Effect of Radial Porosity Oscillation on the Thermal Performance of Packed Bed Latent Heat Storage

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1. Introduction

Recently, solar energy has been extensively used for its advantages of clean energy, safety, and inexhaustibility [1,2]. According to REN21, the capacity of a solar photovoltaic (PV) and concentrating solar power (CSP) was up-regulated from 409.9 GW in 2017 to 510.5 GW in 2018, occupying 60.97% of the renewable energy growth [3]. However, solar energy is intermittent and fluctuating, and requires energy storage technology to address its defects and improve energy efficiency. Considering the thermal utilization of solar energy, latent heat storage (LHS) can exhibit a higher energy density and maintain an almost constant temperature during phase change, which brought widespread attention [4,5]. The main constraint of LHS is the low thermal conductivity of phase change materials (PCMs) (0.2–0.8 W·m⁻¹·K⁻¹), and requires effective heat transfer enhancements [6]. Considering the heat storage unit, a packed bed is considered an efficient approach when compared with a shell-and-tube unit. As reported by Li et al. [7], the charging and discharging rates of a packed bed LHS system is 1.8–3.2 times that of the shell-and-tube heat storage system.

In the packed bed LHS system, as an heat transfer fluid (HTF) directly flows through the PCM capsules, the arrangement of PCM capsules considerably impacts the flow field [8,9]. For a sphere packing, the densest arrangements of the spheres include hexagonal packing and face-centered cubic packing, exhibiting a highest packing density as 74.05% [10]. However, when spheres are randomly packed in a container, they cannot be densely arranged because of the wall, which is called the wall effect [11]. Mueller [12] reported that radial porosity would oscillate along the radial direction in the packed bed. Moreover, the oscillation distribution of radial porosity causes non-uniformity of the flow filed, which would further affect the heat transfer inside the packed bed [13]. Considering a cylindrical container, the wall effect on the average packing density is prominent with a decrease in diameter ratio of the container and spheres (D/dₚ) [14]. When a packed bed is used for latent heat storage, higher heat storage...
capacity leads to smaller tank size and diameter ratio. Accordingly, the radial porosity variation should be considered in a numerical study on packed bed LHS systems, particularly for small diameter ratio ($D/d_p < 10$) [15].

Several numerical models were built to assess the thermal performance of the packed bed LHS system. Based on the requirement for the specific arrangement of PCM capsules, the models can be divided into representative elementary volume (REV) scale model and pore scale model. In REV scale model, governing equations are adopted to calculate the thermal performance of HTF and PCM. Benmansour et al. [16] adopted the two-phase model to express the energy equations of HTF and PCMs, while the porosity employed in the equations is a constant; thus, the radial porosity variation was not considered [17]. Subsequently, a monotonic exponential equation, where the porosity refers to a function of radial distance from the wall, was proposed to replace the constant porosity [18,19]. To obtain the thermal gradients inside the PCM capsules, the dispersion-concentric (DC) model was proposed. Karthikeyan and Velraj [20] compared the two-phase model with the DC model; they reported that the results of the DC model complied better with their experimental results as the internal heat transfer inside the PCM capsules was considered. However, a packed bed with a small diameter ratio ($D/d_p < 10$) cannot be considered as a continuous porous medium. Since representative control volume should be small enough to gain good calculation results, a control volume would not contain even more than one capsule, which fails to satisfy the requirement of the REV scale model [21,22].

In the pore scale model, the concrete arrangement of PCM capsules should be described; subsequently, the flow of HTF and the heat transfer between HTF and PCM capsules can be calculated. Xia et al. [23] developed an effective packed model, where the three-dimensional (3D) packed bed is converted to a two-dimensional packed bed. The corresponding criteria was to ensure that the two packed beds exhibit identical porosity. However, the radial porosity distribution is not considered during the transformation. Moreover, PCM capsules in the effective model are not in contact with each other, leading to the change of flow channels among PCM capsules. Therefore, the flow field is not accurate and heat conduction between capsules is ignored.

