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The effect of pore size and porosity on thermal management performance of phase change material infiltrated microcellular metal foams

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HIGHLIGHTS

- Pore size and porosity of phase change material-microcellular metal foam were investigated.
- A smaller pore size results in a lower temperature at the heat source for a longer period of time.
- The effects were more pronounced at high heating and low cooling conditions.
- Net thermal conductivity doubled by reducing the pore size from 100 μm to 25 μm.

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ABSTRACT

The effect of pore size and porosity on the performance of phase change material (PCM) infiltrated metal foams, especially when the pore size reduces to less than 100 μm, is investigated in this study. A three dimensional finite element model was developed to consider both the metal and PCM domains, with heat exchange between them. The pore size and porosity effects were studied along with other system variables including heat generation and dissipation of the PCM-based thermal management system. It is shown that both porosity and pore size have strong effects on the heating of PCM. At a fixed porosity, a smaller pore size results in a lower temperature at the heat source for a longer period of time. The effects of pore size and porosity were more pronounced at high heat generation and low convective cooling conditions, representing the situation of portable electronics. There is an optimal porosity for the PCM-metal foam system; however, the optimal value only occurs at high cooling conditions. The net effective thermal conductivity of a PCM-microcellular metal foam system could be doubled by reducing the pore size from 100 μm to 25 μm.

1. Introduction

Thermal management systems based on latent heat storage of phase change materials (PCMs) can be widely used in a variety of applications, including microelectronics cooling, solar energy storage, and waste heat recovery [1–5]. The PCM absorb a substantial amount of heat during phase transformation while keeping the temperature nearly constant. This property is highly useful, e.g., to suppress temperature spikes due to the intermittent high power demand in portable electronics and to store a large amount of solar energy without significantly increasing the system temperature. However, PCMs in general suffer from an inherent low thermal conductivity, which can result in slow heat dissipation and an uneven melt front [5–8]. To energy storage systems, this means a slow charging and discharging rate, thus a low system efficiency. For microelectronics cooling, it can cause hot spots and significantly shorten the chip life.

A number of techniques have been developed to enhance the thermal conductivity of PCMs, including adding highly conductive nanofillers [6,9–12], embedding internal fins [13,14], and infiltrating the PCM in graphitic [8,15,16] and metal foams [5,7,17–19]. Infiltrating PCMs in metal foams recently attracted more attention due to the high isotropic thermal conductivity provided by the metal struts, which form a continuous network that spreads the heat more rapidly throughout the PCM matrix.

The performance of metal foam-based PCM systems has been studied both experimentally and numerically. Most of the existing research focuses on demonstrating the performance improvement over pure PCM-based thermal management systems and the free- and forced-convection heat transfer phenomena inside the porous

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media [5,20]. Few have considered the effect of foam morphology including pore size and porosity. In addition, the metal foams studied were all limited by commercial availability, with pore sizes ranging from 0.5 to 5 mm (5–40 PPI). Hong and Herling [21,22] experimentally studied the effect of surface area density on the performance of paraffin infiltrated aluminum foams with pore sizes from 500 μm to 2 mm. The results suggested that heating and cooling time of the system was affected by pore size at a fixed porosity. A smaller pore size resulted in a higher effective thermal conductivity of the overall system. Lafdi et al. [17] also conducted an experimental study with paraffin-infiltrated aluminum foams and found that both pore size and porosity affected the performance of the system. The aluminum foams used had a pore size between 600 μm and 5 mm. Tian and Zhao [19] performed similar experiments with copper foams with pore sizes from 800 μm to 2.5 mm. It was found, however, that the pore size effect was insignificant on the melting time of infiltrated PCM. Numerical models were also developed to predict the temperature profile of PCM metal foam systems [18,19]. These models had an origin in Boomsma and Poulikakos [23], where the effective thermal conductivity (k_e) of an infiltrated porous metal foam was estimated based on a tetrakaidecahedron pore model. The effective k_e was obtained by dividing a unit cell of the pore model into layers and applying the well-known parallel and series average models within and between the layers according to volume fractions of foam ligaments and infiltrated media. Although it contains the geometric information of a pore, the Boomsma and Poulikakos model does not consider the heat exchange between the foam ligaments and infiltrated PCM media.

