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Numerical Study to Investigate the Thickness of the PCM Layer for the Three Layers Tank for the CSP Plants

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In the present study, the phase change material (PCM) layer thickness of the top and bottom PCMs change gradually with constant the middle PCM layer thickness for the three-layers thermocline thermal energy storage (TES) tank. It has been studied using spherical capsules packed with three types of PCMs with different thermophysical properties. A transient two-phase dispersion-concentric (D-C) model is used to calculate the process of phase change inside pellets to identify the temperature allocation. The method of heat transfer among molten salt and PCMs capsules is extensively discussed, with multiple numerical results shown. The results show that the thickness of the PCM layer has a high impact on the thermal performance of the TES tank. As the layer thickness of the top PCM increases, the time required to discharge the thermocline TES tank increases. The (80 % high phase change material (HPCM) -10 % intermediate phase change material (IPCM) - 10 % low phase change material (LPCM)) configuration has 14.6 %, 27.2 %, and 46.8 % higher overall efficiency than (33.3 % HPCM - 33.3 % IPCM -33.3 % LPCM) configuration, (70 % HPCM - 10 % IPCM - 20 % LPCM) configuration, and (10 % HPCM -10 % IPCM - 80 % LPCM) configuration. In contrast, the (80 % HPCM - 10 % IPCM - 10 % LPCM) configuration shows the highest capacity and utilization ratio.

1. Introduction

One of the most significant renewable energy sources is solar power because it is inexhaustible over time and free and has been used on a large scale by photovoltaic (PV) or concentrated solar power (CSP) plants (Richter et al., 2021). Solar energy must be accumulated to satisfy the imbalance among demand and supply due to the erratic existence of the sun's energy. Thermal energy storage (TES) has drawn the interest of many scholars around the world due to its performance and cost-effectiveness in a wide variety of applications at different temperatures (low, medium, and high).

Researchers have performed numerous experimental and numerical studies to strengthen the heat transfer efficiency of the packaged phase change material's (PCM) phase-change mechanism (Cheng et al., 2018). Thermochemical heat storage is still being researched in laboratories, while sensible heat storage is commonly used in industry (Jiang et al., 2019). Storing energy using sensible heat has a big drawback: limited energy storage density. Phase transition storage like TES methodology is better than reasonable thermal storage owing to its high storage density and can accumulate/retrieve energy when the temperature gradient between heat transfer fluid (HTF) capsules and PCM capsules is very little (Elfeky et al., 2019). As a result of its reliability and ability to charge and discharge energy in the fastest period, PCMs are one of the most preferred approaches to retain thermal energy (Ami et al., 2021).

Recent studies have proposed to use PCMs with a high phase change temperature for the thermocline tank in CSP plants; several investigations have looked at how a one PCM layer with various phase change temperatures can increase the charging/discharging performance of the TES tank (Elsanusi et al., 2021), cascaded PCMs (Elfeky et al., 2018), and combination sensible-latent heat TES. Elarem et al. (2021) recently published a study and discussion of the various numerical techniques reported in the literature for predicting the performance of latent packed bed TES systems. Singh et al. (2013) compared the exergy analysis of a packed bed TES system to PCM-based storage. A study of experience feedback and computational modeling of packed-bed TES systems was conducted by Esence et al. (2017). The guiding principle for PCM phase change point selection was examined by Elfeky et al. (2021).

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In light of the aforementioned studies and the previously established dispersion-concentric (D-C) model in the lab (Elfeky et al., 2020), it has been discovered that by using cascaded layers of PCMs, the rate of heat transfer can be preserved constant, and the structure of these layers depends on reducing phase transition temperature over the height of the tank, particularly at the lower and upper parts of the TES tank. The rate of heat transfer during the charge cycle is directly proportional to the temperature difference between HTF and the PCM melting temperature; the rate of heat transfer is estimated to be slower at the bottom of the thermocline tank. By using different stages of PCM capsules and lowering the melting temperature of the PCM layers along the thermocline tank, a high rate of heat transfer can be maintained. The thermal characteristics of the TES tank, which is made up of cascaded layers of PCMs, have been extensively studied in recent years using various numerical approaches, but, no research has been done on the PCM layer thickness criterion for three-layer thermocline TES tank during the charging/discharging processes. It can be seen how the change of thickness of the PCMs layer would be remarkable on the dynamic's performance of the TES thermal tank during the charge and discharge cycles. In the current study, a numerical investigation will be conducted to investigate the change of the thickness of the top and bottom PCMs layers with a constant thickness of the middle PCM layer of the three layers tank for CSP plants.

