

Numerical simulation of paraffin heat storage process in concentric tubes

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Energy storage is an important means to solve the problem of space-time energy mismatch and has become a current research hotspot. The rate of heat absorption and release will affect the application range of heat storage materials, which is worthy of further study. This paper studies the phase change heat storage law of the concentric double-pipe heat exchanger at different fluid inlet temperatures and inlet velocities. The research results show that the influence of inlet velocity is much smaller than that of inlet temperature. The fluid inlet temperature has a great influence on the heat transfer effect, but when the fluid inlet temperature reaches a certain temperature range, further changing fluid inlet temperature to increase the melting rate is no longer effective.

Keywords: Energy storage, phase change heat storage, inlet temperature, inlet velocity

INTRODUCTION

The development of heat storage technology plays an important role in improving energy efficiency [1]. The phase change material is approximately isothermal in the process of phase change and some phase change materials have high heat storage density, which is beneficial to reduce the volume of the device [2]. Therefore, it has wide application prospects in the use of solar energy, the recovery of industrial waste heat, the "peak shifting valley filling" of the power industry, and phase change material composite walls, etc. [3, 4]. It has become a research hotspot worldwide [5-7].

The solid-liquid phase change material has a broad application prospect due to its small volume change during the phase change process. The phase change material can absorb/release a large amount of energy during the melting/solidification process, which is called the latent heat of phase change, and the corresponding melting or solidification temperature is called the phase change temperature. There are many kinds of phase change heat storage materials, which are mainly divided into organic phase change heat storage materials (such as paraffin [8, 9], fatty acid [10], etc.), inorganic phase change heat storage materials (such as hydrated salts [11], metals, etc.) and mixed phase change heat storage materials [12]. Among the organic phase change heat storage materials, paraffin have received widespread attention because of its high heat storage density, safety and stability, no phase separation and low cost [13-15].

This paper simulates the phase change heat storage process of paraffin in concentric tubes. Compare the influence of different inlet temperatures and inlet velocities on phase change heat storage, so as to point out the way to improve the phase change heat transfer.

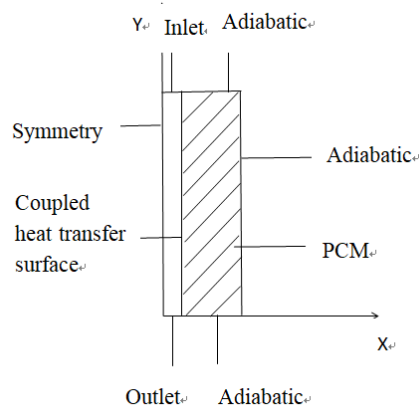


Fig.1. Physical model of paraffin heat storage process in concentric circular tube

PHYSICAL MODEL AND MATHEMATICAL MODEL

The dimensions of the concentric circular tube phase change heat exchanger are as follows: the outer tube has a diameter of 47 mm and a height of 400 mm, and the inner tube has a diameter of 6 mm and a height of 400 mm. The phase change material paraffin is filled in the outer ring. The physical properties of paraffin are shown in Tab.1. The hot water flows longitudinally from top to bottom in the inner tube. When the temperature of hot water is higher than the phase change temperature of paraffin, the phase change material absorbs heat and undergoes a phase change from solid to liquid,

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thereby completing the heat storage process. 1/2 area of the heat storage unit along the flow direction is selected as the calculation area, and the center line of the inner tube is a symmetric boundary to establish a two-dimensional model, as shown in Fig.1.

Basic equation

For the convenience of analysis, simplify the physical model and make the following assumptions.

(1) The solid-liquid two-phase phase change material has uniform and isotropic physical properties.

(2) The liquid phase region is Newton's incompressible fluid.

(3) The natural convection in the liquid phase region is a two-dimensional laminar flow.

(4) Only consider the change of phase change density with temperature when the buoyancy force acts.

(5) The thickness and thermal resistance of the pipeline are negligible.

Based on the above assumptions, the governing equation is as follows:

Mass equation:

$$\nabla(\rho\vec{v})=0 \quad (1)$$

where:

ρ – density, kg/m³;

\vec{v} –velocity vector, m/s.

Momentum equation:

$$\frac{\partial(\rho\vec{v})}{\partial t} + \nabla(\rho\vec{v}\vec{v}) = -\nabla\rho + \nabla(\mu\vec{v}) + S \quad (2)$$

where:

t – time, s;

μ –dynamic viscosity, kg/(m·s);

S – source term.