With the advancement of fabrication techniques for microcellular metal foams [24], the effect of pore size and porosity becomes more interesting due to the extremely large surface area enabled by metal foams with pore sizes under 100 μm. It is also interesting to understand the performance of these microcellular metal foam PCM systems under various heating and cooling conditions in order to design an optimal thermal management system. The purpose of this study is to investigate through a modeling approach the pore size and porosity effects of PCM-metal foam systems, especially when the pore size is reduced to a few micrometers. A three dimensional (3D) finite element model is developed to represent both the metal foam and PCM domains, and therein the heat exchange between them. The pore size and porosity effects are studied along with system variables including heat generation and dissipation to cover various operating conditions of the PCM thermal management system. The effect of convection due to molten PCM flow inside the porous structure is also evaluated.

2. Modeling method

2.1. Heat transfer mechanisms

The heat transfer mechanisms considered in this study include heat conduction though the metal ligaments and PCM, phase change of PCM, heat convection in molten PCM, and convective cooling on the external top surface of the PCM-metal foam system. The conduction heat transfer is represented in Eq. (1),

$$\rho C_p \frac{\partial T}{\partial t} = \nabla\cdot(K\nabla T) + \dot{q} \tag{1}$$

where ρ is the density of the material, C_p is the specific heat capacity, T is the temperature, t is time, K is the thermal conductivity, and $\dot{q}$ is the heat generation rate. The phase change process of PCM can be represented using Eq. (2),

$$K_s\nabla T_s - K_l\nabla T_l = \rho L\frac{dX}{dt} \tag{2}$$

where L is the latent heat of fusion, X is the position of the melting interface, and s and l stand for solid and liquid states of the PCM. In order to account for the phase change behavior in Eq. (1), the specific heat of PCM, $C_{p(PCM)}$, can be defined over different temperature ranges, as shown in Eq. (3),

$$C_{p(PCM)} = \begin{cases} C_{ps}; T \le T_m \\ C_p + \frac{L}{\Delta T}; T_m < T < T_m + \Delta T \\ C_{pl}; T \ge T_m + \Delta T \end{cases} \tag{3}$$

where C_{ps} and C_{pl} are the specific heats of the PCM in solid and liquid state, respectively, T_m is the temperature when melting starts, and ΔT is the temperature range over which PCM melts.

The convective heat transfer within molten PCM is represented using Eq. (4),

$$\rho C_p\frac{\partial T}{\partial t} + \rho C_p\bar{u}\cdot\nabla T = \nabla\cdot(K\nabla T) \tag{4}$$

where $\bar{u}$ is the velocity field of the molten PCM. The flow of molten PCM due to density and gravity can be represented using Eq. (5),

$$\rho\frac{\partial\bar{u}}{\partial t} + \rho(\bar{u}\cdot\nabla)\bar{u} = \nabla\cdot\left[-p\bar{I} + \mu(\nabla\bar{u}) + \mu(\nabla\bar{u})^T\right] + g\rho\beta\left(T - T_{ref}\right) \tag{5}$$

where $\bar{I}$ is the identity matrix, g is the standard gravitational acceleration, ρ and β are density and coefficient of thermal expansion of the PCM, respectively, and T_{ref} is the reference temperature. The non-linear, transient heat transfer Eq. (1)–(5) need to be solved using a numerical procedure to determine the temperature profile in the PCM infiltrated metal foam.

2.2. The finite element model

The metal foam in this study was considered to have a face-centered-cubic (FCC) structure. The morphology of metal foams is dependent on the material and fabrication technique [25]. The use of polymer sphere template is one of the techniques to fabricate small pore size metal foams [26], which results in metal foams with pores arranged in the FCC arrangement. A geometric model of the metal foam was created by deducting 1/8 of a sphere at the eight corners and 1/2 sphere from the six faces of a solid cube. A unit cell of the metal foam in FCC configuration is shown in Fig. 1(a). The unit cell structure of the phase change material was obtained by taking an inverse of the metal foam structure, as shown in Fig. 1(b). The two unit cells can be overlaid to form a single unit cell containing both metal and PCM, which can then be replicated to form a PCM-metal foam model of various dimensions.

Finite element simulation of transport properties of metal foams has been previously conducted with a body-centered-cubic (BCC) packing structure [27]. At a sphere radius of 0.5 of the unit cell size, the BCC structure ceases to be completely open-celled, and the corresponding porosity at this condition is 0.94. BCC models with porosity lower than 94% over predicts experimental results, because of the larger volume fraction of solid in the closed-cell model. The FCC packing structure used in this study was generated with a constant pore size, such that models with porosities above 75% remained an open-celled structure. The same model structure has been used to predict the thermal conductivity of micro- and nano-cellular polymer foams with satisfactory results [28].