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

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Abstract. In this part, the thermal release processes of PCM phase change in the same energy storage unit are analyzed, and the PCM unit model is the same as in Part I: channel number 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 as well. The theoretical calculation and numerical simulation were compared and analyzed. For the release process, it also can be seen that only in the case of smaller or larger flow rate working conditions, the solution results of MATLAB for the changing rate of the average temperature of the phase change material inside the system is quite different from the FLUENT simulation result; the total results are very similar to thermal storage process. When the flow rate is higher, the difference between the two results is even smaller than the release process; the comparison result of the PCM liquid rate is different under the small flow rate condition, and this is obvious for the release process, especially under the condition of small flow rate. However, also the maximum error does not exceed 10%. Conclusion can be drown that the flow rate conditions in the model and working conditions are the important factors for affecting the compared results, but the calculation and simulation results can more accurately describe the thermal release characteristics of the PCM phase change energy storage unit, which was calculated in nearly 90% ranges of working conditions, which furtherly illustrates the effectiveness of analytical method used in this paper.

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

As illustrated in part I, energy storage technology and its application have become one of the key areas to make full use of energy and effectively utilize energy in recent years,. 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 [1-5]. Phase change materials (PCMs) have the characteristics of small size, large energy storage per unit, friendly environment and easy control. 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. Also, phase change energy storage materials have the advantages of environment friendliness, stable output, easy control and high heat storage density, which are incomparable with other energy storage methods [6-8].

In this part, the enthalpy method is also 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 too. The results of the two methods are compared, and the characteristics of the thermal release process of PCM phase change energy storage unit are analyzed, as well as the rationality and validity of the two simulation methods.

2. Physical and mathematical model analysis

2.1. Physical model of PCM heat exchange unit

In this part, the layout and physical model of the phase change energy storage device used is the same as in part I, as 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.

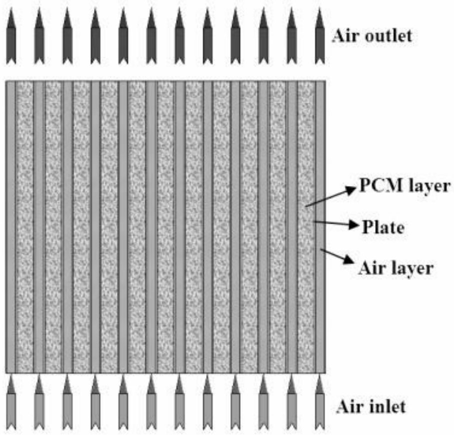


Figure 1. Structure of the PCM heat exchange unit.

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 [9-11].

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 [12-14]. 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.

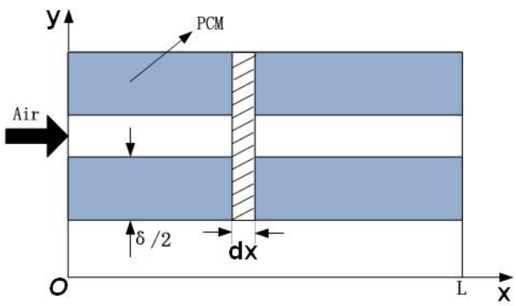


Figure 2. Coordinate system and infinitesimal analysis for the PCM unit.

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

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

The ideal gas equation of state is described as follows:

$$p = \rho_a R_M T_a \quad (2)$$

And the mass conservation equation is:

$$\rho_a u_a = \rho_{a,0} u_{a,0} \quad (3)$$

Energy equation:

$$\frac{\partial(\rho h)}{\partial t}+\mathrm{div}(\rho uh)=\mathrm{div}(\alpha \mathrm{grad} h)+S_h \quad (4)$$

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

The boundary and initial conditions are listed as bellows:
For boundary conditions,

