A NUMERICAL STUDY ON THE THERMAL STORAGE PROPERTIES OF PACKER BED UNDER DIFFERENT ARRANGEMENTS OF PHASE CHANGE MATERIAL CAPSULES

by

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To evaluate the thermal storage properties of packer bed under different arrangements o phase change material capsules, three packing models (strip packing model, in-line packing model and disordered packing model) are developed. The index of thermal storage properties for packer bed such as exergy efficiency, energy efficiency, pressure drop, charging time, temperature uniformity, and thermal storage capacity is studied. The results show that the uniformity of the temperature field of the orderly packing model is obviously better than that of the disorderly ones. In addition, the in-line packing model has obvious advantages on the energy efficiency and the thermal storage capacity compared with the strip packing model. The strip packing model has the highest exergy efficiency, but it has a high pressure drop.

Key words: *phase change material capsules, thermal storage properties, packer bed, numerical simulation*

Introduction

Thermal storage technology is an effective solution for the contradiction between the unstable renewable energy supply and the stable energy demand. It absorbs and stores heat in the form of its own sensible or latent heat. Phase change thermal storage not only has high thermal energy storage density but also has characteristics such as small volume, simple device, process easier to control, and small material temperature fluctuation in the process of thermal storage [1, 2]. Even though these great advantages, most phase change materials (PCM) have a limitation of low thermal conductivity. To solve the problems of poor thermal conductivity, researchers proposed to encapsulate the PCM into small capsules, which increases the heat transfer area and reduces the rate of heat storage and release [3]. Thus, the packer bed of PCM capsules has been widely used in the latent heat thermal energy storage.

In practical application, disordered packing model of PCM capsules is widely used in packer bed because of its simple structure and low cost. However, the packing modes of PCM capsules in packer bed directly affects the thermal storage properties of packer bed. Therefore, some researchers have found and explained a lot about the thermal behavior and phenomena of packer bed by using the different packing modes [4-13].

In order to improve the pressure loss of the heat transfer fluid (HTF) passing through the packer bed, improve the heat transfer performance of the packer bed heat exchange fluid

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and the phase change capsule, Che *et al.* [14] studied the influence of fluid velocity, initial temperature of PCM, capsule diameter and porosity on the performance of heat storage system using numerical simulation method.

Zhao *et al.* [15] numerically analyzed the heat storage process of packer bed. The results show that there is an optimal heat storage time in the packer bed to obtain the highest heat storage efficiency. Wu *et al.* [16] established the disordered accumulation model of the packer bed using DEM-CFD method, and numerically analyzed the performance of the flow and heat transfer by compositing disordered accumulation of different diameters. Wang *et al.* [17] established the disordered stacking model of the 3-D PCM energy storage capsules in order to study the performance of packer bed.

In order to improve the performance of the heat receiver and reduces the temperature fluctuation of the working medium, Cui *et al.* [18] proposed a heat receiver model composed of a variety of PCM with different melting points. Yang [4, 19] studied on the performance of the uniform and non-uniform packer bed, and conducted an appropriate packing mode. The results show that the heat transfer performance of uniform fillers is much better than that of non-uniform fillers in many aspects. Du *et al.* [20] established a heat transfer model of energy storage packer bed, and obtained some ways to improve the heat transfer rate using the theory of porous media. Kang *et al.* [21] established a heat transfer model to study the thermal performance of the phase change thermal storage packer bed, which can calculate and analyze a variety of thermal performance parameters. Guardo *et al.* [22] developed also a turbulence flow and heat transfer model under five different conditions and obtained the pressure drop, velocity field and temperature field in the packer bed.

The assumption of orderly packing model of PCM capsules inside the packer bed is generally adopted in existing studies [23, 24]. In addition, most of studies mainly concentrate on the thermal storage properties of a packing model of PCM capsules [21, 25, 26]. There is little information could help determine the effect of different packing modes on the thermal storage properties of packer bed. The primary objective of the paper is to conduct thermal storage properties analysis of packer bed for three packing modes of PCM capsules. The research results of this paper can provide reference and help for solar energy, distributed energy, other new energy and energy storage modules in industrial application to a certain extent. Karthikeyan *et al.* [13] established two heat transfer models of energy storage packer bed with different flow rates, concluded the effect of axial conduction is negligible compared to the heat transfer by convection by the flowing HTF.