Thus, complying with the actual packing process of spheres, a 3D packed bed LHS model was built to consider the radial porosity oscillation. The mechanism of the radial porosity oscillation and its impacts on the radial velocity of HTF, and radial temperature and liquid fraction of PCMs are analyzed. Further, the effects of different dimensionless parameters (e.g., diameter ratio, Reynolds number, and Stefan number) on the fluid flow, heat transfer, and heat storage performance of the packed bed LHS are discussed.

2. Model description

2.1. Establishment of physical model

In studying a 3D packed bed, a difficulty faced is building an effective sphere packing model; the falling, collision, and friction process of the spheres should be simulated. The existing methods of building a packed bed consist of the discrete equation method (DEM) method [8,24,25], Blender method [26,27], and Monte Carlo method [15,28]. In this study, the open source software Blender was adopted to build a 3D packed bed model. The Blender software was equipped with a prominent physical simulator and bullet physics library; thus, the physical process of spheres when they fall under the influence of gravity can be effectively calculated. In the modelling process, a cylindrical container was first built; then, small spheres were constantly and randomly generated to fall above the container, as illustrated in Fig. 1(a). The position of every sphere was calculated during the packing process. If the positions of all the spheres are stable, the packing process can be considered to be attaining a steady state. Then, the 3D packed bed model is established.

Porosity ($\phi_v$) is the ratio of void volume ($V_{void}$) to total volume ($V$), while surface porosity ($\phi_s$) is the ratio of void area ($A_{void}$) to total area ($A$) on surface, as expressed in Eqs. (1)–(3) [29].

$$\phi_v = \frac{V_{void}}{V}$$

$$\phi_s = \frac{A_{void}}{A}$$

$$\phi_s = \frac{\int_0^R \phi_s(R) \cdot 2\pi rdr}{\pi R^2}$$

where $R$ is the radius of container and $r$ is an independent variable changing from 0 to $R$. Radial porosity, which is discussed in this study, is a phenomenon of surface porosity. To calculate the radial porosity, a series of cylindrical sub-surfaces along the radial direction were cut off. For the corresponding sub-surface, a ray-casting algorithm was adopted to determine the areas pertaining to the interior of the spheres. Then, the areas of all the spheres are added and total area of spheres is divided by the area of the sub-surface, as presented in Fig. 1(b).

In Fig. 2, the radial porosity of the model built in the Blender was compared with the results of the Mueller, and the corresponding diameter ratio obtained is 7.99 [12]. The two curves oscillate
and correspond well with each other, verifying the reliability of the model. Moreover, the oscillation distribution of radial porosity shows that the packed bed cannot be treated as a uniform porous media, further confirming the necessity of establishing a 3D model.

In the packed bed, the contact type between the spheres is point contact, which is not conducive to the mesh generation. Thus, four methods were proposed to address contact points: overlaps, gaps, caps, and bridges. The bridge method can achieve the optimal model. Moreover, the oscillation distribution of radial porosity and correspond well with each other, verifying the reliability of the container. After the diameter of the container was increased by 1 mm, a narrow gap was identified between the spheres and container wall.

Further, a 3D packed bed LHS model was built, as presented in Fig. 3. In the model, 205 PCM capsules were packed into a cylindrical tank with an inner diameter of 240 mm, and the diameter of PCM capsule is 48 mm; thus, the diameter ratio of the packed bed is 5. Ternary carbonate Li₂CO₃–K₂CO₃–Na₂CO₃ (32 wt%–35 wt%–33 wt%) was selected as the PCM, and its thermal properties are listed in Table 1. The packed bed was placed in the middle section, while extended parts were added on the sides of the inlet and outlet to eliminate the impact of the sides.

### 2.2. Mathematical model

#### 2.2.1. Assumptions

(1) The effect of gravity on HTF flow is ignored;
(2) The convection effect of the PCM in the capsules is ignored;
(3) Radiation heat transfer of the HTF and PCM capsules is ignored.

#### 2.2.2. Governing equation of HTF

In the packed bed LHS system, the pore Reynolds number based on mean velocity is expressed as [9]

\[
Re_p = \frac{\rho (u_{in}/\sigma_e) d_p}{\mu}
\]

(4)

where \( \rho \) is density, \( \mu \) is viscosity, and \( u_{in} \) is the inlet velocity.