2. Model Formulation

The layout of the cascaded layers TES tank system using PCMs capsules with various thermophysical properties is illustrated in Figure 1. As can be seen in Figure 1, the (33.3 % HPCM - 33.3 % IPCM - 33.3 % LPCM) configuration is a TES system filled with cascaded PCMs capsules, where the tank is divided into three axial sections evenly, each part has the same thickness of the PCM layer, and these sections are filled with different PCMs materials. The (80 % HPCM - 10 % IPCM - 10 % LPCM) configuration is a TES system filled with cascaded PCMs capsules, where the thickness of the top of the PCM layer is 80 % from the height of the tank, thickness of the bottom of the PCM layer is 10 % from the height of the tank, and the thickness of the central PCM layer is kept constant at 10 % from the height of the tank. Table 1 shows the thermophysical characteristics of the PCMs used in this paper, as stated in (Liu., 2015).

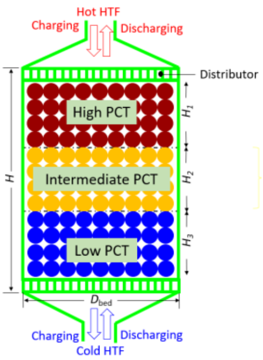

Figure 1: Schematic representation of the TES tank system

Table 1: PCMs thermo-physical properties

Arrangement	Low PCM	Intermediate PCM	High PCM
Melting temperature (°C)	382.1	439.8	505
Solidification temperature (°C)	382.1	439.8	505
Latent heat of fusion (kJ/kg)	197.6	214.9	344
Latent heat of solidification (kJ/kg)	197.6	214.9	344
Solid density (kg/m^3)	2,118	2,109	2,266
Liquid density (kg/m^3)	1,607	1,604	2,160
Solid thermal conductivity (W/m-°C)	1.0	1.0	2
Liquid thermal conductivity (W/m-°C)	1.0	1.0	1.8
Solid specific heat capacity (J/kg-°C)	928	1,005	1,338.8
Liquid specific heat capacity (J/kg-°C)	1,035	1,096	1,757.2

In the other seven configurations, the top PCM layer thickness will decrease gradually by 10 %, the bottom PCM layer thickness will increase gradually by 10 %, and the thickness of the middle layer will keep constant at 10 % from the height of the tank.

2.1 Governing equations

The dispersion-concentric (D-C) numerical analysis is employed in this study to investigate the dynamic characteristics of the TES tank and to illustrate how the HTF moves through the packing area. In this model, the thermocline TES tank is viewed as a porous material made up of individual PCM capsules (Elfeky et al., 2021). The D-C model is used because the thermal distribution within solid capsules can only be solved using this process. The apparent heat capacity approach is used to investigate the phase shift phenomenon of PCM within capsules. The assumptions below are as follows:

1) The tank's interior and exterior surfaces are fully insulated.
2) Through charging, HTF passes from the upper inlet port to the lowest outlet port, and conversely throughout discharging.
3) Because of its negligible importance, the energy lost from the thermocline tank's two ends is overlooked.
4) The inlet and exit temperatures are used to assess the HTF's thermophysical properties, Tave= $(T_{in}+T_{ex})/2$ (Elfeky et al., 2018).
5) The heat generated inside the thermocline TES tank, as well as radiation heat transfer, has been ignored.

