

A Parametric Study of Microporous Metal Matrix-Phase Change Material Composite Heat Spreaders for Transient Thermal Applications

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ABSTRACT

Metal-PCM (Phase Change Material) composite heat spreaders offer a combination of high effective thermal conductivity and high density heat storage capability that are desirable for transient thermal management applications, especially in mobile and wearable electronic devices. In this study, we propose fabrication of microporous metal matrix (MMM)-PCM composite heat spreaders through electrodeposition of metal over a template of PCM microcapsules that result in composites with metal volume fraction of ~ 0.26 . Effective thermal conductivity of these composites equal 74 W/m. K and 44 W/m. K for copper matrix and aluminum matrix respectively. Order of magnitude analysis for time response and thermal energy storage utilization performed on metal-PCM composites, as a function of metal volume fraction, shows that the optimal metal volume fraction range is 0.2-0.5 for the best thermal performance of metal-PCM composite heat spreaders. Furthermore, the temperature response of the MMM-PCM composite heat spreaders to a heat input showed that the use of PCM within a metal matrix can hold the device skin temperature below the ergonomic limit for long durations of time without sacrificing the time response.

KEY WORDS: Composite heat spreader, transient cooling, microporous metal matrix, phase change material, effective thermal conductivity

NOMENCLATURE

k	Thermal conductivity (W/m. K)
f	Volume fraction
c_p	Specific heat capacity (J/ kg. K)
C_p	Volumetric heat capacity (J/ m ³ . K)
ΔH	Latent heat of fusion of PCM (J/kg)
d	Length of the heat spreader (m)
b	Breadth of the heat spreader (m)
h	Height of the heat spreader (m)
t	Time (sec)
U	Storage capacity utilized (J)
MMM	Microporous metal matrix
MCM	Microporous copper matrix
MAM	Microporous aluminum matrix
PCM	Phase change material

Greek Symbols:

ρ	Density (kg/m ³)
α	Thermal diffusivity (m ² /s)

Subscripts:

m	Metal
p	Phase change material
e	Effective property
l	PCM in liquid state
s	PCM in solid State

1 INTRODUCTION

Electronic packaging in 3D integrated circuits and portable electronic devices pose new thermal challenges that can be addressed by the development of novel materials [1]. Thermal management in mobile and wearable electronic devices is a two-pronged problem with stringent requirements on both junction temperature (allowed maximum of 85 °C to 120 °C for device performance) and device skin temperature (ergonomic limit of 40 °C to 45 °C depending on the material of the enclosure [2]). The problem has become more intense in the recent years due to the increased functionality and prolonged usage of these devices. Due to the small form factors in such devices, we are limited to compact thermal technologies such as piezoelectric actuators and synthetic jets [2, 3] that provide active cooling in confined spaces. However, to ensure low power budget for thermal management (for prolonged battery life), effective passive solutions are most attractive.

The use of phase change materials (PCMs) in thermal technologies provide a promising solution to this problem, where the latent heat for phase transition is used for transient thermal cooling. PCMs provide both high energy storage density and small temperature gradients during the release and storage cycles [5]. Of the various PCMs, commercial paraffin waxes are among the least expensive material candidates, are chemically inert, and undergo negligible subcooling. In the past decade, several researchers have extensively studied PCM-based heat sinks with a wide variety of configurations for thermal management in electronic devices. Wang et al., showed that the orientation of the device has a limited effect on the thermal performance of PCM-based heat sinks [6], which makes them attractive for portable electronic cooling as

well. However, the low thermal conductivity of PCMs results in high thermal resistance for heat conduction and slow thermal response of these systems. This severely limits their applications, particularly for thermal management in mobile and wearable electronics where short time response of the thermal solution is desirable. To alleviate the problem, metallic fillers, metal matrix structures, and finned tubes are traditionally used to enhance the thermal conductivity of the composite. Vadwala used copper foam (with copper volume fraction of 5%) to enhance the thermal conductivity of paraffin wax and experimentally demonstrated 2.5 times more PCM utilization compared to the samples without the copper foam, while reducing the energy storage capacity by less than 5% [7].

In this work, we propose high thermal conductivity composite heat spreaders with thermal energy storage capabilities fabricated by electrodeposition of metal over a template of spherical microcapsules made from PCMs for transient passive cooling applications. We call the composites fabricated in this fashion microporous metal matrix (MMM)-PCM composites. In addition, we study the effective thermal properties and time response of metal-PCM composite heat spreaders at various metal volume fractions to determine optimal composition for the composites and compare the results to the composition of MMM-PCM composite heat spreaders.

