Numerical study on the effects of fin parameters on the charging process of PCM-based heat sink

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Abstract: In order to solve the heating problem of electronic devices, an optimal configuration of rectangular cavity straight fin phase change material (PCM) based heat sink is determined to extend the safe operating time in the charging process. With PCM-based heat sink as the object of research, a three-dimensional and transient melting model is constructed. The effects of fin number, height and thickness on phase change heat transfer process and natural convection are explored in depth, and the optimal configuration parameters of PCM-based heat sink are obtained. The results show that the configuration of 8 fins, 15 mm in height and 2 mm in thickness is adopted as the optimal heat sink structure, with the longest safe operating time-1170 seconds. In the stable period of phase transition, the base temperature remains unchanged and the natural convection disturbance is strong. The short and dense fin arrangement can prolong the safe operating time of safety limit temperature 343K better.

1. Introduction
With the increasing power of electronic devices, the temperature rise of electrons is accelerating. High temperature not only shortens the service life of electronic products seriously [1], but also makes the products fail. Therefore, thermal management of electronic equipment [2,3] has become an active research field. PCM-based heat sink can better meet the needs of compactness in small-scale space.

Ali and Arshad [4] studied the heat management of n-eicosane phase change material and circular aluminum pin fin heat sink through experiments. The experimental results show that the base temperature can be kept in a lower range when the fin thickness is 3 mm. Yang et al. [5,6] numerically simulated the cooling of mobile electronic devices with plate fin PCM-based heat sink. In the power range of 2–4 W, the heat sink is composed of zero fin, three fins and six fins filled with n-eicosane. The results show that the heat transfer performance of the six fins is the best, and the heat transfer direction has little effect on the heat transfer rate. Kin [7] used two kinds of phase change materials paraffin and 1-hexadecanol to study the thermal performance of cross fin heat sink with different structures. The results show that the number of cross fins and PCM filling can effectively reduce the base temperature. The existing research mainly considers the influence of single fin parameters of PCM-based heat sink on phase change heat transfer, but the investigation combined with fin parameters and flow field is few.

The purpose of this paper is to build a three-dimensional, transient melting model of the PCM-based heat sink, and deeply explore the influences of the number, height and thickness of fins on the phase change heat transfer process and natural convection in the charging process. The optimal PCM-based heat sink configuration parameters are obtained, which provides a theoretical basis for the practical engineering design of PCM-based heat sink.
2. Numerical simulations

2.1. Physical model

The Fig. 1 shows one of the basic structures of the phase change material-based heat sinks in present study. The heat sink is mainly composed of a base section, the surrounding walls and several straight fins connected with the basement, which are all made from aluminum. Meanwhile, the heat sink is filled with RT42 as a phase change material. The dimensions of the whole heat sink is $60 \times 60 \times 47\text{mm}$. The bottom of the heat sink is heated by the constant heat flux generated by the operation of electronic components. Except the top of the heat sink in contact with the air, the walls around the heat sink are insulated with insulation materials.

![Fig. 1. PCM-based heat sink physical model.](image)

2.2. Mathematical models

In the present study, three-dimensional transient simulation based on enthalpy-porosity method is used to simulate the phase change heat transfer and flow process of heat sink. In order to solve the heat transfer and flow problems of PCM-based heat sink, the following governing equations are presented:

\[
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0 \tag{1}
\]

\[
\frac{\partial (\rho \mathbf{u})}{\partial t} + \mathbf{u} \cdot \nabla (\rho \mathbf{u}) = \nabla P + \rho \nabla^2 \mathbf{u} + \rho \mathbf{g} + \mathbf{S} \tag{2}
\]

\[
\frac{\partial (\rho H)}{\partial t} + \nabla \cdot (\rho \mathbf{u} H) = \nabla \cdot (K \nabla T) \tag{3}
\]

where $\rho$ represents the density of the PCM, $\mathbf{u}$ is the mean velocity, $P$ is the pressure, $\mu$ is the viscosity of the PCM, $k$ is the thermal conductivity and $T$ is the temperature.

The definition of momentum source term can be described as:

\[
\mathbf{S} = A_{\text{mush}} \left( \frac{1 - \beta^2}{\beta^3 + \epsilon} \right) \mathbf{u} \tag{4}
\]

where $\epsilon$ is a small constant to prevent the denominator from being zero, with a value of 0.001. $A_{\text{mush}}$ is the constant of mushy zone, and it is set to $10^5$. $\beta$ represents the liquid fraction.

The sensible enthalpy can be described as:

\[
h = h_{\text{ref}} + \int_{T_{\text{ref}}}^{T} C_p dT \tag{5}
\]

where $h_{\text{ref}}$ is the reference enthalpy, $T_{\text{ref}}$ is the reference temperature and $C_p$ is the specific heat capacity.

The latent enthalpy can be described as:

\[
\Delta H = \beta L \tag{6}
\]

where $L$ denotes the latent heat of PCM. The total enthalpy of PCM can be described as follows:
\[ H = h + \Delta H \]  

(7)

The liquid fraction can be described as:

\[
\beta = \begin{cases} 
0, & T < T_s \\
\frac{T - T_s}{T_l - T_s}, & T_s \leq T \leq T_l \\
1, & T > T_l 
\end{cases}
\]  

(8)

where \( T_s \) and \( T_l \) represent respectively the solidification temperature and melting temperature.

