Numerical study on the thermal performance of high-temperature latent heat packed-bed with a rectangular heat storage unit

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Abstract. As one of the most effective methods of thermal energy storage, packed-bed (PB) systems using phase change material (PCM) as heat storage media have been vigorously developed. To obtain the thermal performance of brick structure heat storage unit (HSU) in high-temperature latent heat PB, a 3-D PB system based on Navier-Stokes equations for heat transfer fluid, phase change model for PCM, and surface-to-surface (S2S) radiation model is established. The idea of changing the geometric structure of the brick HSU is proposed to improve the thermal performance of PB system. The influence of three-dimensional size of carbonate-based composite PCM with brick structure on the thermal performance of high-temperature PB is studied systematically. The numerical analyses show that the influence of three-dimensional size of brick-type HSU in different directions on the thermal performance of the PB system is independent. And the system has a higher energy efficiency (66.5%) and lower heat loss when the width and height of HSU are around 25 mm. The research results can guide the optimization of high-temperature composite PCM PB system.

1. Introduction
Among all renewable energy resources, solar energy is the most abundant energy source, it has been vigorously promoted by photothermal[1,2], photoelectricity [3,4], and photochemistry [5,6]. At the same time, the development of thermal energy storage (TES) technology has greatly improved the intermittency and instability of solar energy [7,8]. Nowadays, the latent heat TES (LHTES) system using phase change materials (PCM) as heat storage medium has great application potential. Among various LHTES, the packed-bed LHTES has been widely studied for its ability to achieve stable heat output.

Several scholars have undertaken numerical, experimental, and simulation researches to evaluate the system performance. Li et al. [9] experimentally investigated the pressure drop of a double-layer glass sphere packed-bed with horizontal and vertical stratification and compared it with a homogeneous bed composed of mono-size particles. Li et al. [10] established a macro-encapsulated high-temperature PB system, and experimentally studied the thermal performance in different working conditions. Bellan et al. [11] carried out numerical and experimental studies on the dynamic thermal performance of the spherical shell high-temperature PB TES, and studied the influence of velocity, Stefan number, and thermal conductivity. Ma et al. [12] investigated the performance of the packed bed LHTES system using Al-Si alloy. They found that the Al-Si alloy gives a better performance than the rock. Li et al. [13]
designed a rectangular PB system with brick-type HSU, they found that radiation heat transfer can not be ignored in the system.

The literature review indicates that the research of high-temperature packed-bed mainly focuses on the packed-bed LHTES with spherical heat storage unit (HSU). Few research works are focusing on the geometric parameters of HSU with rectangular structure. At the same time, many studies ignore the thermal radiation in the numerical model, which has a significant influence in high-temperature heat transfer. In this paper, based on the surface-to-surface (S2S) radiation model, the idea of changing the geometry of rectangular HSU is proposed to optimize the system performance of high-temperature PB. The influence of the geometric shape of brick-type HSU on the thermal performance of high-temperature PB LHTES system is studied by numerical methods. The results of this work can provide a theory of majorization for LHTES system under high-temperature conditions.

2. Methodology

Figure 1 shows the geometric model and boundary conditions of the brick-type packed-bed system. A typical packed-bed LHTES consists of a tank filled with HSU and heat transfer fluid (HTF). The HSU in this paper is a brick structure composed of CPCM, which is made of PCM (NaLiCO$_3$, 50%), ceramic skeleton material (MgO, 20%), and thermal conductivity enhancement material (graphite flakes, 30%). The effective thermal conductivity of the CPCM is calculated through the Zehner-Schlunder and Maxwell model [14]. The thermophysical properties of CPCM and material used in this paper are presented in table 1.

|                      | Air (200-1000 K) | CPCMS  | NaLiCo$_3$ | MgO  | Graphite flake |
|----------------------|------------------|--------|------------|------|---------------|
| $\rho$ (kg/m$^3$)    | 0.81764-4.7*10$^4T$ | 2504   | 2100       | 3580 | 1800          |
| $c_p$ (J/kg K)       | 1043.9608-0.3277$T$+7.7933*10$^4T^2$-3.5606*10$^7T^3$ | 1082   | 1300       | 1000 | 660           |
| $\lambda$ (W/m K)    | 0.0096+5.975*10$^{-5}T$ | 3.8481 | 2          | 3    | 129           |
| $H$ (J/g)            | /                | 174.25 | 348.5      | /    | /             |
| $\mu$ (kg/m s)      | 1.45893*10$^{-5}$+2.8*10$^{-9}T$ | 0.0042 | /          | /    | /             |
| $T_m$ (K)            | /                | 773.35 | 773.35     | 3125 | 3773          |