The present numerical model's mathematical equations that explain the temperature gradient between HTF and PCM capsules are formulated using the hypotheses described above:
For the HTF:

$$\varepsilon\rho_f c_{p,f}\frac{\partial T_f}{\partial t}+\varepsilon u_f\rho_f c_{p,f}\frac{\partial T_f}{\partial x}=\varepsilon\lambda_f\frac{\partial^2 T_f}{\partial x^2}+h_f\left(T_s-T_f\right)+h_w\left(T_w-T_f\right) \quad (1)$$

where *ε* is average bed porosity, ρ_f is the HTF density, $c_{p,f}$ is the specific heat capacity of the HTF, u_f is the HTF inlet velocity, T_f is the temperature of HTF, T_s is the temperature of the PCM, T_w is the tank wall temperature, h_f is the volumetric heat transfer coefficient between fluid and solid, h_w is the volumetric heat transfer coefficient between tank and ambiance, λ_f is the thermal conductivity of the HTF.
For the PCMs capsules:

$$\left(1-\varepsilon\right)\rho_s c_{p,s}\frac{\partial T_s}{\partial t}=\left(1-\varepsilon\right)\lambda_s\frac{\partial^2 T_s}{\partial x^2}+h_f\left(T_f-T_s\right) \quad (2)$$

where ρ_s is the PCM density, $c_{p,S}$ is the specific heat capacity of the PCM, λ_S is the thermal conductivity of the PCM.
The following formula can be used to measure the temperature distribution on the PCM capsule surface:

$$\rho_s c_{p,s}\frac{\partial T_p}{\partial t}=\frac{1}{r^2}\frac{\partial}{\partial r}\left(\lambda_s r^2\frac{\partial T_p}{\partial r}\right) \quad (3)$$

where r is radius of PCM capsule.

2.2 Numerical approach

The thermocline tank's packing area is divided into equivalent parts for each control volume. For all of the present configurations considered, the axial and radial directions were divided into an equal number of parts (Nx) and (Rx), as shown in Figure 1. The D-C mathematical models, which describe the heat transfer coefficient between the PCMs pellets and the HTF, are calculated using MATLAB by explicitly estimating the finite difference approach within the totally implicit scheme. Both the advective and temporal terms in the mathematical formula Eq. (1) are solved simultaneously using the first-order upwind approach; the diffusion term is solved using the second-order central method. The corresponding boundary conditions specify the temperature allocation of PCMs capsules and HTF at the beginning of charging and discharging processes, and afterward, the D-C model solutions are obtained simultaneously.

2.3 Performance analysis

The thermocline tank's performance indicators, such as overall efficiency, capacity ratio, and utilization ratio, provide a basic calculation for TES tank design and assessment. All of these criteria have been described in previous laboratory work (Elfeky et al., 2018).

3. Results and discussion

The study and evaluation of the PCM layer thickness is among the key parameters used to improve the thermal performance of the thermal line TES tank used in CSP plants. The TES process in the thermocline tank maintains the CSP plants running; the heat transfer process within this tank during the charge/discharge processes is crucial and will be studied in depth in this analysis.

3.1 Model validation

The latest numerical analysis of the two-phase D-C model is compared to the experimental study performed by (Pacheco et al., 2002). During the charging period, the discrepancy between numerical and experimental effects of adjustments in HTF temperature profiles over thermocline TES tank height has been demonstrated. As shown in Figure 2, the average difference between the present numerical analysis and experimental data is approximately 14.32 % at the tank's bottom and 5.62 % at its top.

