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Thermal Performance Evaluation of Combined Sensible-Latent Heat Storage Tank with a Different Storage Medium

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The key technology for the continuous supply of electricity from solar power plants is a thermal energy storage (TES) approach. The selection of the best storage system and the correct thermal storage material remains a significant challenge in solar power research and development. The thermocline TES system is a cost-effective choice for storing latent and sensible heat by comparing it to the liquid storage substance in a two-tank TES system. The study is performed to assess the thermal characteristics of thermocline tank structure by using a hybrid sensible latent heat storage system. The dispersion-concentric simulation studies were first examined using the MATLAB code, and afterward, the current findings of the research were verified. The major goal of this study is to look into and assess the effect of changing the sensible storage material layer of a hybrid sensible, latent heat storage system on the TES tank's thermal performance. The findings reveal that employing a sensible heat storage material with a high specific heat capacity, such as slag pebble, permits the TES tank to charge for the most extended duration feasible and discharge more stored energy with greater efficiency. The recovered energy of hybrid slag pebble phase change materials (HSPPCMs) configuration is 142.6 MWh, which is more significant than all other configurations examined. The HSPPCMs arrangement demonstrates the maximum capacity ratio and the utilization ratio of 82.39 % and 80.91 %.

1. Introduction

Thermal energy storage (TES) is a cost-effective and straightforward solution to resolve energy market and economic mismatches in numerous major industries (Yu et al., 2020). In high-temperature fields, TES has a range of applications, including solar power plant facilities, compressed air TES (Zhou et al., 2019), and technology and applications for recovering waste heat (Ortega-Fernández et al., 2019). TES is beneficial for improving the adaptability of concentrating solar power plant (CSP) plants by enhancing the thermal equilibrium of the system components.

In the previous, conventional sensible heat storage (SHS) in molten salts was the most common TES utilized by CSP facilities. Because of the advantages of being cheap and having a high energy storage density, a one-thermocline TES tank incorporating phase change materials (PCMs) is gaining popularity. One tank-type thermocline TES units are 20 to 37 % more cost-effective than the two tank-type TES systems (Pietruszkiewicz al., 2010). The thermal stability of conventional substances (e.g., solar salt) at maximum temperatures of roughly 600 degrees Celsius and below (Pfleger et al., 2015) prevents coupling with efficient energy cycles that work at greater temperatures and efficiency. To overcome the temperature restriction, chloride salts can be employed, although they are exceedingly corrosive and receive adequate tank materials. A further alternative is to store sensible heat in solid materials such as rocks, but this reduces the efficiency of the combined thermodynamic power cycle by lowering energy densities and adding the potential problem of a lower output temperature (Xu et al., 2021) that varies over time (Zuo et al., 2021), all of which decrease the effectiveness of the combined thermodynamic steam generator.

Ahead they are widely ready for sale purposes, the techno-economic difficulties connected with sensible and latent heat TES systems must be resolved (Elfeky et al., 2021). The adoption of a hybrid material that combines latent and sensible heat storage materials can produce a beneficial effect that combines the benefits of both techniques while also addressing some of the concerns that sensible and latent heat TES have (Elfeky et al.,

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2020). Due to the significantly more excellent thermal conductivity and the wider contact area between the passive TES units employing concrete as the sensible storage medium, tubular heat exchangers are frequently installed, resulting in more excellent heat transfer rates.

According to a recent literature review, limited research has focused on determining the thermal characteristics of the hybrid sensible, latent heat storage (HSLHS) thermocline scheme when layers of SHS material with various thermal properties are used. The thermal performance of the thermal storage tank, which comprises three identical layers of PCM and SHS, has already been thoroughly examined using a different numerical technique. For the HSLHS thermal storage scheme, the performance of this system has not been explored using layers of SHS material with varying thermal characteristics. To solve these weaknesses, the current study assesses the possibility of six different HSLHS configurations for usage as a high-temperature TES system based on the dispersion-concentric (D-C) computational numerical model prepared in lab research in earlier studies (Elfeky et al., 2018). The paper's main goals are to (1) analyze the temperature distribution of the fluid flow and PCMs throughout charging and discharging periods for each configuration; (2) evaluate the response of storage materials to the charging and discharging rate; and (3) examine performance parameters such as overall efficiency, capacity ratio, utilization ratio, and restored energy.

