

COMPARATIVE INVESTIGATION OF PHASE CHANGE MATERIAL ON HEAT TRANSFER CHARACTERISTICS UNDER THEORETICAL AND PRACTICAL PERIODIC TEMPERATURE BOUNDARY

by

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Original scientific paper
<https://doi.org/10.2298/TSC210825351W>

In this paper, heat transfer characteristics of phase change material in rectangular containers are numerically analyzed. The inclination angles of the container refer to 0°, 90°, and 180°. Both theoretical and practical periodic temperature boundary conditions are taken into consideration, in which the periodic temperature boundary conditions include 50-80 °C and 65-80 °C. The comparison study is carried out through the liquid fraction and temperature histories during the heat transfer process under these different boundary conditions. It is indicated that there are large differences between the calculated results under the theoretical and the practical periodic temperature boundary conditions when the temperature boundary is 50-80 °C, while the theoretical and the practical periodic temperature boundary conditions of 65-80 °C have relatively little effect on the numerical results of the heat transfer process of the phase change material. Furthermore, compared with the temperature increasing stage, the numerical results calculated under the theoretical and the practical boundary conditions have more significant differences in the temperature decreasing stage. The research conclusion of this paper can provide a theoretical basis for the application of phase change material under periodic temperature boundary conditions.

Key words: *heat transfer characteristics, periodic temperature boundary, numerical simulation, inclination angles, phase change material*

Introduction

Phase change material (PCM) has been commonly used in heat exchangers [1, 2], solar energy storage systems [3-7], and electronic component thermal management systems [8-11] due to its stable phase change temperature and high energy storage density. With the development of electronic devices to miniaturization and high power, higher requirements are put forward for their heat dissipation performance [12, 13]. In order to prevent heat generated by controllers from affecting the infrared stealth performance of the aircraft, it is necessary to store the heat generated by electronic devices to ensure that the aircraft can complete its mission. Furthermore, the surface temperature of electronic devices is constantly changing during the mission, so the phase change process of PCM under variable temperature boundary should be investigated. Besides, the influence of the installation direction on the heat transfer process also needs to be considered.

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In recent years, many scholars have investigated the heat transfer process of PCM with constant heat source boundary while considering the influences of the inclination angle and heating position of the container on the heat transfer performances. Zhang *et al.* [14] illustrated a numerical model on the heat transfer process of PCM in a container. Their conclusions evidenced that the heat source location can significantly affect the heat transfer process of PCM. Duan *et al.* [15] appraised the heat transfer process of PCM in rectangular containers with three aspect ratios under constant temperature boundary conditions, which provided a theoretical basis for the container designs. Kamkari [16-18] investigated the heat transfer process of PCM under constant temperature boundary conditions by numerical calculation and experiment verification. Besides, the visualization imaging technology was used by Avci *et al.* [19] to evaluate thermal performances of PCM radiator with seven attitudes from 0° to 90° . The results evidenced that thermal performances were related to inclination angles. Furthermore, Wang *et al.* [20] also established a heat transfer model of PCM with an inclined rectangular structure. The heat transfer processes of PCM under constant temperature boundary conditions with seven inclination angles from 0° to 180° were simulated.

However, in the process of thermal management on electronic components, their surface temperature is not constant but constantly change with the operating power. Saha and Dutta [21, 22] established a 1-D heat conduction mathematical model to discuss influences on the melting and solidification process under periodic thermal boundary conditions. Ahmed *et al.* [23, 24] illustrated the effects of different heat source directions on PCM heat transfer in thermal management of electronic devices. The temperature responses of PCM during the periodic thermal boundary process were analyzed. Nevertheless, in the thermal management application of electronic components, there is still a lack of research on the heat transfer process of PCM under non-constant boundary conditions with different heat source locations.

Therefore, this paper investigates the phase change characteristics of PCM in the container with different inclination angles under periodic temperature boundary conditions. The inclination angles of the container include 0° , 90° , and 180° , while the temperature boundary conditions include $55\text{-}80^\circ\text{C}$ and $65\text{-}80^\circ\text{C}$. Then, the differences between heat transfer characteristics of PCM under theoretical periodic temperature boundary conditions and practical periodic temperature boundary conditions are compared.

Physical and mathematical model

Physical model

A sealed container filled with PCM is investigated in this paper. The physical model is shown in fig. 1(a), and the locations of temperature monitoring points are shown in fig. 1(b).

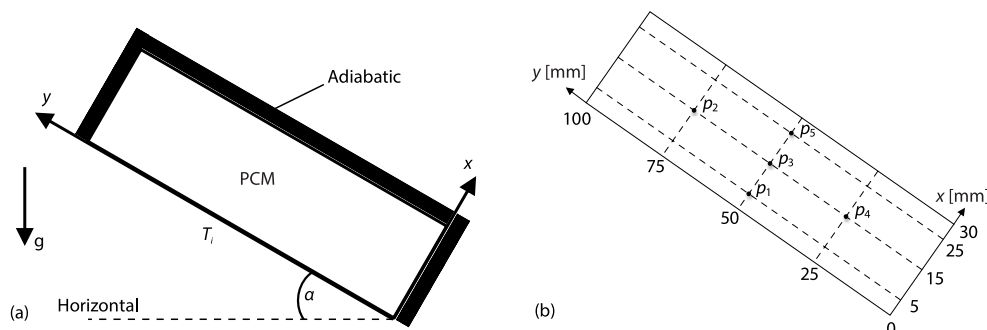


Figure 1. Physical model and temperature monitoring points under this investigation

The size of the PCM inside the container is a rectangular domain with a length of $y = 100$ mm and a width of $x = 30$ mm, while the inclination angles refer to 0° , 90° , and 180° . The heating wall ($x = 0$) is set at a periodic temperature, T_i , while other walls are adiabatic. The thermophysical properties of paraffin used in this paper are shown in tab. 1 [20].

Table 1. Thermophysical properties of paraffin used in this paper

Parameters	Value
Density, ρ	805.9 kg/m ³
Latent heat, L	110280 J/kg
Melting temperature	56.4-64.3 °C
Thermal conductivity, λ	0.20 W/(m°C) (solid), 0.11 W/(m°C) (liquid)
Specific heat capacity, c_p	$2.10 \cdot 10^3$ J/(kg°C)
Dynamic viscosity, μ	$3.59 \cdot 10^{-3}$ kg/ms
Thermal expansion coefficient, β	$1.10 \cdot 10^{-4}$ °C

Mathematical model

Some assumptions are considered in the mathematic model. The liquid paraffin is assumed to be incompressible Newtonian fluid, and the density is subjected to the Boussinesq approximation. The volume change during the phase change process is neglected. Except the thermal conductivity of paraffin, other thermophysical properties including specific heat are assumed to be constant and do not change with temperature [25-28]. The mathematical model of the phase change process is established based on the enthalpy-porosity approach [29]. Therefore, the governing equations are written:

– Continuity equation

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \quad (1)$$

– Momentum equations

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

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

– Energy equations

$$\frac{\partial}{\partial t}(\rho H) + \frac{\partial}{\partial x}(\rho u H) + \frac{\partial}{\partial y}(\rho v H) = \lambda \nabla^2 T \quad (4)$$

where $\rho, \beta, \mu, \lambda$ are the density, thermal expansion coefficient, and dynamic viscosity of paraffin, thermal conductivity, respectively, A_{mush} – the mushy zone constant, and its suitable value is 10^7 for the PCM used in this paper. Besides, f is the liquid fraction which is defined:

$$f = \frac{H - h}{L} = \begin{cases} 0 & T < T_s \\ \frac{T - T_s}{T_\ell - T_s} & T_s \leq T \leq T_\ell \\ 1 & T > T_\ell \end{cases} \quad (5)$$

The initial temperature of the PCM is 25 °C, and there are no-slip boundary conditions at all walls ($u = v = 0$). Except for the heating wall ($x = 0$), other walls are adiabatic. Four temperature boundary conditions, T_i , are established to analyze the phase change process with periodic boundary conditions. Equation (6) refers to the theoretical periodic boundary condition from 50-80 °C, while eq. (7) is the theoretical periodic boundary condition and practical periodic boundary condition from 65-80 °C:

$$T_1 = \begin{cases} 80 & 9000j < t \leq 9000j + 3600, & j = 0,1 \\ 50 & 9000j + 3600 < t \leq 9000(j+1), & j = 0,1 \end{cases} \quad (6)$$

$$T_2 = \begin{cases} 80 & 9000j < t \leq 9000j + 3600, & j = 0,1 \\ 65 & 9000j + 3600 < t \leq 9000(j+1), & j = 0,1 \end{cases} \quad (7)$$

Besides, the practical temperature boundary condition of the heating plate measured by a thermocouple is much more complex. Firstly, when the plate is heating from room temperature to the target temperature of 80 °C, the boundary condition is shown:

$$T_0 = \begin{cases} 25.93 + 0.155t - 1.102 \times 10^{-4} t^2, & 0 < t \leq 650 \\ 80 & 650 < t \leq 3600 \end{cases} \quad (8)$$

Then, the boundary conditions of practical temperature variation are shown:

$$T_3 = \begin{cases} T_0 & 0 < t \leq 3600 \\ 16.9 \times \exp[-(t - k_i) \times 3.6 \cdot 10^{-3}] + 23.3 \times \exp[-(t - k_i) \times 2.4 \cdot 10^{-3}] + 40 & k_i < t \leq k_i + 3600 \\ 50 & k_i + 3600 < t \leq k_i + 5400 \\ 50 + 1.96 \cdot 10^{-3} [t - (k_i + 5400)] + 4.67 \cdot 10^{-4} [t - (k_i + 5400)]^2 & k_i + 5400 < t \leq k_i + 5988 \\ -1.02 \cdot 10^{-6} [t - (k_i + 5400)]^3 - 6.25 \cdot 10^{-10} [t - (k_i + 5400)]^4 & \\ 80 & k_i + 5988 < t \leq k_i + 9000 \end{cases} \quad (9)$$

$$T_4 = \begin{cases} T_0 & 0 < t \leq 3600 \\ 16.11 \times \exp[-(t - k_i) / 322.16] + 63.88 & k_i < t \leq k_i + 1458 \\ 65 & k_i + 1458 < t \leq k_i + 5400 \\ 65 + 0.01 \times [t - (k_i + 5400)] + 4.7 \times 10^{-4} [t - (k_i + 5400)]^2 & k_i + 5400 < t \leq k_i + 5745 \\ -1.56 \times 10^{-6} [t - (k_i + 5400)]^3 + 1.34 \times 10^{-10} [t - (k_i + 5400)]^4 & \\ 80 & k_i + 5745 < t \leq k_i + 9000 \end{cases} \quad (10)$$

in which $k_1 = 3600$ and $k_{i+1} = k_i + 9000$, $i = 1, 2$.

In order to describe the boundary conditions more clearly, fig. 2 shows the boundary curves mentioned in eqs. (6)-(10), in which fig. 2(a) gives the practical and the theoretical periodic boundary condition curves from 50-80 °C while fig. 2(b) depicts the periodic boundary condition curves from 65-80 °C.

Numerical procedure and validation

The governing equations are solved using the finite volume technique. Several UDF are developed based on the boundary conditions from eqs. (6)-(10). Due to Shmueli *et al.* [30]

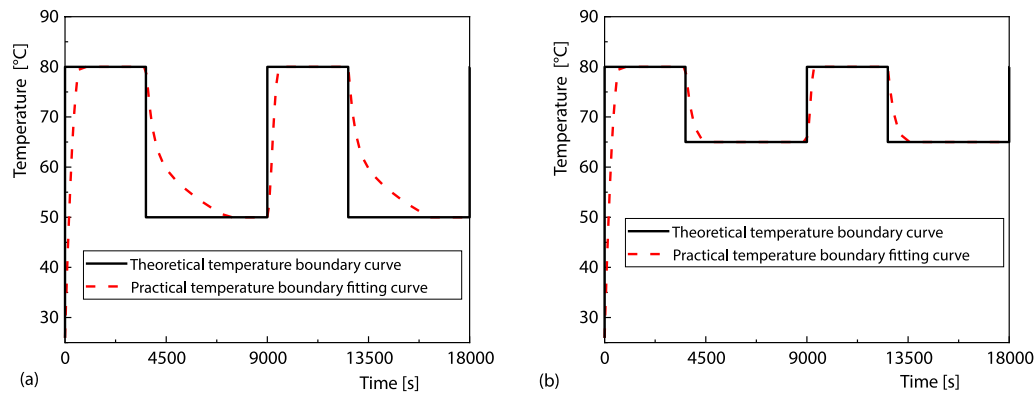


Figure 2. The theoretical and the practical boundary condition

evidenced that PRESTO! Scheme is the most suitable to achieve the best match between experimental data and numerical results, the pressure is discretized by PRESTO! Scheme in this paper. Besides, the SIMPLE algorithm is employed for the pressure-velocity coupling field, and the governing equations for momentum and energy are discretized by the QUICK scheme. The convergence is checked at each time-step with the convergence criterion of 10^{-4} , 10^{-4} , and 10^{-6} for continuity equation, velocity components, and energy equation, respectively.

A 2-D numerical calculation is conducted in this paper. The specimen inclination angle of 90° ($\alpha = 90^\circ$) is selected for independent test and model validation. The grid size sensitivity is checked to ensure the numerical results are grid size independent, while the time step sensitivity is examined to guarantee that the numerical results are time step independent. Different grid sizes including $1.0 \text{ mm} \times 1.0 \text{ mm}$ (3000 grids), $0.5 \text{ mm} \times 1.0 \text{ mm}$ (6000 grids), and $0.3 \text{ mm} \times 1.0 \text{ mm}$ (10000 grids) at different time-steps (1 second, 2 seconds, and 4 seconds) are examined for liquid fraction, respectively. Besides, in order to quantify the influence of grid size independence and time step independence, relative error analysis is calculated by eq. (11) in which Δf represents the difference between the measured value and the standard value and f_{std} represents the standard value:

$$e = \left| \frac{\Delta f}{f_{\text{std}}} \right| \times 100\% \quad (11)$$

For grid size independent test, the liquid fraction result with 10000 grids is regarded as the standard value. For time step independent test, the liquid fraction result at 4 seconds is chosen as the standard value. The results of the grid size independent test and the time step independent test are shown in fig. 3.