For a packed bed with low diameter ratio, the flow is normally turbulent flow. Considering that the heat transfer surface of the PCM capsule is spherical, renormalization group (RNG) \( k-\varepsilon \) turbulence model was selected to facilitate the wall treatment. Subsequently, the governing equations of the HTF in the packed bed LHS system can be written as follows [31]:

- **Continuity equation:**

\[
\frac{\partial \rho}{\partial t} + \frac{\partial (\rho u_i)}{\partial x_j} = 0
\]

(5)

- **Momentum equation:**

\[
\frac{\partial (\rho u_i)}{\partial t} + \frac{\partial (\rho u_i u_j)}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{1}{Re_p} \left( \frac{\partial}{\partial x_j} \left( \mu \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3} \frac{\partial u_i}{\partial x_i} \delta_{ij} \right) \right) - \left( \mu_t \frac{\partial u_i}{\partial x_j} \right) - \frac{\partial q_{eq}}{\partial x_j} \right)
\]

(6)

- **Energy equation:**

\[
\frac{\partial \left( \rho e \right)}{\partial t} + \frac{\partial (\rho e u_i)}{\partial x_j} = \frac{\partial}{\partial x_j} \left( \frac{\partial}{\partial x_j} \left( \frac{\mu_t}{\sigma_e} \frac{\partial T}{\partial x_j} \right) \right) + G_k - \rho \varepsilon
\]

(7)

- **\( \varepsilon \) equation:**

\[
\frac{\partial (\rho \varepsilon)}{\partial t} + \frac{\partial (\rho \varepsilon u_i)}{\partial x_j} = \frac{\partial}{\partial x_j} \left( \frac{\partial \varepsilon}{\partial x_j} \right) + C_1 \varepsilon \frac{\varepsilon}{K} - C_2 \rho \frac{\varepsilon^2}{K} - R_c
\]

(8)

where \( x_i \) and \( x_j \) are the distance in \( i \) and \( j \) directions, respectively; \( u_i \) and \( u_j \) are the velocity of HTF in \( i \) and \( j \) directions, respectively; \( \delta_{ij} \) is the Kronecker delta; \( E \) is the energy; \( (\tau_{ij})_{eff} \) is the effective Reynolds-stress tensor; \( k \) is the turbulent kinetic energy; \( \varepsilon \) is the turbulence dissipation rate; \( \sigma_e \) is the Prandtl number in turbulent dissipation rate equation; \( C_1 \) and \( C_2 \) are two model constants. The turbulent kinetic energy \( \mu_t \), generation of turbulence kinetic energy \( G_k \), and additional term \( R_c \) are expressed as [32]

\[
\mu_t = \rho C_{\mu} \frac{k^2}{\varepsilon}
\]

(10)

\[
G_k = \mu_t \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \frac{\partial u_i}{\partial x_j}
\]

(11)

\[
R_c = C_4 \rho \gamma^3 \left( 1 - \frac{\gamma}{\gamma_0} \right)^{\frac{3}{2}} \frac{\varepsilon^2}{0.012}
\]

(12)

\[
\gamma = S k / \varepsilon, \quad S = \sqrt{2S_f S_y}, \quad S_f = \frac{1}{2} \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right)
\]

(13)

where \( C_4 \) is the model constant; \( \gamma \) is the RNG \( k-\varepsilon \) turbulence model coefficient; \( \gamma_0 \) is the RNG \( k-\varepsilon \) turbulence model coefficient in the initial state; \( S \) denotes the mean strain-rate of the flow; and \( S_f \) is the deformation tensor.