2 STRUCTURE OF THE MMM-PCM COMPOSITES

The MMM-PCM composites proposed in this work can be fabricated through electrodeposition of metal [8] over a template of spherical microcapsules of PCMs. Heat spreaders fabricated using this method are free standing with PCM sealed within the metal matrix. When electrodeposition is used to grow metal around the PCM microcapsule template, the metal is deposited around each of the microcapsules, resulting in an optimal geometry for heat transfer from the highly conductive metal to the poorly conductive PCM material. This is due to the maximized metal-PCM surface contact area for a given microcapsule diameter. The size of the microcapsules can vary from sub-micron to a few hundred microns depending on the method employed to synthesize them [9], [10]. One of the many methods studied extensively in literature, including drop casting, spin coating, electrostatic deposition, and self-assembly, can be used to form microcapsule templates, where the microcapsules arrange themselves in a hexagonal close packed (HCP) structure in every method. This results in a packing fraction of ~ 0.74 , the highest packing fraction possible for spherical microcapsules of equal diameters. Higher packing fractions can be achieved if a variation in particle size is present. The packing fraction is, however, independent of the diameter of the spheres; it is only the normalized diameter distribution and the effectiveness of the method used to prepare the microcapsule template that ultimately affects the packing fraction. When the above-mentioned method is used for fabrication of the composites, the volume fraction of PCM in the resulting composite will be equal to the packing fraction of the

microcapsules in the template. Accounting for a small variation due to the formation of voids within the HCP structure of the template and a size distribution of the microcapsules, the volume fraction of metal and PCM will be within a few percent of 0.26 and 0.74, respectively.

A schematic of such a template with spheres of equal diameters and the resulting composite structure can be seen in Figure 1. This structure is created in COMSOL by mimicking the steps in the fabrication process, by creating a HCP template of spheres, overlaying a metal block on the template, and finally, trimming the edges. This structure is later used to determine the thermal conductivity of MMM-PCM composites in COMSOL.

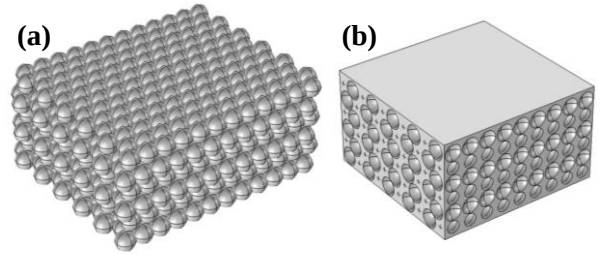


Figure 1. Schematic of the structure of MMM-PCM composites. (a) PCM microcapsule template with the spheres in HCP arrangement. (b) MMM-PCM composite obtained by overlaying metal over the microcapsule template and trimming the edges.

In this study, we consider copper and aluminum for the metal foam and paraffin wax P116, used in the literature by several other investigators, for the PCM. Relevant thermal properties of these materials are listed in Table 1. While the melting temperature and latent heat of fusion are obtained from ref [4], the other properties of P116 listed in the table are only representative values for paraffin waxes.

Table 1. Thermal properties of copper, aluminum and paraffin wax

		ρ (kg/m ³)	c_p (kJ/kg.K)	k (W/m.K)	T_m (°C)	ΔH (kJ/kg)
Copper		8933	0.39	400	-	-
Aluminum		2702	0.91	237	-	-
Paraffin Wax	(s)	900	2.5	0.21	47	210
	(l)	800	2.5	0.12		

3 EFFECTIVE THERMAL PROPERTIES

3.1 Thermal conductivity

As can be seen from the structure depicted in Figure 1, the MMM-PCM composite can be classified as one with internal porosity. The metal forms a continuous phase and the PCM microcapsules are dispersed inside the metal matrix. The Maxwell-Eucken equation (Eqn. 1) can be used to evaluate the effective thermal conductivity of such composites with one phase dispersed inside a continuous second phase.

$$k_e = k_m \frac{2k_m + k_p - 2(k_m - k_p)f_p}{2k_m + k_p + (k_m - k_p)f_p} \quad \dots (1)$$