Figures 3(a) and 3(b) give the results of grid size independent test. It can be found that the relative error of liquid fraction results between 6000 grids and 10000 grids are less than 2.0%, while the relative error of 3000 grids is approximately 7.0%. Figures 3(c) and 3(d) depict the results of time step independent test. It shows that the relative error of liquid fraction results between the time step of 2 seconds and 1 second is less than 0.05%, which is much less than the relative error of 4 seconds. Therefore, it can be concluded that a grid size of $0.5 \text{ mm} \times 1.0 \text{ mm}$ (6000 grids) at time-step of 2 seconds is appropriate to balance the computational time and the result accuracy.

Furthermore, the model is verified by comparing the experimental results and the numerical results. During the model validation experiment, the specimen is heated from room

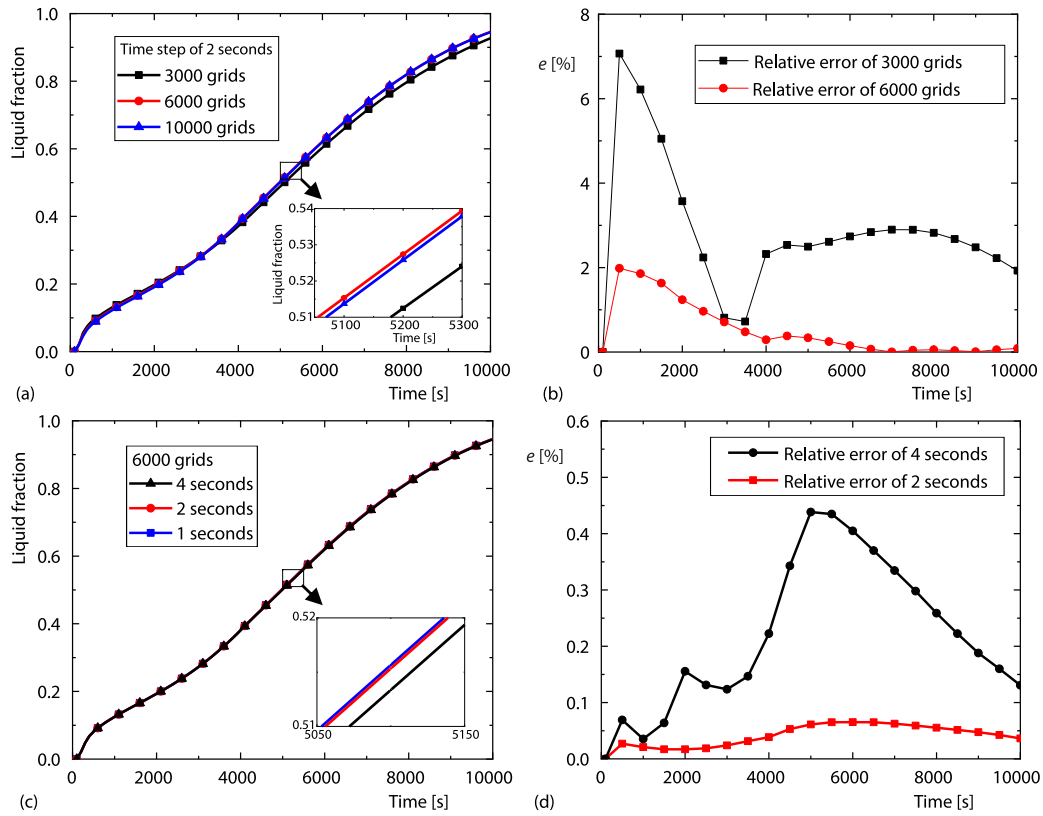


Figure 3. Results of independent test

temperature to the target heating temperature of 80 °C, and the temperature variation of the specimen heating wall is regarded as the heating boundary condition. Figure 4 shows the model validation results, in which fig. 4(a) depicts the experimental and the numerical results of solid-liquid interface changes at 15 minutes, 30 minutes, 60 minutes, and 90 minutes, while fig. 4(b) depicts the temperature histories of the numerical, T_1 to T_5 , and the experimental results, (T_1) to (T_5) , at temperature monitoring points. It can be found that the liquid fraction of the

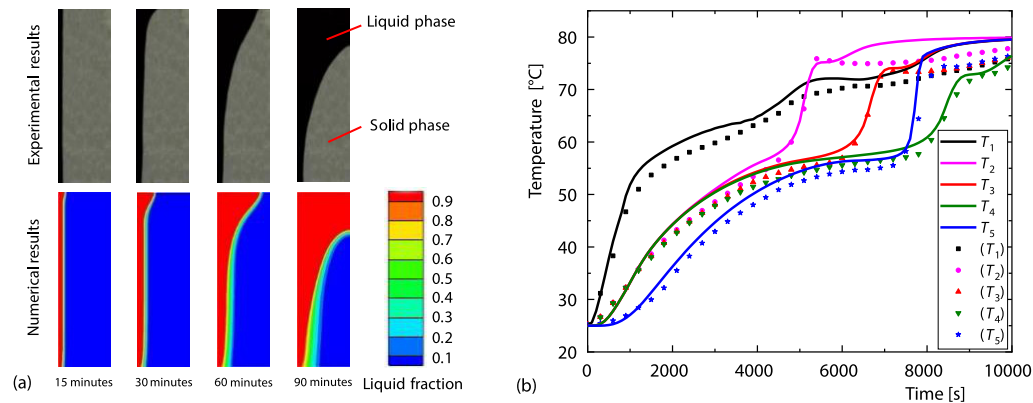


Figure 4. The results of model validation

numerical results and the experimental results are in good agreement. Besides, the temperature data calculated by numerical analysis are slightly higher than the measured value of the experiment, which is due to the inability to achieve adiabatic insulation during the experiment.

Results and discussions

The heat transfer process of PCM with different inclination angles under theoretical and practical temperature boundary conditions is investigated in this paper. The inclination angles include 0° , 90° , and 180° , corresponding to bottom horizontal heating, vertical heating, and top horizontal heating, respectively. The periodic temperature boundary conditions include two ranges: $50\text{--}80^\circ\text{C}$ and $65\text{--}80^\circ\text{C}$, and the expressions of the theoretical and the practical temperature boundary conditions are shown in eqs. (6)–(10). The results and conclusions are discussed based on liquid fraction and temperature history during the numerical calculation under the theoretical and the practical boundary conditions.

Liquid fraction comparison

Figure 5 depicts the comparison of liquid fraction between the theoretical and the practical periodic temperature boundary conditions from $50\text{--}80^\circ\text{C}$ at 0° , in which fig. 5(a) illustrates the curves of liquid fraction while fig. 5(b) gives the contours of liquid fraction.

In fig. 5(a), it can be found that in the first temperature increase stage, liquid fraction variations under the theoretical and the practical temperature conditions are nearly the same. In contrast, in the first temperature decrease stage, there is a large gap between the theoretical and the practical temperature conditions. It is because there is a phase change process during the temperature decrease process. In this process, the practical temperature boundary is smoother than the theoretical temperature boundary, which makes the temperature decrease rates of monitoring points inside the PCM much slower, so the liquid fraction calculated based on the practical temperature boundary condition is higher than the liquid fraction calculated under the theoretical temperature boundary condition. As a result, in the second temperature increase stage, the highest liquid fraction the PCM can reach under the practical temperature boundary condition is higher than that under the theoretical temperature boundary condition.

