Assessment of the Thermal Efficiency of a Solar Storage Tank Employing Cascaded Phase Change Materials (CPCM)

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Abstract. This study assesses the thermal energy storage capabilities of a solar thermal storage system comprising multiple triplex-tube units. These triplex-tube systems incorporate three distinct phase change materials (PCMs), specifically RT44HC, RT54HC, and RT62HC. The heat transfer fluid employed here, namely water, captures solar thermal energy and subsequently conveys it to the cascaded PCM materials, where it is stored as latent heat. A numerical model is developed to combine the phase change and heat transfer processes using the enthalpy method. To validate the numerical model, a comparison is made with existing published data. The thermal efficiency of the triplex-tube storage system is examined in two scenarios: one involving a single PCM and the other utilizing cascaded PCMs. The analysis is conducted considering the meteorological data for Marrakesh city, Morocco.

1 Introduction

As the demand for energy continues to grow across various sectors, researchers are increasingly focused on enhancing the utilization of renewable energy sources. Among these sources, solar energy has gained significant attention due to its environmentally friendly and abundant characteristics. Nonetheless, a significant hurdle in harnessing solar energy lies in its intermittent availability. To tackle this issue, the fusion of thermal energy storage systems with solar energy sources has garnered substantial attention. Over the recent years, a multitude of research endeavors have delved into the benefits of employing latent heat thermal energy storage (LHS) in the context of solar energy applications [1, 2].
The efficiency of these systems is affected by the gradual decrease in the temperature of the heat transfer fluid (HTF) during its flow. This decline in temperature results in a decrease in the rate of heat exchange, thereby slowing down the energy storage unit's charging process. To circumvent this constraint on heat transfer, the adoption of cascaded phase change materials (CPCM) has emerged as an effective strategy for augmenting energy storage. For instance, the study by Mao and Zhang [3] scrutinized the utilization of CPCM to enhance the thermal efficiency of a packed bed system, revealing a significant enhancement in the system's storage capacity. Similarly, Singh et al. [4] delved into the performance of a CPCM

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shell-and-tube system, demonstrating a noteworthy 26% reduction in melting time when compared to a system employing a single-phase change material (SPCM). To further enhance the thermal performance of energy storage units, various techniques have been proposed in the literature, including the incorporation of additives such as nanoparticles and fins into PCM [5], innovative storage system designs [6], and the utilization of cascaded PCMs [7-8]. In this study, a novel approach is explored by combining an innovative storage design, represented by the triplex-tube storage unit, with the CPCM technique to enhance the thermal performance of LHS systems. It's noteworthy that this combination of techniques represents a new and promising avenue for improving both thermal and storage capabilities. Additionally, the HTF conditions are modelled to correspond to the outlet conditions of a solar collector connected to the triplex-tube unit. The performance of the CPCM unit is compared with that of the triplex-tube unit filled with SPCM.

2 Problem situation

The solar collector-integrated system under investigation is depicted in Fig. 1. This system comprises six triplex-tube elements, each filled with CPCM. It operates by circulating hot heat transfer fluid (HTF) collected from the flat-plate solar collector throughout the storage unit. The system features outer, middle, and inner pipe diameters of 14 cm, 13 cm, and 3 cm, respectively. The tube length is fixed at 1 m, and the solar collector has a collection area of 2 m^2. Within the unit, three distinct phase change materials (RT44HC, RT54HC, and RT62HC) are employed, each with respective melting points of 43°C, 54°C, and 63°C. The thermal performance of this solar triplex-tube system is evaluated over a duration of 9 hours, specifically from 08:00 am to 05:00 pm.