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

$$\partial T_s(0,\tau)/\partial x=\partial T_s(L,\tau)/\partial x=0 \quad (7)$$

For initial conditions,

$$T_s(x,0)=f(x) \quad (8)$$

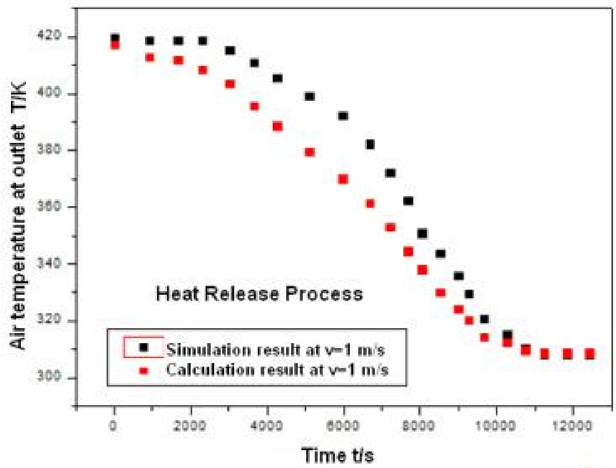
Considering the non-steady phase change process for heat storage and discharge in device, it is difficult to obtain the analytical solution under this problem [15-16]. Therefore, numerical method is used to simulate the heat storage and discharge process of heat storage device, time and space are discretized in the solution area, and partial differential mathematical model equation is approximated by forward difference.

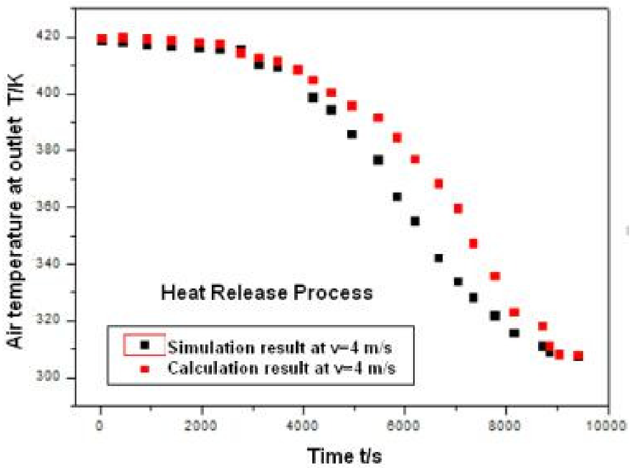
3. Results and discuss

3.1. Analysis of air temperature change rate

Hereby also 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 results in thermal storage process. And the reason for this is also due to the large temperature difference; at the later stage of heat release, the heat transfer rate in the system gradually decreases, and the average temperature of phase change material decreases slowly.

Two points with different slope (heat discharging rate) on the air temperature distribution curve of Fig.3 are analyzed, and it showed the same law as described in part I. That is to say, the calculation methods are suitable for both thermal storage and release heat transfer processes based the model in this paper.


Air temperature at outlet T/K
Heat Release Process
Simulation result at v=1 m/s
Calculation result at v=1 m/s
Time t/s


Air temperature at outlet T/K
Heat Release Process
Simulation result at v=4 m/s
Calculation result at v=4 m/s
Time t/s

