Compared Analysis of Calculation and Simulation on Heat Transfer Characteristics in PCM Heat Exchange Unit, Part I: Thermal Storage Process

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Abstract. Based on the temperature change and thermal storage processes of PCM phase change energy storage unit, the PCM channel number of which is 39, the plate spacing is 0.01 m, the air channel is 40 with its plate spacing of 0.003 m, and the unit length is total of 1.62 m. MATLAB solution about the above PCM energy storage unit was performed according to the model and physical property data, and the numerical simulation was carried out by using Fluent software. The theoretical calculation and numerical simulation were compared and analyzed. It is found that only in the case of smaller or larger flow rate working conditions, the solution results of MATLAB for the increase rate of the average temperature of the phase change material inside the system is quite different from the FLUENT simulation result; the comparison of the phase change process degree of advancement is found that at a higher flow rate, the difference between the two results is small, but the difference is larger when the flow rate is smaller; the comparison result of the PCM liquid rate is different under the small flow rate condition. However, the comparative analysis of heat storage shows that the maximum error does not exceed 10%. It can be seen that the flow rate conditions in the model and working conditions are the obvious factors affecting the two results, but the calculation and simulation results can more accurately describe the heat storage characteristics of the PCM phase change energy storage unit, which was calculated in nearly 90% ranges of working conditions, which can prove that the results of MATLAB and FLUENT are consistent.

Nomenclature

C1	Solid specific heat, J/(kg K)
C2	Liquid specific heat, J/(kg K)
h	Enthalpy, J/kg
Δh	Enthalpy increase, J/kg
K1	Solid conductivity, W/(m K)
K2	Liquid conductivity, W/(m K)
q	External heat flux, W/m^2
T1	Solid temperature, K
T2	Liquid temperature, K
T_f	Fluid working temperature, K
V	Velocity vector, m/s
ρ	Density, kg/m^3

Subscripts

M	Material
a	Air
0	Inlet state

1. Introduction

With the rapid development of today's world economy, energy and environment have become two major topics attracting worldwide attention. Especially, energy storage technology has been widely concerned because of its obvious advantages and functions [1]. Energy storage technology and its application have become one of the key areas to make full use of energy and effectively utilize energy. Among them, the application of phase change energy storage materials in energy storage has gradually attracted the attention of scholars all over the world. It has been widely used in water heaters, air conditioning, medical engineering, even military, Aerospace Engineering and other fields [2-5]. Using PCMs, thermal energy can be stored in the material in the form of latent heat by phase change, and then converted into other forms of energy when used. The output temperature and energy are stable and the storage density is high. The storage heat per unit volume is 5-14 times that of sensible heat storage. The advantage is obvious [6-7]. But at the same time, the phase transition process is more complex and difficult to analyze [8-12].

In this paper, the enthalpy method is used to calculate and analyze the performance of PCM phase change energy storage unit by MATLAB, and the numerical simulation is carried out by Fluent 12.0 software. The results of the two methods are compared, and the characteristics of the heat storage of PCM phase change energy storage unit are mainly analyzed, as well as the rationality and validity of the two methods for phase change process analysis.

2. Physical and mathematical model analysis

2.1. Physical model of PCM heat exchange unit

The layout and physical model of the phase change energy storage device used is shown in Figure 1. The structure of the energy storage device is a kind of plate heat exchanger, in which the composite phase change material is encapsulated between staggered parallel plates. The heat transfer fluid (air) flows through the outer parallel channel and exchanges heat with the internal phase change material to achieve the purpose of thermal energy storage and release. In the heat storage process, the heat transfer fluid enters from the inlet above the device and flows out through the lower outlet; in the exothermic process, the flow direction of the heat transfer fluid is opposite to that of the heat storage process, and enters from the lower part and flows out from the upper part. The structure dimension of energy storage device is as follows: veneer area is 0.81 m^2, plate size is 1.6 m *0.505 m, steel plate is as thin as possible, i.e. about 1.0 mm, plate spacing is asymmetric channel, PCM channel is 0.010 mm, air channel is 0.003 mm, corresponding single channel cross-sectional area PCM channel is 0.00505 m, air channel is 0.001515 m^2. A summary of the unit structure parameters and material physical properties has been listed in Table 1 and Table 2.