**Figure 1.** Geometric model of packed-bed TES system.

In this paper, a 3-D coordinates mathematical model is developed to describing the transient process in PB system, the enthalpy-porosity method and S2S radiation model are used to describe the phase
transition process in PCM. The following assumptions and simplifications are employed in the present modeling: (1) The PCM and HTF are treated as homogeneous and isotropic materials, and the PCM has only one melting point. (2) The volume of CPCMS does not change with temperature. (3) The inner wall of the tank and the surface of the HSU is considered gray and diffuse. According to Kirchoff’s law, emissivity is equal to absorptivity. (4) The HTF is regarded as a kind of radiative transparent medium and does not participate in radiative heat transfer. The effects of different widths, $x$, (16.8, 21, 27.5, 38, and 60 mm) and heights, $z$, (10, 16.18, 21, 26.18, 35, 52, and 70 mm) on the system performance with $y = 10$ and 35 mm are studied under the same effective volume. Based on the above mentioned hypotheses, the governing equations of HTF and CPCM are illustrated as:

$$\frac{\partial \rho_{HTF}}{\partial t} + \nabla \cdot (\rho_{HTF} \vec{V}) = 0$$ (1)

$$\frac{\partial (\rho_{HTF} \vec{u}_{HTF})}{\partial t} + \vec{V} \cdot \nabla \left( \rho_{HTF} \vec{u}_{HTF} \right) = -\frac{\partial \rho_{HTF}}{\partial x} + \mu_{HTF} \nabla^2 \vec{u}_{HTF}$$ (2)

$$\frac{\partial (\rho_{HTF} c_{p,HTF} T_{HTF})}{\partial t} + \vec{V} \cdot \nabla \left( \rho_{HTF} c_{p,HTF} T_{HTF} \right) = \nabla^2 \left( k_{HTF} T_{HTF} \right)$$ (3)

The Reynolds number, $Re$, used to determine the flow state of HTF can be calculated by the following equation:

$$Re = \frac{\rho_{HTF} U D_b}{\mu_{HTF}}$$ (4)

where $U$ and $D_b$ are the characteristic velocity and hydraulic diameter, and the $D_b$ can be expressed by the characteristic length of the PB:

$$D_b = \frac{4A_s}{S_w}$$ (5)

where $A_s$ and $S_w$ represent the cross-sectional area and corresponding wetted perimeter of the PB, respectively. The calculation results show that the $Re$ number of the system is below 600, indicating that the HTF flows in a laminar flow in the packed-bed system of this study.

The phase change process inside the CPCM is analyzed by the enthalpy-porosity method, and the energy equation can be described as [15]:

$$\frac{\partial \rho_{CPCM}}{\partial t} = k_{CPCM} \nabla^2 T_{CPCM} + S_{rad}$$ (6)

$$H = h + \Delta H = h_{ref} + \int_{T_{ref}}^{T} c_{p,CPCM} dT + \beta L$$ (7)

$$\beta = \begin{cases} 0 & T < T_s \\ \frac{T - T_s}{T_i - T_s} & T_s < T < T_i \\ 1 & T_i < T \end{cases}$$ (8)

Term $S_{rad}$ in equation (6) represents the radiation source term. The surface to surface radiation model is adopted to model the radiation heat transfer inside the system, and the heat loss of a certain surface $i$ can be expressed as:

$$q_{out,i} = \delta T_i^4 + \phi_i \sum_{j=1}^{N} \Psi_{ij} q_{out,j}$$ (9)

$$\Psi_{ij} = \frac{1}{A_i} \int_{A_i} \int_{A_j} \frac{\cos \theta_i \cos \theta_j}{\pi r^2} \Phi_{ij} dA_i dA_j$$ (10)

where $r$ and $\theta$ are the distance and angle between the two surfaces, and $\Phi_{ij}$ can be obtained through the visibility of $dA_i$ to $dA_j$ [13].
3. Model validation
In the present work, a three-dimensional PB model is established and studied. The pressure-velocity coupling field is solved by the Semi-Implicit Pressure-Linked Equation (SIMPLE) algorithm. The Pressure Staggering Option Scheme (PRESTO) scheme is used to calculate the pressure correction equation. The energy and momentum equations are described by the second-order upwind scheme, and the finite volume method is adopted to discretize the governing equations. The variable thermophysical properties of HTF and CPCM are realized by compiling user-defined functions (UDFs). The grid independent verification results indicate that the members of 2,000,000 can sufficiently guarantee the accuracy of the results of this model. And the convergence criteria of the continuity equation, momentum equations, and the energy equation are $10^{-4}$, $10^{-4}$, and $10^{-7}$ respectively. The validation of the developed mathematical model is performed based on the experimental results reported by Li et al. [10]. Figure 2 shows the temperature evolution comparison between the numerical results of this paper and the experimental results of Ref. [10] at different positions of the PB. It is observed that the simulation temperature evolution is in reasonable agreement with the experimental curves in Ref. [10], so it can be concluded that the results obtained from this study are accurate and precise.

![Figure 2. Comparison of numerical results with experimental data from Ref. [10].](image)

4. Result and discussion
In this chapter, the first two sections analyze the influence of width (range from 16.18 to 60mm) and length (range from 10 to 70mm) of the HSU on the system performance. Then the combined influence of the two dimensions of the packed-bed is analyzed in section 4.3.