Carson et al., compared the predictions from the Maxwell-Eucken equation with experimental results for various composites and showed that they are in good agreement for a wide variety of composites[11]. Figure 2 shows the variation of thermal conductivity of both the metal-PCM composites and the metal foam, with the volume fraction of the metal evaluated using the Maxwell-Eucken equation. It can be seen that the thermal conductivity of the metal-PCM composite is the same as the thermal conductivity of the bare metal foam, which indicates that the contribution of the PCM to the overall thermal conductivity of the metal-PCM composite is negligible. This is due to the three orders of magnitude difference between the thermal conductivity of the metal and the PCM for both copper and aluminum. The same conclusion can be drawn from Figure 3, which shows the simulated temperature and heat flux fields in a repeating unit of the MCM-PCM composite, obtained by applying a temperature gradient across the geometry shown and performing the simulation in COMSOL using the heat transfer module. As indicated by the heat flux lines, the path of the heat flow is primarily through the metal foam, and the PCM is effectively bypassed. This allows us to separate the heat transfer physics in the MMM and the phase change physics in the PCM at time scales that are higher than the diffusion time scale for the microcapsules. For a microcapsule of radius 100 μm , the diffusion time scale is on the order of 0.1 sec; this time scale decreases quadratically with decreasing microcapsule length scale. The short diffusion timescale of the microcapsules leads to short time response of the heat spreader, which in turn results in smooth charge and discharge characteristics of the heat spreader and can therefore be effectively used for transient cooling of electronic components.

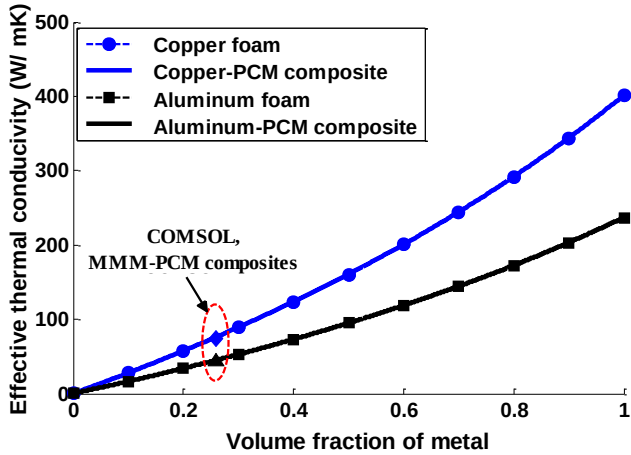


Figure 2. Variation of thermal conductivity of metal-PCM composites with volume fraction of the metal. Solid lines and circular and square markers are generated by applying the Maxwell-Eucken model to metal-PCM and metal-air respectively. Diamond and triangular markers enclosed within the dotted line are simulation results for MMM-PCM composites from COMSOL for copper and aluminum respectively.

Figure 2 also shows the thermal conductivity of MMM-PCM composites at a metal volume fraction of 0.26

(enclosed in the dotted ellipse), evaluated using COMSOL by applying a heat flux boundary condition to one of the faces of the structure shown in Figure 1b and evaluating the resulting temperature gradient. The simulation predicts an effective thermal conductivity of ~ 74 W/m. K for MCM-PCM composites and ~ 44 W/m. K for MAM-PCM composites, and the results match well with the thermal conductivity evaluated using the Maxwell-Eucken equation.

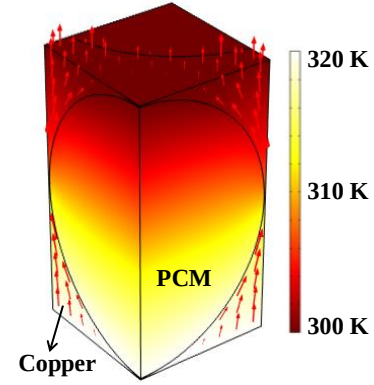


Figure 3. Temperature and heat flux fields in a repeating unit of the MCM-PCM composite.

3.2 Volumetric heat capacity and thermal diffusivity

Effective volumetric heat capacity and thermal diffusivity are calculated using Eqns. 2 and 3 respectively:

$$C_{pe} = f_m C_{pm} + f_p C_{pp} \quad \text{.....(2)}$$

$$\alpha_e = \frac{k_e}{C_{pe}} \quad \text{.....(3)}$$

where the volumetric specific heat, $C_p = \rho c_p$, is the product of density and specific heat. The effective thermal properties evaluated in this section are used for all subsequent analyses.

4 STORAGE CAPACITY AND TIME RESPONSE

An order of magnitude analysis is performed on the storage capacity utilization and the time response of the heat spreaders made from the copper-PCM and aluminum-PCM composites using the effective thermal properties evaluated in the previous section. A heat spreader of dimensions 10 cm x 5 cm x 3 mm ($d \times b \times h$) that is appropriate for a tablet is considered for the purpose of this analysis. The size of the microcapsules is assumed to be small enough such that the thermal properties of the heat spreader can be considered to be homogeneous, and the diffusion time scale of the microcapsules is small compared to the time scales of interest in the analysis. Microcapsules of radius ~ 100 μm sufficiently satisfy these conditions.

