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Thermal analysis of molten salt thermocline thermal storage system with packed phase change bed

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Abstract

Energy storage performances of molten salt thermocline thermal storage system with packed phase change bed are numerically studied by using transport model of porous media and phase change model of thermocline bed. The results show that the packed phase change bed can remarkably increase the energy storage density and discharging efficiency. The thermocline with phase change material can be divided into three stages, or high temperature thermocline, low temperature thermocline and phase change layer. As the melting point of phase change material approaches to the outlet temperature, the effective discharging energy remarkably increases, so the optimal melting point should be equal to the outlet temperature for good heat storage performance. As the phase change material content increases, the phase change layer thickness and discharging time increases.

Keywords: energy storage; thermocline system; molten salt; phase change materials; solar thermal power

1. Introduction

The molten salt thermal energy storage system [1, 2] is widely used in concentrating solar power (CPS), and the thermocline system [3] is a very promising technology for high heat capacity and low cost. Pacheco et al. [4] first demonstrated packed-bed molten salt thermocline system with 2.3 MWh in Sandia National Laboratory. Brosseau et al. [5] suggested that quartzite rocks and sands were the low-cost and efficient solid fillers for packed bed. Zuo and Li [6] proposed a molten-salt hybrid thermocline thermal storage system with two storage subsystems. Yang et al. [7] and Xu et al. [8] numerically studied the thermal performance of a packed-bed molten salt thermocline thermal storage system. Since phase change materials have high energy storage density, the thermal storage system with packed phase change bed is expected to have good heat storage performance.

In this paper, the thermocline storage system with packed phase change bed is proposed, and the numerical model is developed by using the transport model of porous media and phase change model of thermocline bed. Based on the simulation results, the thermocline layer structure, discharging efficiency and optimal melting point of the thermocline system with phase change bed are further described.

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2. Numerical model

The molten salt thermocline thermal storage system with packed phase change bed is a cylindrical tank that contains storage material. The tank has an inlet and an outlet on the bottom and top for the hot and cold molten salt. The storage material includes molten salt and packed bed. In order to increase the energy storage density, the packed bed is made of ceramic sphere that containing phase change material, and the porosity and particle diameter of the bed are \( \varepsilon \) and \( d \).

According to the thermocline thermal storage system, the numerical model is established by using transport model of porous media and phase change model of thermocline bed. The flow and heat transfer is axisymmetrical, and a uniform flow is imposed at the inlet. Packed phase change bed is a continuous, homogeneous and isotropic porous media, and molten salt through the bed is laminar and incompressible. The transport model of porous media and its validation can refer to available literature [7-9]. In the present article, phase change occurs in the bed, so the energy equation has the source \( q = (1-\varepsilon) \rho_p c_p \partial f_p / \partial t \) at the melting point \( T_m \), where \( h_{sl} \) denotes the latent heat of phase change material, and \( f_p \) means the phase change material content (volume) in the bed.

The radius and length of tank are 1.5 m and 5.9 m, and \( \varepsilon=0.22, d=0.019 \) m. The properties of molten salt (60wt%NaNO\textsubscript{3}-40wt%KNO\textsubscript{3}) are [2]: \( \rho_l=2090-0.636t \) kg m\(^{-3}\), \( c_l=1443-0.172t \) Jkg\(^{-1}\)K\(^{-1}\), \( \lambda_l=0.443-0.00019t \) Wm\(^{-1}\)K\(^{-1}\), \( \mu_l=22.714-0.12t+0.0002281t^2 \) gm\(^{-1}\)s\(^{-1}\), where \( t \) means degree Celsius. The properties of ceramic material are: \( \rho_c=2500 \) kgm\(^{-3}\), \( c_c=830 \) Jkg\(^{-1}\)K\(^{-1}\), \( \lambda_c=5.69 \) Wm\(^{-1}\)K\(^{-1}\). The effective conductivities of fluid and bed [10] are \( k_{eff,f} = 0.5PrRe_k \), \( k_{eff,s} = k_l(k_l/k_s)^m \), \( m=0.28-0.757\log_{10}(0.057\log(k_l/k_s)) \). The heat transfer coefficient between solid and fluid is \( h=6(1-\varepsilon)k_l(1+1.1Re^{0.6}Pr^{1/3})/d^2 \). The heat transfer coefficient of heat loss through insulation is 0.5 W/K. The inlet, outlet and surrounding temperatures are respectively 290°C, 390°C and 0°C. The properties of phase change material are presented in Table 1.

