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INFLUENCE OF THE PCM VOLUME FRACTION ON THE THERMAL PERFORMANCE OF THERMOCLINE THERMAL ENERGY STORAGE TANK USED IN CSP PLANTS

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ABSTRACT

In the current paper, we investigated the phase change material (PCM) volume fraction for three-layers thermocline thermal energy storage (TES) tank system by using spherical capsules filled with high temperature PCM of different thermo-physical properties. A transient one-dimensional dispersion-concentric (D-C) model is modified to calculate the phase change process within capsules so as to determine the temperature distribution. Detailed characteristics of heat transfer between molten salt and the PCMs capsules are discussed, and various numerical results are presented, including the temperature distributions of molten salt and exit temperature. The results show that the volume fraction has a significant impact on the stored/recovered time energy. As the volume fraction of bottom PCM increases, the time required to discharge the thermocline TES tank increases.

Keywords: thermal energy storage; concentrating solar power plants

NONMENCLATURE

c_p	specific heat capacity, $J{\cdot}kg^{-1}{\cdot}K^{-1}$
E_{stored}	energy stored in tank, J
$E_{recovered}$	energy recovered from tank, J
h	heat transfer coefficient, $W{\cdot}m^{-2}{\cdot}K^{-1}$
k	thermal conductivity, $W{\cdot}m^{-1}{\cdot}K^{-1}$
T	temperature, K
t	time, s
u_f	fluid velocity, $m{\cdot}s^{-1}$
x	axial direction
GREEK SYMBOLS	
ε	average bed porosity
μ	dynamic viscosity, $kg{\cdot}m^{-1}{\cdot}s^{-1}$
ρ	density, $kg{\cdot}m^{-2}$
SUBSCRIPTS	
f	fluid
s	solid

1. INTRODUCTION

One of the most important sources of renewable energy is solar energy because It is free and with time is inexhaustible, and has been widely used through photovoltaic (PV) or concentrating solar power (CSP) plants [1]. In spite of this, energy needs to be stored to meet the mismatch between energy supply and demand, because of the intermittent nature of solar radiation. Thermal energy storage (TES) has attracted considerable attention from researchers around the world because of its effectiveness in terms of efficiency and cost for all applications of solar energy at low, medium and high temperatures.

Many researchers have carried out experimental and numerical studies in order to improve the heat transfer performance of the phase change process of the encapsulated PCM [2]. During the charging/discharging cycles, the heat transfer process is a function of the temperature difference between the molten salt and the PCM melting temperature; the heat transfer rate is expected to be lower at the top and lower part of the thermocline TES tank. For this reason, the heat transfer rate can be maintained constant by using three-layers of PCM and the design of these layers depend on decreasing melting temperature over the tank height. Based on the above studies and the developed (D-C) model in our previous work [3-5], it can be found that the volume fraction of the PCM layers during the charging/discharging cycles would be remarkable on the

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thermal performance of the thermocline TES tank. Therefore, in the present study, the thermal performance of the three-layers thermocline TES tank is numerically investigated at different PCM volume fraction during the charging /discharging cycles.

2. MODEL FORMULATION

2.1 Model description

The schematic of the thermocline TES tank system using PCMs capsules with different thermo-physical properties is shown in Fig 1. The thermocline tank is filled with three types of PCMs capsules with the same diameter and at the different melting point, and the molten salt flows through the void region which exists between the capsules. As illustrated in Fig. 1, case (1) is a TES system filled with cascaded PCMs capsules, where the bed is divided equally into three axial-sections, each section has the same volume fraction of PCM and these sections are filled with different PCM materials i.e. phase change temperature (PCT $^{(a)}$), PCT$^{(b)}$, and PCT $^{(c)}$ in sequence. In the other three cases, the PCM volume fraction changes frequently.

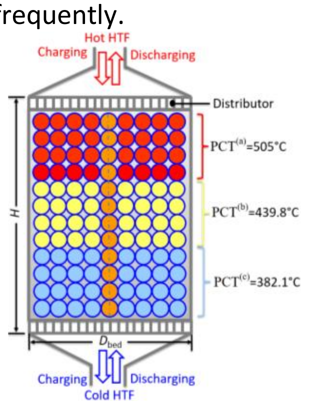


Fig 1 Schematic diagram of thermocline TES tank

2.2 Packed bed model and governing equations

In the current study, the two-dimensional transient Dispersion-Concentric (D-C) numerical model used to investigate the thermal performance of the thermocline TES tank and explain how the molten salt travels through the packing region. The thermocline TES tank in this model is considered as a porous structure consisting of separate capsules of the PCMs [6].

For the molten salt:

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

For the solid phase:

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

2.3 Initial and boundary conditions

The initial conditions of the first cycle shall be determined only. After that, the initial values of molten salt temperature and PCMs capsules for each next cycle during the discharge cycle shall be equal to those at the end of the charging cycle. For each charge/discharge cycle, at the entrance and exit of the thermocline TES tank, the boundary conditions have been defined and the temperature has been measured continuously.

