Numerical analysis of influencing factors on heat storage time of phase change material in an inclination rectangular cavity based on orthogonal method

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Abstract. In this paper, factors affecting the completely melting time of phase change material (PCM) in a rectangular cavity are analyzed. The influence of three factors including inclination angle of the cavity, heating temperature, and geometry of the cavity on completely melting time is discussed under the boundary condition of single size heating and double sizes heating respectively, while other sides are considered to be adiabatic. A two-dimensional mathematical model is established for the simulation analysis and verified by experiments. In order to analyze the influence of all factors on the completely melting time, the orthogonal analysis method is adopted, and the range analysis method is used to determine the influence of three factors on the completely melting time. Based on the orthogonal analysis, it can be found that the heating temperature is the most significant factor during single side heating, while geometry of the cavity is the most important factor during double sides heating. The results will be helpful to optimize the structure of PCM component used for energy storage system or temperature control structure.

1. Introduction
Phase change material (PCM) is widely used in energy storage [1, 2], electronic thermal management [3, 4], and solar energy [5], because it has stable temperature and large latent heat storage in the phase transition region. In order to prevent contamination caused by leakage of liquid PCM during heat storage in practical applications, PCM is usually encapsulated in a container such as rectangular container [6-8], cylindrical container [9,10], and annular container [11]. Besides, the melting of PCM in the rectangular cavity has attracted much attention because of its fundamental and importance in various engineering applications. Furthermore, the structure geometry and inclination angle of the container, as well as the heating temperature loaded on sides of the container, can affect the melting heat transfer process. Therefore, an investigation on the factors affecting the thermal storage time of PCM in the rectangular cavity needs to be carried out.

Heating temperature is a significant factor affecting the melting rate of PCM. Shokouhmand and Kamkari [12] studied the melting characteristics of PCM by loading different temperatures on a rectangular cavity. The results showed that the heating temperature can significantly affect the melting rate of PCM. Wang et al. [13] compared the completely phase transition time of paraffin wax by heating from bottom at different heating temperatures. They found that the completely phase transition
time decreased while heating temperature increased, and the rate decreased with the increase of heating temperature. In addition, other scholars have also obtained the similar relationship between melting time and heating temperature [14-15]. Besides, the geometry of the cavity is also a factor which can affect the melting process. Ye [16] investigated the effects of eleven aspect ratios on melting heat transfer process. They pointed out that when the aspect ratio increased, the melting rate of PCM increased. Omari et al. [17] compared melting processes of PCM in five geometric containers with same volume. The computational results show the greatly influence of varying geometry. Furthermore, the inclination angle of the cavity can also affect the rate of melting process due to the influence of gravity on natural convection during the melting of PCM. Kamkari et al. [18] found that the angles of the inclination cavity played an important role in formation of natural convection which affected the completely melting time. Wang et al. [19] investigated the melting process of paraffin in a rectangular cavity with seven different angles. The cavity was heated by one side while others were considered to be adiabatic. The results showed that the completely melting time increased non-linearly while the angle changed from 0° to 180°. Avci and Yazici [20] carried out an experimental study to found effects of inclination angle of a flat-type heat sink. They concluded that the inclination angle can enhance the thermal performance of the heat sink with PCM.

Based on previous studies, scholars have generally studied the melting process with the heating source on one side and the single factor affecting the melting heat transfer process of PCM, such as heating temperature, geometry of the cavity, and inclination angle. However, in practical applications, there may be heating sources at both sides of PCM. In addition, the three factors which have the greatest impact on the melting process also need to be considered. Furthermore, in the analysis of influencing factors, orthogonal analysis method can significantly reduce the number of experiments [21, 22]. Therefore, in this paper, the sensitivity of three factors (heating temperature, geometry of the cavity and inclination angle) on both single heating side and two heating sides affecting the completely melting time are studied by using the orthogonal test.

2. Physical model and experimental apparatus

In this paper, paraffin is chosen as the PCM. Table 1 shows the thermophysical properties of paraffin which provided by the supplier [19].

| Parameters                        | Value       |
|-----------------------------------|-------------|
| Density of solid (kg·m⁻³)         | 805.90      |
| Latent heat (J·g⁻¹)               | 110.28      |
| Melting temperature (K)           | 329.6 K – 337.5 K |
| Thermal conductivity (W·m⁻¹·K⁻¹)  | 0.20 (solid); 0.11 (liquid) |
| Specific heat (J·kg⁻¹·K⁻¹)        | 2.10×10⁵    |
| Dynamic viscosity (kg·m⁻¹·s⁻¹)    | 3.59×10⁻³   |
| Thermal expansion coefficient (K⁻¹)| 1.10×10⁻⁴  |

The physical model for thermal validation is shown in Figure 1, and schematic of experimental verification apparatus is shown in Figure 2.