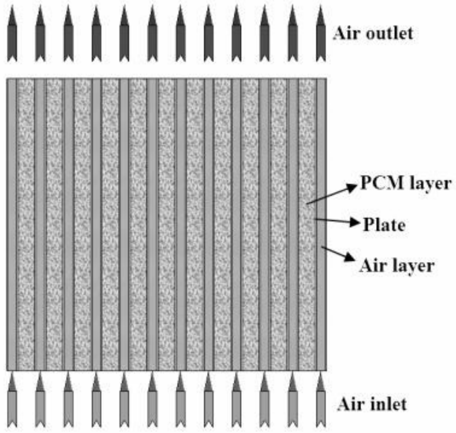


Figure 1. Structure of the PCM heat exchange unit.

In order to obtain more accurate simulation result, the following assumptions are made: 1) the heat conductivity and density of phase change media are constant and do not change with temperature; 2) the temperature of phase change is constant; 3) the heat transfer in phase change media is dominated by heat conduction, ignoring the effect of natural convection; 4) the initial temperature of phase change materials is close to the melting temperature [13-15].

Table 1. The PCM unit structure parameters.

No.	Structure parameters	Values
1	Air flow plate spacing/ m	0.003
2	PCM spacing/ m	0.01
3	Heat transfer area of veneer/ m^2	0.81
4	Cross section area of single channel/ m^2	0.001515
5	Section area of PCM in single channel/ m^2	0.00505
6	PCM channels number	39
7	Total heat transfer area/ m^2	63

Table 2. The PCM physical properties.

No.	Performance parameters	Values
1	Phase change temperature/ ℃	138
2	Energy storage density of materials/ kJ/kg	300
3	Density / kg/m^3	~1000
4	Thermal conductivity/ W/(mK)	~1
5	Specific heat / J/(kgK)	1.9
6	PCM quantity/ kg	200
7	Heat storage capacity /kWh	16.7
8	PCM volume / m^3	0.200
9	Thermal resistance / mK/W	0.005

2.2. Mathematical model of PCM heat exchange unit

For the plate energy storage unit shown in the figure above, because the heat transfer along its thickness direction is very small compared with the flow direction, its internal heat storage and discharge area can be simplified to a two-dimensional structure for simulation calculation [16-18]. In the process of simulation calculation, the average temperature of the PCM area and the outlet temperature of the heat transfer fluid are taken as the criteria, that is, when the average temperature of the PCM area is consistent with the temperature of the heat transfer fluid, or when the outlet temperature of the heat transfer fluid is consistent with the inlet temperature, the PCM inside the device is considered to be completely melted or solidified, other words, the heat energy storage or release are complete.

According to the air exothermic process, a coordinate system with the air inlet position as the origin and the x-axis direction parallel to the air flow direction has been established, as shown in Figure 2.

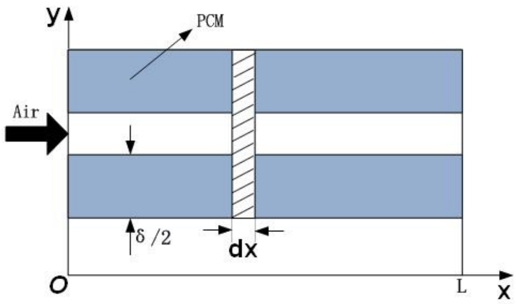


Figure 2. Coordinate system and infinitesimal analysis for the PCM unit.

Therefore, the following heat conduction equation can be established by analyzing the energy balance of dx volume from the origin of x.

$$S\rho_s c_{p,s}\partial T_s / \partial \tau = S\lambda_s \partial^2 T_s / \partial x^2 + KU(T_a - T_s) \tag{1}$$

The ideal gas equation of state is described as follows:

$$p = \rho_a R_M T_a \tag{2}$$

And the mass conservation equation is:

$$\rho_a u_a = \rho_{a,0} u_{a,0} \tag{3}$$

Energy equation:

$$\frac{\partial(\rho h)}{\partial t} + \mathrm{div}(\rho u h) = \mathrm{div}(\alpha \,\mathrm{grad} h) + S_h \tag{4}$$

$$\frac{\partial(\rho h)}{\partial t} = \lambda \nabla^2 T = \frac{\partial}{\partial t}\left(\lambda \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial t}\left(\lambda \frac{\partial T}{\partial y}\right) \tag{5}$$

The boundary and initial conditions are listed as bellows:

For boundary conditions,

$$T_a(0,\tau) = T_{a,0} \tag{6}$$

$$\partial T_s(0,\tau) / \partial x = \partial T_s(L,\tau) / \partial x = 0 \tag{7}$$