### Table 1

**Thermal properties of PCM.**

<table>
<thead>
<tr>
<th>PCM</th>
<th>( T_i (^\circ C) )</th>
<th>( T_l (^\circ C) )</th>
<th>( \Delta H (kJ \cdot kg^{-1}) )</th>
<th>( \lambda (W \cdot m^{-1} \cdot K^{-1}) )</th>
<th>( c_p (kJ \cdot kg^{-1} \cdot K^{-1}) )</th>
<th>( \rho (kg \cdot m^{-1}) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Li₂CO₃–K₂CO₃–Na₂CO₃</td>
<td>395.1</td>
<td>413.0</td>
<td>273.0</td>
<td>1.69 (s); 1.60 (l)</td>
<td>1540 (s); 1640 (l)</td>
<td>2310</td>
</tr>
</tbody>
</table>

\( T_i \): solid state temperature; \( T_l \): liquid state temperature; \( \Delta H \): specific enthalpy; \( \lambda \): thermal conductivity; \( c_p \): specific heat capacity; \( \rho \): density; \( s \): solid state; \( l \): liquid state.
The constants in the aforementioned equations are \( \sigma_T = 1.0, \quad \sigma_t = 0.72, \quad C_p = 0.0845, \quad C_1 = 1.42, \quad C_2 = 1.68, \quad \) and \( \gamma_0 = 4.38. \)

### 2.2.3. Governing equation of the PCMs in the capsules

For the PCMs in the capsules, as the internal natural convection is ignored, the energy equation can be expressed as [23]

\[
\frac{\partial}{\partial t} \left( \rho \cdot H_{pcm} \right) - \nabla \cdot \left( \rho \cdot \nabla T_{pcm} \right) = 0
\]

(14)

where \( H_{pcm} \) is the enthalpy of PCM and defined as the sum of sensible heat and latent heat; \( \nabla \) is the gradient operator.

\[
H_{pcm} = H_{0,pcm} + \int c_p,pcm \, dt_{pcm} + \Delta H
\]

(15)

where \( H_{0,pcm} \) is the enthalpy of the PCM at the initial temperature. \( \Delta H \) represents the latent heat released during the charging process and defined as \( \Delta H = \beta L. L \) is the latent heat and \( \beta \) is the liquid fraction of PCM, which, at different temperatures, is written as follows:

\[\beta = 0, \quad \text{while} \quad T_{pcm} < T_s\]

(16)

\[\beta = 1, \quad \text{while} \quad T_{pcm} > T_l\]

(17)

\[\beta = \frac{T_{pcm} - T_s}{T_l - T_s}, \quad \text{while} \quad T_s \leq T_{pcm} \leq T_l\]

(18)

where \( T_{pcm}, \quad T_s, \quad \) and \( T_l \) denote the temperature of the PCM, initial temperature, onset melting temperature, and ending melting temperature, respectively. Furthermore, the charging process of the PCM demonstrates a ratio of sensible heat to latent heat, which is defined as the Stefan number [33]:

\[S_t = \frac{c_{p,pcm}(T_{in} - T_l)}{L}\]

(19)

where \( T_{in} \) refers to the temperature of the inlet HTF.

### 2.2.4. Boundary conditions and initial conditions

At the initial state, the packed bed LHS system was maintained at a constant temperature and heat transfer fluid temperature \( T_f = T_{pcm} = T_0. \) During the charging process, the HTF at the inlet was maintained at a constant temperature and mass flow rate \( (q) \), while heat flux of the HTF in the direction normal to the outlet was assumed to be zero. Therefore, the boundary conditions of the HTF in the packed bed are expressed as follows:

\[T_f = T_{in}, \quad q = q_{in}, \quad \text{at the inlet}\]

(20)

\[\partial T_f/\partial z = 0, \quad \text{at the outlet}\]

(21)

where \( z \) is the height.

To understand the effect of radial porosity distribution on the radial characteristics of the HTF, the container wall is set to be adiabatic.

\[\partial T_{wall}/\partial r|_g = 0\]

(22)

### 2.3. Heat storage of packed bed LHS system

The total heat storage in the packed bed LHS system consists of the heat stored in the PCM, PCM capsule shells, and heat stored in the tank wall. The heat stored in the PCM includes the sensible heat in the solid and liquid state, and latent heat during phase change. The heat stored in the PCM capsule shells and tank refers to the sensible heat. The charging time of the system is defined as the time when the central temperature of the PCM capsule at the outlet reaches 1 K lower than the inlet temperature. Hence, the total heat storage \( (Q_{total}) \) in the packed bed LHS system can be expressed as follows:

\[Q_{total} = Q_{pcm} + Q_{shell} + Q_{tank}\]