The performance of an encapsulated latent heat thermal storage unit with PCM dispersed with high conductivity particles has been studied numerically for the energy discharging process by Lakshmi *et al.* [27]. An addition of high conductivity particles by about 30% to the PCM results in a decrease in the time taken for complete solidification by about 26%. The role of particle fraction on the performance enhancement is more when compared to particle PCM thermal conductivity ratio.

Model description

Physical models and material properties

In this paper, the 3-D model of the packer bed is shown in fig. 1. For comparative analysis, three kinds of packing modes (strip packing, in-line packing and disordered packing) are developed in the Cartesian co-ordinate. The packer bed consists of cuboid container and

810 spherical PCM capsules. The PCM capsules fill the entire cuboid heat storage tank. The side length of the cuboid thermal storage tank is 95 mm, the radius of PCM capsule is 5 mm.

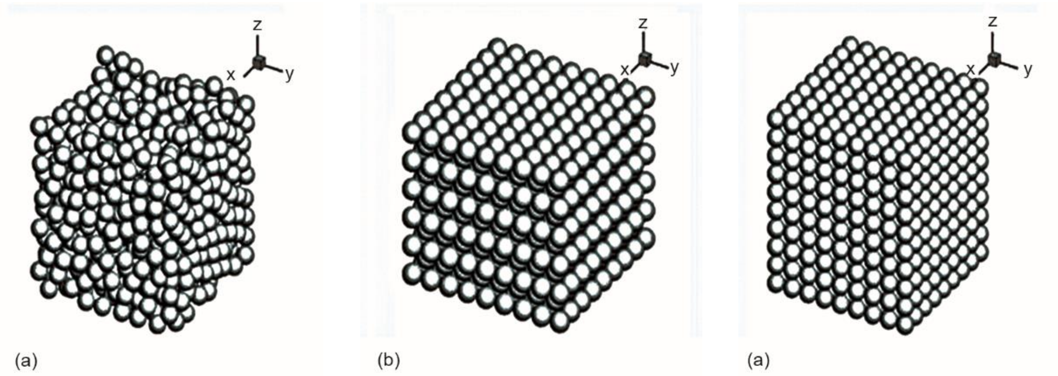

Figure 1. Fundamental geometry configurations of capsules with packing modes; (a) disordered packing, (b) strip packing, and (c) in-line packing

In this project, the heat storage material uses paraffin wax organic PCM RT44. Part of the physical properties of RT44 are provided by RUBITHERM Co. Ltd. The melting temperature of RT44 is suitable for low temperature (daily life) heat storage system such as heating. In the heat storage system, water is used as HTF, and steel with high thermal conductivity is used to make the shell of PCM capsules. In this paper, the average values of density, thermal conductivity, and specific heat capacity are used in PCM capsules phase change simulation. Table 1 also lists the latent heat, density, specific heat capacity and phase change temperature of PCM. During the heat storage process, high temperature water flows into the top of the packer bed, and flows out from the outlet of the bottom of the packer bed after heat transfer by the capsule.

Table 1. Thermophysical parameters of material

Materials	ρ [kgm^{-3}]	λ [Wm^{-1}K^{-1}]	c_p [Jkg^{-1}K^{-1}]	L [kJkg^{-1}]	Melting temperature [K]	Thermal expansion coefficient [K^{-1}]
RT44	770 (liquid)	0.2	–	250	314~317	0.008
	880 (solid)	0.2	–			
Water	971.8	0.6	4195			
Steel	8030	16.27	502.48			

Governing equations and boundary conditions

According to the proposed physical model, all 3-D simulation models established in this paper adopt the following assumptions.

– During the phase change, the thermophysical properties of PCM are constant in different states.
– In the process of phase change, ignore the influence of natural convection on heat transfer.
– Ignore the radiative heat transfer between the PCM capsule and the HTF.
– Ignore the heat loss between the packer bed and environment.

Based on the previous assumptions, the governing equations are developed by way of the enthalpy method [25]. The enthalpy method is incorporated into the commercial software FLUENT18. The energy conservation equation, excluding the convection term is:

$$\rho_{\mathrm{p}} \frac{\partial H}{\partial t} = k_{\mathrm{p}} \nabla^2 T_{\mathrm{p}} \tag{1}$$

where ρ_{p} is the density, H – the total enthalpy, k_{p} – the thermal conductivity, and T_{p} – the temperature.