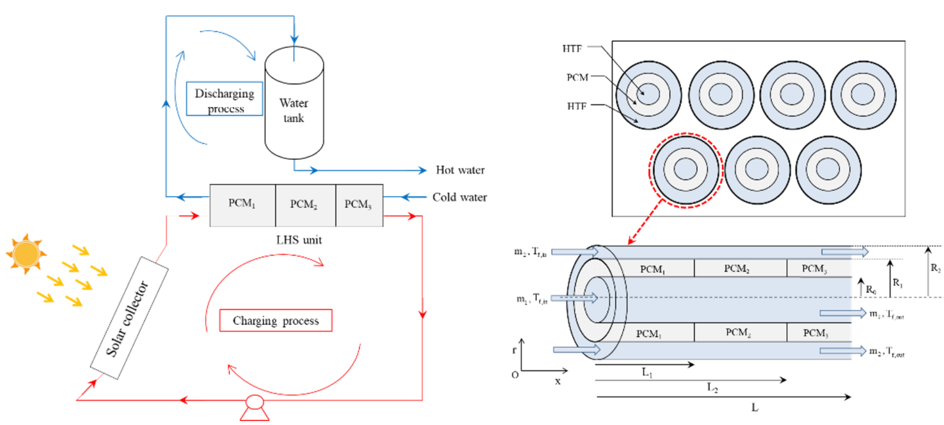

Fig. 1. Schematic illustration of the solar triplex-tube system with CPCM.

3 Governing equations

To mathematically describe the heat transfer and phase change processes, we employed the enthalpy method. The governing equations are derived under the following assumptions: (1) the study is conducted in two dimensions (2D); (2) the flow of water in the triplex-tube system is assumed to be laminar and hydrodynamically developed; (3) the thermophysical properties of both CPCM and water are considered temperature-independent; (4) the impact of natural convection in liquid CPCM is incorporated through an effective conductivity term.

The energy equations for water in the tubes are expressed as follows:

$$\frac{\partial T_{f1}}{\partial t}+u_{f1}\frac{\partial T_{f1}}{\partial x}=\frac{\partial}{\partial x}(\alpha_f\frac{\partial T_{f1}}{\partial x})+\frac{1}{r}\frac{\partial}{\partial r}(r\alpha_f\frac{\partial T_{f1}}{\partial r}) \tag{1}$$

$$\frac{\partial T_{f2}}{\partial t}+u_{f2}\frac{\partial T_{f2}}{\partial x}=\frac{\partial}{\partial x}(\alpha_f\frac{\partial T_{f2}}{\partial x})+\frac{1}{r}\frac{\partial}{\partial r}(r\alpha_f\frac{\partial T_{f2}}{\partial r}) \tag{2}$$

The velocity profiles of a Poiseuille flow in the inner and outer tubes, u_{f1} and u_{f2}, are given by:

$$u_{f1}=\frac{2m_1}{\rho_f\pi R_0^2}(1-(\frac{r}{R_0})^2) \tag{3}$$

$$u_{f2}=\frac{2m_2}{\rho_f\pi(R_2^2-R_1^2)\left[1+(\frac{R_1}{R_2})^2+\frac{1-(R_1/R_2)^2}{\ln(R_1/R_2)}\right]}\times\left[1-(\frac{r}{R_2})^2-\frac{1-(R_1/R_2)^2}{\ln(R_1/R_2)}\ln(r/R_2)\right] \tag{4}$$

The energy equation for CPCM is as follows:

$$\frac{\partial h}{\partial t}=\frac{\partial}{\partial x}(\frac{k_p}{\rho_p c_{p,p}}\frac{\partial h}{\partial x})+\frac{1}{r}\frac{\partial}{\partial r}(r\frac{k_p}{\rho_p c_{p,p}}\frac{\partial h}{\partial r})-\rho_p\Delta H\frac{\partial f}{\partial t} \tag{5}$$

where h, f, and ΔH denote the heat of fusion, volumetric sensible enthalpy, and liquid fraction, respectively.
Initially, the PCMs are in a solid state, and their temperatures are set to the ambient temperature. The initial and boundary conditions are as follows:

$$At\ t=0:\quad T_p=T_{f1}=T_{f2}=T_a \tag{6a}$$

$$At\ x=0:\quad T_{f1}=T_{f2}=T_{f,in},\ \frac{\partial T_p}{\partial x}=0 \tag{6b}$$

$$At\ x=L:\quad \frac{\partial T_{f1}}{\partial x}=\frac{\partial T_{f2}}{\partial x}=\frac{\partial T_p}{\partial x}=0 \tag{6c}$$

$$At\ r=0:\quad \frac{\partial T_{f1}}{\partial r}=0 \tag{6d}$$

$$At\ r=R_2:\quad \frac{\partial T_{f2}}{\partial r}=0 \tag{6e}$$

where $T_{f,in}$ represents the inlet water temperature, and it is defined as:

$$T_{f,in} = T_{f,out} + \frac{A_c F_R \left[I_T(\tau\alpha) - U_L(T_{f,out} - T_a) \right]}{m c_{p,f}} \tag{7}$$

4 Validation

To verify the accuracy of the self-developed numerical code, a comparison was made between the melting results of RT35 PCM in a triplex-tube system obtained with our code and those from Esapour et al. [9]. The HTF inlet temperature and mass flow rate were set at 60°C and 0.024 kg/s, respectively. The outer, middle, and inner tube diameters were 12.5 cm, 9.5 cm, and 3 cm, respectively. Figure 2 illustrates the comparison of melting fraction changes between the developed code and the study by Esapour et al. [9], showing excellent agreement.

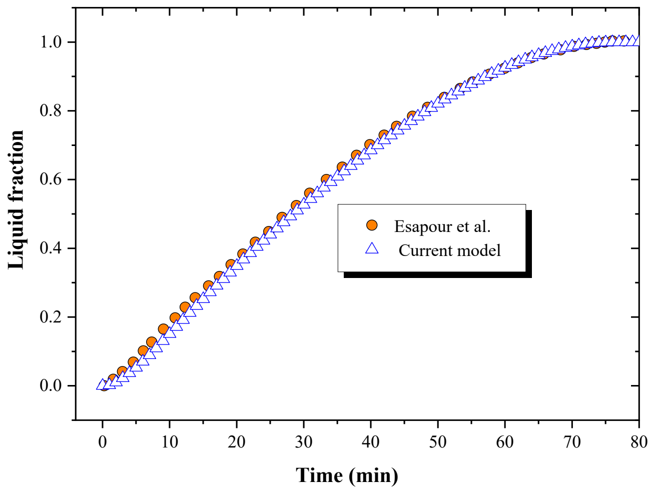

Fig. 2. Comparison between the results obtained using the self-developed code and the data presented by Esapour et al. [9] for melting in a triplex-tube storage system.

5 Results

The performance improvement of the solar triplex-tube unit is evaluated under the unique climatic conditions of Marrakesh city, with a specific focus on the month of July. Fig. 3 provides a comprehensive representation of essential data concerning solar radiation and ambient temperature. It's important to note that throughout this evaluation, the water mass flow rate within the collector remains consistently set at 0.12 kg/s. This parameter is a critical factor influencing the overall performance of the system, governing the rate at which heat is absorbed and transferred within the unit.