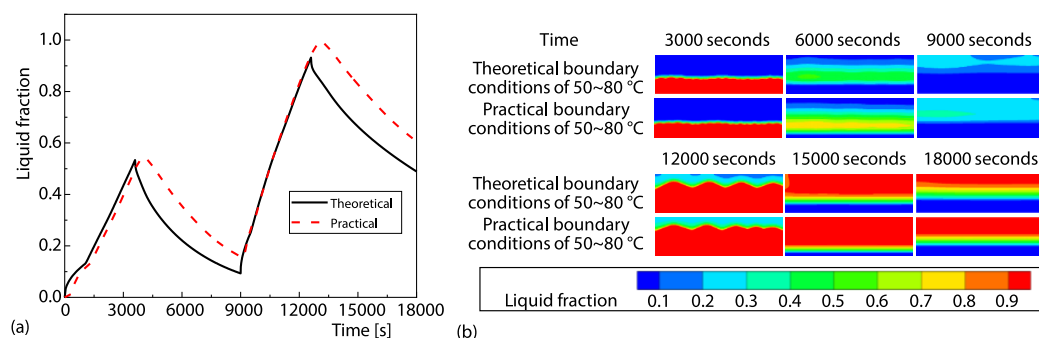


Figure 5. Comparison of liquid fraction between the theoretical and the practical periodic temperature boundary conditions from $50\text{--}80^\circ\text{C}$ at 0°

In fig. 5(b), in the temperature increase stage, the solid-liquid interface appears wavy because the melting PCM is affected by Benard convection cells. The Benard convection cells are formed under the influence of buoyancy and gravity. During the melting process, the PCM with high temperature near the hot wall rises vertically in the central area of each Bénard convection cell under the action of buoyancy. After reaching the solid-liquid interface, the tempera-

ture of the PCM decreases, and the PCM falls along the edges of each Bénard convection cell under the action of gravity [17, 31, 32]. Moreover, the numerical results of liquid fraction under the theoretical and the practical periodic temperature boundary conditions are closed, such as contours of the liquid fraction at 3000 seconds and 12000 seconds. The shape characteristics of the solid-liquid interface during the melting process are similar to those given by Kamkari *et al.* [17]. However, the proportion of the PCM solid phase zone obtained by numerical calculation under the theoretical periodic temperature boundary condition is significantly higher than that under the practical periodic temperature boundary condition, such as contours of the liquid fraction at 6000 seconds 9000 seconds, 15000 seconds, and 18000 seconds.

However, the numerical results under the periodic temperature boundary conditions from 65-80 °C show different characteristics, shown in fig. 6.

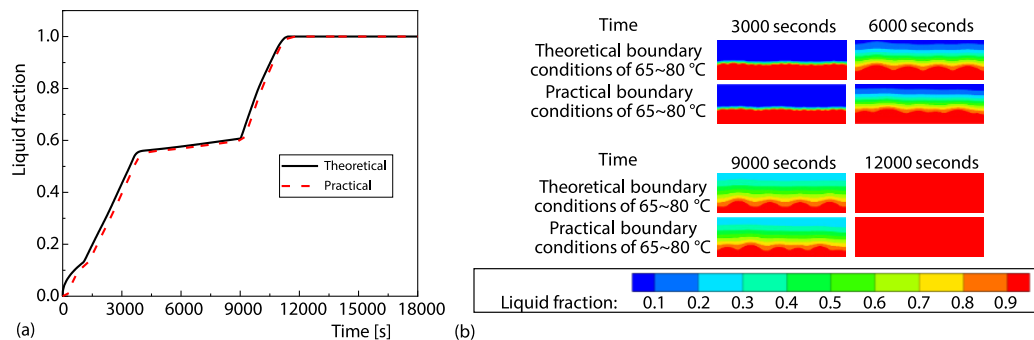


Figure 6. Comparison of liquid fraction between the theoretical and the practical periodic temperature boundary conditions from 65-80 °C at 0°

Due to the minimum temperature of the periodic temperature boundary conditions is 65 °C which is higher than the maximum temperature of the phase change range (56.4-64.3 °C), the liquid fraction increases continuously under this periodic temperature boundary conditions. Figure 6(a) gives the curves of the liquid fraction for both theoretical and practical periodic temperature boundary conditions, while fig. 6(b) presents the contours of the liquid fraction. Compared with the large difference shown in fig. 5, the liquid fractions calculated under the theoretical and the practical periodic temperature boundary conditions from 65-80 °C are similar. After the end of the first temperature increase stage, the maximum difference of liquid fraction between the theoretical and the practical temperature boundary conditions is 6.2%, and the shape of the solid-liquid interface is also very similar. Besides, the PCM under both temperature boundary conditions completely melts at nearly 12000 seconds.

Figure 7 gives the comparison of the liquid fraction at 90°. Similarly, when the periodic temperature boundary changes from 50-80°C, there is a significant difference between the liquid fraction calculated numerically under the theoretical periodic temperature boundary condition and the practical periodic temperature boundary condition, shown in fig. 7(a). When the minimum temperature of the boundary condition is 50 °C, the PCM closed to the heating wall under the theoretical boundary condition solidifies immediately, resulting in a rapid decrease in the liquid fraction of the PCM. However, under the practical boundary condition, the temperature of the PCM near the heating wall decreases relatively slowly, so the reduction rate of liquid fraction is lower than that under the theoretical boundary condition. In contrast, the liquid fraction tends to be same when the periodic temperature boundary changes from 65-80 °C, shown in fig. 7(c).

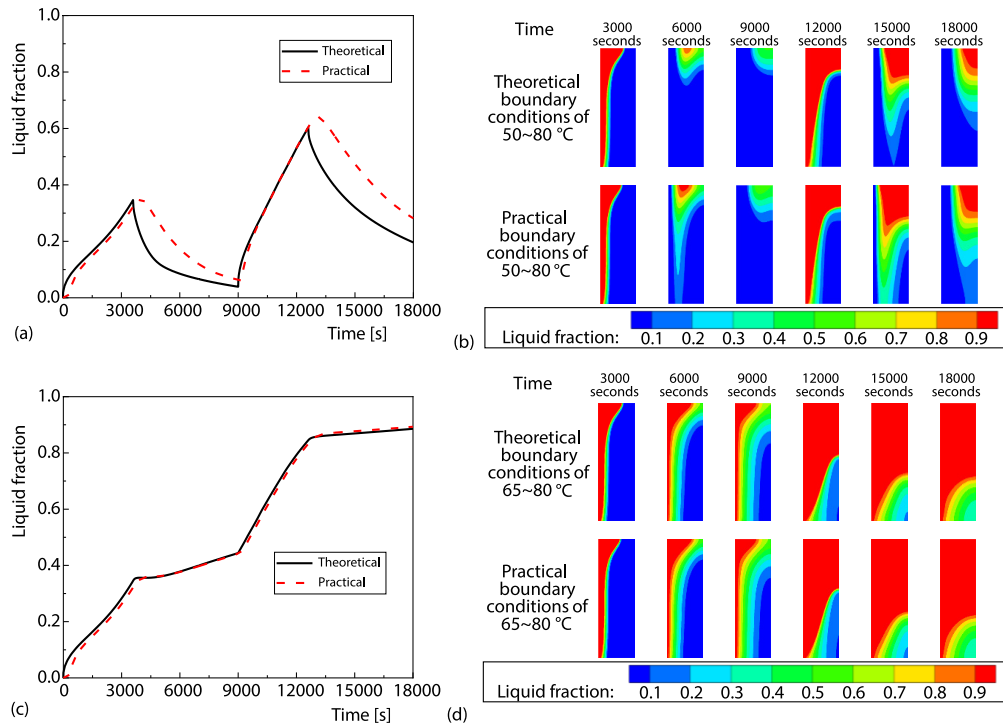


Figure 7. Comparison of liquid fraction between the theoretical and the practical periodic temperature boundary conditions at 90°