2. Model Formulation

Table 1 demonstrates a graphical representation and thermal properties of the layers of the thermal storage tank, which utilized hybrid layers of PCMs and SHS material with various thermophysical features. The HSLHS tank form consists of a vertically stacked cylindrical tank with two holes for molten salt entry and escapes throughout charge and discharge intervals, one from the top and the other from the bottom.

The thermal characteristics of the HSLHS thermal storage tank will be investigated in six distinct arrangements. The hybrid quartzite rock phase change materials (HQRPCMs) structure is a thermal storage tank separated into three segments, each produced with various PCTs (phase change temperatures), i.e., high phase change temperature (HPCT), SSHS, and low phase change temperature (LPCT), from the uppermost part to the base (Table 1). In Table 1, the height of the PCM layer and the sort of packaging material for the other arrangements are shown in detail, e.g., hybrid rock phase change materials (HRPCMs), hybrid Taconite phase change materials (HTPCMs), hybrid Cofalit ® phase change materials (HCPCMs), hybrid Slag Pebble phase change materials (HSPPCMs), and hybrid Alumina ceramics phase change materials (HACPCMs).

Table 1: The various arrangements of the HSLHS tank.

Configurations	HPCT (%)	Solid filler (%)	LPCT (%)
HQRPCMs	15 %	70 % Quartzite rock	15 %
HRPCMs	15 %	70 % Rock (granite)	15 %
HTPCMs	15 %	70 % Taconite	15 %
HCPCMs	15 %	70 % Cofalit ®	15 %
HSPPCMs	15 %	70 % Slag Pebble	15 %
HACPCMs	15 %	70 % Alumina ceramics	15 %

2.1 Governing equations

The D-C numerical methodology was conducted to assess the thermal characteristics of the HSLHS tank layouts in this study. The present numerical analysis was also utilized to depict how molten salt moves within the packaging zone. The thermal storage tank has been treated in this study as a porous substance made up of encapsulated PCMs pellets and solid SHS spherical grains. The following presumption must be taken into account:

1) The inside and outside sides of the tank are thoroughly insulated.
2) While charges, the high-temperature fluid travels from the upper to the lower section and conversely during discharges.
3) The SHS material and encapsulated PCM pellets have the same diameter.
4) All SHS material particles and encapsulated PCM pellets are treated the same and are separated at the exact distances. The current D-C approach does not discuss the effects of distributors.
5) Due to its small value, the energy lost from the upper and lower ends of the tank is overlooked.
6) Based on the entrance and output temperatures, the thermo-physical characteristics of the fluid have been computed, T_{ave}= (Tin+Tout)/2.
7) The thermal energy generation and radiant heat exchanges within the tank have been overlooked.

The heat transmission process between fluid, SHS material, and encapsulated PCMs pellets was described using the numerical model applied in this research, which was calculated using the accompanying mathematical formulas and the assumption mentioned above:
For the fluid:

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

where ε (-) is average bed porosity, ρ_f (kg/m^2) is the HTF density, $c_{p,f}$ (J/(kg.°C)) is the specific heat capacity of the HTF, u_f (m/s) is the HTF inlet velocity, T_f (°C) is the temperature of HTF, T_s (°C) is the temperature of the PCM, T_w (°C) is the tank wall temperature, h_f (W/(m^3.°C)) is the volumetric heat transfer coefficient between fluid and solid, h_w (W/(m^3.°C)) is the volumetric heat transfer coefficient between tank and ambiance, λ_f (W/(m.°C) is the thermal conductivity of the HTF.
For the PCMs capsules:

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

where ρ_s (kg/m^2) is the PCM density, $c_{p,s}$ (J/(kg.°C) is the specific heat capacity of the PCM, and λ_S (W/(m.°C) is the thermal conductivity of the PCM.
The temperature allocation can be determined on the outer surface of the SHS material or encapsulated PCMs pellets as follows:

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

where r (m) is the radius of the PCM capsule.
When the thermophysical parameters of the PCMs capsule shift during charging / discharging processes, the effective heat capacity technique was used to describe the occurrence of phase shift (Elfeky et al., 2021). The phase shift phenomenon is hypothesized to occur within a temperature range.

2.2 Numerical approach

The package zone of the HSLHS tank is divided into an identical number of control units. For all of the examples currently under study, the axial and radial orientations were split into an equal number of elements (N_x) and (R_x). The temperature difference between the thermal storage material and the fluid determines the success of heat transfer between the solid SHS material, encapsulated PCMs pellets, and the fluid. The D-C mathematical models that distinguish the rate of heat transfer among solid SHS materials encapsulated PCMs pellets and the fluid is solved using MATLAB by calculating the finite element explicitly within the suggested structure. The first-order upwind method would be chosen to simultaneously handle advective and temporal circumstances calculated from the formula (Eq.(1)); the diffusion theory would be determined using the second-order finite-difference methodology.

2.3 Performance analysis

The thermocline tank's performance indicators, such as overall efficiency, capacity ratio, and utilization ratio, provide a basic TES tank design and assessment calculation. 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 are among the key parameters 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 practical effects of adjustments in HTF temperature profiles over thermocline TES tank height has been demonstrated. As shown in Figure 1, 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.

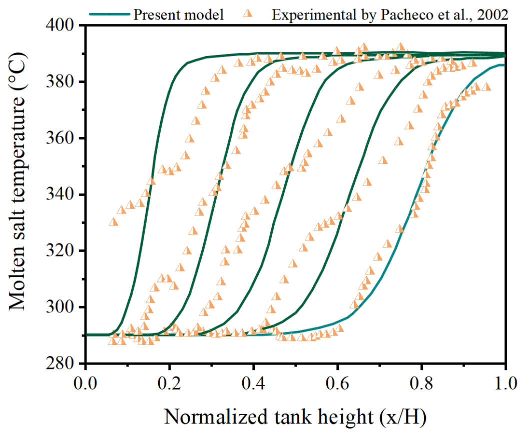

Figure 1: Validation of the current numerical model

3.2 HTF temperature distribution

For all of the research studied currently, Figure 2 depicts the HTF axial temperature profile through the altitude of the tank throughout the charging process. The designs of the HSLHS tank significantly impact the thermocline tank's thermal characteristics. The phase-transition propagation movement travel rate is affected by the latent heat, the phase transition temperature of the top and bottom encapsulated PCMs layer, and the thermal characteristics of the solid SHS material throughout the charging process.