For initial conditions,

$$T_s(x,0) = f(x) \tag{8}$$

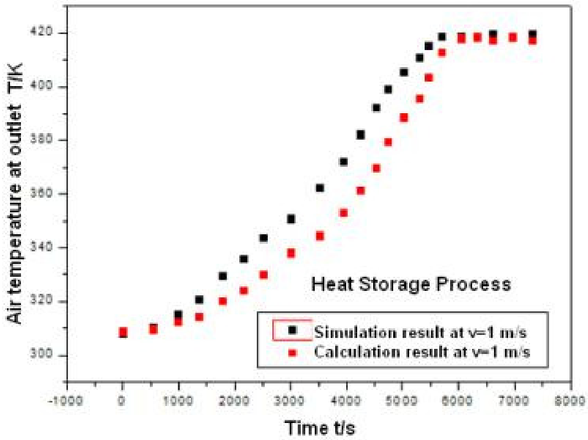
Considering the non-steady phase change process for heat storage and discharge in device, it is difficult to obtain the analytical solution under this problem [19-20]. Therefore, numerical method is used to simulate the heat storage and discharge process of heat storage device, time and space are discretized in the solution area, and partial differential mathematical model equation is approximated by forward difference.

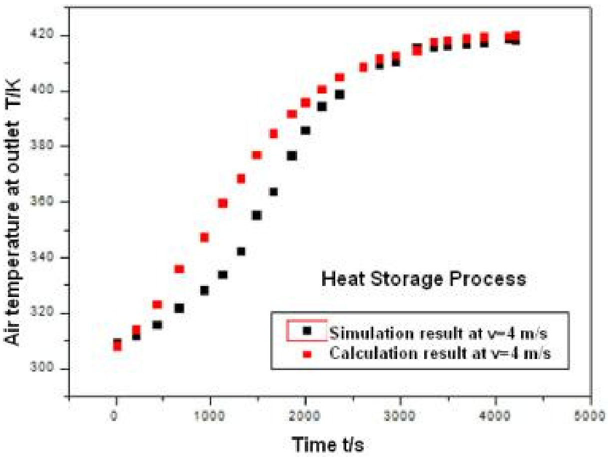
3. Results and discuss

3.1. *Analysis of air temperature change rate*

Taking the inlet velocity range of heat transfer fluid from 30% to 300% of the design value (3.14 m/s), i.e. 1-9 m/s, the MATLAB discrete solution results are compared with the simulation results of FLUENT under the same conditions. The air temperature rise curve is compared with the time change in Fig. 3. It can be seen that within the calculation range of heat transfer fluid velocity, the average temperature increase rate of phase change material side at the initial stage of overall heat storage process is greater than that at the later stage of heat storage. This is consistent with the previous analysis, because of the large temperature difference in the initial stage of heat storage, the corresponding heat transfer rate is larger; in the later stage of heat storage, with the increase of the temperature of phase change material, the temperature difference between the phase change material and the heat transfer fluid gradually reduces, and then the heat transfer rate in the system gradually decreases, while the average temperature of phase change material increases at the initial stage of heat storage.

Two points with different slope (heating rate) on the air temperature distribution curve of Fig.3 are analyzed. At a certain time during the heat transfer process, two points with different positions in the air passage are analyzed. The slope of these two points, i.e. the heating rate, is obtained by the simulation results at that time. Then using the discrete mathematical analytic method of equation and using MATLAB to program and solve, the heating rate of these two points at the corresponding time is obtained, and then the two points are compared and analyzed.