For PCM, its sensible enthalpy and the latent heat constitute the total enthalpy:

$$H = h + \Delta H \tag{2}$$

$$h = h_0 + \int_{T_0}^{T_1} c_p \mathrm{d}T \tag{3}$$

$$\Delta H = \gamma L \tag{4}$$

where h_0 is reference enthalpy, T_0 – the PCM initial temperature (in order to melt PCM as soon as possible and save simulation time, the initial temperature of PCM is set as 40 °C), T_1 – the temperature of PCM when phase change begins, and c_p – the specific heat capacity.

The liquid fraction γ is:

$$\gamma = \left\{ \begin{array}{l} 0(T_{\mathrm{p}} \prec T_{\mathrm{solidus}}) \\ \dfrac{T_{\mathrm{p}} - T_{\mathrm{solidus}}}{T_{\mathrm{liquidus}} - T_{\mathrm{solidus}}} (T_{\mathrm{solidus}} \prec T_{\mathrm{p}} \prec T_{\mathrm{liquidus}}) \\ 1(T_{\mathrm{p}} \succ T_{\mathrm{liquidus}}) \end{array} \right\} \tag{5}$$

The initial and boundary conditions for PCM is defined:

$$T_{\mathrm{P}} \Big|_{(x,y,z)|t=0} = T_0 \tag{6}$$

$$-k_{\mathrm{p}} \frac{\partial T_{\mathrm{P}}}{\partial r} = h(T_{\mathrm{P}} - T_{\mathrm{f}}) \tag{7}$$

Numerical simulation methodology

The computer used in this paper is 6-core Intel (R) Xeon (R) CPU w3670 at 3.20 GHz 3.20 GHz 12.0 GB (RAM). All the simulation work took about half a year.

The simulation in this article must use the melting/solidification model in FLUENT, which is a pressure-based solver. The spatial discretization adopts the second order upwind scheme, and the temperature discretization adopts the second-order implicit time integration. The convergence criterion of the energy equation is set to 10^{-6}, and its accuracy is tested [28].

The unstructured tetrahedral grid is used because of the complex and changeable internal structure of the disordered stacking channel. In order to save computational resources, the wall thickness of the thermal storage capsule is not considered. Before the iterative calculation, it is necessary to check the mesh size of the model and the convergence of the iteration time step. In this paper, the models with 0.5, 1.1, 1.5, and 2.3 million cells are established respectively, and the grid independence verification is analyzed. It is found that the influence of the number of grids on the simulation results can be ignored. By using the same method, the five time steps of dt = 0.001, 0.002, 0.004, 0.005, and 0.008 seconds are independently verified. It is also found that the time step has little influence on the simulation results. Therefore, this paper adopts the model with 1.5 million grids and the time step is set to 0.005 seconds.

Performance analysis

Energy efficiency

The instantaneous energy efficiency of the heat storage system in the heat storage process can be written:

$$\eta_{\mathrm{energy}} = \frac{T_{\mathrm{f.in}} - T_{\mathrm{f.out}}}{T_{\mathrm{f.in}} - T_{\mathrm{f.init}}} \tag{8}$$

where $T_{\mathrm{f.in}}$ is the inlet temperature of heat exchange fluid, $T_{\mathrm{f.out}}$ – the outlet temperature of heat exchange fluid, and $T_{\mathrm{f.init}}$ – the initial temperature of heat exchange fluid.

Storage capacity

The heat exchange, Q_{f}, between the HTF and the heat storage bed can be written:

$$Q_{\mathrm{f}} = \int_0^t \dot{m}_{\mathrm{f}} c_{p,\mathrm{f}} (T_{\mathrm{f.in}} - T_{\mathrm{f.out}}) \mathrm{d}t \tag{9}$$

where $\dot{m}_{\mathrm{f}}$ is the mass-flow rate of heat exchange fluid and c_{f} is the specific heat capacity of heat exchange fluid.