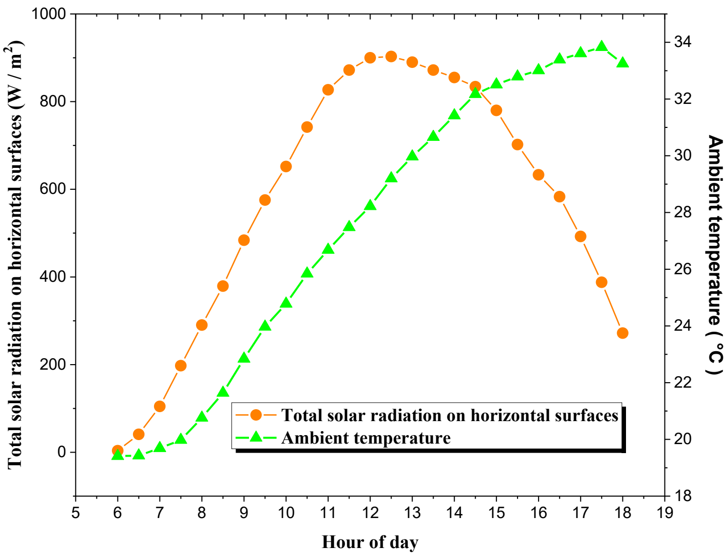

Fig. 3. Hourly total solar radiation and ambient temperature.

5.1 Optimization of PCMs lengths

To determine the optimal length for each type of CPCM, an optimization study was conducted with the objective of achieving complete melting of the cascaded PCMs within the triplex-tube unit at the conclusion of the storage process. The optimization approach involved systematically varying the length of one PCM during each simulation iteration. The resulting optimal lengths for each CPCM, namely RT62HC, RT54HC, and RT44HC, were found to be 24 cm (L_1 = 24 cm), 36 cm ($L_2 - L_1$ = 36 cm), and 40 cm ($L - L_2$ = 40 cm), respectively. Fig. 4 illustrates the temporal evolution of the melting fractions for this optimized CPCM configuration. It is evident from the results that all CPCM are completely liquefied precisely at the end of the storage process.

5.2 Effect of cascading PCMs on the melting progress

The temporal advancement of the melting process is illustrated in Fig. 5 for the CPCM-filled unit at various time intervals: t = 120 min, 180 min, 240 min, 300 min, 360 min, 420 min, 480 min, and 540 min. To provide a basis for comparison, Fig. 6 displays the evolution of the melting front positions at the same time intervals for the SPCM-filled unit. Initially, at the onset of charging, the heat transfer from the solar collector to the CPCM leads to a gradual increase in temperature until it reaches the melting point. At t = 120 min, no phase change has occurred in the storage units. By t = 180 min, RT44HC begins to melt, evident from the appearance of melting fronts between RT44HC and HTF. In the case of the SPCM-filled unit (RT62HC), no melting occurs until noon. As time progresses, both melting fronts gradually move deeper into the PCM domain. It is noteworthy that in both storage units (SPCM and

CPCM storage units), the solid-liquid interface advances further into the interior of the CPCM, especially near the inlet. This behavior is influenced by the decreasing water temperature profile along the flow direction. By the end of the storage period (05:00 pm), the CPCM is completely melted. In contrast, the SPCM charged in the storage unit has not fully melted, as depicted in Fig. 6.

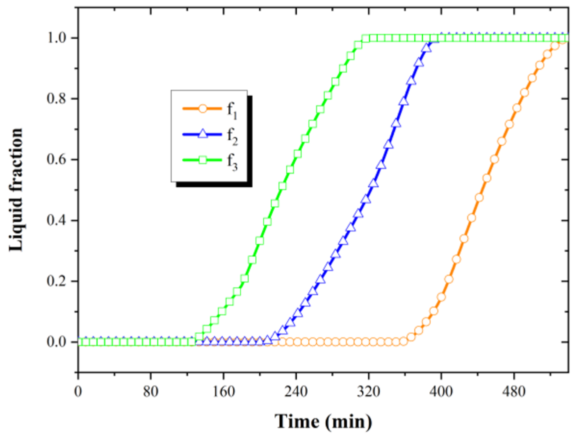

Fig. 4. Temporal evolution of liquid fractions for optimal CPCM lengths.