Energy equation:

$$\rho \frac{\partial H}{\partial t} = \lambda \nabla^2 T \quad (3)$$

where:

H – the specific enthalpy at any time, J/kg;

λ – thermal conductivity, W/(m·K);

T – temperature, K.

$$H = h + \Delta H \quad (4)$$

$$h = h_{ref} + \int_{T_{ref}}^T c_p dT \quad (5)$$

$$\Delta H = \beta L \quad (6)$$

where:

h – specific enthalpy of sensible heat, J/kg;

h_{ref} – specific enthalpy at reference temperature, J/kg;

T_{ref} – reference temperature, K;

C_p – specific heat at constant pressure, J/(kg·K);

β – liquid fraction;

L – latent heat, J/kg.

Table1. The thermal properties of paraffin

Name	Density	C _p	Thermal conductivity
	kg/m ³	kJ/(kg·K)	W/(m·K)
paraffin	760	2100	0.25
viscosity	Latent heat	Freezing point	Melting point
kg/(m·s)	kJ/kg	K	K
0.00324	170	324.15	330.15

Boundary conditions and parameters

Considering the axial symmetry of the physical model, a two-dimensional axisymmetric transient numerical model is established to study the heat transfer of phase transition. SIMPLE algorithm is used to couple the pressure-velocity term. Meanwhile, the energy and momentum equations are discretized by adopting second order upwind schemes, and PRESTO! approach is selected to discretize the pressure equation. Considering the natural convection in the liquid region, the phase change material density term selects Boussinesq model, and the thermal expansion coefficient is 0.0006 K⁻¹ [16]. At the boundary inlet, the velocity-inlet boundary condition is selected. At the boundary outlet, the outflow boundary condition is defined. The external boundaries of the phase change material are considered adiabatic. In the simulation, the change of the liquid phase volume fraction of the phase change material with time is monitored.

RESULTS AND ANALYSIS

Model validation

In order to verify the correctness of the model, the numerical simulation results are compared with

Jin's [17] experimental results under the same working conditions (the initial temperature of paraffin is 301.15 K, the inlet temperature of hot fluid is 336.15 K, and the inlet velocity of hot fluid is 0.028 m/s). Fig.2 shows the curve of outlet temperature with time. It can be found that the trend of the numerical simulation results is basically consistent with the experimental results, and the error is very small.

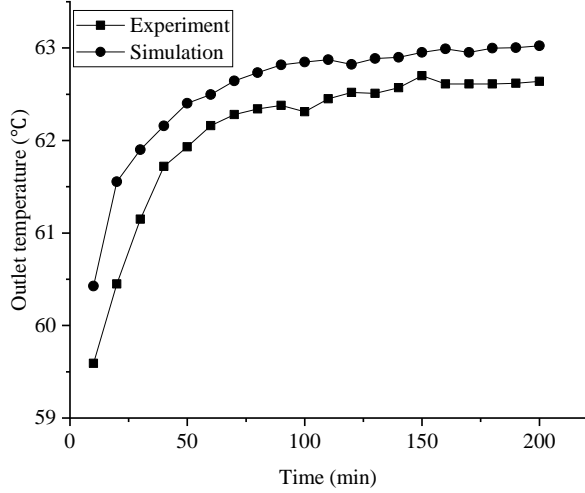


Fig.2. Variation curve of outlet temperature with time
Grid independence validation

The models with 8260, 16300 and 28740 grids are selected for numerical simulation, and the outlet temperatures of thermal fluid with time under different grid sizes are compared as shown in Fig.3. When the number of grid increases, the calculation is more accurate, but the calculation time will also increase. Under comprehensive consideration, the model with 16300 grids is selected.

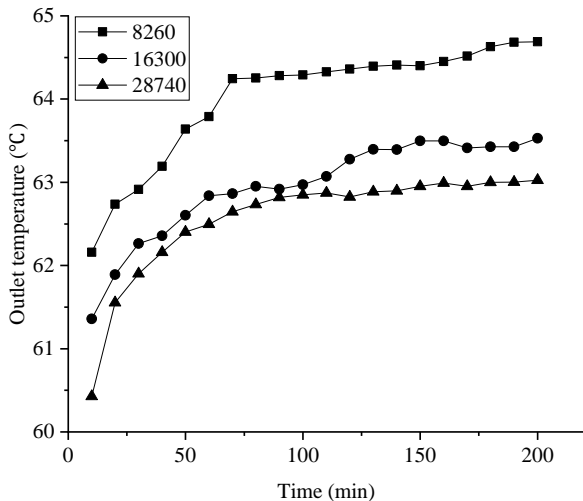


Fig.3. The curve of outlet temperature with time under different grid sizes

Simulation results

1. Influence of inlet velocity

The paraffin melting process is simulated with an initial temperature of 298.15 K, a thermal fluid inlet temperature of 360.15 K, and a thermal fluid inlet velocity of 0.035 m/s, 0.045 m/s and 0.055 m/s. The simulation results are as follows.

