Numerical Investigation of an Innovative Metal Structure in a PCM Based Heat Sink

Jinlong Xie$^{1,3}$, Kok Fah Choo$^2$, Jianhua Xiang$^1$, and Hsiao Mun Lee$^1$

1 School of Mechanical and Electric Engineering, Guangzhou University, 230 Wai Huan Xi Road, Guangzhou Higher Education Mega Center, Guangzhou 510006, P.R.China
2 Temasek Laboratories@NTU, Nanyang Technological University, 50 Nanyang Avenue, Singapore 639798, Singapore
E-mail: hmlee@gzhu.edu.cn

Abstract. Numerical simulations were performed to examine the time-dependent melting in a PCM enclosure with two designs of conductive metal fins: a baseline design with conventional heat sink fin structure and a topologically optimized innovative structure. Two orientations of the PCM enclosures were investigated to characterize the orientation effects on the behaviours of PCM melting. The proposed simulation model was firstly validated by the published experimental results. The simulated device temperature, material phases and flow fields within the PCM enclosure developed under different operating conditions were presented and discussed. The simulation results showed that the optimized design generally outperformed the baseline design by obtaining a lower device temperature and alleviating the effects of orientations. At $q = 50,000\text{W/m}^2$, the optimized design achieved a maximum temperature reduction of 8°C under Orientation 1 and 2.5°C under Orientation 2 in comparison to the baseline during the main stage of PCM melting. It was suggested that the promoted heat transfer performance by the optimized design was attributed to the improved heat diffusion capability as well as the intensified natural convection provided by its innovative metal structure.

1. Introduction

Excess heat of mobile electronic device needs to be removed in order to keep the device operating in a safe temperature level and these temperature control methods are so called the thermal management schemes. In the past decades, a lot of thermal management schemes are developed by scientists, for example, the forced liquid/air convection cooling. However, these techniques are not acceptable to be used in some compact mobile devices because the equipment involved is very massive and bulky. Therefore, a practical and simple passive thermal management solution so-called the phase change materials (PCMs) cooling technique is developed by researchers to replace the traditional thermal management schemes [1]. This technique stores the excess heat generated from an electronic device by employing the latent heat of PCM melting when the device is operating. After that when the device is idle, the melted PCM releases heat to environment and turns into a solid phase again for use in the next operation cycle. PCM is a favourable material for the thermal management of mobile device because its melting temperature is almost constant and it can provide good energy storage density due to the high latent heat of fusion.

However, PCMs have very low thermal conductivity and this shortcoming prevent these materials from being widely used in practical application. Many techniques haven been suggested to solve this...
issue in order to maximize the heat storage capacity of PCMs [1]. Among them, inserting highly conductive metal structures into PCMs is one of the popular techniques to improve the overall thermal conductivity of a PCM based thermal storage enclosure [2]. Setoh et al. [3] experimentally investigated the cooling of electronics using a PCM based heat storage unit and n-eicosane was the applied PCM. They reported that the PCM based enclosure with embedded metal fins had great potential for the thermal management of mobile electronics and the implementation of this technique should have a judicious consideration on the PCM usage, fin number and power of heat source. Fok et al. [4] conducted experiments to characterize the functions of embedded metal fin structure on the heat transfer performance of a PCM based heat sink. They found that the melting rate of PCM can be accelerated by using metal fins to improve the heat spreading efficiency. In addition, they also mentioned that phase change heat transfer efficiency did not affected by the orientation of the internal fin.

Some fundamental numerical studies have been conducted to investigate the enhanced heat transfer mechanisms resulted from integrating conductive metal fins. Shatikian et al. [5] performed numerical studies to explore the PCM melting process in a heat storage unit with building partition metal fins. They found that the melting rate was accelerated by reducing fin spacing, and the convection heat transfer invoked by the liquid PCM cannot be ignored in the design where the partition fin spacing was wide. Ji et al. [6] conducted simulations to investigate the effects of internal plate fins with different inclination angles on the PCM melting behaviours in a PCM based heat sink. They claimed that properly inclined metal fins can give rise to strong natural convection in the molten PCM, which was in favour of achieving a uniform temperature within the PCM enclosure.