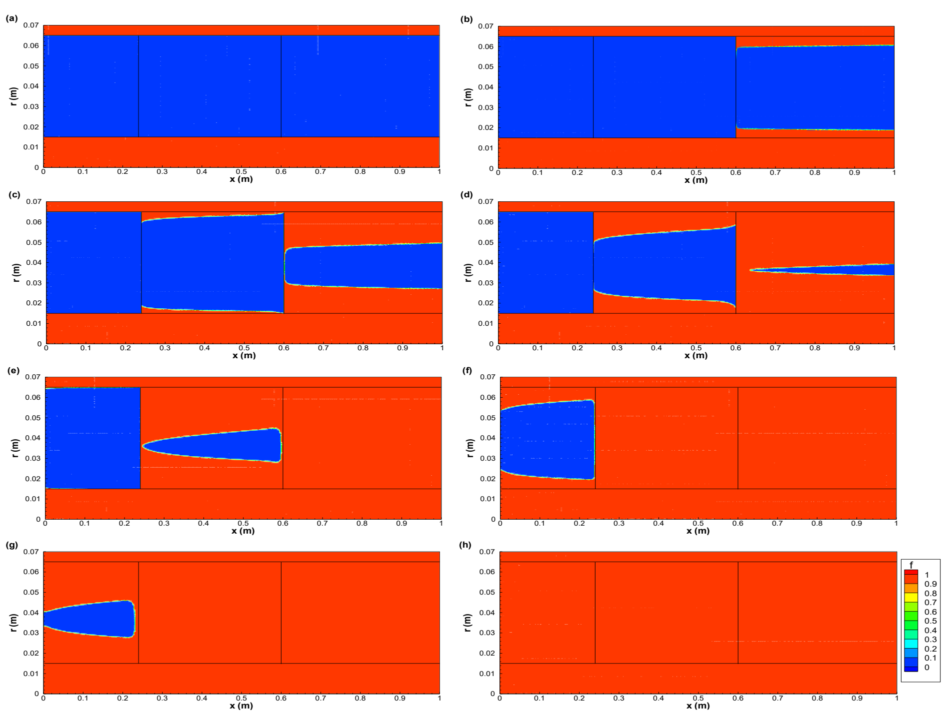

Fig. 5. Position of melting front for CPCM filled-unit at times: (a) t = 120 min, (b) 180 min, (c) 240 min, (d) 300 min, (e) 360 min, (f) 420 min, (g) 480 min, and (h) 540 min.