Figures 7(b) and 7(d) visualize the liquid fraction contours with periodic temperature boundary conditions of 50-80 °C and 65-80 °C, respectively. There is an obvious difference between the liquid fraction contours at 6000 seconds, 9000 seconds, 15000 seconds, and 18000 seconds in fig. 7(b). When the PCM near the heating wall is heated, the liquid PCM with high temperature floats upward along the heating wall under the action of natural-convection. This makes the temperature of the PCM with higher position in the container higher than that of the PCM with lower position, so that the PCM at the top melts faster. The similar conclusions are given by Kamkari *et al.* [17] and Joneidi *et al.* [33]. Moreover, unlike the PCM at the top of the container having a higher melting rate during the melting stage, the solidification rate at the bottom of the container is faster than that at the top. It is because the PCM at the bottom of the container has lower temperature than the PCM at the top. When the temperature of the heating wall decreases below the phase change temperature of the PCM, the PCM at the bottom with lower temperature solidifies first. Compared with the numerical results under the theoretical periodic temperature boundary conditions, the proportion of mushy zone obtained by numerical calculation under the practical periodic temperature boundary conditions is much higher. The reason is that temperature decreasing rate of PCM is relatively smoothly under the practical temperature conditions, which keeps the temperature of more PCM within the phase change temperature range, resulting in a higher proportion of mushy zone. However, in fig. 7(d), the liquid fraction contours show little difference between the numerical calculation results of liquid fraction under the theoretical and the practical periodic temperature boundary conditions.

By using the data in fig. 7(c), it can be calculated that the maximum difference of liquid fraction between the theoretical and the practical periodic temperature boundary conditions after the first temperature increase stage is 4.0%.

Finally, the liquid fraction at 180° is compared, and the results are shown in fig. 8. Both the theoretical and the practical periodic temperature boundary conditions are also taken into consideration. Although the heat transfer process at 180° is much slower, the influence on liquid fraction under the theoretical and the practical periodic temperature boundary conditions is still obvious, as shown in fig. 8(a). Besides, fig. 8(b) indicates that the effects of the two periodic temperature boundary conditions on liquid fraction, which are shown at the liquid fraction contours at 6000 seconds, 15000 seconds, and 18000 seconds. In addition, the solid-liquid interface is always straight, which is also reported by Zhang *et al.* [34]. It is indicated that the heat transfer process only needs to overcome the vertical upward buoyancy. This may be the theoretical basis that the heat source is usually placed on the top of the specimen in the steady-state method of thermal conductivity measurement. Figures 8(c) and 8(d) shows the liquid fraction values under the two periodic temperature boundary conditions nearly the same. After the first temperature rise stage, the maximum difference of liquid fraction values is no more than 3.9%.

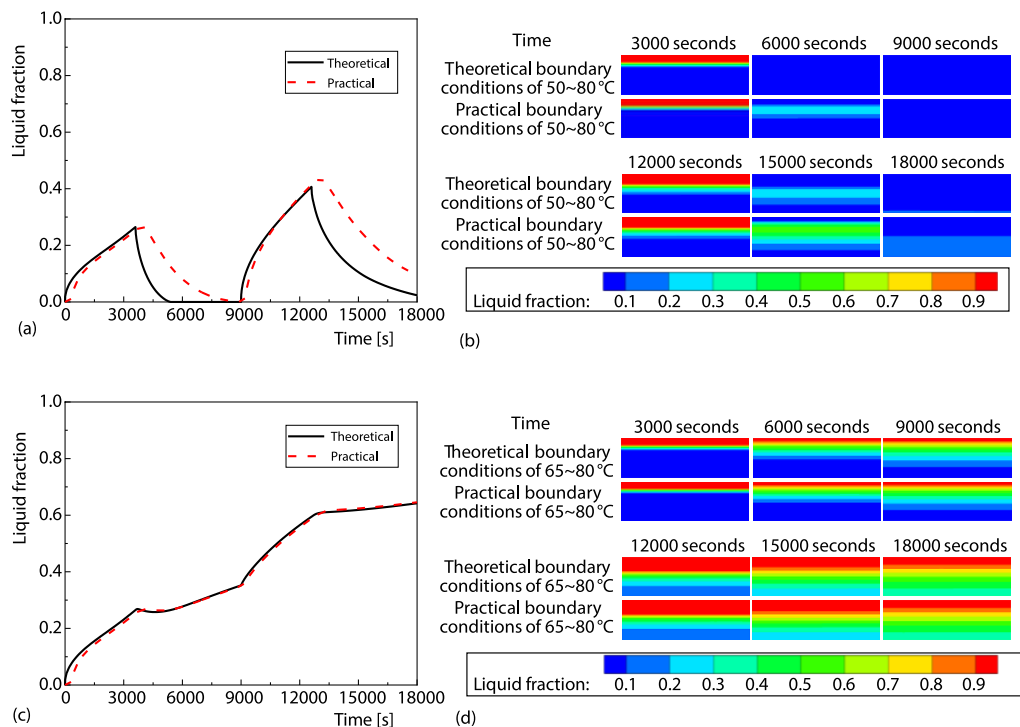


Figure 8. Comparison of liquid fraction between the theoretical and the practical periodic temperature boundary conditions at 180°

Temperature histories of monitoring points

This part investigates the temperature histories of monitoring points inside the PCM under the theoretical and the practical periodic temperature boundary conditions, in which T_1 - T_5 refer to temperatures of monitoring points calculated by the theoretical boundary conditions and $T_{(1)}$ - $T_{(5)}$ present temperatures calculated by the practical boundary conditions.

Figure 9 gives the curves of temperature variations during the melting process under the periodic temperature boundary conditions of 50-80 °C and 65-80 °C. The temperatures of monitoring points under the practical periodic temperature boundary conditions are lower than those under the theoretical periodic temperature boundary conditions in the temperature increase stages. Besides, the opposite characteristics are shown in the temperature decrease stages. This phenomenon depicts the hysteresis of temperature change at monitoring points under the practical periodic temperature boundary conditions.

