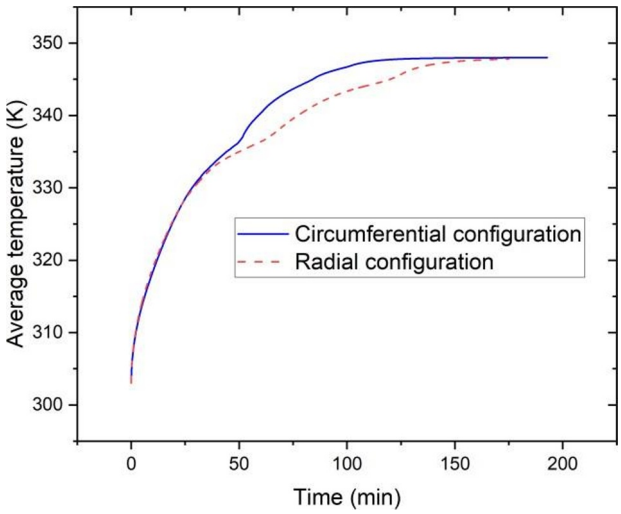

Fig. 4. Time evolution of the average temperature of PCMs in the triplex-tube heat exchanger for radial and circumferential arrangements.

Figure 5 shows the liquid fraction contours in the triplex-tube LHS system with PCMs arranged circumferentially and radially at different times (13 min, 41 min, and 103 min). At the early stage (13 min), heat transfer is mainly governed by conduction, resulting in a melting front that appears as parallel and concentric circles in both radial and circumferential configurations. As time advances (41 min) in the radial configuration, natural convection currents emerge in the upper region of the PCM-1 layer and the lower part of the PCM-3 layer, disrupting the concentric melting front and distorting the liquid fraction contours. In the circumferential configuration, natural convection currents form in the upper regions of the PCM-2 and PCM-3 layers near the inner tube surface, as well as in the lower region of the PCM-1 layer, leading to a distortion of the initially concentric liquid fraction contours. At a later stage (103 min), the PCMs in the circumferential configuration are fully melted, whereas in the radial configuration, a portion of solid PCM still persists in the lower region of the triplex-tube LHS system. This behavior is primarily attributed to stronger natural convection currents in the circumferential configuration, while in the radial configuration these currents are weakened due to the separating surfaces between PCMs.

Figure 6 depicts the temperature contours in the triplex-tube LHS system for PCMs arranged in circumferential and radial configurations at different times (13 min, 41 min, and 103 min). At 13 min, heat transfer within the PCMs is dominated by thermal conduction, resulting in nearly parallel and concentric isotherms in both the circumferential and radial configurations. As time advances (41 min), natural convection currents emerge within the molten regions of the PCMs, causing deformation and non-uniformity in the temperature distribution. In both configurations, natural convection currents carry the heated liquid PCM in the upper section, enhancing the melting rate in this region before directing the flow downward along the melting front. At 103 min, the PCMs are fully melted in the circumferential configuration, whereas melting remains incomplete in the radial configuration. This is evidenced by the higher temperature distribution observed in the circumferential configuration compared to the radial configuration.

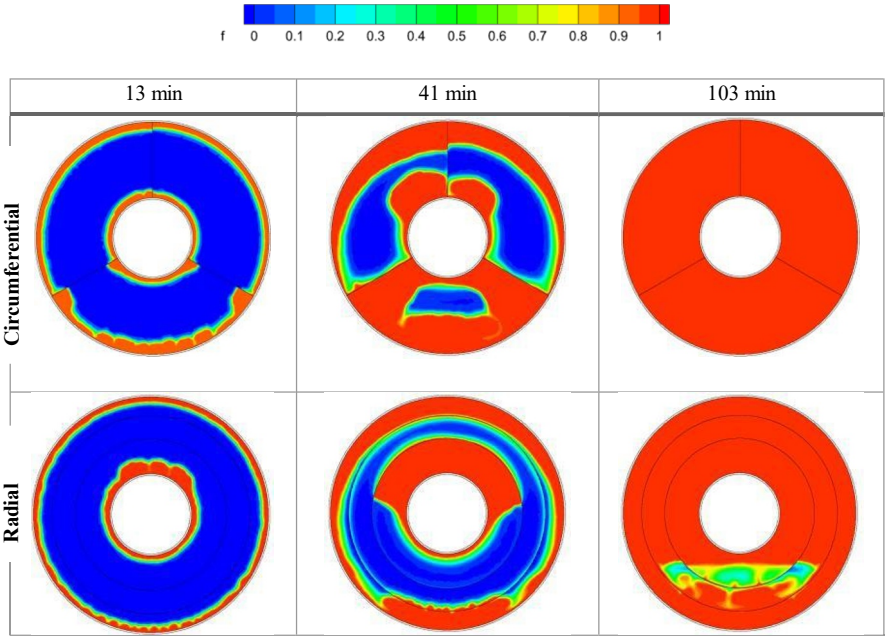

Fig. 5. Liquid fraction contours in the triplex-tube LHS system for PCMs cascaded circumferentially and radially at various time intervals (13 min, 41 min, and 103 min).

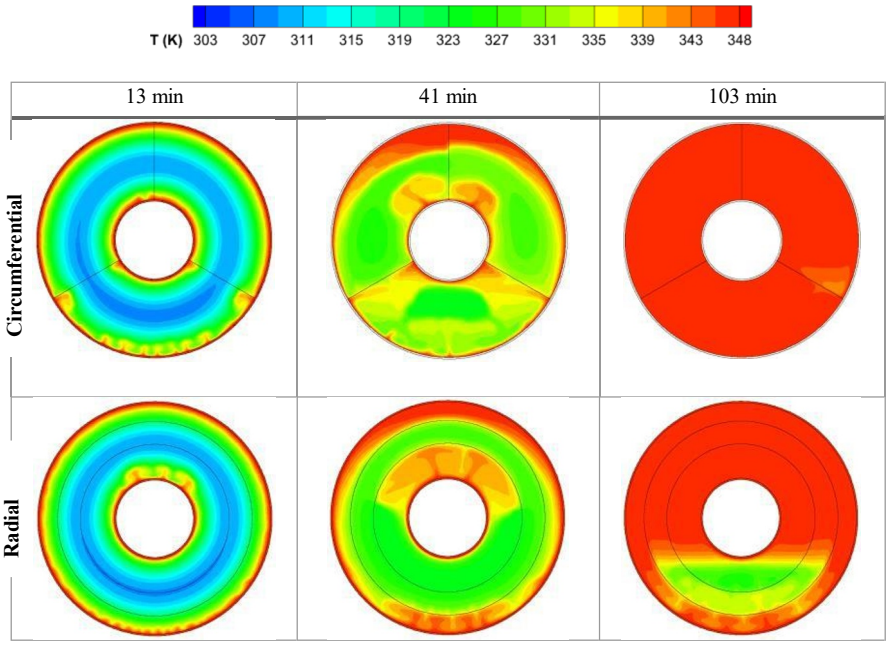

Fig. 6. Temperature distribution in the triplex-tube LHS system for PCMs cascaded circumferentially and radially at various time intervals (13 min, 41 min, and 103 min).

4 Conclusion

The present study investigates the melting behavior of multiple PCMs filled in a triplex-tube heat exchanger. Based on a two-dimensional numerical model employing the finite volume method and experimentally validated, the thermal response and storage performance of the LHS system are numerically evaluated. The effect of arranging PCMs in radial and circumferential orientations is investigated to determine the optimal configuration. The results reveal that the circumferentially configuration of PCMs reduces the melting time by about 17.3% compared to the radial arrangement.

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