In this apparatus, temperature of heating plate is measured by a K-type thermocouple. The heating plate is heated to 353.15 K and stabilized at 353.15±0.1 K using a PID controller and electric relay. Data acquisition card is used to collect temperature data inside the specimen which measured by five K-type thermocouples into the middle of the specimen (z=50 mm), shown in Figure 3. Expect for the heating side, other sides of the specimen container are made of Plexiglass to realize the visualization of the solid-liquid interface during the experiment verification. In addition, Aluminium silicate insulation cotton of sufficient thickness is used to make the specimen container nearly adiabatic.
3. Mathematical model

Several assumptions are made to simplify the mathematical model. Firstly, the density of paraffin subjects to the Boussinesq approximation and the liquid phase of paraffin is regarded as an incompressible Newtonian fluid. Secondly, the paraffin is homogenous and isotropic. Thirdly, the flow in the liquid paraffin is laminar and the thermal properties of paraffin in the phase change region vary linearly with temperature. Then, the governing equations are written in Equation (1) to Equation (4) [19].

Continuity equation:

\[ \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \]  

Momentum equations:

\[ \rho \frac{\partial u}{\partial t} + \rho \left[ \frac{\partial (uu)}{\partial x} + \frac{\partial (uv)}{\partial y} \right] = -\frac{\partial P}{\partial x} + \mu \nabla^2 u + A_{mush} \left(\frac{1-f}{f^3 + \xi}\right) u + \rho g \beta (T - T_m) \cos \alpha \]  

\[ \rho \frac{\partial v}{\partial t} + \rho \left[ \frac{\partial (vu)}{\partial x} + \frac{\partial (vv)}{\partial y} \right] = -\frac{\partial P}{\partial y} + \mu \nabla^2 v + A_{mush} \left(\frac{1-f}{f^3 + \xi}\right) v + \rho g \beta (T - T_m) \sin \alpha \]  

Energy equations:

\[ \frac{\partial}{\partial t} (\rho H) + \frac{\partial}{\partial x} (\rho u H) + \frac{\partial}{\partial y} (\rho v H) = \lambda \nabla^2 T \]  

in which \(u, v\) refer to the velocity in \(x\) direction and \(y\) direction, respectively. \(\rho\) presents the density of paraffin, which subjects to the Boussinesq approximation. \(t\) refers to the time while \(P\) refers to the pressure. \(\mu\) is the dynamic viscosity and \(\beta\) presents the thermal expansion coefficient of liquid paraffin. \(\alpha\) refers to the inclination angle. Furthermore, \(A_{mush}\) is a mushy zone constant and its value is \(10^7\) and \(\xi\)
is a constant to avoid being divided by zero. \( \lambda \) is the thermal conductivity, and \( H \) refers to the enthalpy including sensible enthalpy and latent enthalpy. \( f \) is the liquid fraction within 0 and 1, shown in Equation (5)

\[
f = \begin{cases} 
0 & T < T_{m1} \\
\frac{T - T_{m1}}{T_{m2} - T_{m1}} & T_{m1} \leq T < T_{m2} \\
1 & T \geq T_{m2}
\end{cases}
\]  

(5)

The initial condition is set to 298.15 K. The boundary conditions on the heating walls of the specimen are heated from 298.15 K to the target temperature which includes 353.15 K, 363.15 K, and 373.15 K, while other sides are adiabatic. Besides, there are no moving boundaries on all walls.

In the present numerical investigation, Fluent 14.5 is used to build a two-dimensional transient model with Second order Implicit Method for Pressure-Linked Equations (SIMPLE) algorithms and Pressure Staggering Option (PRESTO) scheme. Firstly, a two-dimensional vertical model \((\alpha = 90^\circ)\) heated on the left wall is used for independent analyses which include grid independent analysis and time step independent analysis.

During the independence analyses, grids consisting of 3000, 6000 and 10000 grids at time steps of 1 s, 2 s, and 4 s respectively are all tested for liquid fraction. Figure 4(a) shows the results of grid independent analysis, while Figure 4(b) shows the results of time step independent analysis. It is concluded that the grid of 6000 and the time step of 2 s is an appropriate grid number to balance the result accuracy and the computational time.

**Figure 4.** Results of independent analysis (a) grid independent results, (b) time step independent results.

### 4. Results and discussion

#### 4.1. Model validation

Before the design of orthogonal test, it is necessary to do the model validation by comparing the position of solid-liquid interface and temperature data inside the specimen between experiment and numerical simulation. Figure 5 shows both the solid-liquid interface between experimental and numerical results at 15 min, 30 min, 60 min, and 90 min, respectively when the target heating temperature is 353.15 K. The results show that the numerical results are in good agreement with the experimental results.