4.1. The influence of width on the thermal performance of packed-bed system
Figure 3 presents the distribution of temperature (left) and liquid fraction (right) along the flow direction (x-z plane) for different width values 3000s after starting the charging process. The melting rate of the brick-type HUS neat the wall of the PB is slightly slower than that in the central area, and this phenomenon diminishes with the increase of width. For the single HSU, the two sides of the HSU melt first, and it melts slowly at the middle part due to the weak convection. The charging process can be completed more quickly in small-size HSU because of a larger heat transfer area.
Figure 3. Distribution of temperature (left) and liquid fraction (right) with different widths at 3000s.

Figure 4 illustrates the differences of outlet temperature with the charging time for different width values. As can be seen from the figure, the time required for the outlet temperature to reach stability increases with the increase of the width. In particular, the charging time increases by 34% when the width increases from 16.18mm to 60mm. As the results of Ma et al. [12], three different regions can be determined from the time evolution of the temperature curve in HSU: sensible heat storage before phase change (I), constant temperature in phase change (II), and sensible heat storage after phase change (III). In the third stage, the temperature difference between HTF and HSU decreases and most of the HTF outflows with little heat convection. The energy utilization rate of the system is the lowest at this stage, and its energy loss accounts for 40% of the total energy loss. Figure 5 shows the energy loss and efficiency for different width values during the charging process. The energy efficiency is the ratio of actual heat storage to ideal heat storage, and their difference is equal to energy loss. The energy loss increases with the width, and the energy efficiency first increases and then decreases with the increase of width. The packed-bed system has a higher energy utilization when the width is 27.5mm (66.5%), and the energy loss is 6.4% less than that of 60mm.

Figure 4. Variations in the outlet temperature with the charging time for different widths.

Figure 5. The Energy loss and efficiency with the charging time for different widths.

4.2. The influence of height on the thermal performance of packed-bed system

Figure 6 presents the distribution of temperature (left) and liquid fraction (right) along the flow direction (x-z plane) for different height values 4000s after the start of the charging process. In Fig.6, one can see
that the results are consistent with the distribution contour of the packed-bed with brick structure HSU studied by Li et al. [13]. The HSU is melted from the front part of the PB and an obvious temperature gradient is observed at the front of the phase transition. It also can be seen that the heat transfer area of HTF along the flow direction of the tank increases with the increase of the HSU height, but it does not change along the direction perpendicular to the flow direction. The total liquid fraction in the PB has little difference at the same time. The smaller-size HSU has more flow space around it, resulting in a faster melting process and thinner thermocline. However, it leads to a smaller total heat storage capacity.

**Figure 6.** Distribution of temperature (left) and liquid fraction (right) with different widths at 3000s.

Figure 7 presents the differences of the outlet temperature with the charging time for different height values. The charging process still can be divided into three stages and the heat storage capacity increases with the increase of height. The charging time increases with height, but the increase rate gradually decreases. Time required for stage II increases by 133.6% when the height increases from 10 mm to 70 mm. Figure 8 shows the energy loss and efficiency for different height values during the charging process. The energy utilization decreases significantly as height increases. The packed-bed has a higher energy utilization when \( z = 21 \) mm (66.6%), and the energy loss is 19% less than that of 70 mm.

**Figure 7.** Variations in the outlet temperature with the charging time for different heights.

**Figure 8.** The Energy loss and efficiency with the charging time for different heights.

4.3. The combined influence of different dimensions on the thermal performance of packed-bed system

In this section, the combined effects of length (10 and 35 mm) and width (16.18, 21, 27.5, 38, and 60 mm) variations on the thermal performance of the PB system are studied. Figure 9 describes the coupled
influence of different dimensions of heat storage rate. The charging time increases with the width of HSU under the same height, and the two groups of curves have the same trend with the change of width. Figure 10 shows the effect of width on energy utilization and average charging rate at two heights. All four lines showed a trend of first increase and then decreases, and reached the maximum value near 25 mm, with the energy utilization rate and average charging rate of 66.5% and 88 J/s, respectively.

The above results show that the influence of the size change of brick-type HSU in one direction on the thermal performance of the PB LHTES system is not affected by the size change in the other direction. They are independent and superimposed on each other.

5. Conclusions
To improve the thermal performance of PB system with brick-type HSU, the effect of the geometric shape of the brick-type CPCM HSU of the PB system is analyzed through numerical simulations based on Navier-Stokes equations for HTF, phase change model for PCM and S2S radiation model. The main conclusions are:

- The total heat storage capacity increases with the geometric parameters of HSU under the same accumulation volume.
- The optimization results show that under the simulation conditions studied in the present work, the system has a higher energy efficiency (66.5%) and lower heat loss when the width and height of HSU are around 25 mm.
- The influence of dimension change of brick-type HSU in different directions on the system performance is independent and superimposed on each other.

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