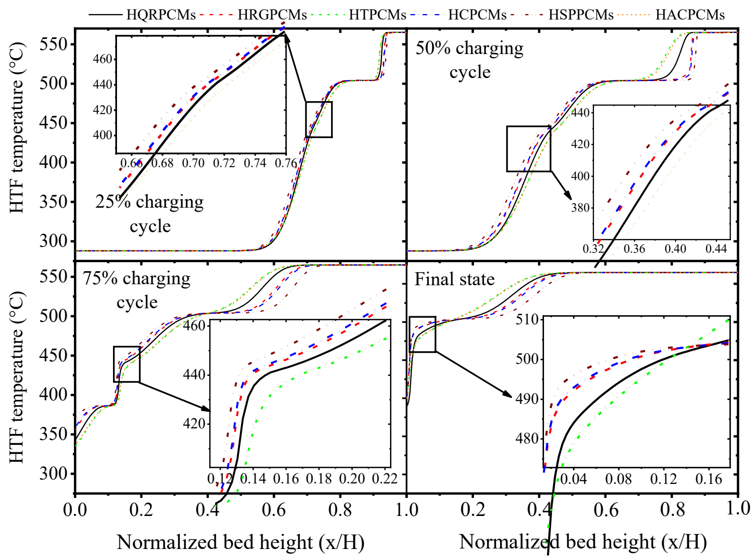

Figure 2: Temperature distribution of fluid throughout the charging process for six various designs

Whenever the heat of fusion and phase transition temperature of encapsulated PCMs pellets and thermal characteristics of the SHS solid material is high or when the temperature gradient between the fluid and thermal storage materials is minimal, the phase-transition propagation velocity will move at a slower rate throughout the charging process.

3.3 Temperature distributions vs. charge/discharge time

For all scenarios examined at various heights for the charging process, Figure 3 shows the fluid temperature distribution vs. charge period. The graphic depicts the advantages of combining the HSLHS arrangement with different SHS materials. The HSLHS tank effectiveness is influenced by the thermophysical characteristics of the encapsulated PCMs pellets and the thermal properties of the solid SHS material, both of which influence the energy performance throughout the charging process. The top and bottom encapsulated PCMs pellets act as a cushion during the charge cycle, allowing the device to store more energy.

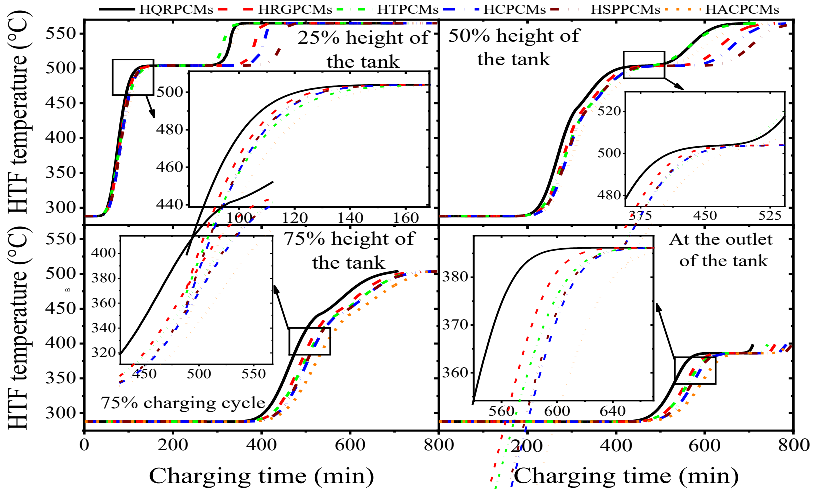

Figure 3: The temperature distribution of the fluid for six different configurations as a function of the charging period

3.4 Performance analysis

The capacity ratio, utilization ratio, retrieved energy, and overall efficiency of the HSLHS thermal storage tank scheme with six distinct arrangements, which were addressed in depth in recent articles, are explained.
Figure 4 depicts the capacity ratio and utilization ratio for various HSLHS tank system configurations. For the HSLHS tank arrangements analyzed, both the capacity ratio and the utilization ratio rise as the specific heat capacity of the solid SHS material increases, which is placed in the middle of the tank. With capacity ratios of 82.39 % and utilization ratios of 80.91 %, the HSPPCMs arrangement has the highest capacity and utilization ratios. The HCPCMs arrangement is second-order, with correspondingly a capacity ratio of 80.19 % and a utilization ratio of 78.57 %. The HQRPCMs configuration has the lowest value, with a capacity ratio and utilization ratio of 77.57 % and 75.93 %. The HSPPCMs has the highest overall efficiency of 84.3 %, following by HACPCMs, HCPCMs, HRPCMs, HTPCMs, and HQRPCMs with 82.4 %, 80.43 %, 76.3 %, 74.4 %, and 68.9 %, as shown in Figure 5.