Exergy analysis

The exergy efficiency is defined as the ratio between total exergy stored in HTF and PCM and the exergy supplied by HTF:

$$\eta_{\mathrm{ex}} = \frac{Ex_{\mathrm{f}} + Ex_{\mathrm{p}}}{Ex_{\mathrm{sup}}} \tag{10}$$

The exergy stored in HTF can be written:

$$Ex_{\mathrm{f}} = \dot{m}_{\mathrm{f}} c_{p,\mathrm{f}} \left(T_{\mathrm{f}} - T_{\mathrm{init}} - T_0 \ln \frac{T_{\mathrm{f}}}{T_{\mathrm{init}}} \right) \tag{11}$$

The exergy stored in PCM can be written:

$$Ex_{\mathrm{PCM}} = Q_{\mathrm{s}} \left(1 - \frac{T_0}{T_{\mathrm{PCM}}} \right) + Q_{\mathrm{l}} \left(1 - \frac{T_0}{T_{\mathrm{m}}} \right) \tag{12a}$$

$$Q_{\mathrm{s}} = \int_{T_0}^{T_{\mathrm{PCM}}} m_{\mathrm{p}} c_p \mathrm{d}T \tag{12b}$$

$$Q_{\mathrm{l}} = m_{\mathrm{p}} \beta \Delta H_{\mathrm{m}} \tag{12c}$$

where Q_s is the sensible heat storage of phase change capsule, Q_1 – the latent heat storage capacity of phase change capsule, T_m – the phase change temperature of PCM, β – the liquid phase ratio of PCM, and ΔH_m – the pure solvent melting heat of PCM.

The exergy of HTF at the inlet and outlet of packer bed can be written:

$$Ex_{\text{in}} = \int_0^t \dot{m}_{\text{f}} c_{p,\text{f}} \left(T_{\text{f,in}} - T_0 - T_0 \ln \frac{T_{\text{f,in}}}{T_0} \right) \text{d}t \tag{13}$$

$$Ex_{\text{out}} = \int_0^t \dot{m}_{\text{f}} c_{p,\text{f}} \left(T_{\text{f,out}} - T_0 - T_0 \ln \frac{T_{\text{f,out}}}{T_0} \right) \text{d}t \tag{14}$$

The exergy supplied by HTF can be calculated by the difference between the total exergy brought in and the total exergy brought out by HTF:

$$Ex_{\text{sup}} = Ex_{\text{in}} - Ex_{\text{out}} = \int_0^t \dot{m}_{\text{f}} c_{p,\text{f}} \left(T_{\text{f,in}} - T_{\text{f,out}} - T_0 \ln \frac{T_{\text{f,in}}}{T_{\text{f,out}}} \right) \text{d}t \tag{15}$$

Results and discussions

Modelling verification

Figures 2 and 3 are the system diagram and the physical diagram of the experimental apparatuses, respectively. The water in the water tank is heated by the electric boiler and flows from the upper part of the packer bed to the lower part, and the temperature is monitored by the thermocouple arranged. The feasibility of the simulation is proved by comparing the experimental device with the simulated outlet temperature.

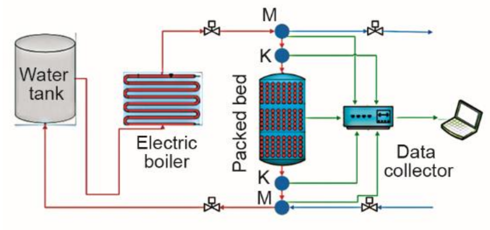

Figure 2. Experimental platform system diagram

Figure 3. Real view of the experimental platform

The correctness and reliability of the numerical model are verified by comparison with experimental results. Figure 4 depicts the outlet temperature resulted in experimental and present numerical simulation. The overall trend of the numerical model and the experimental results are roughly the same, and they are in good agreement. The error between the experimental Analysis of pressure drop and charging time and the simulated charging time is 2.5%, which verifies the correctness of the model.

Analysis of pressure drop and charging time

The pressure drop and charging time of the packer bed are important indicators to characterise the heat storage performance of the packer bed. Figure 5 presents the influence of packing modes on the pressure drop and charging time of packer bed. As the figures show, the disordered packing of PCM capsules attains the lowest pressure drop, in-line packing the second and strip packing the worst in the row for $V = 0.01$ m/s and $V = 0.002$ m/s. In addition, the in-line packing attains the longest charging time, disordered packing the second and strip packing the shortest in the row, when the velocity is kept to be 0.002 m/s. However, three packing modes have nearly the same charging time, when the flow rate is kept to be 0.01 m/s. The increase in HTF speed enhances heat transfer, resulting in an increase in the melting speed of RT44 and consequently decreased the charging time of packer bed. It was found that the velocity has a more obvious influenced on the charging time of in-line packing, especially when the velocity is low.