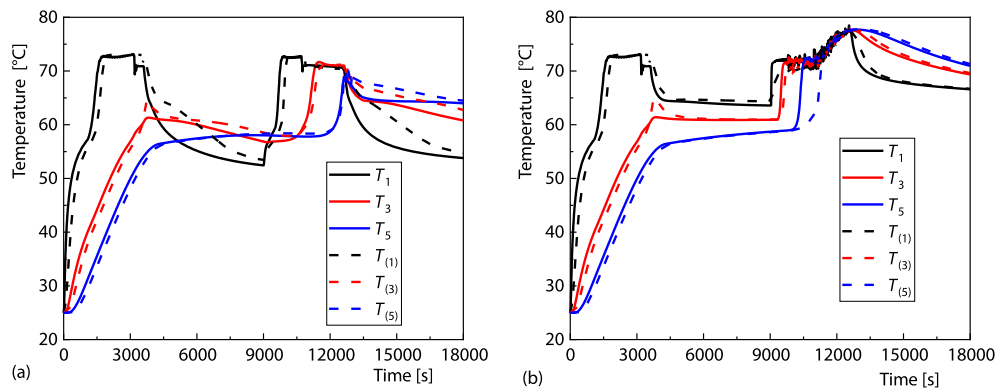


Figure 9. Comparison of temperature histories between the theoretical and the practical periodic temperature boundary conditions at 0°

In fig. 9(a), it can be found that in the temperature increasing stage, the temperatures of these three monitoring points have similar variation characteristics, and the values of T_1 , T_3 , and T_5 are lower than $T_{(1)}$, $T_{(3)}$, and $T_{(5)}$ at each time point, respectively. However, in the temperature decreasing stage, the temperature values of T_1 and $T_{(1)}$ are quite different. The maximum temperature difference between T_1 and $T_{(1)}$ reaches 6.0 °C. The reason is that monitoring Point 1 (p_1) is closed to the heat source, and the temperature is greatly affected by the heat source due to the heat conduction and heat convection. In comparison, the temperature differences between T_3 and $T_{(3)}$, T_5 and $T_{(5)}$ are relatively small, but the maximum temperature differences also reach 3.2 °C and 2.8 °C, respectively.

In fig. 9(b), the characteristics shown in the first temperature increasing stage are the same as those in fig. 9(a). However, in the second temperature increasing stage, the temperatures of T_5 and $T_{(5)}$ are greatly different, which is due to the influence of Bénard convection cells [17, 31, 32]. Furthermore, after the PCM is completely melted, the temperatures of all monitoring points under the theoretical and the practical temperature boundary conditions are almost the same. However, there are some fluctuations in the temperatures of internal monitoring points. This thermal phenomenon can be attributed to the regular convection cells in the liquid PCM and development of turbulent convection in the melt layer [17, 35]. Besides, the temperatures of the monitoring points obtained under the theoretical and practical temperature boundary conditions only have some deviations in each temperature decrease initial stage. In the first temperature decrease stage, the maximum temperature differences between T_1 and $T_{(1)}$, T_3 and $T_{(3)}$, T_5 and $T_{(5)}$ are 3.6 °C, 3.6 °C, and 1.3 °C, respectively. In the second temperature decrease stage, the PCM has completely melted. The maximum temperature differences become 3.6 °C, 0.9 °C, and 0.5 °C, respectively.

Figure 10 gives the curves of temperature variations during the melting process under the periodic temperature boundary conditions of 50-80 °C and 65-80 °C, in which figs.

10(a) and 10(b) give the temperature histories of p_1 to p_5 under both boundary conditions from 50-80°C while figs 10(c) and 10(d) depict those from 65-80 °C.

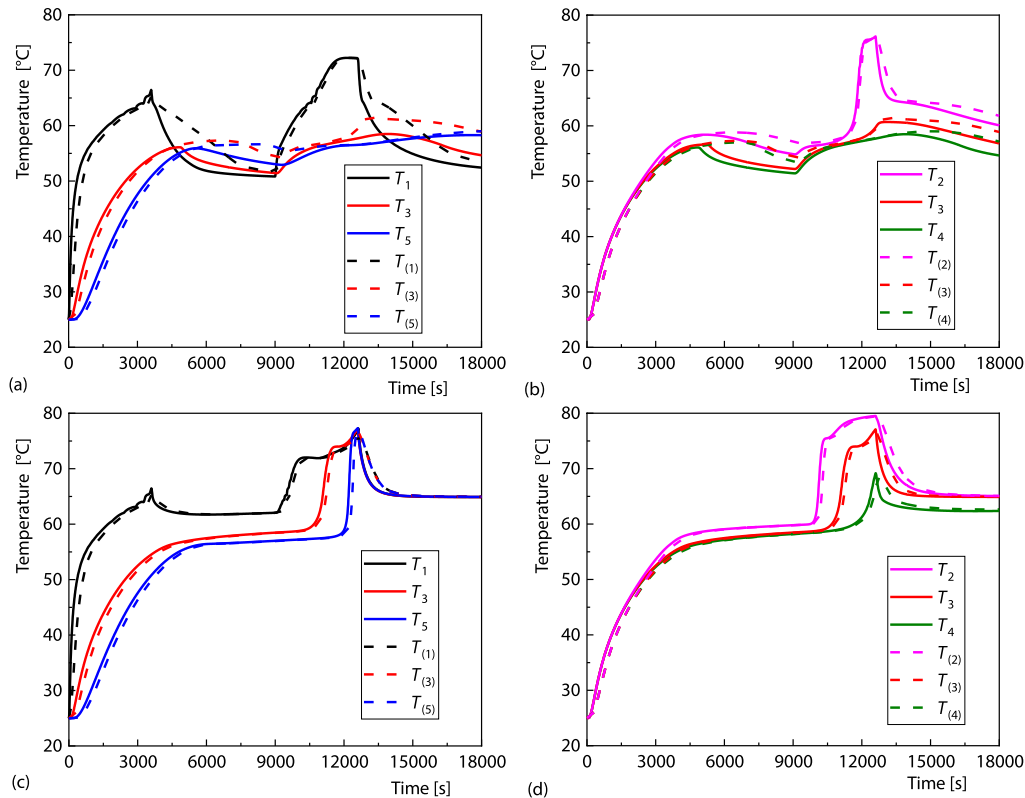


Figure 10. Comparison of temperature histories between the theoretical and the practical periodic temperature boundary conditions at 90°

In the first temperature increasing stage, the heat conduction dominates the heat transfer process, which shows that the temperature curves of p_2 , p_3 , and p_4 are coincident under both the theoretical and the practical temperature boundary conditions. However, the temperature values calculated by the practical temperature boundary conditions are lower than those obtained by the theoretical temperature boundary conditions. This is because the temperature of heat source under the practical condition is gradually increased to the target temperature, while the theoretical boundary condition is directly changed to the target temperature. Besides, the temperature at p_1 grows faster than the temperatures at other monitoring points. It is because the p_1 is affected not only by heat conduction but also by more intense natural-convection. Since p_1 is closer to the heat source, its temperature also changes faster than the temperatures at other monitoring points during the temperature decreasing stage. Moreover, at the end of the second temperature increasing stage (12600 seconds), the maximum temperature difference of p_2 under both boundary conditions is 0.1 °C, shown in figs. 10(b) and 10(d). This means that the theoretical and the practical boundary conditions only affect the temperature change process of the monitoring point, but have no effect on the final temperature value.