Fig.4 shows the curve of the liquid phase volume fraction of paraffin with time at different inlet velocities. It can be seen from Fig.4 that the liquid phase volume fraction of paraffin increases with time, showing a tendency that the melting velocity is faster at the beginning and slower afterwards. This is mainly because at the beginning of melting, the temperature difference between the phase change material and the thermal fluid is large, and the heat transfer is fast. As the heating time increases, the content of liquid paraffin is more and more, and the amount of liquid paraffin near the wall also increases. After the liquid near the wall is heated, the temperature increases and the density decreases. As a result, under the driving force of the density difference, the high-temperature liquid near the wall surface and the low-temperature liquid near the phase interface appear natural convection.

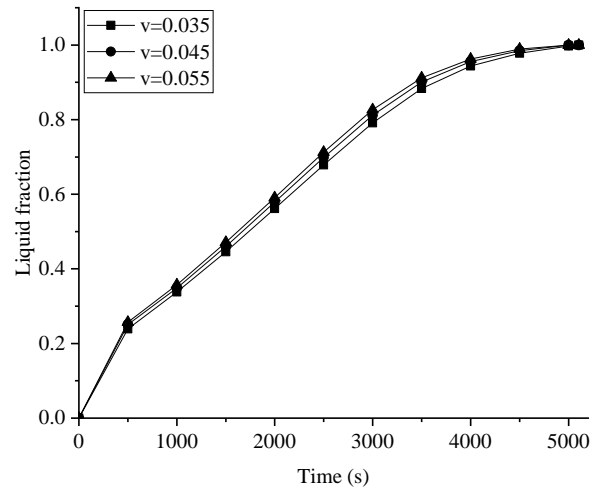


Fig.4. Variation curve of liquid phase volume fraction of paraffin with time

Fig.5 shows the velocity field distribution of paraffin when the fluid inlet velocity is 0.045 m/s and the inlet temperature is 360.15 K. It can be seen that due to the relatively large ratio of length to diameter of the concentric circular tube, natural convection disappears after a period of time along the radial direction, and then develops downward along the length direction. As the heat transfer

progresses, the temperature difference between the phase change materials becomes smaller and smaller, and the natural convection will weaken until it disappears. Due to the disappearance of natural convection, the heat transfer becomes weaker and the melting rate of the phase change material becomes slower. The three curves in Fig.4 have very little difference, which shows that the inlet velocity has little effect on the melting process of paraffin.