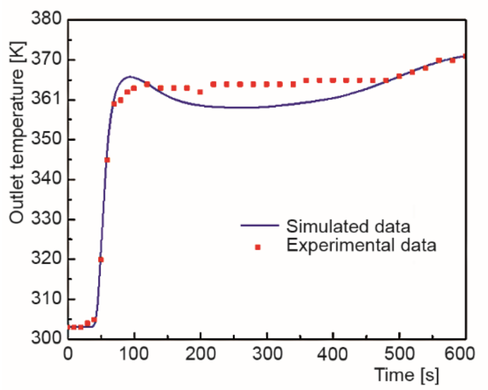

Figure 4. The validation of the simulation

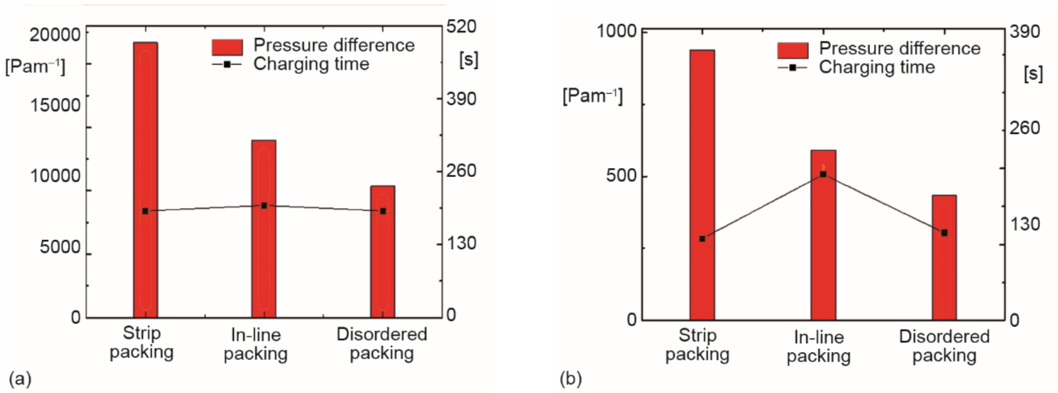

Figure 5. Pressure drop and charging time in different packing modes;
(a) liquid phase ratio 98% V = 0.01 m/s and (b) liquid phase ratio 90% V = 0.002 m/s

Temperature distribution

Figures 6(a)-6(c) show the temperature distribution of central flow field with time and space for different packing modes of heat storage capsules, respectively. It can be seen from the figure that as the heat storage process advances, the temperature of each part of the heat storage system will gradually rise, but the trend of temperature rise tends to stabilize. The reason is that the PCM melts almost completely as the heat storage process progresses, which causes the latent heat storage capacity of the PCM to gradually decrease as the heat storage process progresses. In fig. 6(a) the heat storage efficiency of the heat storage system will decrease with the increase of time. The average temperature inside the system in in-line packing state is significantly lower than that of the strip packing state and disordered packing state. This is because the heat transfer status of the system is better when strip packing state is used, which also indirectly confirms that the energy efficiency of the system must be higher when in-line packing state is used. For strip and in-line packing state, the temperature field of the heat storage system tends to decrease firstly and then increase slightly from the inlet to the outlet in the same heat storage time, while there is almost no such phenomenon in the case of disordered packing state. This paper specifically studied on the center section temperature field of heat storage system under different packing mode in order to find the cause of this phenomenon appears and to improve the heat storage system.