2.4 Numerical method

The packing region of the thermocline tank is sectioned to an equal number of control volumes. Moreover, the axial and the radial direction have been divided to an equal number of sections (Nx) and (Rx), respectively, for all the current cases studied. The heat exchange process between the PCMs capsules and the molten salt is a function in temperature difference between them.

3. RESULTS AND DISCUSSION

3.1 Model validation

The current transient one-dimensional (D-C) model numerical study is verified vs. the experimental study which was made by Pacheco et al. [7].

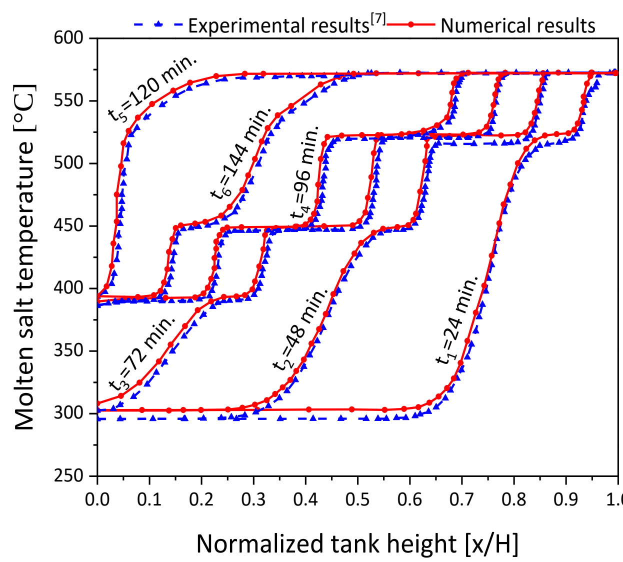
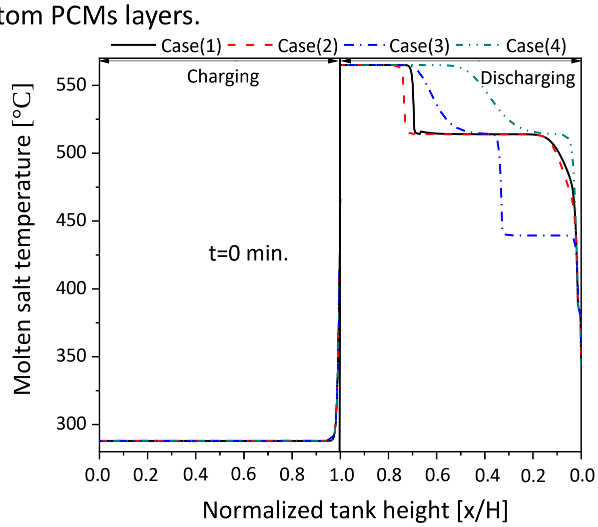


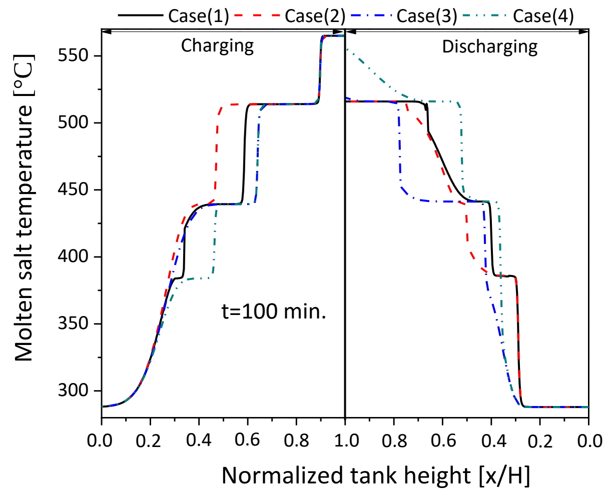
Fig 2 Comparisons of molten salt axial temperature for the current study and Pacheco et al. [7]

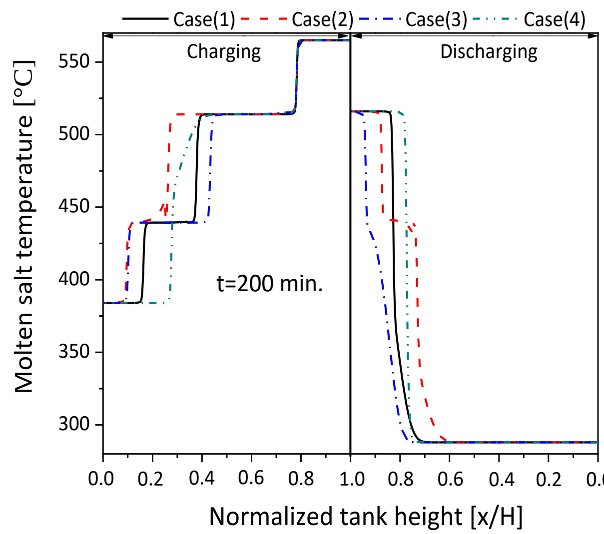
The numerical results of changes in molten salt temperature profiles over the height of the thermocline TES tank during the charging cycle for the current numerical model (solid line) and the experimental (dash line) data in Ref. [7] demonstrated in Fig 2. The average deviation between the present numerical model and experimental data are approximately 14.32% at the bottom of the tank and 5.62% at the top of the tank, respectively as in Fig 2. The results obtained from the current transient two-dimensional (D-C) model are clearly consistent with the results contained in the in Ref. [7].so, it can be said that the current model can provide reasonable predictions.