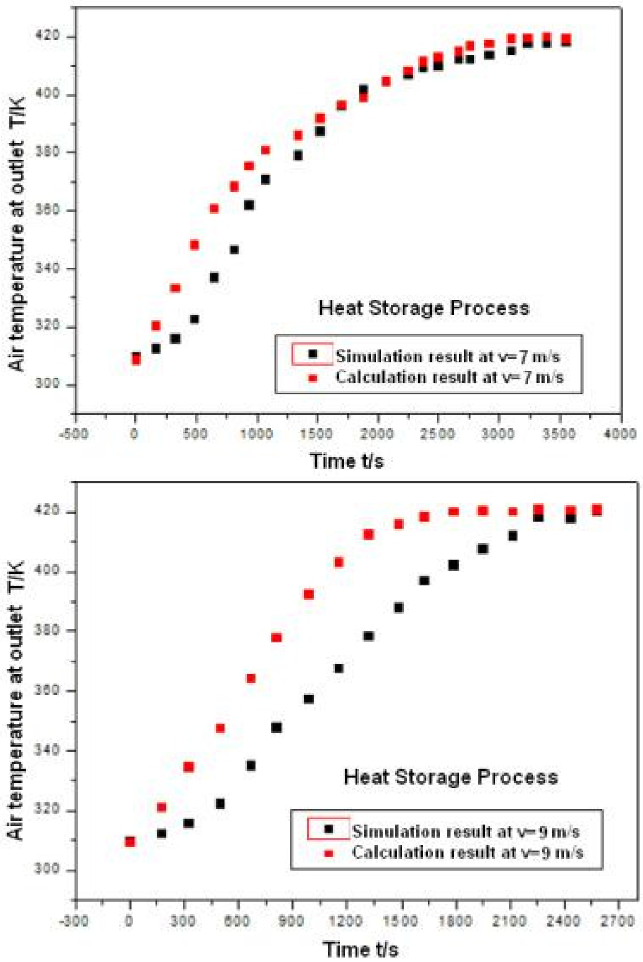


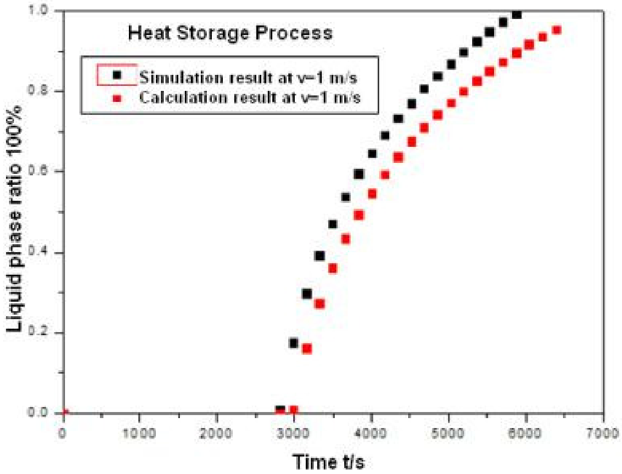
Figure 3. Air temperature change rate at outlet.

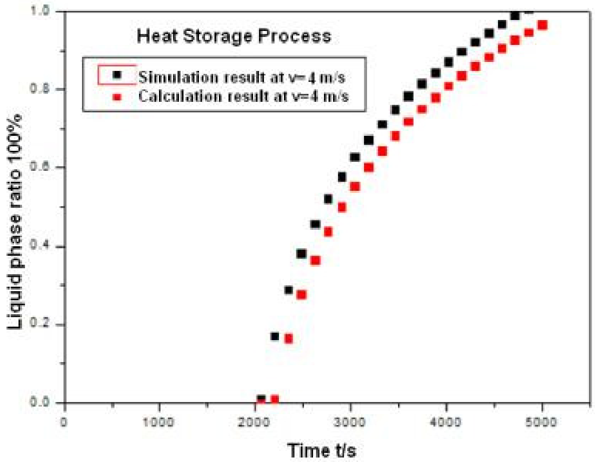
It can be seen from Fig.3 that the average temperature increase rate of phase change material in the system increases with the increase of the inlet velocity of heat transfer fluid. The results of MATLAB calculation show that the heat storage time is shorter than that of FLUENT simulation, especially when the flow rate is smaller and larger [21]. The difference of heat storage time between 1 m/s and 9 m/s is more than 200 s and 500 s, respectively, while at medium flow rate. The difference is small. Under the condition of 7 m/s, the difference of heat storage time is less than 100 s. See Fig. 3. Overall, the results show that the thermal storage time of FLUENT simulation results is longer when the flow rate is small, such as phase change thermal storage time more than 7500s under 1m/s condition.

When the velocity of flow is 1 m/s, 4 m/s and 9 m/s, the results of MATLAB and FLUENT simulation show great difference. The average errors of calculation are 16.2%, 13.9% and 17.0% respectively. When the velocity of flow is 7 m/s, the calculated results are in good agreement with the simulation results, the curve coincidence is high, and the average error is reduced to less than 10%. At the same time, it can be seen that the storage time and the temperature rise range of the two algorithms are both reasonable, and the reference velocity can be chosen.