In literature, it is well known that planting conductive metal structures can enhance the heat transfer performance of a PCM based heat sink. Nevertheless, the issue of added volume and mass of metal structures need to be solved in an engineering point of view, so as to develop a light, compact and efficient thermal management system. Thus, in the current study, a topological structural optimization method was proposed to develop some innovative metal structures with less metal material but higher heat spreading capability for a PCM based heat sink. Afterwards, the thermal performance of the structure optimized PCM based heat sink was studied and compared with that of a conventional fin structured baseline design through 2-D transient simulations. The device temperature evolution curves, PCM melting contours and liquid PCM flow fields are compared for these two designs. This study could serve as an optimization design reference for passive thermal management solutions in industry applications.

2. Problem Descriptions

In this study, thermal management of a specifically configured electronic device is described in figure 1(a).

![Figure 1 Description of the problem in the present study.](image)

The heat generated from the electronic device is designed to be temporarily absorbed by a PCM (paraffin wax) based enclosure during operation. The heat conduction from the heat area (a length of 1.5 cm with $q = 50,000 \text{ W/m}^2$) to the PCM domain in the baseline design is assisted through the
application of a conventional aluminium plate fin structure and its detailed dimensions are described in figure 1(a). The volume fraction of the metal fin structure is 20% to the entire PCM enclosure and these metal fins are distributed uniformly in the PCM domain. The topological structure optimization algorithm proposed by Liu and Tovar [7] is used to develop innovative metal structure with optimized heat spreading capability based on the aforementioned PCM enclosure. In this study, thermal conductivity of the metal structure (Aluminium 6010, $\lambda = 202$ W/m·K) is about 1000 times as that of the PCM material ($\lambda = 0.2$ W/m·K as shown in Table 1). Hence, applying topological structure optimization to improve the heat spreading performance of the metal structure in the PCM enclosure is workable. Specifically, the structure optimization was conducted based on the specifics of the aforementioned problem where they are including the thermal conductivities of the applied materials, location and dimensions of the heat source, volume fraction of the material with a higher thermal conductivity ($\lambda = 202$ W/m·K in the present study), and the targeted heat spreading area (the PCM domain with $\lambda = 0.2$ W/m·K). As shown in figure 1(b), the final optimized tree shape structure is generated according to the restrictions as described above, and the final metal volume fraction is converged at 18.7% which is slightly less than the predefined value at 20%.

### Table 1 Properties of the PCM material

| Properties                        | Typical values       | Units       |
|-----------------------------------|----------------------|-------------|
| Melting temperature               | 34-36 (main peak: 35)| ºC          |
| Congealing temperature            | 36-34 (main peak: 35)| ºC          |
| Latent heat of fusion             | 186                  | kJ/kg       |
| Specific heat capacity            | 2                    | kJ/kg·K     |
| Density solid at 15 ºC            | 880                  | kg/m³       |
| Density liquid at 45 ºC           | 760                  | kg/m³       |
| Heat conductivity (both phases)   | 0.2                  | W/(m·K)     |

3. Numerical Model

As shown in figure 1, since the configuration of the aforementioned thermal management design is symmetric, computation cost was reduced by simulating only half of the configuration as depicted in figure 2. In this numerical model, the physics including the natural convection, volumetric expansion resulted from the phase change of PCM were considered. Specifically, compressible air was predefined to occupy a total volume of 20% in order to accommodate the expansion of PCM during the phase change process. Additionally, the orientation effects on the heat transfer performance of the PCM based heat sink was explored with considering the downward (Orientation 1) and upward (Orientation 2) orientations. The enthalpy-porosity approach [8] combined with the Volume of Fluid method [9] were adopted to characterize the melting process of PCM according to the following governing equations.