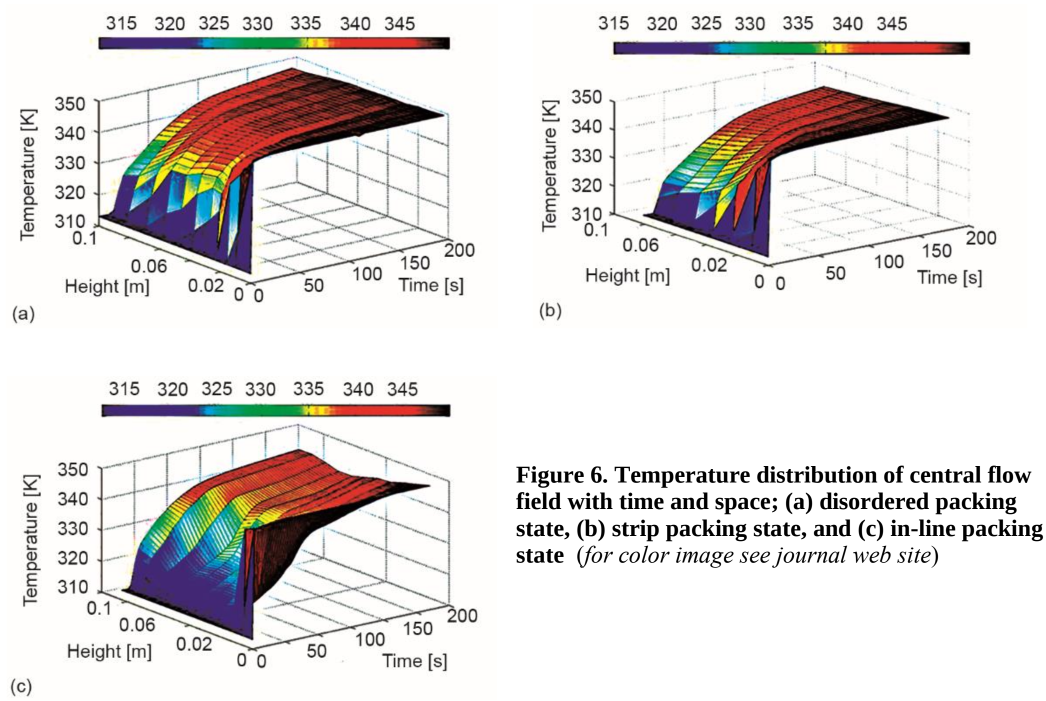

Figure 6. Temperature distribution of central flow field with time and space; (a) disordered packing state, (b) strip packing state, and (c) in-line packing state (*for color image see journal web site*)

Figures 7(a)-7(c) show the temperature cloud diagram of the heat storage system at different time periods under different arrangements of phase change capsules. It can be seen that the temperature field of the heat storage system is more uniform and regular for strip and in-line packing than disorderly packed.

Analysis of heat storage capacity

The heat storage capacity of a packer bed is an important index to measure its heat storage performance. The heat storage capacity of different packing model is given in fig. 8.

As the figure shows, in-line packing model of packer bed attains the highest heat storage capacity, strip packing model the second and disordered packing model the worst in the row. The heat storage capacity of in-line packing is 57% and 94% higher than that of strip and disordered packing, respectively.

Instantaneous energy efficiency analysis

Figure 9(a) displays the instantaneous energy efficiency of the heat storage system with time under different packing modes for $V = 0.002$ m/s. The completed heat storage process of strip packing state, in-line packing and disordered packing is the least 180, 298, and 195 seconds, respectively.