(23)

\[Q_{pcm} = m_{pcm} [c_p,s(T_m - T_0) + \Delta H + c_p,l(T_{in} - T_m)]\]

(24)

\[Q_{shell} = m_{shell} [c_p,shell(T_{in} - T_0)\]

(25)

\[Q_{tank} = m_{tank} [c_p,tank(T_{in} - T_0)\]

(26)

where \( Q_{pcm}, Q_{shell}, \quad \) and \( Q_{tank} \) are the heat storage in the PCM, shell of PCM capsules, and the tank, respectively; \( m_{pcm}, m_{shell}, \) and \( m_{tank} \) are the quality of PCM, shell of PCM capsules, and the tank, respectively; \( c_p,pcm, \quad c_p,shell, \) and \( c_p,tank \) are the specific heat capacity of the PCM in solid state and liquid state, respectively; \( T_m, T_0, \) and \( T_{in} \) are the melting temperature, the initial temperature, and the inlet temperature, respectively; \( c_p,shell \) and \( c_p,tank \) are the heat capacity of the shell and tank, respectively.

During the charging process, heat storage of the packed bed LHS system \( (Q_{stored}) \) can be obtained using the first law of thermodynamics:

\[Q_{stored} = \int m_f (c_p,in T_{in} - c_p,out T_{out}) \, dt\]

(27)

where \( m_f \) is the mass flow rate of HTF; \( c_p,in \) and \( c_p,out \) are the specific heat capacity of HTF at the inlet and outlet, respectively; \( T_{in} \) and \( T_{out} \) are the temperature of HTF at the inlet and outlet, respectively.

The average charging power \( P_{ave} \) can be defined as [7]

\[P_{ave} = \frac{Q_{stored}}{\tau_{charge}}\]

(28)

where \( \tau_{charge} \) is the charging time.

### 2.4. Numerical procedure and validation

As there are hundreds of PCM capsules randomly filled in the packed bed, unstructured grids were adopted to generate the meshes. The shrink-wrap method was employed to generate the surface mesh, and then, the volume was filled with the polyhedral meshes [34]. Subsequently, the effects of grid size on the charging time and pressure drop in the packed bed were determined, and a grid size of \( d_{max} = 18 \) was selected for the mesh generation, as shown in Fig. 4. During the calculation, pressure and velocity fields were computed using the SIMPLE algorithms. The spatial discretization and transient formulation were calculated using the second order upwind scheme and second order implicit scheme, respectively.

Li et al. [7] built a packed bed LHS system filled with 385 PCM capsules. The inner diameter of the container was 260 mm, while the capsule diameter was 34 mm; thus, a diameter ratio of 7.65...
was achieved. The PCM in the capsules was ternary carbonate Li₂CO₃–K₂CO₃–Na₂CO₃ (32 wt%–35 wt%–33 wt%); its thermal properties are listed in Table 1. The PCM temperature variations at different heights during the charging process were selected to verify the established 3D packed bed LHS model. The locations of the PCM capsules along the height were z/h = 0.25, 0.5, 0.75, as shown in Fig. 5(a). During the charging process, the mass flow rate \( q_m \) was 260 kg h\(^{-1}\) while the initial temperature \( T_0 \) of the packed bed was 325 °C and inlet temperature \( T_{in} \) of the HTF reached 465 °C.

As shown in Fig. 5(b), the simulation data of the model complied well with the experimental results, and the results at z/H = 0.5 were optimally matched. At the beginning of the charging process, the simulation was faster than the experiment, whereas, after the phase change process of the PCM capsule was achieved, the simulation data and experimental results were synchronized. On one hand, the heating process of the HTF to be heated from initial temperature (e.g. 325 °C) to the inlet temperature (e.g. 465 °C) was time-consuming, whereas, this transformation was attained immediately in the simulation. On the other hand, when the PCMs were in the liquid phase, the differences of the heat storage attributed to the different inlet temperature transition mode will be small when compared with the overall heat storage of the system. Accordingly, the simulation becomes more accurate over time. The 3D packed bed LHS system model exhibits a good accuracy.