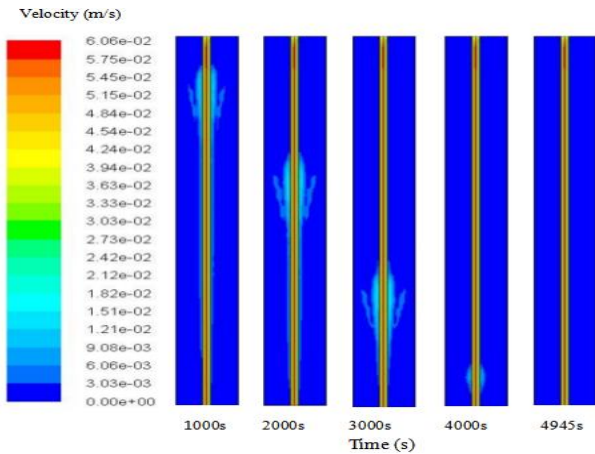


Fig.5. Velocity field distribution at the fluid inlet temperature of 360.15 K

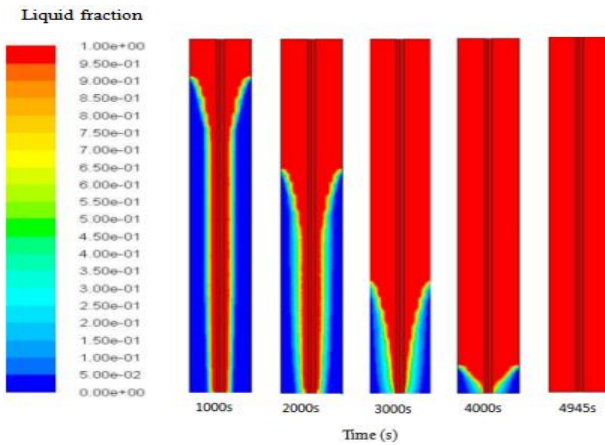


Fig.6. Liquid fraction distribution at the fluid inlet temperature of 360.15 K

Fig.6 and Fig.7 are the cloud pictures of the liquid phase volume fraction and temperature field distribution of paraffin at different time when the fluid inlet velocity is 0.045 m/s and the inlet temperature is 360.15 K. When the melting time reaches 1000 s, the temperature of the phase change material first rises near the inner tube and near the entrance, and the phase change material near the inlet begins to melt. As the melting progresses, the heating zone gradually expands downward, and the liquid phase volume fraction becomes larger and

larger. As the melting time increases, the natural convection in the lower region weakens until it disappears, and the heat conduction is dominated. The melting time of the phase change material near the fluid outlet is longer. According to the cloud chart of the liquid phase volume fraction and the temperature field distribution, it can be seen that the area near the fluid outlet is the most difficult to melt.

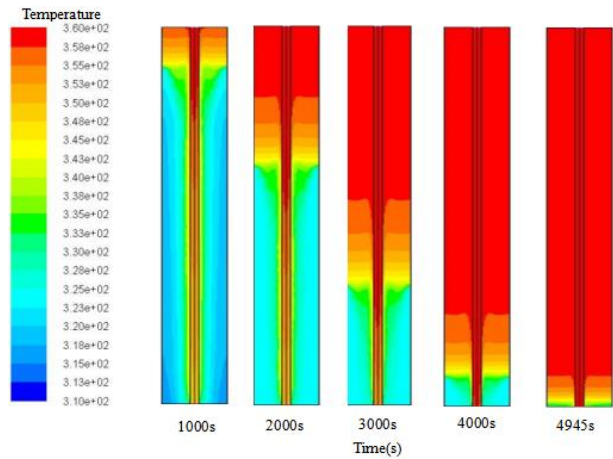


Fig.7. Temperature field distribution at the fluid inlet temperature of 360.15 K

2. Influence of inlet temperature

The paraffin melting process with an initial temperature of 298.15 K, a thermal fluid inlet velocity of 0.045 m/s, and a thermal fluid inlet temperature of 350.15 K, 360.15 K and 370.15 K are simulated.

It can be seen from Fig.8 that when liquid phase ratio is between 0 and 0.8, the slopes of the three curves are relatively large and basically unchanged. When the ratio is between 0.8 and 1, the slopes of the curves gradually decrease. This is because as the proportion of paraffin increases, natural convection occurs and the heat transfer rate is relatively fast. In the late melting stage, the heat transfer effect of natural convection is weakened and the heat transfer is mainly heat conduction, which causes the melting rate to decrease and the curve slope becomes smaller. It can also be found from Fig.8 that at three different fluid inlet temperatures, when the fluid inlet temperature is 370.15 K, the slope of the curve is the largest. That is, increasing the fluid inlet temperature will increase the melting rate of paraffin and shorten the melting time. Comparing Fig.5, Fig.9 and Fig.10, it can be found that as the temperature increases, the downward development of natural convection accelerates, and the radial development does not change much.