**Figure 2** Schematic of the simulation model.

Continuity equation,

$$\frac{\partial \rho}{\partial t} + \nabla (\rho \mathbf{u}) = 0$$ (1)
Momentum equation,
\[
\frac{\partial}{\partial t} (\rho \mathbf{u}) + \nabla \cdot (\rho \mathbf{u} \mathbf{u}) = -\nabla p + \mu \nabla^2 \mathbf{u} + \mathbf{F}_{ST} + \rho \mathbf{g} + S_M
\]  
(2)

Energy equation,
\[
\frac{\partial}{\partial t} (\rho H) + \nabla \cdot (\rho \mathbf{u} H) = \nabla \cdot (\lambda \nabla T) - \dot{Q} 
\]  
(3)

where, \( \rho, \mathbf{u}, p, \lambda, \) and \( \mu \) are the material density (kg/m\(^3\)), velocity (m/s), pressure (Pa), thermal conductivity (W/m K), and dynamic viscosity (N s/m\(^2\)), respectively.

In the momentum equation, \( \mathbf{F}_{ST} \) is the surface force acting on the interface, and \( S_M \) is the source term attributed to the change of porosity in the mushy zone:
\[
S_M = A \left[ \frac{(1-\beta)^2}{\beta + 0.001} \right] \mu
\]  
(4)

where, \( A \) is a constant that reflects the morphology of the mushy zone, and \( \beta \) is the liquid fraction at the melting front \((T_i > T > T_s)\) and it is defined by:
\[
\beta = \begin{cases} 
0 & \text{if } T < T_i \\
1 & \text{if } T > T_s \\
\frac{T - T_i}{T_s - T_i} & \text{if } T_i < T < T_s 
\end{cases}
\]  
(5)

Specifically, the dynamic viscosity of liquid PCM depends on the temperature and can be estimated as [10]:
\[
\mu = 0.001 \times \exp(-4.25 + 1790/T_i)
\]  
(6)

In order to capture the melting front, the phase indicator function \((0 \leq \alpha \leq 1)\) in the simulations is evaluated by the following equation,
\[
\frac{\partial (\alpha)}{\partial t} + \nabla \cdot (\alpha \mathbf{u}) = 0
\]  
(7)

Simulations were performed on a high-performance workstation with ANSYS Fluent 18.1 as the simulation platform. The energy and momentum equations were discretized using the 2\(^{nd}\) order upwind scheme. The pressure correction equations were solved by the PRESTO! Scheme. The pressure-velocity coupling was adopted by the SIMPLEC algorithm. A mesh independent study was conducted before numerical investigation and the final computational cells for the optimized design and baseline design models were 25300 and 18600, respectively. The time step in the current study was evaluated at 0.01s. At the initial stage, the temperatures of the solid PCM, aluminium structures were all fixed at 26.9°C.

4. Results and Discussion

4.1. Model validation

Prior to conduct the numerical investigation, a validation study of the proposed simulation model has been carried out to ensure its capability in simulating the heat transfer process during the melting of PCM. As shown in figure 3, comparison between the experiment [11] and simulation suggests that the proposed model is valid and feasible for the current study.

![Figure 3](image-url)  
Figure 3 Comparison between the experiments [11] and simulations.

4.2. Effect of thermal metal structures

In this study, the simulated period of each investigated case is selected at 2100s. At that moment, the applied solid PCM is calculated to be fully melted. As shown in figure 4, the evolutions of the heat source temperatures in four simulated cases are presented. Generally, it can be observed that there are
three distinct stages during the PCM melting for both PCM enclosures: the start-up stage (0–90s), main stage of PCM melting (optimized design 90–1350s, baseline design 90–1650s), and later stage of PCM melting.