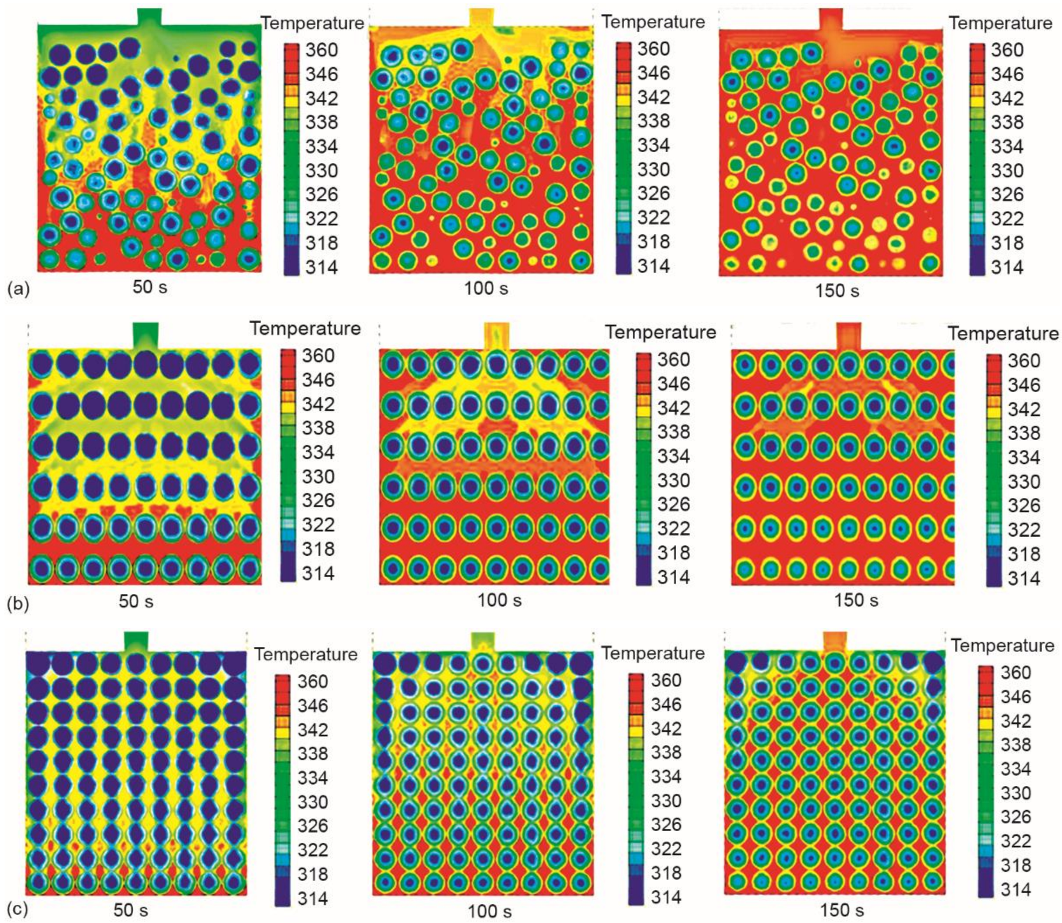

Figure 7. Temperature distribution of the central section; (a) disordered packing state, (b) strip packing state, and (c) in-line packing state (*for color image see journal web site*)

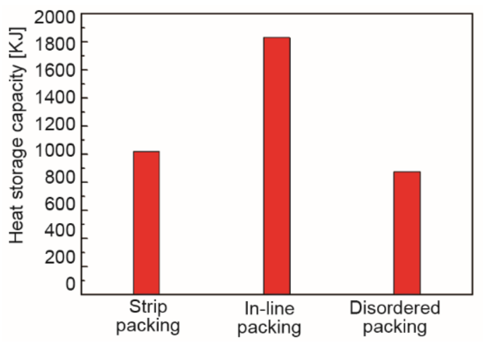

Figure 8. Heat storage capacities in different packing modes

Figure 9(b) shows that by increasing the speed of HTF, the instantaneous energy efficiency of the thermal storage system changes with time (V = 0.01 m/s). It can be seen from fig. 9(b) that the completed heat storage process can be greatly reduced for increasing the velocity of HTF, and the instantaneous energy efficiency of the system decreases sharply in a short time. It is difficult to achieve the goal of efficient heat storage for high velocity of HTF. This is caused by the short time having an effect on heat transfer between the HTF and the heat storage capsules.

From figs. 9(a) and 9(b), we can see that the instantaneous energy efficiency of strip packing is lower than that of in-line packing and disordered packing during the whole heat storage process. Reasons attribute to the laminar inner layer thickness of the HTF on the surface of capsules, which is function of the temperature difference between the heat storage capsules and the HTF.

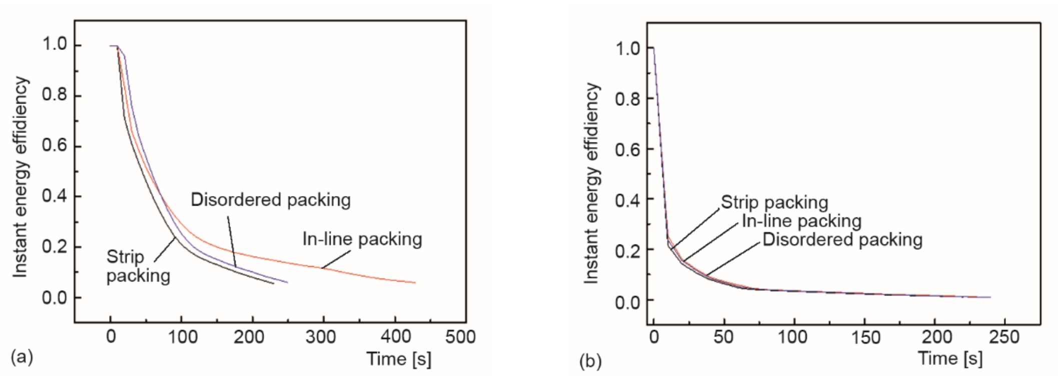

Figure 9. Variation of instantaneous energy efficiency with time; (a) *V* = 0.002 m/s and (b) *V* = 0.01 m/s (*for color image see journal web site*)