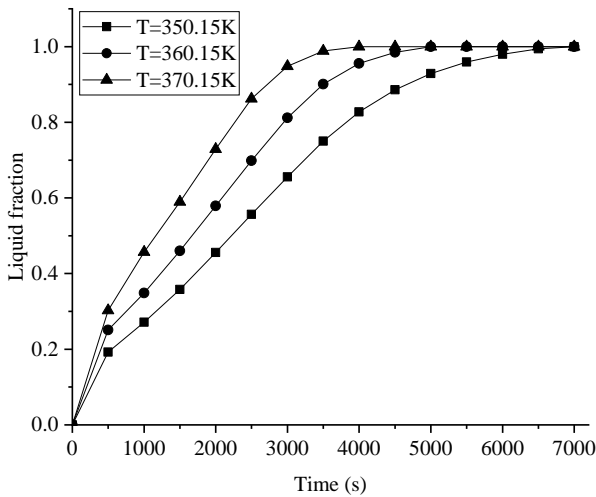


Fig.8. Variation curve of liquid phase volume fraction of paraffin with time

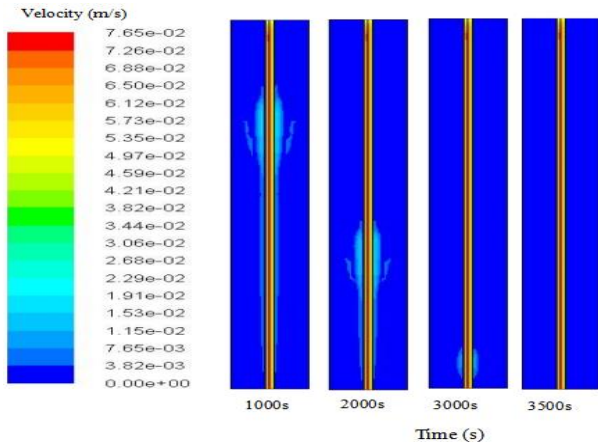


Fig.9. Velocity field distribution at the fluid inlet temperature of 370.15 K

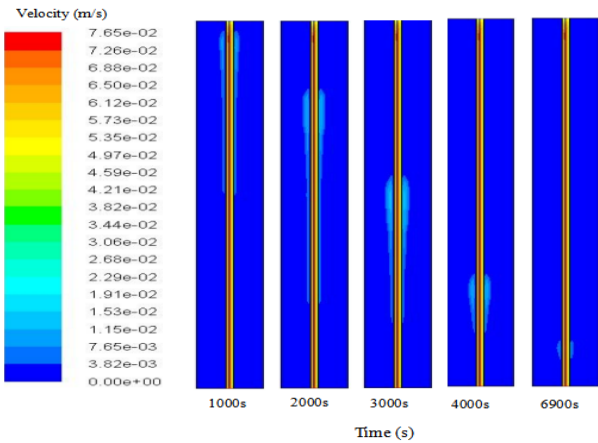


Fig.10. Velocity field distribution at the fluid inlet temperature of 350.15 K

It can be seen from Fig.6, Fig.11 and Fig.12 that when the thermal fluid inlet temperature is 350.15 K, 360.15 K, 370.15 K, the paraffin is completely melted at 6900 s, 4945 s and 3800 s, respectively. When the hot fluid inlet temperature increases from 350.15 K to 360.15 K and from 360.15 K to 370.15 K, the complete melting time is shortened by 1955 s and 1145 s, respectively. The corresponding reduction rates are 28.3% and 23.1%. As the temperature increases, under the same temperature difference, the shortening of the melting time will decrease. Therefore, when the inlet temperature of the thermal fluid rises to a certain range, the effect of continuously increasing the temperature on shortening the complete melting time of the phase change material will be weakened.