3. Results and discussion

3.1. Flow and thermal performance analysis

In this part, the initial temperature \( T_0 \) of the packed bed is 325 °C, inlet temperature \( T_{in} \) of HTF is 465 °C, and mass flow rate reaches 260 kg h\(^{-1}\). As the average porosity is 0.437 in the packed bed exhibiting the diameter ratio of 5, the Reynolds number \( Re_p \) is calculated to be 4998.72, thus confirming that the flow in the packed bed is turbulent.

3.1.1. Reason for radial porosity oscillation

For the packed bed LHS system model with a diameter ratio of 5, the distribution of the radial porosity is illustrated in Fig. 6. Several cylindrical sub-surfaces at different radial positions inside the packed bed were intercepted. The distance of the sub-surfaces from the tank wall reaches 0, 0.25dₚ, 0.5dₚ, 0.75dₚ, dₚ, 1.25dₚ, 1.75dₚ, and 2dₚ, respectively. Considering the surface porosity, the porosity of the sub-surfaces (0, dₚ, and 2dₚ away from the wall) is suggested to be higher than that of the other sub-surfaces. The oscillating distribution of the radial porosity is related to the process of packing capsules and spherical shape of the capsules. During the packing process, capsules tend to fill the space close to the wall first and subsequently fill the space in the center [35]. At the wall surface, the PCM capsules exhibit point contacts with the tank wall. Hence, the porosity of this position is close to 1, indicating that the sub-surface is almost HTF. At the position 0.5dₚ away from the wall, the sub-surface passes through the center of the capsules, revealing that the PCM area will occupy most of the area of the sub-surface, and the porosity will decrease to 0.15. Similarly, at the sub-surface dₚ away from the wall, the capsules near the wall are in point contacts with the inner capsules. Gaps are formed near the contact points, and the porosity increases with a value of 0.67. Thus, the porosity of the sub-surfaces in the radial direction complies with an oscillating distribution.

3.1.2. Flow velocity distribution

Similar to radial porosity, radial velocity is the average value of HTF velocity on the sub-surface, defined as Eq. (29). In this study, the relative velocity (\( U(r) \)) is determined by the ratio of the radial velocity (\( u(r) \)) to the inlet velocity (\( u_{in} \)).

\[
U(r) = \frac{u(r)}{u_{in}}
\]  

(30)

where \( \Omega_f \) is the area of HTF on the sub-surface and \( A_i \) is the area value of HTF. The relative velocity distribution of the HTF at different radial positions is presented in Fig. 7, also indicating an oscillation trend. It is observed that although the porosity at the wall is close to 1, the flow velocity is 0 due to wall viscosity. However, in the radial direction away from the wall, velocity increases significantly and subsequently varies with the oscillation of radial porosity. When the HTF ascends into the packed bed, it flows through the gaps among the PCM capsules. Locations with more gaps allow more HTF to flow through; thus, the HTF velocity is faster where the porosity is larger. To facilitate the analysis and comparison of the velocity distribution, the relative velocity distribution was divided into two parts: near wall region and center region. The distance of the near wall region varies from the wall to 0.5dₚ, where velocity varies drastically, while the center region is from 0.5dₚ to the center, and the velocity varies more regularly.

![Fig. 5. (a) Position illustrations of thermocouples; (b) comparison of calculation results with experimental data.](image-url)
In the near wall region, velocity varies drastically. Hence, the most important parameter here is the maximum relative velocity near the wall. In this case, the maximum relative velocity at the near wall region is 3.49. According to the continuity equation, under the same flow rate, the variation of velocity is inversely proportional to the variation of flow channel area, as expressed in Eq. (31). Accordingly, the velocity of the incompressible HTF increases with a sudden contraction of flow channel. Fig. 8 illustrates the velocity distributions on several cross-sections in the packed bed. The velocity increases in the area near the wall for the contraction of flow channel.

\[
\frac{u_1}{u_0} = \frac{A_0}{A_1} \quad (31)
\]

The relative velocity distribution in the center region exhibits a more regular oscillation that is consistent with the radial porosity distribution. To assess the non-uniformity of the HTF, the standard deviation of relative velocity was adopted. A higher standard deviation complies with a less uniform velocity distribution. For the packed bed with a diameter ratio of 5, when the Reynolds number \(Re_p\) is 4998.72, the standard deviation of the relative velocity \(s_{u_0}\) in the center region is 0.39.

\[
s_{u_0} = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (U_i - \bar{U})^2}
\]

where, \(N\) is the number of sub-surfaces, \(U_i\) is the relative velocity at the No. \(i\) sub-surface; \(\bar{U}\) is the average relative velocity of all the sub-surfaces.