However, in the temperature decreasing stage, there are large temperature differences between the theoretical and the practical temperature boundary conditions, especially in

figs. 10(a) and 10(b). The temperature p_1 also changes faster than the temperatures at other monitoring points. The maximum differences of the temperatures at p_1 even reach 6.7 °C, while the temperature differences of p_2 , p_3 , p_4 , and p_5 reach 5.1 °C, 4.4 °C, 2.7 °C, and 0.7 °C, respectively. At the end of the second temperature decreasing stage, the temperatures of each monitoring point still have some differences between the theoretical and the practical temperature boundary conditions. In figs. 10(c) and 10(d), the temperature difference of p_1 to p_5 are mainly reflected in the initial stage of the second temperature decreasing process. At the end of the second temperature decreasing stage, the temperature of each monitoring point gradually reaches a stable value. The temperature values are the same whether they are obtained from the theoretical temperature boundary or the practical temperature boundary.

Figure 11 compares temperature histories between the theoretical and the practical periodic temperature boundary conditions at 180°, in whichf. 11(a) investigated the temperature histories of p_1 , p_3 , and p_5 when the periodic temperature condition is from 50-80 °C while fig. 11(b) gives the results under the periodic temperature condition from 65-80 °C.

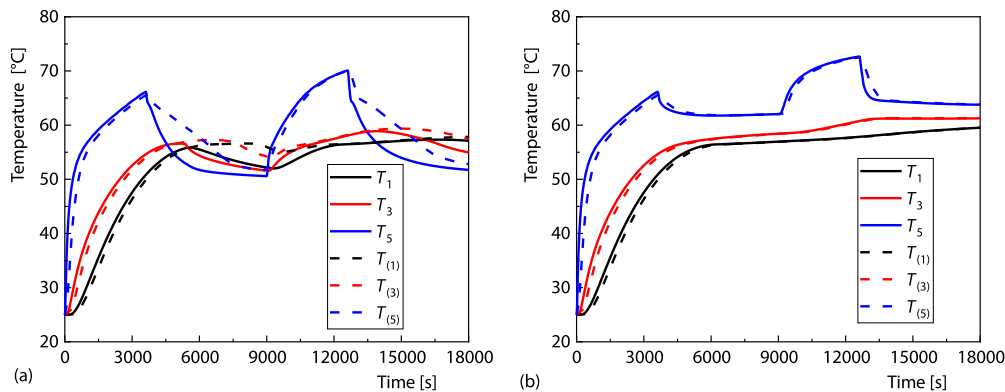


Figure 11. Comparison of temperature histories between the theoretical and the practical periodic temperature boundary conditions at 180°

In the temperature increasing stage, the characteristics of the temperature histories of the monitoring points are the same as those at 0 °C and 90 °C, such as the temperatures of the monitoring points calculated by the practical temperature boundary conditions are lower than those calculated by the theoretical temperature boundary conditions. Besides, in fig. 11(a), during the temperature decreasing stage, the temperature values of the monitoring points calculated through the theoretical and the practical temperature boundary conditions are quite different. The maximum temperature difference at p_5 reaches 6.8 °C, while the temperature differences at p_3 and p_1 are 4.3 °C and 4.0 °C, respectively. Furthermore, the temperature difference of each monitoring point at the second temperature decreasing stage is slightly smaller than that at the first temperature decreasing stage. In fig. 11(b), it is obvious that under the two boundary conditions, only the temperature difference of T_5 and $T_{(5)}$ reaches 4.0 °C at 12840 seconds, while the temperature differences between the other two monitoring points are less than 0.9 °C. At the end of the second temperature decreasing stage (18000 seconds), the temperatures of all monitoring points under both temperature boundary conditions tend to be the same, and the temperature differences are less than 0.1 °C. This phenomenon also shows that when the target temperature of the boundary condition is stable for an enough long time, the final temperature value in the PCM is only related to the target temperature of the boundary condition but not to the temperature decreasing process.

Conclusions

In order to further deepen understanding of heat transfer characteristics of the PCM in the inclined rectangular enclosure under the theoretical and the practical periodic temperature boundary conditions, the numerical simulations were conducted, and the characteristics of the liquid fraction and internal monitoring temperatures at different inclination angles were compared. The inclination angles of the container include 0° , 90° , and 180° , and the periodic temperature boundary conditions include $50\text{--}80^\circ\text{C}$ and $65\text{--}80^\circ\text{C}$. The following conclusions can be drawn from the obtained results are as follows.

- At the inclination angles of 0° , 90° , and 180° , the differences between the numerical results calculated under the theoretical and the practical periodic temperature boundary condition of $65\text{--}80^\circ\text{C}$ is smaller than those under the theoretical and the practical periodic temperature boundary condition of $50\text{--}80^\circ\text{C}$. The numerical results include liquid fraction and temperatures of monitoring points.
- In the numerical calculation of all inclination angles, the liquid fraction and the temperature histories calculated by the practical periodic temperature boundary conditions are lower than those obtained by the theoretical periodic temperature boundary conditions in initial stage. In contrast, the results calculated by the practical periodic temperature boundary conditions are higher in terminal stage.
- Whether the periodic temperature boundary conditions are $50\text{--}80^\circ\text{C}$ or $65\text{--}80^\circ\text{C}$, the maximum differences between the numerical results of liquid fraction and temperature calculated by the theoretical and the practical periodic temperature boundary conditions occur in the temperature decreasing stage.
- The research results of this paper can provide references for practical applications. If the periodic temperature boundary contains the phase change range of PCM, the influence of the practical change of the temperature boundary during the heat transfer process cannot be ignored. However, if the minimum value of the periodic temperature boundary is higher than the phase change temperature range, the boundary conditions can be simplified according to actual needs in the numerical calculation.

Acknowledgment

This work is supported by the Fundamental Research Funds for the Central Universities (Grant No. 3132020104).

Nomenclature

A_{mush}	– mushy zone constant, [–]
C_p	– specific heat, [$\text{Jkg}^{-1}\text{C}^{-1}$]
f	– liquid fraction, [–]
g	– gravitational acceleration, [ms^{-2}]
H	– enthalpy, [Jkg^{-1}]
h	– sensible enthalpy, [Jkg^{-1}]
L	– latent heat, [Jkg^{-1}]
P	– pressure, [Pa]
p	– temperature monitoring point, [–]
T	– temperature
t	– time, [s]
u	– horizontal velocity component, [ms^{-1}]
v	– vertical velocity component, [ms^{-1}]

Greek symbols

α	– inclination angle, [$^\circ$]
β	– thermal expansion coefficient, [$^\circ\text{C}$]
μ	– dynamic viscosity, [kgms^{-1}]
λ	– thermal conductivity, [$\text{Wm}^{-1}\text{C}^{-1}$]
ρ	– density, [kgm^{-3}]