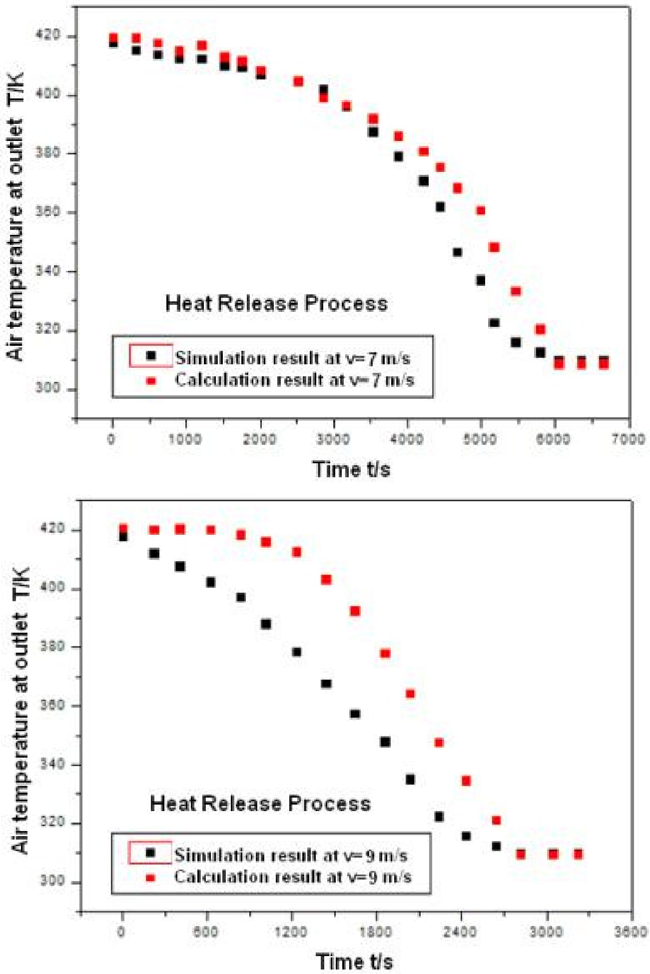


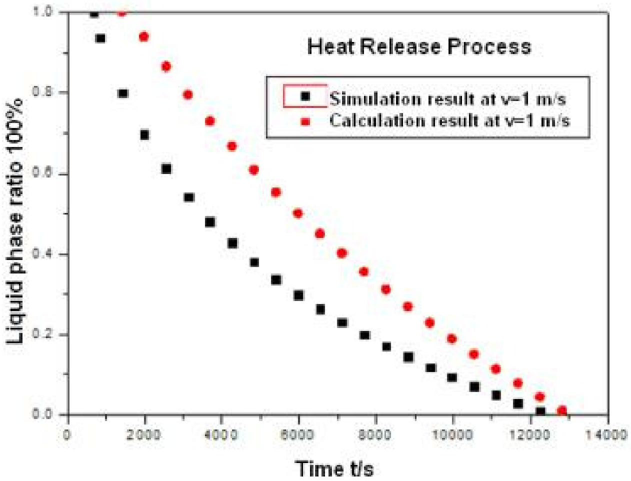
Figure 3. Air temperature change rate at outlet.

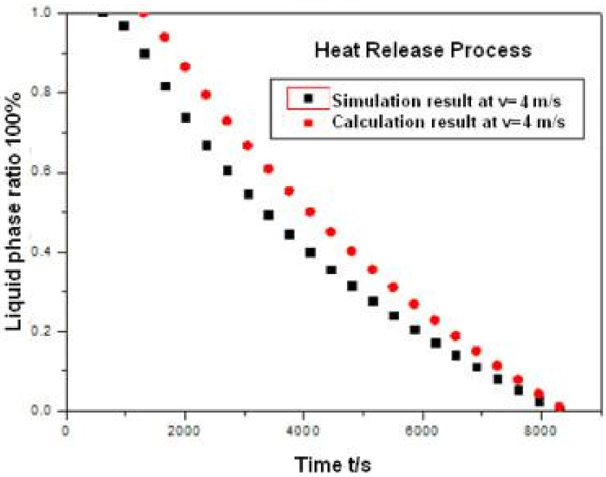
Also tt can be seen that the average temperature decrease rate of phase change material in the system decreases with the increase of the inlet velocity of heat transfer fluid. The results of MATLAB calculation show that the thermal release time is shorter than that of FLUENT simulation, especially when the flow rate is smaller and larger. This results are also consistent with the heat storage process. 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 as well. The average errors of calculation are 17.3%, 15.5% and 19.1% 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%. This result is also consistent with the heat storage process.

3.2. Analysis of liquid phase ratio of PCM material

By calculating the liquid phase ratio of PCM material at a certain time, the simulation results and design results can be compared and analyzed. 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, especially in the case of lower flow rate, the error of release process is larger, such as under 1 m/s flow rate. These trends are consistent with the heat storage process. It is noticed that under the

1 m/s flow rate the difference is more than 12%, but the appearance of this situation cannot explain the inappropriateness of the design results. From the comparison results of 4m/s and 9m/s, good consistency has been achieved.