### 2.3. Initial and boundary conditions

In the process of numerical simulation, in order to avoid unnecessary influence, the numerical model has the following assumptions: (1) The influence of fluid compressibility is ignored. Phase change materials are considered isotropic and homogeneous. (2) In order to consider the effect of natural convection, Boussinesq approximation is used because of the small change of density.

\[
\rho = \rho_0 \left[ 1 - \alpha (T - T_0) \right]
\]

where \( \alpha \) represents the expansion coefficient of PCM, and its value is selected as 0.001 K\(^{-1}\). \( \rho_0 \) is the liquid density of PCM.

At the same time, the following boundary conditions are needed to solve the above control equations.

1. Constant heat flux is applied to heat from the bottom of heat sink. The top of heat sink contacts with ambient to form natural convection boundary condition. The coefficient of natural convection, which is taken as 10 W/(m·K). The remaining four walls on the side of the heat sink are used as adiabatic boundary conditions. The thermal properties of materials are shown in Table 1. In order to simplify the computational complexity, symmetric boundary conditions are used.

The initial condition:

\[ T_{\text{initial}} = 24^\circ C, \; t = 0, \; \beta_{\text{PCM}} = 0 \]

### Table 1 The thermal properties of materials.

| Properties                        | RT42   | Al    |
|-----------------------------------|--------|-------|
| Thermal conductivity (W/(m·K))    | 0.2    | 202   |
| Specific heat (J/(kg·K))         | 2000   | 871   |
| Density (kg/m\(^3\)), solid      | 880    | 2719  |
| Density (kg/m\(^3\)), liquid     | 760    | -     |
| Melting temperature (K)           | 315    | -     |
| Solidification temperature (K)    | 311    | -     |
| Latent heat (kJ/kg)               | 165    | -     |
| Dynamic viscosity (kg/(m·s))      | 0.0235 | -     |
| Thermal expansion coefficient (1/K)| 0.0001 | -     |

### 2.4. Numerical methods

The Melting/Solidification model based on enthalpy method is used for numerical simulation in this study by ANSYS fluent 18.1 software. The energy and momentum equations are discretized by the second order upwind scheme. The PRESTO! is used to modify the pressure equation. The SIMPLE algorithm is used to realize the pressure-velocity coupling. The sub relaxation factors of pressure, density, volume force, momentum, liquid rate and energy are 0.3, 1, 1, 0.7, 0.9 and 1, respectively.

### 2.5. Numerical model validation

To verify the numerical model, it is vital to compare the simulation results with the credible data. Thus, Fig.2 shows the comparison between the numerical simulation and the experimental results by Saad Mahmoud et al. [8]. Through quantitative analysis, it is found that the maximum temperature difference between simulation and experiment is within 9%. It illustrates that the Melting/Solidification model can accurately predict the heat transfer process of PCM-based heat sink.
3. Results and discussion

The effects of fin number, fin height and fin thickness on phase change heat transfer process and natural convection are investigated systematically by PCM-based heat sink. The safe operating time of base, temperature field and flow field of PCM-based heat sink with time are studied.

It can be found that the entire phase change heat transfer process can be divided into five periods (A, B, C, D and E) in Fig. 3. In phase A, PCM is solid and the temperature rises rapidly. In stage B, the PCM near the heat source begins to melt and the temperature slope decreases. In stage C, the natural convection is strengthened and the temperature is decreased. In the stable period D, the natural convection develops steadily and the temperature is basically unchanged. In the last stage E, PCM has melted completely and the temperature rises sharply.

Fig. 4 shows the distribution of temperature, liquid fraction and velocity in the longitudinal section of 520S PCM-based heat sink. At this time, corresponding to the D stage in Fig. 3, the natural convection near the bottom of the fin is strong, and the base temperature is low and uniform. The vortex generated at the bottom of the PCM increases the heat transfer between the bottom of the heat sink and the PCM.
3.1. Effects of the number of fins
The number of fins is a significant factor affecting the thermal conductive network of PCM. The time to reach several safety limit temperatures of base for different number of fins are studied in Fig. 5. It illustrates that with the increase of the number of fins, the safe operating time of base increases gradually, but the increase decreases gradually. When the fin number is 8, the maximum safe operating time of base is 1170 seconds. Higher safety limit temperature (343K) has longer safe operating time than lower safety limit temperature (323K and 333K).

3.2. Effects of the height of fins
In order to investigate the effects of the height of fins variation, a series of simulations are carried out. It illustrates the effects of the height of fins to the safe operating time in Fig.6. With the increase of height of fins, the safe operating time of the safety limit temperature of 343K increases first, then decreases, but the safe operating time increases slowly at 343K and 323K safety limit temperature. In this research area, the PCM-based heat sink with 15mm fin height has the longest safe operating time-1170 seconds.
3.3. Effects of the thickness of fins

Fig. 7 indicates the relationship between the thickness of fins and safe operating time. The smaller the fin thickness is, the longer the operation time is. And it is easy to find that the safe operating time at 343K is much longer than that at 323k and 333k.

4. Conclusions

The effects of fin parameters on phase change heat transfer process and natural convection are investigated deeply by numerical simulation of PCM-based heat sink in the charging process.

In the stable period D of phase transition, the base temperature is basically unchanged, and the natural convection disturbance is strong in this stage. As the increase of fin number, the increase of safe operating time of base decreases. When the number of fins is 8, the base has the maximum safe operating time. With the increase of height of fins, the safe operating time of the safety limit temperature of 343K increases first, then decreases. The 15mm fin height has the longest safe operating time. The contribution of fin thickness to the safe operating time is weak. The PCM-based heat sink of 8 fins, 15 mm high and 2 mm thick has the best performance, and the longest safe operating time is 1170 seconds.

Acknowledgments

The authors gratefully acknowledge the financial support by the Foundation of the Graduate Innovation Center, Nanjing University of Aeronautics and Astronautics (Grant NO.kfjj20200206).

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