Figure 5(a) shows the experimental results. At the initial stage of heating, the solid-liquid interface is nearly parallel to the heating wall due to the heat conduction plays a dominant role at this time. With the elapse of time, the convection heat transfer begins to play a dominant role. At this time, the hotter liquid paraffin near the heating wall moves upward vertically under the effect of buoyancy, so that the melting rate of paraffin at the top is faster than that at the bottom. As a result, the solid-liquid interface
becomes curved. Figure 5(b) shows the numerical results simulated by Fluent. Similar to the experimental results, the dominant mode of heat transfer during phase change is from heat conduction to convection heat transfer. Besides, it can be seen that there is a mushy region between the solid phase and the liquid phase. The mushy region area on the top is narrower than that on the bottom, which may illustrate that the melting rate of paraffin in the mushy region at the top is faster due to the influence of convection heat transfer while the paraffin at the bottom is more affected by conduction heat transfer.

Furthermore, the model is also validated with temperature variation inside the specimen between experiment and numerical analysis. Figure 6 shows the comparison of temperature variations inside the specimen, in which $T_1$ - $T_5$ refer to numerical results and $(T_1)$ - $(T_5)$ refer to experimental results. It can be found that the numerical results of all five temperature monitor points agree well with the experimental data, and the maximum relative error is less than 7%. However, with the process of phase change, the temperature values of numerical calculation are higher than those of experiment. The reason is the boundary of the specimen can not be adiabatic in the experiment.

4.2. Influences of factors on completely melting time of PCM

In this paper, three influencing factors (inclination angles of the cavity, heating temperature, and geometry of the cavity) are taken into consideration for both boundary conditions of single side heating and double sides heating. The volumes of rectangular cavities on different geometry structures are equal, and the geometry structures of cavities are designed to be 75 mm $\times$ 40 mm, 100 mm $\times$ 30 mm, and 150 mm $\times$ 20 mm. Except for the heating boundary, other boundaries are considered to be adiabatic. In the orthogonal method, both single size heating and double sizes heating are taken into consideration. Besides the geometry structures of cavities, the levels of inclination angles are 0°, 30°, 60°, and 90°, while the levels of heating temperatures are 353.15 K, 363.15 K, and 373.15 K. Therefore, the influencing factors of completely melting time of PCM are shown in Table 2.

| Factors          | Inclination angle (A) | Heating temperature (B) | geometry of the cavity (C) |
|------------------|-----------------------|-------------------------|-----------------------------|
| Level 1          | 0°                    | 353.15 K                | 75 mm $\times$ 40 mm        |
| Level 2          | 30°                   | 363.15 K                | 100 mm $\times$ 30 mm       |
| Level 3          | 60°                   | 373.15 K                | 150 mm $\times$ 20 mm       |
| Level 4          | 90°                   | 353.15 K                |                             |
According to the principle of arrangement and combination in mathematical statistics, the total number of simulations is \(C_4^1 \times C_3^1 \times C_3^1 = 36\). However, orthogonal method uses the balanced distribution idea to give an orthogonal table, so that the information of whole region through a small number of typical test points. For factors of unequal levels in Table 2, an improved orthogonal table \(L_9(3^4) + 3\) is established, which is improved by repeated experiments at Level 2 and Level 3 of two \(L_9(3^4)\) tables. Table 3 shows the orthogonal table and the simulation results. It can be found that the number of simulation is only 12. Furthermore, Factor D in orthogonal table is a blank column on three levels for analysis of test deviations.

**Table 3.** Simulation results of the orthogonal test.

| Case | A   | B    | C    | D   | Melting time of single side heating (\(T_{\text{single}}\)) | Melting time of double sides heating (\(T_{\text{double}}\)) |
|------|-----|------|------|-----|-------------------------------------------------|-------------------------------------------------|
| 1    | 0°  | 353.15 K | 75 mm \(\times\) 40 mm | 1   | 9964 s                                      | 5572 s                                      |
| 2    | 0°  | 363.15 K | 100 mm \(\times\) 30 mm | 2   | 4566 s                                      | 2538 s                                      |
| 3    | 0°  | 373.15 K | 150 mm \(\times\) 20 mm | 3   | 2156 s                                      | 1394 s                                      |
| 4    | 30° | 353.15 K | 100 mm \(\times\) 30 mm | 3   | 8178 s                                      | 4458 s                                      |
| 5    | 30° | 363.15 K | 150 mm \(\times\) 20 mm | 1   | 3314 s                                      | 2672 s                                      |
| 6    | 30° | 373.15 K | 75 mm \(\times\) 40 mm | 2   | 4994 s                                      | 3308 s                                      |
| 7    | 60° | 353.15 K | 150 mm \(\times\) 20 mm | 2   | 8028 s                                      | 3564 s                                      |
| 8    | 60° | 363.15 K | 75 mm \(\times\) 40 mm | 3   | 8020 s                                      | 4842 s                                      |
| 9    | 60° | 373.15 K | 100 mm \(\times\) 30 mm | 1   | 5328 s                                      | 3056 s                                      |
| 10   | 90° | 353.15 K | 75 mm \(\times\) 40 mm | 1   | 14934 s                                     | 7162 s                                      |
| 11   | 90° | 363.15 K | 100 mm \(\times\) 30 mm | 2   | 7948 s                                      | 3822 s                                      |
| 12   | 90° | 373.15 K | 150 mm \(\times\) 20 mm | 3   | 4514 s                                      | 2182 s                                      |