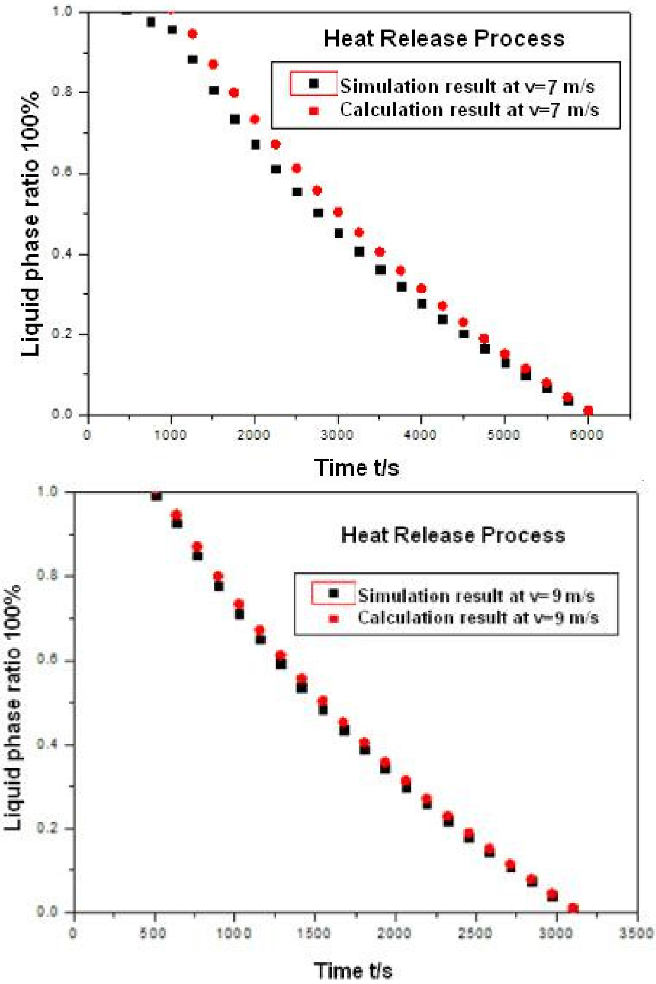
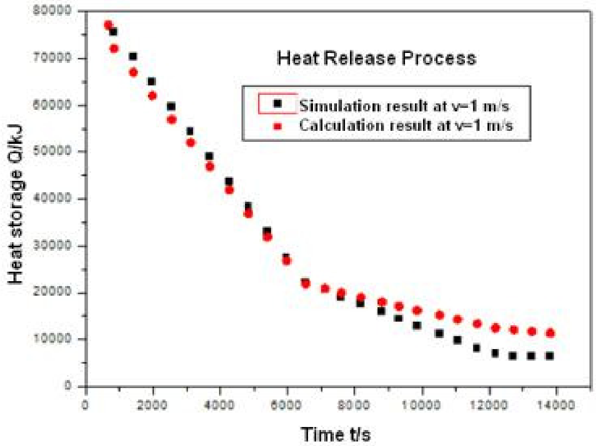
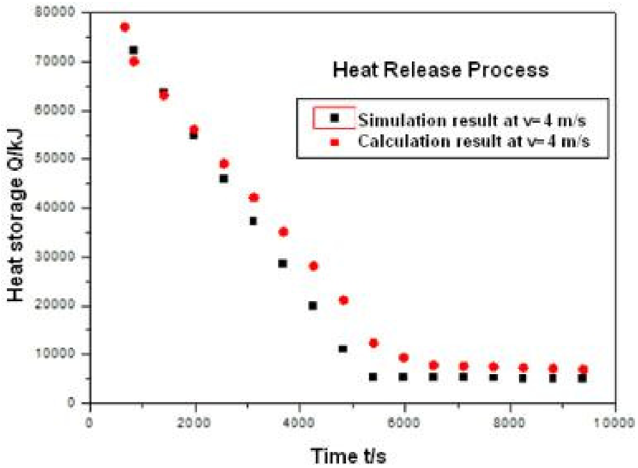


Figure 4. Liquid phase ratio of PCM material.

3.3. Heat release amount of PCM materials

For the total heat release amount of PCM, the residual heat release of PCM materials continue to change with the continuous heat transfer process. In this part, these changes also has been analyzed.


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


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

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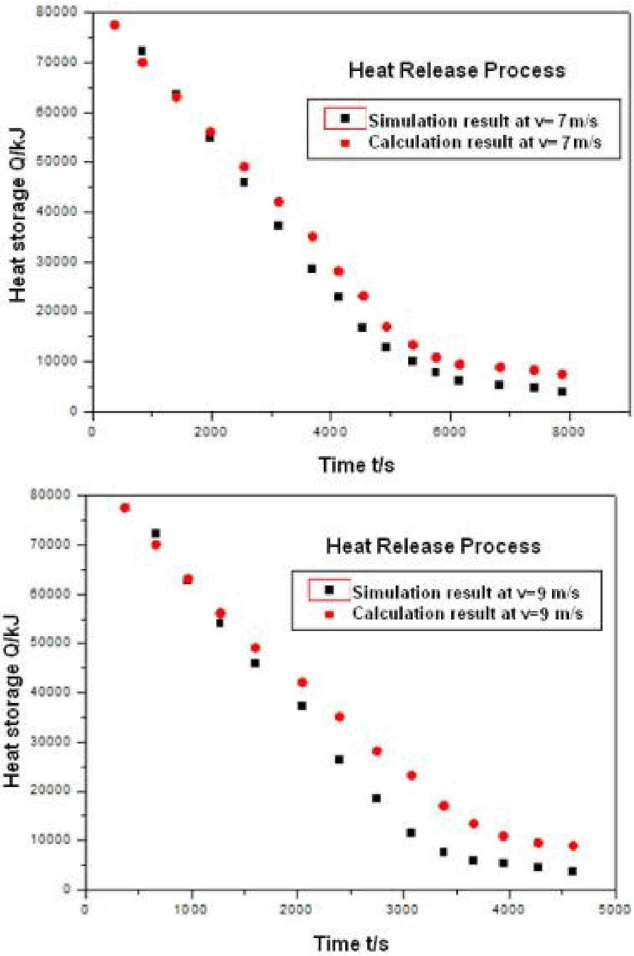