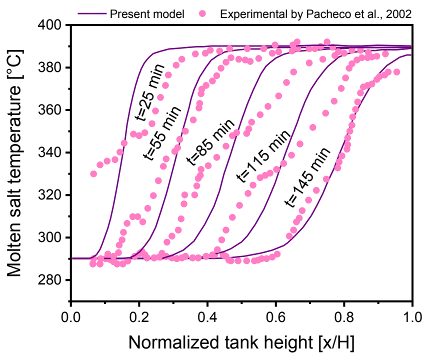

Figure 2: Validation of the current numerical model

3.2 HTF temperature distribution

Figure 3 demonstrates the HTF axial temperature distribution along with the thermocline TES tank height during the charge and discharge processes for the seven studied structures after 300 min. The performance of the thermocline TES tank is robustly influenced by the thickness of each PCM layer inside it, as demonstrated in Figure 3. The figure illustrates that the thickness of each PCM layer has a high impact on the distribution of stored and recovered energy. For the charge and discharge processes, when the PCMs material properties' melting and solidifying temperatures are high, this helps in enhancing the heat transfer rate between both the PCMs substances and the HTF. Increasing the thickness of the top PCM helps to maximize the variation between the temperature of the PCM material and the HTF during discharging cycles. The (80 % HPCM - 10 % IPCM - 10 % LPCM) configuration has a thermal performance that covers more than 55.5 % of the tank height at a higher temperature during the charging period and 47.8 % of the tank height at a lower temperature during the discharging cycle, making it the recommended configuration in the current study.

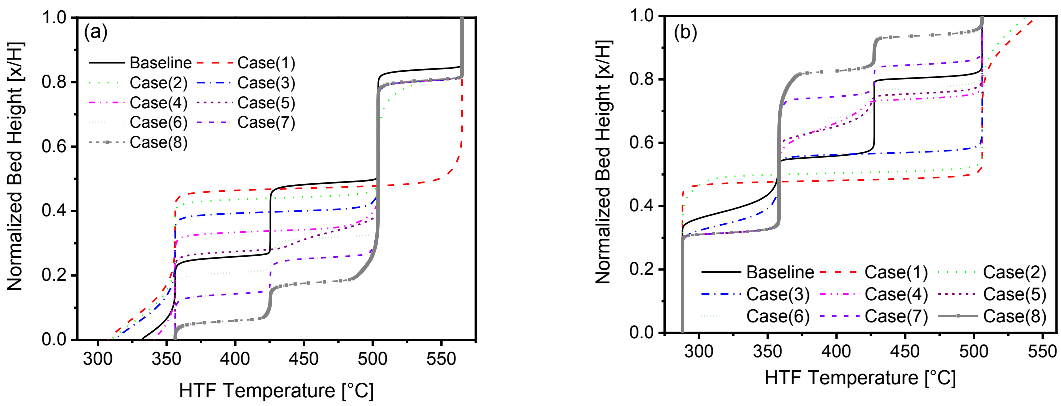

Figure 3: HTF axial temperature distribution over height after 300 min for (a) Charge and (b) Discharge cycles

3.3 Exit HTF temperature allocation

Figure 4 shows the HTF exit temperature overtime for all studied configurations. From the figure, the findings conclude that the thickness of each PCM has a great influence on the discharge time as in configurations (80 % HPCM - 10 % IPCM - 10 % LPCM) and (70 % HPCM - 10 % IPCM - 20 % LPCM), affects the amount of energy that might be restored. Because of the thickness of the PCM, which is located at the lower part of the tank, decreases, the time required to discharge the thermocline TES tank increases until 60 % from the height of the tank; after that the discharging time decrease. This helps to complete the melting/ solidification process for the PCM which is situated at the top section of the TES tank prior to the pinch-point interface crashing. The lower the bottom PCM layer thickness, the more amount of energy can be stored at higher temperatures.