<table>
<thead>
<tr>
<th>Number</th>
<th>Phase change material</th>
<th>( \rho_p ) (kgm(^{-3}))</th>
<th>( c_p ) (Jkg(^{-1})K(^{-1}))</th>
<th>( \lambda_p ) (Wm(^{-1})K(^{-1}))</th>
<th>( T_m ) (°C)</th>
<th>( h_{sl} ) (kJ/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>NaF-BeF\textsubscript{2}</td>
<td>2010</td>
<td>2176</td>
<td>0.87</td>
<td>340</td>
<td>376</td>
</tr>
<tr>
<td>2-4</td>
<td>Material 2-4</td>
<td>2010</td>
<td>2176</td>
<td>0.87</td>
<td>310, 360, 390</td>
<td>376</td>
</tr>
<tr>
<td>5</td>
<td>MgCl\textsubscript{2}-NaCl-KCl</td>
<td>2250</td>
<td>960</td>
<td>0.95</td>
<td>385</td>
<td>461</td>
</tr>
</tbody>
</table>

3. Results and Discussions

3.1. Basic heat transfer and storage performances

![Fig. 1 Temperature profiles of molten salt at the axis](image1)

![Fig. 2 Temperature profile and temperature difference between solid and fluid](image2)
Figs. 1-4 present the basic heat transfer and storage performances of molten salt thermocline system, where the phase change material (NaF-BeF$_2$) content in the bed is 0.5. Because of phase change material, the thermocline can be divided into three stages: the high temperature thermocline, low temperature thermocline and phase change layer. In Fig. 2, the temperature difference between solid and fluid has two peaks in the high temperature thermocline and low temperature thermocline regions, and its maximum is less than 2.3°C. Compared with the system without phase change material in Fig. 3, the discharging time with high outlet temperature can be significantly increased. In addition, the thicknesses of the high temperature thermocline, low temperature thermocline and phase change layer can be further defined as $Y_3(t_{out} < t < t_{sat} - A)$, $Y_1(t_{sat} + A < t < t_{sat} - A)$, $Y_2(t_{sat} - A < t < t_{sat} + A)$, and $A=5^\circ$C. In Fig. 4, the phase change layer is usually very large with maximum of 3.53 m, while the low temperature thermocline is very thin.

![Fig. 3](image1.png)  
**Fig. 3** The outlet temperature variation during the discharging process

![Fig. 4](image2.png)  
**Fig. 4** Thermocline thickness during the discharging process

3.2. Heat storage performances under different melting points

![Fig. 5](image3.png)  
**Fig. 5** The whole discharging time and effective discharging time

![Fig. 6](image4.png)  
**Fig. 6** The effective discharging energy

Figs. 5-6 presents the heat storage performances of molten salt thermocline under different melting points, where $f_p=0.5$, and materials 2-4 in Table 1 are used to investigate the effects of melting point. As the melting point increases, the whole discharging time $t_{tot}$ ($T_{out}>T_m$) remarkably drops, while the effective charging time $t_{eff}$ ($T_{out}>T_{sat}+B$, $B=20^\circ$C in present article) increases. Compared with the system without phase change material (Ref in Fig. 6), the packed phase change bed can increase the effective discharging energy. When the melting point approaches to the outlet temperature, the effective discharging energy is
remarkably increased, so the melting point of phase change material should be a little below the outlet temperature for good energy storage performance.

3.3. Heat storage performances under different phase change material content

Table 2 presents the heat storage performances of molten salt thermocline under different phase change material contents, where \( f_p \) (MgCl\(_2\)-NaCl-KCl) = 0, 0.5, 0.7. As the phase change material content increases, the phase change layer thickness and effective discharging energy increase, and the effective discharging efficiency also rises. When the phase change material content rises from 0 to 0.7, the effective discharging energy rises from 2.21 MWh to 8.30 MWh.

<table>
<thead>
<tr>
<th>( f_p )</th>
<th>( \tau_{\text{eff}} ) (h)</th>
<th>( Q_{\text{tot}} ) (MWh)</th>
<th>( Q_{\text{eff}} ) (MWh)</th>
<th>( \eta ) (-)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>3.18</td>
<td>2.52</td>
<td>2.21</td>
<td>87.6%</td>
</tr>
<tr>
<td>0.5</td>
<td>9.13</td>
<td>7.25</td>
<td>6.57</td>
<td>90.6%</td>
</tr>
<tr>
<td>0.7</td>
<td>11.51</td>
<td>9.14</td>
<td>8.30</td>
<td>90.8%</td>
</tr>
</tbody>
</table>

4. Conclusions

Molten salt thermocline thermal storage system with packed phase change bed has high heat storage density for latent heat. The thermocline with phase change can be divided into three stages: the high temperature thermocline, low temperature thermocline and phase change layer. As the melting point below outlet temperature and phase change material content increases, the effective discharging energy and efficiency both increase.

5. Acknowledgements

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6. References