Figure 5. Heat storage amount during the phase change process.

From Fig. 5, it can be seen that the overall heat release change trend of simulation results and design results is consistent. Four comparisons show that the growth rate of heat release is relatively small at the beginning stage the following. When phase change occurs, it increases approximately linearly, and the growth rate is relatively large, these results are similar to the storage process. From the four comparison figures, it can draw the conclusion that the maximum check error is also not more than 10%, which shows the accuracy of the comparing results.

4. Conclusions

(1) By comparing and analyzing the change rate of air temperature, it is found that the similar results are for both thermal storage and release processes. And the results show that the errors of air temperature changing 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, which is consistent with the results in part I.
(3) With the constant total heat amount of PCM and the continuous heat transfer process, the residual storage heat and release heat of PCM materials are also changing continuously. The analysis and

comparison show that the overall release heat trend of simulation results and design results is similar to storage process.

References

[1] Hammond M J. Reversible Liquid/Solid Phase Change Compositions [P]. US Pat.: 5785884, 1998−07−28.
[2] Y. L. Li, Y. Jin, Y. Huang, etc., Fundamentals of Heat Storage Technology (I) - Basic Principles of Heat Storage and New Trends of Research, Energy Storage Science and Technology, 2013 (01): 69-72.
[3] Feldman D, Shapiro M M, Banu D. Organic Phase Change Materials for Thermal Energy Storage [J]. Sol. Energy Mater, 1986, 13(1): 1−10.
[4] Syed M T, Kumar S, Moallem I M K, et al. Thermal Storage Using Form Stable Phase Change Materials [J]. ASHRAE J., 1997, 39(5): 45−50.
[5] Akiyama T, Yagi J. Encapsulation of Phase Change Materials for Storage of High Temperature Waste Heat [J]. High Temp. Mater. P., 2000, 19(4): 219−222.
[6] Akiyama T, Yagi J. Encapsulation of Phase Change Materials for Storage of High Temperature Waste Heat [J]. High Temp. Mater. P., 2000, 19(4): 219−222.
[7] Vigo T L, Frost C M. Temperature Adaptable Fibers [J]. Text. Res. J., 1986, 56(12): 737−740.
[8] Chen Xiao, Zhang Renyuan, Mao Lingbo. Progress in research and application of paraffin wax phase change material [J] .Materials Research and Application, 2008 (2):89-92.
[9] Soares N, Costa J J, Gaspar A R, et al. Review of passive PCM latent heat thermal energy storage systems towards buildings' energy efficiency[J]. Energy & Buildings, 2013, 59:82-103.
[10] Tyagi V V, Buddhi D. Thermal cycle testing of calcium chloride hexahydrate as a possible PCM for latent heat storage [J]. Solar Energy Materials & Solar Cells, 2008, 92(8):891-899.
[11] Mekaddem N, Ali S B, Mazioud A, et al. A numerical study of latent thermal energy storage in a phase change material/carbon panel[C]// 2016.
[12] Touati B, Kerroumi N, Virgone J. Solar thermal energy discharging from a unit contains multiple phase change materials[C]// Renewable Energy Congress. 2017.
[13] Qiang S, Xing Y, Mu L, et al. Numerical research of solid-liquid phase change process in porous media[C]// International Conference on Materials for Renewable Energy & Environment. 2011.
[14] Al-Saadi S N, Zhai Z. Systematic evaluation of mathematical methods and numerical schemes for modeling PCM-enhanced building enclosure[J]. Energy & Buildings, 2015, 92:374-388.
[15] Alsaadi S N. Modeling and simulation of PCM-enhanced facade systems[J]. Dissertations & Theses - Gradworks, 2014.
[16] Touati B, Kerroumi N, Virgone J. Solar thermal energy discharging from a unit contains multiple phase change materials[C]// Renewable Energy Congress. 2017.

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