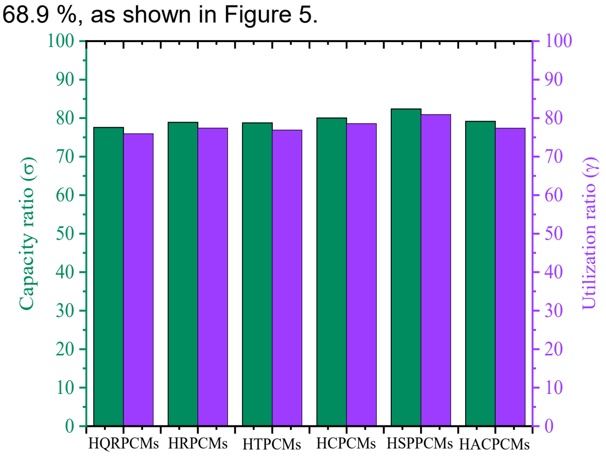

Figure 4: The variance of the capacity ratio and utilization ratio for six different configurations

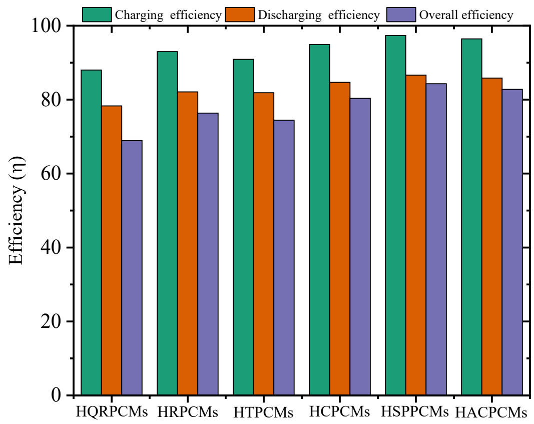

Figure 5: The change in the overall efficiency for six different configurations.

4. Conclusions

The major goal of this research is to look into and evaluate the impact of changing the solid SHS material layer for the HSLHS configuration on the thermocline tank system's thermal characteristics. The D-C mathematical problem is implemented with MATLAB code, and the original search results have been compared to published results. The fluid temperature assignment, charging time, discharging time, capacity ratio, utilization ratio, restored energy, and overall efficiency are all investigated in the present study. The findings are described below, along with the most important and notable observations in the development and implementation of the HSLHS tanks. This current work can open the door for the optimal design of the hybrid thermocline TES tank configuration, which works to improve the overall efficiency of the TES tank system used in CSP plants. The current study's limitation is that it does not examine the c cost-effectiveness of each configuration, which will be addressed in future research.

(1)The phase-transition propagation velocity of the HQRPCMs configuration travels at a rate of 0.33 times the fluid flow value, followed by the HRPCMs configuration at 0.30 times the fluid movement, and the HSPPCMs configuration at only 0.28 times the fluid velocity for the charging phase.

(2)The HSPPCMs configuration exhibits the highest capacity ratio and the utilization ratio of 82.39 % and 80.91 %. While the HCPCMs configuration comes in the second order with a capacity ratio and the utilization ratio of 80.19 % and 78.57 %.

(3)The recovered energy of HSPPCMs configuration is 142.6 MWh, which is 14.2 %, 7.2 %, 9.3 %, 3.9 %, and 3.7 % higher than the HQRPCMs, HRPCMs, HTPCMs, HCPCMs and HACPCMs configurations.

(4)The HSPPCMs configuration reaches the maximum overall efficiency of 84.3 %, followed by the configuration HACPCMs, HCPCMs, HRPCMs, HTPCMs and HQRPCMs exhibiting 82.4 %, 80.43 %, 76.3 %, 74.4 % and 68.9 %.

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