In order to analyse the order of A, B, and C, a range method is taken into consideration. Table 4 and Table 5 show the range analysis of orthogonal test for single size heating and double sizes heating, respectively. \(R_j\) represents extreme difference value of each factor and \(k_{ij}\) to \(k_{4j}\) represent the arithmetic mean values of the completely melting time (\(T_{\text{single}}\) and \(T_{\text{double}}\)) of each factor at level 1 to level 4. The formula to calculate \(R_j\) is shown in Equation (6). Based on the orthogonal theory, the factor with larger \(R_j\) represents a greater influence on the completely melting time.

\[
R_j = \max[k_{ij},k_{2j},k_{3j},k_{4j}] - \min[k_{ij},k_{2j},k_{3j},k_{4j}]
\]

**Table 4.** Extreme difference analysis results for single side heating.

| Parameters | A        | B        | C        | D        |
|------------|----------|----------|----------|----------|
| \(k_{ij}\) | 5562.0 s | 9685.0 s | 8487.7 s | 7030.3 s |
| \(k_{2j}\) | 5628.7 s | 5863.7 s | 6721.0 s | 6426.3 s |
| \(k_{3j}\) | 7125.3 s | 4552.3 s | 4892.3 s | 6644.3 s |
| \(k_{4j}\) | 9132.0 s |          |          |          |
| \(R_j\)   | 3570.0 s | 5132.7 s | 3595.3 s | 604 s    |

**Table 5.** Extreme difference analysis results for double sides heating.

| Parameters | A        | B        | C        | D        |
|------------|----------|----------|----------|----------|
| \(k_{ij}\) | 3168.0 s | 4796.3 s | 4839.0 s | 4031.7 s |
| \(k_{2j}\) | 3479.3 s | 3564.7 s | 3564.7 s | 3350.7 s |
| \(k_{3j}\) | 3820.7 s | 2717.3 s | 2674.7 s | 3696.0 s |
| \(k_{4j}\) | 4388.7 s |          |          |          |
| \(R_j\)   | 1220.7 s | 2079.0 s | 2164.3 s | 681.0 s  |
For effect of single factor, both tables show a same result. When the inclination angle increases, the completely melting time increases. However, when the heating temperature or the geometry of the cavity increases, the completely melting time decreases.

Moreover, the results of Table 4 show that the extreme difference analysis of heating temperature is 5132.7 s, which has the greatest influence of completely melting time. Besides, the effect of geometry of the cavity (3595.3 s) is a little greater than that of inclination angle (3570.0 s). Therefore, within the test range, the order of the effects on completely melting time is B, C, and A.

However, Table 5 shows a different result. When the material is double heated, heating temperature and geometry of the cavity has become significant factors of completely melting time. Compared with heating temperature, the extreme difference in geometry of the cavity is 2164.3 s, which has the greatest influence on the completely melting time. Furthermore, the extreme difference of heating temperature is 2079.0 s, which also has a great influence on the completely melting time. The extreme difference of inclination angle, only 1220.7 s, has little effect on completely melting time. Thus, within the test range, the order of the effects on completely melting time is C, B, and A. Compared with the results of the orthogonal test for single size heating and double sizes heating, it can be concluded that the effect of inclination angle is the lowest, while the effects of other factors are based on the number of heating sizes.

Therefore, in practical application, it is necessary to realize the optimization of phase change energy storage system according to three factors (including heating temperature, inclination angle, and geometry of the cavity) and the number of heating sizes.

5. Conclusions
In practical applications, it is necessary to optimize structures of PCM products according to actual need. During the melting process of PCM, the factors affecting the completely melting time include heating temperature, inclination angle, and geometry of the cavity. In this paper, numerical investigations are established to simulate the melting process of PCM under different conditions. Heating boundary conditions are loaded on single size and two opposite sides of the rectangle cavity, respectively. The results show that the order of factors affecting the completely melting time is heating temperature, size of cavity, and inclination angle when heating on one side, while the order of factors affecting the completely melting time is size of cavity, heating temperature, and inclination angle when heating on both sides. Therefore, the results can provide important reference for PCM engineering design.

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