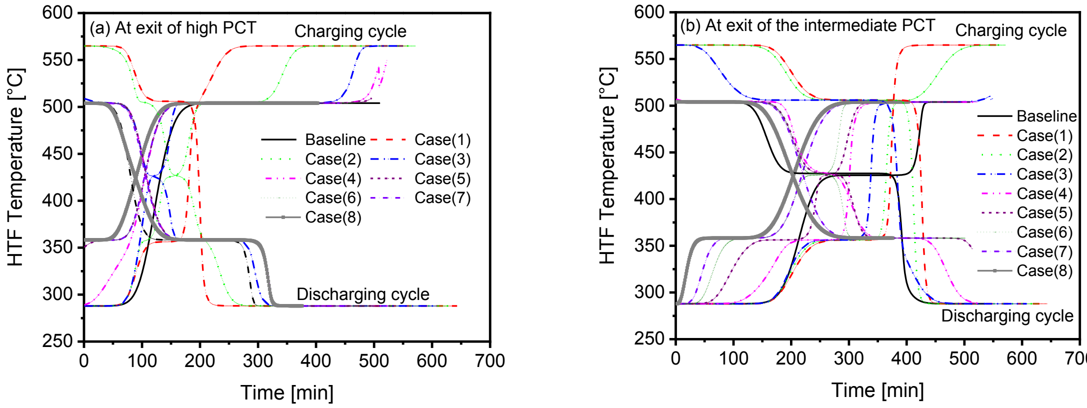

Figure 4: HTF temperature at the exit of high and intermediate PCM

3.4 Performance analysis

The following research discusses the thermal performance of seven different configurations for thermocline tank in the context of the charge/discharge efficiency and capacity/utilization ratio during the charge and discharge processes, as displayed in Table 2. The storage capacity of the tank is determined by the rate of heat transfer among PCMs materials and HTF, and a significant temperature gradient between them implies that a powerful force is seeking to strengthen the heat transfer process, which will result in an increased pinch point interface region movement. During the charge/discharge processes, the results indicate that (80 % HPCM – 10 % IPCM -10 % LPCM) configuration has 14.6 %, 27.2 %, and 46.8 % higher overall efficiency than (33.3 % HPCM - 33.3 % IPCM - 33.3 % LPCM) configuration, (30 % HPCM – 10 % IPCM - 60 % LPCM) configuration, and (10 % HPCM – 10 % IPCM - 80 % LPCM) configuration, respectively, because of comparatively higher matching between PCM capsule and HTF temperature distribution. Table 2 shows the capacity/utilization ratio for all studied configurations. It reveals that (80 % HPCM -10 % IPCM -10 % LPCM) configuration accomplishes the highest thermal performance, (70 % HPCM - 10% IPCM - 20 % LPCM) configuration design the second, and the (33.3 % HPCM - 33.3 % IPCM - 33.3 % LPCM) configuration the worst in the row. Because of the significant temperature gradient between the HTF and the phase transformation temperature of the PCM layers, (80 % HPCM - 10% IPCM - 10 % LPCM) configuration has the maximum rate of heat transfer.

Table 2: Steady-state performance for all configurations

Configurations	η_{ch} %	η_{disch} %	η_{cyclic} %	σ %	γ %	$E_{recovered}$ (MWh)
33.3 % HPCM - 33.3 % IPCM - 33.3 % LPCM	87.9	83.5	73.4	76.4	74.6	159.2
80 % HPCM - 10 % IPCM - 10 % LPCM	94.9	89.9	84.6	81.5	80.3	203.2
70 % HPCM - 10 % IPCM - 20 % LPCM	89.2	85.5	76.9	82.7	81.5	198.1
60 % HPCM - 10 % IPCM - 30 % LPCM	88.9	83.2	73.9	80.1	78.8	183.8
50 % HPCM - 10 % IPCM - 40 % LPCM	86.1	82.1	71.3	76.2	72.8	154.4
40 % HPCM - 10 % IPCM - 50 % LPCM	84.2	80.9	68.5	72.4	66.3	151.4
30 % HPCM - 10 % IPCM - 60 % LPCM	83.8	79.8	66.4	68.7	59.6	147.4
20 % HPCM - 10 % IPCM - 70 % LPCM	81.7	77.3	62.5	65.1	51.1	132.9
10 % HPCM - 10 % IPCM - 80 % LPCM	77.2	73.6	57.6	60.2	39.2	111.2

4. Conclusions

In this research, the thermal performance of a three-layer thermocline TES tank is numerically investigated during charging and discharging cycles at varied PCM layer thicknesses. The differences in heat transfer between HTF and PCM capsules are discussed in depth. The findings reveal that the thickness of the PCM layer has a significant impact on the distribution of retrieved energy. The arrangement with the thickest PCM layer in the upper section had the highest overall efficiency and recovered energy of 84.6 %, 203.2 MWh, according to the results. The current work can be expanded by examining how the thickness of the middle and lower PCM layers can be altered while the thickness of the top PCM layer remains unchanged. Because of the intermittent nature of solar radiation, this current research could pave the way for the best design of the cascaded thermocline TES tank configuration, which aims to increase the overall efficiency of the TES tank system used in CSP plants to meet the mismatch between supply and demand for energy.

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