Subscripts

init	– initial
ℓ	– liquid phase
m	– Melting temperature
s	– solid phase

References

- [1] Juaifer, H. J. A., *et al.*, Melting Process of Paraffin Wax Inside Plate Heat Exchanger: Experimental and Numerical Study, *Journal of Thermal Analysis and Calorimetry*, 140 (2020), 3, pp. 905-916
- [2] Karami, R., Kamkari B., Experimental Investigation of the Effect of Perforated Fins on Thermal Performance Enhancement of Vertical Shell and Tube Latent Heat Energy Storage Systems, *Energy Conversion and Management*, 210 (2020), Apr., 112679
- [3] Esen, M., Ayhan, T., Development of a Model Compatible with Solar Assisted Cylindrical Energy Storage Tank and Variation of Stored Energy with Time for Different Phase Change Materials, *Energy Conversion and Management*, 37 (1996), 12, pp. 1775-1785
- [4] Esen, M., *et al.*, Geometric Design of Solar-Aided Latent Heat Store Depending on Various Parameters and Phase Change Materials, *Solar Energy*, 62 (1998), 1, pp. 19-28
- [5] Esen, M., Thermal Performance of a Solar-Aided Latent Heat Store Used for Space Heating by Heat pump, *Solar Energy*, 69 (2000), 1, pp. 15-25
- [6] Latibari, S. T., Sadrameli, S. M., Carbon Based Material Included-Shaped Stabilized Phase Change Materials for Sunlight-Driven Energy Conversion and Storage: An Extensive Review, *Solar Energy*, 170 (2018), Aug., pp. 1130-1161
- [7] Emam, M., *et al.*, Performance Study and Analysis of an Inclined Concentrated Photovoltaic-Phase Change Material System, *Solar Energy*, 150 (2017), July, pp. 229-245
- [8] Rao, Z., *et al.*, Experimental Investigation of Battery Thermal Management System for Electric Vehicle Based on Paraffin/Copper Foam, *Journal of the Energy Institute*, 88 (2015), 3, pp. 241-246
- [9] Debich, B., *et al.*, Design Optimization of PCM-Based Finned Heat Sinks for Mechatronic Components: A Numerical Investigation and Parametric Study, *Journal of Energy Storage*, 32 (2020), Dec., 101960
- [10] An, Z., *et al.*, A Review on Lithium-ion Power Battery Thermal Management Technologies and Thermal Safety, *Journal of Thermal Science*, 26 (2017), 5, pp. 391-412
- [11] Rao, Z., *et al.*, Simulation of Heat Dissipation with Phase Change Material for Cylindrical Power Battery, *Journal of the Energy Institute*, 85 (2012), 1, pp. 38-43
- [12] Thenmozhi, R., *et al.*, Transient Thermal Management Comparison of a Microprocessor Using PCM in Various Configurations, *Journal of Thermal Science*, 20 (2011), 6, pp. 516-520
- [13] Pal, D., Joshi Y. K., Melting in a Side Heated Tall Enclosure by a Uniformly Dissipating Heat Source, *International Journal of Heat and Mass Transfer*, 44 (2001), 2, pp. 375-387
- [14] Zhang, Q., *et al.*, Numerical Study on Solid-Liquid Phase Change in Paraffin as Phase Change Material for Battery Thermal Management, *Science Bulletin*, 61 (2016), 5, pp. 391-400
- [15] Duan J., *et al.*, On the Melting Process of the Phase Change Material in Horizontal Rectangular Enclosures, *Energies*, 12 (2019), 16, 3100
- [16] Shokouhmand, H., Kamkari B., Experimental Investigation on Melting Heat Transfer Characteristics of Lauric Acid in a Rectangular Thermal Storage Unit, *Experimental Thermal and Fluid Science*, 50 (2013), Oct., pp. 201-212
- [17] Kamkari B., *et al.*, Experimental Investigation of the Effect of Inclination Angle on Convection-Driven Melting of Phase Change Material in a Rectangular Enclosure, *International Journal of Heat and Mass Transfer*, 72 (2014), May, pp. 186-200
- [18] Kamkari B., Amlashi H. J., Numerical Simulation and Experimental Verification of Constrained Melting of Phase Change Material in Inclined Rectangular Enclosures, *International Communications in Heat and Mass Transfer*, 88 (2017), Nov., pp. 211-219
- [19] Avci, M., Yazici, M. Y., An Experimental Study on Effect of Inclination Angle on the Performance of a PCM-Based Flat-Type Heat Sink, *Applied Thermal Engineering*, 131(2018), Feb., pp. 806-814
- [20] Wang Y., *et al.*, Numerical Investigations on Melting Behavior of Phase Change Material in a Rectangular Cavity at Different Inclination Angles, *Applied Sciences*, 8 (2018), 9, 1627
- [21] Saha, S. K., Dutta, P., Performance Analysis of Heat Sinks with Phase Change Materials Subjected to Transient and Periodic Heating, *Heat Transfer Engineering*, 36 (2015), 16, pp. 1349-1359
- [22] Saha, S. K., Dutta P., Thermal Management of Electronics Using PCM-Based Heat Sink Subjected to Periodic Heat Load, *IEEE Transactions on Components Packaging and Manufacturing Technology*, 2 (2012), 3, pp. 464-473
- [23] Ahmed, T., *et al.*, Passive Thermal Management of Tablet PC Using Phase Change Materials: Intermittent Operation, *Applied Sciences*, 9 (2019), 5, 902
- [24] Ahmed, T., *et al.*, Passive Thermal Management of Tablet PC Using Phase Change Materials: Continuous Operation, *International Journal of Thermal Sciences*, 134 (2018), Dec, pp. 101-115

- [25] Liu, Z., *et al.*, Numerical Modelling for Solid-Liquid Phase Change Phenomena in Porous Media: Shell-and-Tube Type Latent Heat Thermal Energy Storage, *Applied Energy*, 112 (2013), SI, pp. 1222-1232
- [26] Tian, Y., Zhao, C., Thermal and Exergetic Analysis of Metal Foam-Enhanced Cascaded Thermal Energy Storage (MF-CTES), *International Journal of Heat and Mass Transfer*, 58 (2013), 1-2, pp. 86-96
- [27] Hayat, M. A., *et al.*, Phase Change Material/Heat Pipe and Copper Foam-Based Heat Sinks for Thermal Management of Electronic Systems, *Journal of Energy Storage*, 32 (2020), Dec., 101971
- [28] Farahani, S. D., *et al.*, Numerical Simulation of NEPCM Series Two-Layer Solidification Process in a Triple Tube with Porous Fin, *Case Studies in Thermal Engineering*, 28 (2021), Dec., 101407
- [29] Brent, A. D., *et al.*, Enthalpy-Porosity Technique for Modelling Convection-Diffusion Phase Change: Application the Melting of a Pure Metal, *Numerical Heat Transfer*, 13 (1988), 3, pp. 297-318
- [30] Shmueli, H., *et al.*, Melting in a Vertical Cylindrical Tube: Numerical Investigation and Comparison with Experiments, *International Journal of Heat and Mass Transfer*, 53 (2010), 19-20, pp. 4082-4091
- [31] Nayak K. C., *et al.*, A Numerical Model for Heat Sinks with Phase Change Materials and Thermal Conductivity Enhancers, *International Journal of Heat and Mass Transfer*, 49 (2006), 11-12, pp. 1833-1844
- [32] Favier, B., *et al.*, Rayleigh-Benard Convection with a Melting Boundary, *Journal of Fluid Mechanics*, 858 (2019), Jan., pp. 437-473
- [33] Joneidi, M. H., *et al.*, Experimental Investigation of Phase Change in a Cavity for Varying Heat Flux and Inclination Angles, *Experimental Thermal and Fluid Science*, 88 (2017), Nov. pp. 594-607
- [34] Zhang, Q., *et al.*, Numerical Study on Solid-Liquid Phase Change in Paraffin as Phase Change Material for Battery Thermal Management, *Science Bulletin*, 61 (2016), 5, pp. 391-400
- [35] Zennouhi, H., *et al.*, Effect of Inclination Angle on the Melting Process of Phase Change Material, *Case Studies in Thermal Engineering*, 9 (2017), Mar., pp. 47-54