3.1.3. Radial temperature and liquid fraction distribution

For the corresponding sub-surface, the radial temperature and liquid fraction of the PCMs are calculated as Eq. (33) and Eq. (34), where \(A_{pcm}\) is the area of the PCMs on the sub-surface and \(A_{pcm}\) is the area of the PCMs.

\[
T(r) = \frac{1}{A_{pcm}} \int_{A_{pcm}} T dA
\]

\[
\beta(r) = \frac{1}{A_{pcm}} \int_{A_{pcm}} \beta dA
\]

To illustrate the radial distribution variations of PCMs during the charging process, the temperature and liquid fraction of the PCMs on the sub-surfaces at different time are presented in Figs. 9(a) and (b), fluctuating along the radial direction. When
Parameters of the packed bed LHS systems with different diameter ratios.

<table>
<thead>
<tr>
<th>Diameter ratio</th>
<th>Capsule diameter (mm)</th>
<th>Capsule number</th>
<th>Shell thickness (mm)</th>
<th>Average porosity</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>60</td>
<td>105</td>
<td>2</td>
<td>0.458</td>
</tr>
<tr>
<td>5</td>
<td>48</td>
<td>205</td>
<td>2</td>
<td>0.437</td>
</tr>
<tr>
<td>6</td>
<td>40</td>
<td>354</td>
<td>2</td>
<td>0.428</td>
</tr>
</tbody>
</table>
a diameter of 48 or 40 mm. A smaller diameter indicates a shorter heat transfer distance, whereas it will further result in a denser packing arrangement and promotes a decrease in pressure. The calculated results show that the decrease in pressure in the packed beds are 142.97, 213.34, and 257.13 Pa, respectively. Hence, higher pump power is required to maintain the operation of the packed bed LHS system. Accordingly, when the packed bed LHS system is employed for practical use, the charging time, charging power, and pressure drop should be comprehensively considered.

3.3. Effect of Reynolds number on the flow and thermal performance

Three different Reynolds numbers (4229.69, 4998.72, and 5767.75) are compared, which comply with inlet flow rates of 220, 260, and 300 kg h⁻¹, respectively. The diameter ratio of packed bed is 5, and the Stefan number is 0.31. Fig. 14(a) shows that the relative velocities of the HTF along the radial direction for different Reynolds numbers comply with a similar distribution. The maximum relative velocities of the HTF at the near wall region are 3.40, 3.49, and 3.55, while the standard deviations of relative velocity at the center region are 0.40, 0.39, and 0.39, demonstrating...
that an increase in the Reynolds number would result in a proportional improvement in velocity. Correspondingly, convection heat transfer in the packed bed is enhanced, and the charging processes of the PCMs would accelerate (Fig. 14(b)). The PCMs melt faster with an increase in the Reynolds number when \( t = 1200 \) s.

Fig. 14(c) shows that an increase in the Reynolds number will not promote heat storage of the system, while the charging time can be shortened and charging power can increase accordingly. The charging time of the system with \( Re_p = 4229.69 \) is 97.53 min, while those of the systems with \( Re_p = 4998.72 \) and \( Re_p = 5767.75 \) are 89.73 and 83.63 min, and 8% and 14.25% faster, respectively. However, an increase in the Reynolds number would increase the dissipation of the HTF when flowing through capsules and improve the pressure drop at the inlet and outlet. The corresponding pressure drops in the three conditions reach 162.84, 213.34, and 270.06 Pa, respectively.