Exergy analysis

To analyze the impact of packing mode on exergy efficiency and exergy stored of packer bed, the numerical solutions of several parameters are calculated. Figure 10 presents the influence of the packing mode on exergy efficiency and exergy stored, when the velocity is kept to be 0.01 m/s and 0.002 m/s. It can be seen in the figure that the packing mode has a significant influence on the exergy efficiency of packer bed. Figure 10 shows the charging process indicates that the strip packing model attains the highest exergy efficiency, disorder model the second and in-line packing model the worst in the row.

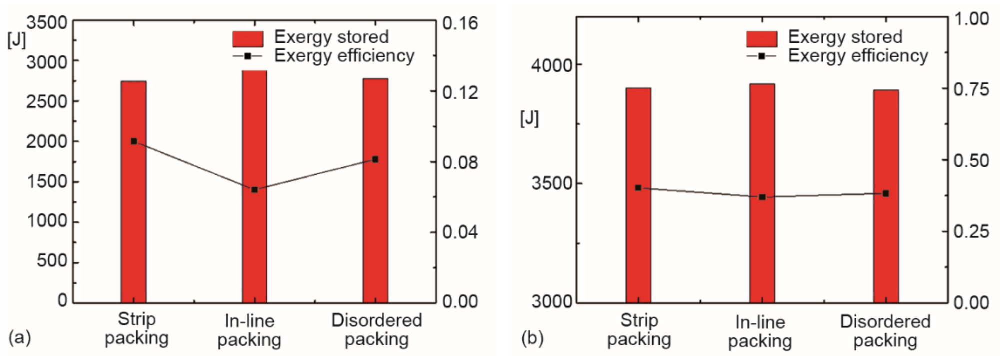

Figure 10. Exergy efficiency and exergy stored in different packing modes; (a) liquid phase ratio = 90%, *V* = 0.002 m/s and (b) liquid phase ratio = 98%, *V* = 0.01 m/s

However, in-line packing model attains the largest exergy stored, the exergy stored of disorder model is about as large as strip packing. From fig. 8 we can know that changing the speed of HTF can also improve the efficiency of packer bed exergy, and it is also one of the important means to change the exergy efficiency, especially high velocity. The higher the velocity, the fewer the differences of exergy efficiency during the discharging process.

Conclusions

In this paper, the 3-D models of PCM capsules in different packing states are established. Study their heat storage performance during charging. Detailed comparison of the impact of PCM packaging methods on thermal storage performance. The main conclusions are as follows.

- Under the same conditions, the in-line packing of packer bed has high heat storage efficiency, exergy stored, and total heat storage capacity, but it has low exergy efficiency and long charging time during the charging process. In addition, the stacking packing of packer bed has the highest exergy efficiency and pressure drop, and obtains also the lowest instantaneous energy efficiency and the shortest charging time.
- The temperature field uniformity of ordered packing are better than that of disordered packing.
- The arrangements of PCM capsules may significantly influence the thermal storage properties during the charging process. Thus, orderly and disorderly packed of PCM capsules is also effective way to improve the thermal storage properties in packer bed.

Acknowledgment

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Nomenclature

c_p – specific heat, [$\mathrm{Jkg^{-1}K^{-1}}$]
Ex – exergy, [kJ]
m – mass, [kg]
$\dot{m}$ – mass-flow rate, [$\mathrm{kgs^{-1}}$]
Q – thermal energy, [kJ]
T – temperature, [K]
t – time, [s]

Greek symbols

η – efficiency
η_{ex} – exergy efficiency

Subscripts

ex – exergy
f – fluid
in – inlet
init – initial
l – liquid phase region
out – phase region outlet
p – two-phase region
sup – supplie fluid
s – solid phase region

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