At the start-up stage where the heat conduction heat transfer dominates, the thermal responses between these two PCM enclosures behaves differently when they operate under Orientation 1 and 2. For the baseline design, the heat source temperature under Orientation 1 rises much faster than that under Orientation 2. This is reasonable since under Orientation 2 the applied PCM seamlessly sits above the heated wall, by which the heat input from the heated area can be transferred into the PCM domain timely. Therefore, the sensible heat storage by the PCM is relatively fast under Orientation 2. Whereas, under Orientation 1, the heated wall and filled PCM are separated by the air zone which works as insulation to deteriorate heat spreading from the heated wall into the filled PCM. However, for the optimized design, there is no obvious difference displayed for the heat source temperatures achieved under Orientations 1 and 2. This could imply that the heat conduction through the optimized structure is efficient enough that the heat transfer across the air gap under Orientation 1 is almost immediate as that under Orientation 2. As melting progresses, the phase change heat transfer becomes dominating and the temperature of heat source under different orientations becomes further apart in the main stage of PCM melting (90 ≤ t ≤ 1350s). This could be attributed to the unique natural convections formed under different orientations as shown in figure 5.

![Figure 4](image1.png) Temperature profiles of heat source under different operation conditions.

![Figure 5](image2.png) Phase and flow fields in simulations at different instants.

For the baseline design under Orientation 1, the solid PCM starts melting first on the top since it is closer to the heat source. As the melting time increases, the melted PCM accumulates on the top and the un-melted PCM becomes further away as the melting front advances. Therefore, in order to melt
the rest solid PCM, the heat source temperature has to build up continuously to provide sufficient temperature gradient for melting. On the contrary, under Orientation 2, the melted PCM flows upward and the un-melted solid PCM falls down to the bottom to replace the melted solid PCM according to the density difference. As a result, a short conduction path between the heated wall and un-melted solid PCM is maintained consistently. Hence, in the main stage of PCM melting, there exists a long period where the heat source temperature is relatively stable under Orientation 2. Similar phenomena can be observed in the optimized design. It can be seen in figures 5(d-e) that the natural convection observed in the optimized design is much stronger than that in the baseline design under both orientations. Thus, apart from its better heat spreading effect, the intensified natural convection heat transfer could be another important factor that the optimized design has achieved a better heat transfer performance in this stage.

As melting progresses, the later stage of PCM melting is reached when the remaining solid PCM is limited and the PCM melting rate is significantly reduced as shown in figures 4 and 5. It is noteworthy that at the later melting stage, the baseline design outperforms the optimized design by achieving a lower heat source temperature. As shown in figure 5(f) at t=1800s, the remained solid PCM in the optimized design is much more than that in the baseline design. This could explain the poorer heat transfer performance obtained by the optimized design at the later stage of PCM melting.

5. Conclusions

For actual electronics cooling, the main stage of PCM melting is the primary phase for the applications of temperature control. Taking it as the main object of observation, it is obvious that the optimized design has clear advantage over the baseline design. At $q = 50,000\text{W/m}^2$ in the current study, the optimized design can achieve a maximum temperature reduction of 8°C under Orientation 1 and 2.5°C under Orientation 2 as compared to the baseline as shown in figure 4. Although the absolute values are not so impressive, considering the PCM melting temperature is 35°C, the reduction by the optimized design in the degree of superheat of the heat source is significant. For instance, under Orientation 2, the superheat degree of the heat source during the main stage of PCM melting is about 10°C from the baseline design. By adopting the optimized design the achieved superheat degree of the heat source is about 25% less, which is quite attractive in industry applications especially when the applied heat flux is higher than that in the current study. However, as indicated in figure 4, the baseline design can prolong the duration of the main melting stage (90–1650s) under Orientation 1 since the metal fins are distributed more uniformly in the PCM enclosure and hence PCM melts more completed in the main stage of PCM melting. The current study indicates that utilizing the topological structure optimization technique to develop innovative thermal metal structures for PCM based heat sinks is applicable in the passive thermal management solutions for mobile devices.

6. References

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