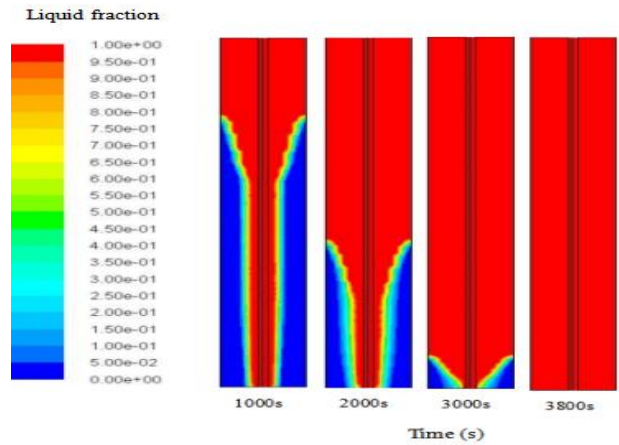


Fig.11. Liquid fraction distribution at the fluid inlet temperature of 370.15 K

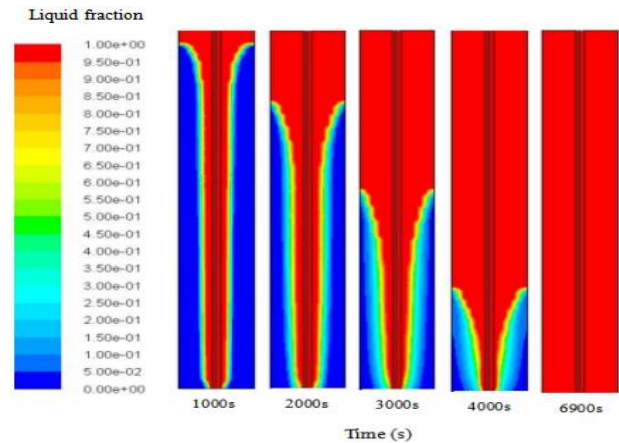


Fig.12. Liquid fraction distribution at the fluid inlet temperature of 350.15 K

Fig.13 and Fig.14 show the temperature field distribution at different fluid inlet temperatures. It can be seen from Fig.7, Fig.13 and Fig.14 that as the inlet temperature of the thermal fluid increases, the temperature change of the phase change

material accelerates, and the isotherm becomes more irregular. Since the ratio of length to diameter of the heat exchanger is relatively large, the radial heat transfer ends quickly, so the upper high-temperature liquid paraffin can quickly exchange heat with the paraffin in the lower mushy area, thereby speeding up the heat transfer. When the paraffin has completely melted, the heat transfer of the tail is still going on.

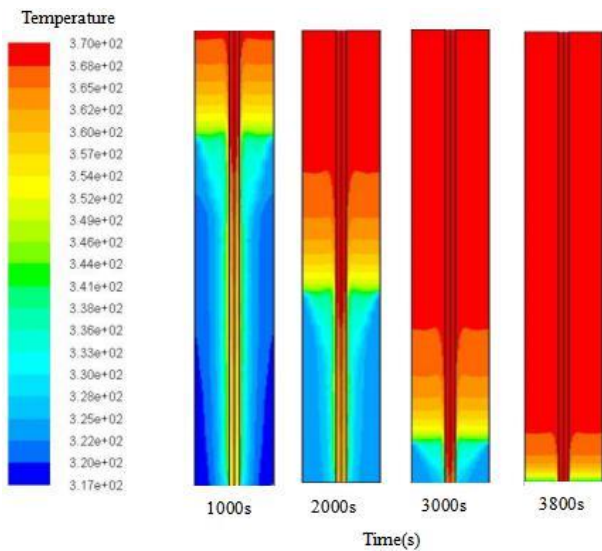


Fig.13. Temperature field distribution at the fluid inlet temperature of 370.15 K

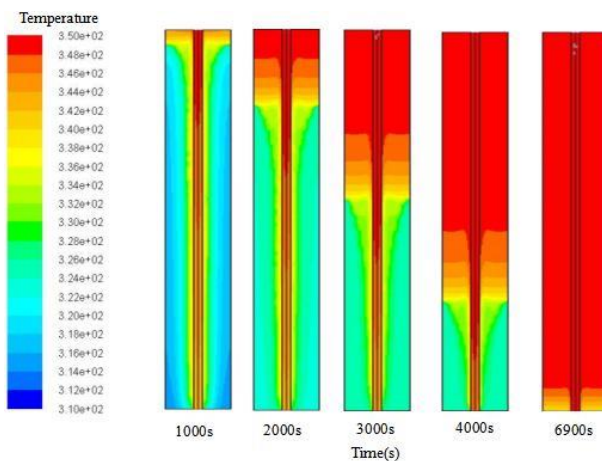


Fig.14. Temperature field distribution at the fluid inlet temperature of 350.15 K

CONCLUSIONS

(1) As the melting progresses, natural convection appears on the near wall side. Due to the relatively large ratio of length to diameter, natural convection disappears after a period of time along the radial direction, and then develops downward along the length direction.

(2) Compared with the inlet temperature, the inlet velocity has less influence on the phase change heat transfer process.

(3) When the inlet temperature of the hot fluid increases from 350.15 K to 360.15 K and from 360.15 K to 370.15 K, the decrease rates of the complete melting time are 28.3% and 23.1% respectively. With the increase of inlet temperature, the effect of increasing the inlet temperature on shortening the complete melting time of the phase change materials decreases.

(4) At different inlet temperatures of the thermal fluid, when the liquid fraction of paraffin is between 0 and 0.8, the curve slope of the liquid volume fraction of paraffin over time is relatively large and basically remains unchanged. When the liquid fraction of paraffin is between 0.8 and 1.0, the curve slope gradually becomes smaller. The curve slope increases with the increase of the fluid inlet temperature.

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