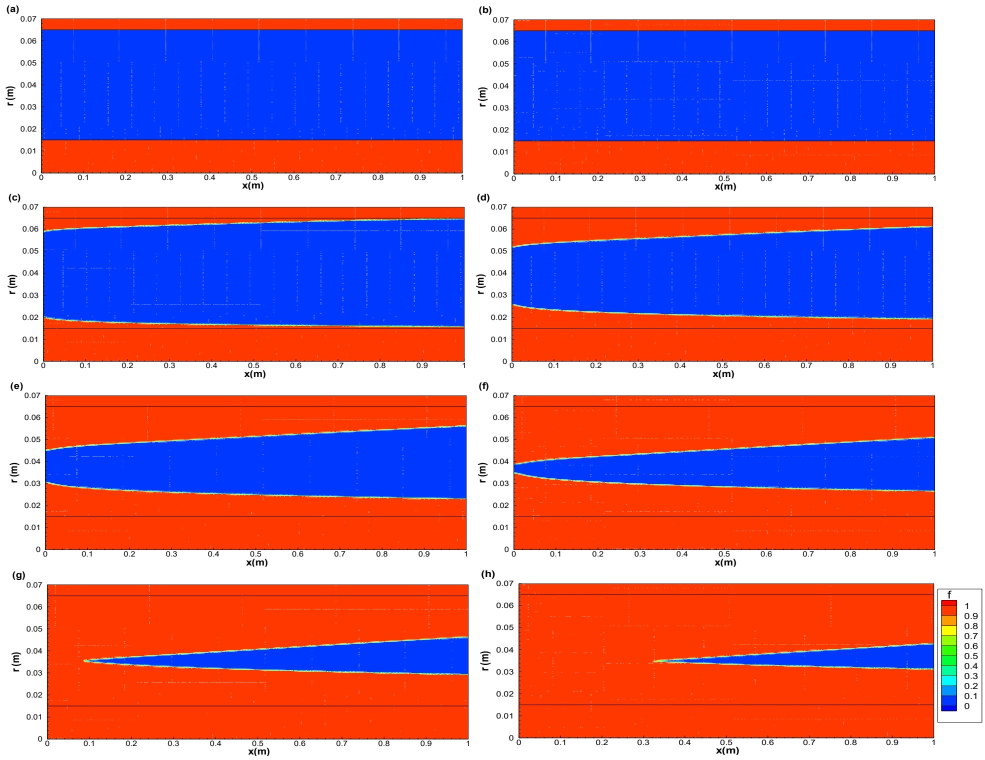

Fig. 6. Position of melting front for the SPCM filled-storage unit at times: (a) t = 120 min, (b) 180 min, (c) 240 min, (d) 300 min, (e) 360 min, (f) 420 min, (g) 480 min, and (h) 540 min.

5.3 Effect of cascading PCMs on collection efficiency of solar collector

Fig. 7 depicts the changes in average collection efficiency over time for both the CPCM and SPCM systems within the solar collector. Initially, at the commencement of the charging process, the average collection efficiency reaches its zenith due to the minimal temperature difference between the absorber and the surrounding environment, approximately 0.673. Nonetheless, as time elapses, the temperature of the solar collector's absorber progressively ascends, resulting in a gradual reduction in the collection efficiency. It is noteworthy that until t = 145.2 min, the average collection efficiency remains nearly indistinguishable for both the CPCM and SPCM-filled configurations. Furthermore, it's imperative to underscore that in contrast to the CPCM system, the collection efficiency in the SPCM system declines as time progresses, eventually reaching its ultimate value upon the culmination of the storage procedure. Additionally, it's crucial to accentuate that the CPCM-based solar storage system consistently maintains a superior average collection efficiency throughout the entire process.

6 Conclusion

This study focuses on enhancing the thermal performance of a solar triplex-tube unit through numerical investigation. A custom numerical model, utilizing the finite volume approach and

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the enthalpy method, was developed and subsequently validated by comparing its results to existing literature data for triplex-tube storage units. Prior to evaluating the storage performance, an optimization process was conducted to identify the optimal configuration for CPCM length. The unit's performance was assessed under meteorological data specific to Marrakesh, Morocco. The outcomes of this investigation highlight several advantages associated with the use of CPCM-filled units. These include higher melting efficiency, improved storage capabilities, and increased collection efficiency.

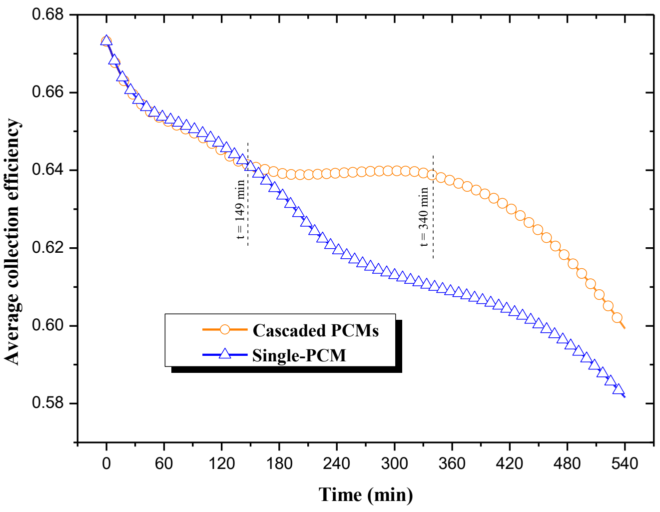

Fig. 7. Time change of average collection efficiency for CPCM and SPCM solar units.

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