3.4. Effect of Stefan number on the flow and thermal performance

Similar to the previous section, the diameter ratio of the packed bed is 5 and Reynolds number is 4998.72. Subsequently, the HTF inlet temperatures are set to 445, 465, and 485 °C, leading to Stefan numbers of 0.19, 0.31, and 0.43, respectively. A comparison of the relative velocity distributions is drawn in Fig. 15(a). It is observed that the increase in Stefan number slightly impacts the flow velocity and its radial distribution is almost constant. Hence, the convection effect between the HTF and PCM capsules is the same. However, an increase in the Stefan number can increase the temperature differences between the HTF and PCM capsules, which enhances the heat transfer to the PCMs. Thus, the charging processes of the PCMs is facilitated and PCMs melt faster, as presented in Fig. 15(b).

An increase in the Stefan number further indicates that the sensible heat stored in the PCMs increase, thus, the heat storage of the packed bed LHS system is improved (Fig. 15(c)). When the Stefan number is 0.19, the charging time is 99.2 min, and the charging time becomes 89.73 and 84.7 min with an increase in the Stefan number to 0.31 and 0.43, respectively. Accordingly, an increase in the Stefan number can shorten the charging time while increasing the heat storage and average charging power.

4. Conclusion

In this study, a 3D packed bed LHS model was built, where the radial porosity oscillation caused by the wall effect was considered. The model was validated by comparing the temperature variations of PCM capsules with the experimental results. The impact of the radial porosity oscillation on the radial velocity of HTF, radial temperature of PCMs, and liquid fraction of PCMs were studied. Moreover, the effects of different dimensionless parameters (e.g., diameter ratio, Reynolds number, and Stefan number) on the radial characteristics of the HTF and PCMs were discussed. The main conclusions are as follows:

1. The oscillating distribution of the radial porosity is analyzed by intercepting different cylindrical sub-surfaces along the radial direction. For the sub-surface where the capsules are in point contact with the container wall or inner capsules, the gaps formed result in high porosity. However, for the sub-surfaces that pass through the capsules, the PCMs occupy most of the area on the surface, and a lower porosity is observed.

2. The oscillating distribution of the radial porosity leads to a non-uniform distribution of the HTF velocity. The velocity would change sharply at the near wall region while an oscillating distribution at the center region is observed. The radial temperature distribution of the PCMs is consistent with the radial relative velocity distribution of the HTF. Hence, the PCMs melt faster at the radial positions with higher porosity.

3. With an increase in the diameter ratio, the maximum velocity at the near wall region increases. However, as the packing of the PCM capsules in the center of the tank becomes more random, the velocity non-uniformity in the center region decreases. Furthermore, the charging time of the packed bed LHS system decreases drastically and average charging power can be improved, whereas larger pressure drops are observed.

4. An increase in the Reynolds number would result in a proportional improvement of the velocity and accelerate the charging processes of the PCMs, which further shortens the charging time.
and increases the average charging power. This can cause larger pressure drops.

5 An increase in the Stefan number slightly impacts the velocity distribution of the HTF, whereas it can enhance the temperature differences between the HTF and PCMs, and the sensible heat stored in PCMs. Thus, the charging time can be shortened and heat storage of the packed bed LHS system increases.

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Compliance with ethics guidelines

H. B. Liu and C. Y. Zhao declare that they have no conflict of interest or financial conflicts to disclose.

Nomenclature

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<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>( V )</td>
<td>volume (m(^3))</td>
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<tr>
<td>( A )</td>
<td>area (m(^2))</td>
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<tr>
<td>( d_p )</td>
<td>diameter of PCM capsule (m)</td>
</tr>
<tr>
<td>( R )</td>
<td>radius of container (m)</td>
</tr>
<tr>
<td>( D )</td>
<td>diameter of container (m)</td>
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<tr>
<td>( T )</td>
<td>temperature (°C)</td>
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<td>( H )</td>
<td>specific enthalpy (kJ·kg(^{-1}))</td>
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<td>( c_p )</td>
<td>specific heat capacity (J·kg(^{-1})·K(^{-1}))</td>
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<tr>
<td>( L )</td>
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<td>( \text{Ste} )</td>
<td>Stefan number</td>
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<td>( \Omega )</td>
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<table>
<thead>
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<th>Subscripts</th>
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<td>( i, j )</td>
<td>coordinate direction</td>
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<td>( f )</td>
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References