3.2. Analysis of liquid phase ratio of PCM material

Since PCM material exists in two-phase state (liquid phase and solid phase) during the process, the ratio of the mass of PCM material in liquid phase state to the mass of PCM material in general is defined as the liquid phase ratio of PCM material. With the continuous heat transfer process, the liquid phase ratio of PCM material is also changing continuously, that is, from 0% to 100%. By calculating the liquid phase ratio of PCM material at a certain time, the simulation results and design results can be compared and analyzed.





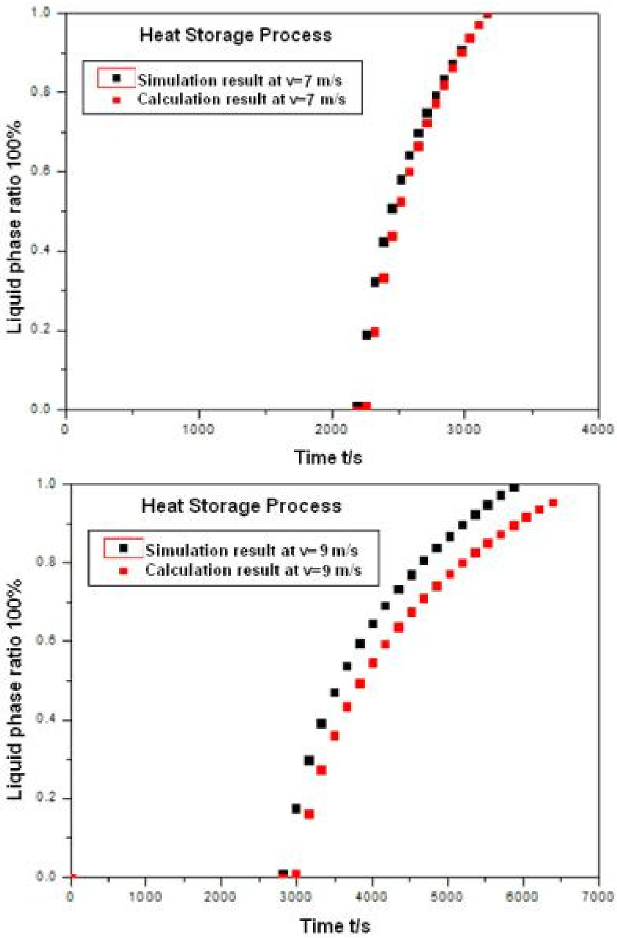
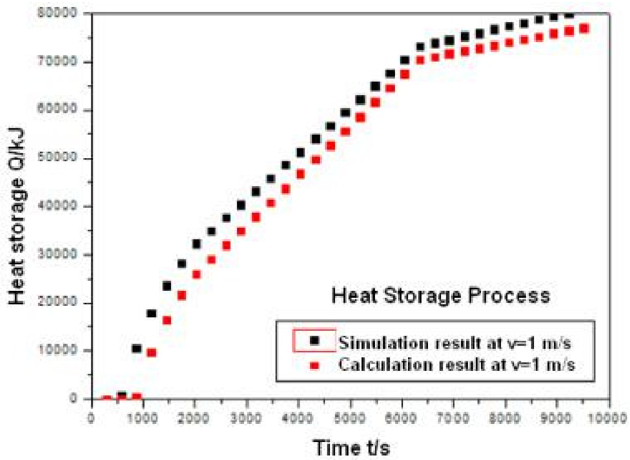


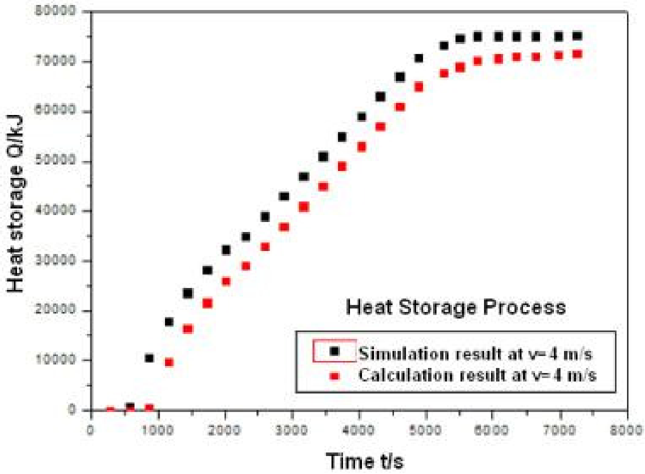
Figure 4. Liquid phase ratio of PCM material.