3.2 *Molten salt* axial temperature distribution

Figure 3 demonstrates the molten salt axial temperature distribution along the thermocline TES tank height during the charging/discharging cycles for all the studied cases at a different time step. The design of the thermocline TES tank is strongly affected by the volume fraction of each PCM layer inside it as shown in Fig.3. The figure illustrates that the volume fraction has a significant impact on the distribution of stored and recovered energy. During the charging/discharging process, whenever the melting/solidifying temperature of the PCMs layers is high, this will increase the rate of heat transfer between the molten salt and the PCM capsules. Increasing the volume fraction of the top PCM help to reduce the difference between the temperature of the PCM capsule and the molten salt during discharging cycles. This reduces heat transfer rate during discharging cycles. The molten salt comes out at the solidification temperature of the top PCMs layer of the thermocline tank until it reaches the discharging cut off temperature. Therefore, using the top PCM layer with low volume fraction helps to increase the discharge temperature of the molten salt and in some cases, the molten salt exit temperature will be higher than the solidification temperature of the middle and bottom PCMs layers.







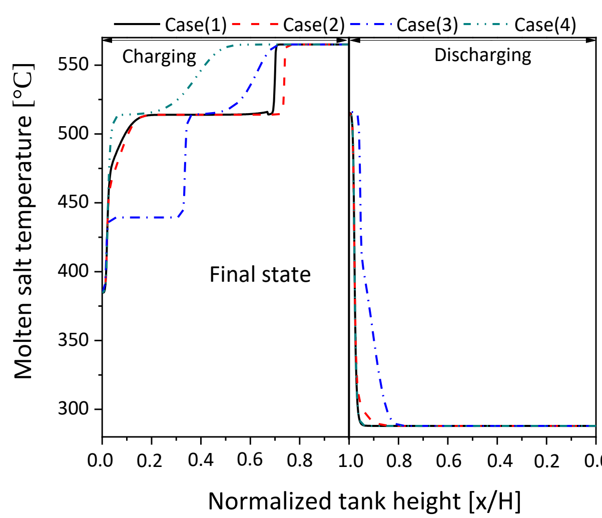


Fig 3 Molten salt axial temperature distribution over height at different time step for the charging/discharging cycles

3.3 *Molten salt exit temperature distribution*

Figure 4 shows the molten salt exit temperature over time for all studied cases. From the figure, we can conclude that the volume fraction of each PCM has a significant effect on the discharge time and therefore affects the amount of energy that could be recovered. Because of the volume fraction of the PCM which is located at the bottom of the tank increases, the time required to discharge the thermocline TES tank increases. This helps to complete the melting/ solidification process for the PCM which is located at the top part of the tank before the pinch point interface can collapse. Therefore, the lower the volume fraction of the top PCM, the more amount of energy can be stored at the operating temperature. The PCM layer in the middle of the tank works as a buffer. Thus, increasing the volume fraction of the bottom of the PCM at the account of both the top and middle of the PCMs, it helps the system to work for a longer period of time and recover the maximum amount of energy during the process of discharge.

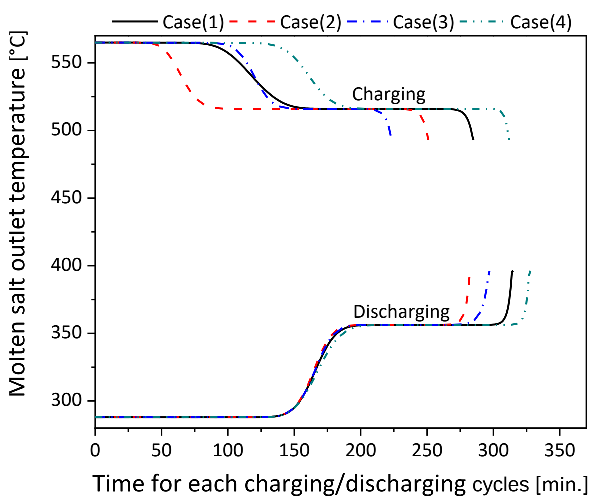


Fig 4 Molten salt exit temperature over the time for charging/discharging cycles

4. CONCLUSIONS

In the current paper, a transient one-dimensional dispersion-concentric (D-C) model is modified to calculate the phase change process within capsules so as to determine the temperature distribution and phase change front within each capsule. The thermal performance of the three-layers thermocline TES tank is numerically investigated at different PCM volume fraction during the charging/discharging cycles. Detailed characteristics of heat transfer between molten salt and the PCM capsules are discussed. The results show that the volume fraction has a significant impact on recovered time. As the volume fraction of bottom PCM increases, the time required to discharge the thermocline TES tank increases. This current work can open the door for the optimal design of the thermocline TES tank system, which works to improve the efficiency of CSP plants.

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