From Fig.4, it can be seen that the overall liquid phase change rate trend of the simulation results and the design results is the same, but comparing the four different flow rate conditions, it is found that the difference between the two results is smaller at higher flow rate, but larger at smaller flow rate.

3.3. Heat storage amount of PCM materials

With the constant total heat storage amount of PCM, the residual heat storage of PCM materials continue to change with the continuous heat transfer process. The numerical value can be calculated at a certain time in the heat transfer process, and then compared with the simulation value.


Heat storage Q/kJ
Time t/s
Heat Storage Process
Simulation result at v=1 m/s
Calculation result at v=1 m/s


Heat storage Q/kJ
Time t/s
Heat Storage Process
Simulation result at v=4 m/s
Calculation result at v=4 m/s

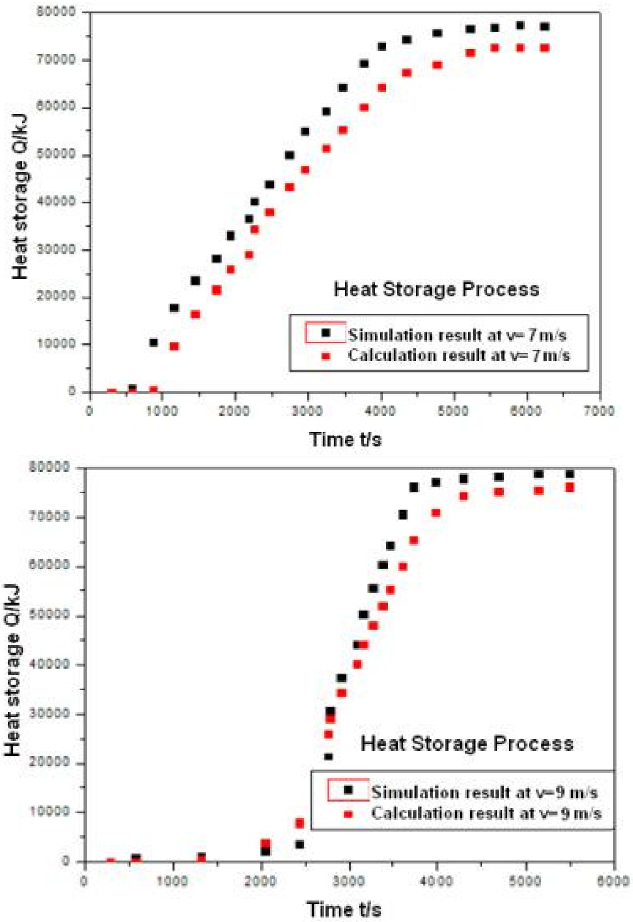


Figure 5. Heat storage amount during the phase change process.

From Fig. 5, it can be seen that the overall heat storage change trend of simulation results and design results is consistent. Four comparisons show that the growth rate of heat storage is relatively small at the beginning stage of heat storage. When phase change occurs, it increases approximately linearly, and the growth rate is relatively large. Until the phase change heat storage stage ends, the change trend of heat storage decreases; 1 m/s, 4 m/s, 7 m/s and 9 m/s flow rate. Under the condition, the time period for the increase of storage heat is gradually shortened, which is about 3000s, 2600s, 1700s and 900s, respectively. The comparison results prove the correctness of the design results, and the maximum check error is not more than 10%, which shows the accuracy of the design results.

4. Conclusions

(1) By comparing and analyzing the change rate of air temperature, it is found that in the calculation range of heat transfer fluid flow rate, the increase rate of the average temperature of phase change material side in the initial stage of overall heat storage process is greater than that in the later stage of heat storage. The increase rate of the average temperature of phase change material inside the system increases with the increase of the inlet velocity of heat transfer fluid. The results show that the errors of air temperature rise rate under different flow velocities are less than 10%.

(2) With the continuous heat transfer process, the liquid phase ratio of PCM material also changes continuously. The trend of the overall liquid phase change rate of the simulation results and the design results is the same, but comparing four different flow velocity conditions, it is found that the difference between the two results is smaller at higher flow velocity.

(3) With the constant total storage heat of PCM and the continuous heat transfer process, the residual storage heat amount of PCM materials are also changing continuously. The analysis and comparison show that the overall storage heat trend of simulation results and design results is the same. The growth rate of storage heat is relatively small at the beginning of thermal storage, and increases linearly when phase change occurs, and the growth rate is similar. It is large until the phase change heat storage stage is over.

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