The maximum energy storage capacity during the PCM melting process is the product of the volumetric latent heat of

fusion of the PCM, the volume of the heat spreader, and the volume fraction of the PCM; it does not depend on the thermal properties of the metal matrix. As depicted by the dotted red and blue lines in Figure 4, the maximum energy storage capacity and the thermal conductivity of the heat spreader follow opposite trends. Therefore, the relative volume fraction of metal-PCM in the composites must be chosen appropriately for optimal time response and thermal storage capabilities. The storage capacity utilized at a given time depends on the volume through which the heat radiating from the center of the heat spreader diffuses and is calculated using Eqn. 4, where the thickness and width of the heat spreader reach the diffusion length scale limits first, after which the heat continues to spread lengthwise.

$$U = \Delta H \rho_{p,l} (2bh\sqrt{\alpha_{e,l}t}) f_p \quad \text{..... (4)}$$

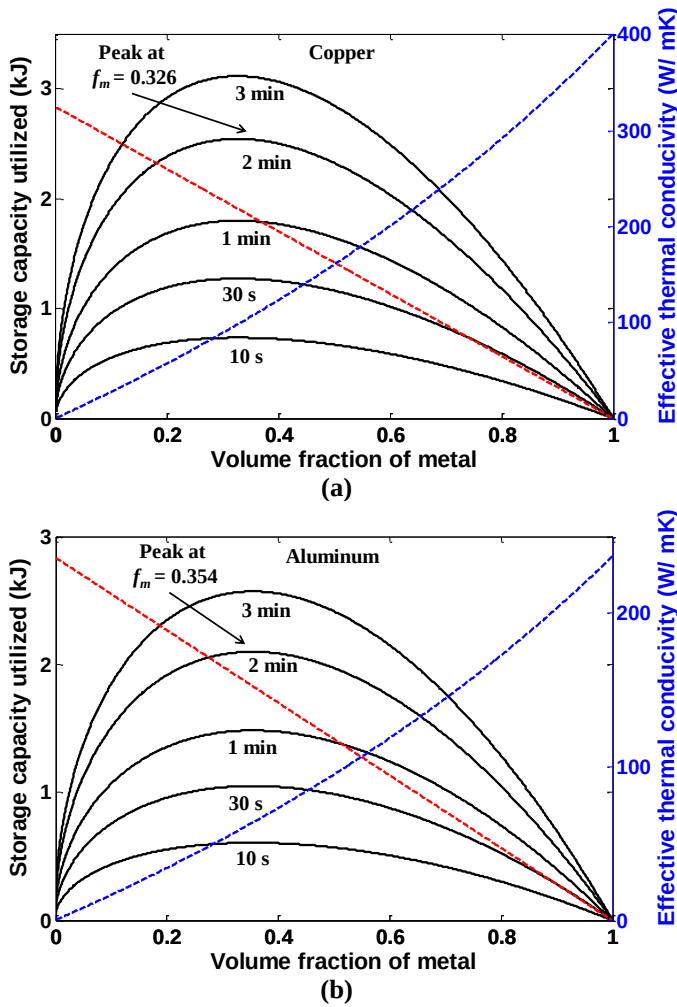


Figure 4. Maximum available storage capacity (red dotted line), storage capacity utilization with respect to time (black solid lines), and effective thermal conductivity (blue dotted line) of (a) copper-PCM and (b) aluminum-PCM composites. Storage capacity utilization is calculated based on diffusion length scale analysis using Eqn. 4, and effective thermal conductivity is calculated using the Maxwell-Eucken equation (Eqn. 1)

Figure 4 shows the storage capacity utilized as a function of the metal volume fraction for both copper and aluminum as the melting process commences. The points of intersection of the storage capacity utilization curves with the maximum available storage capacity line (red dotted line) indicate the times required to fully utilize the storage capacity for a given metal volume fraction. Although there is a maximum for the capacity utilization for any given time, at a metal volume fraction of 0.33 and 0.35, respectively, for copper and aluminum, the metal volume fraction range of ~ 0.2 -0.5 can be considered as the optimal range for thermal storage capacity utilization. However, within this range, lower metal volume fractions are preferable to maximize total available storage capacity. Figure 4 indicates that the available storage capacity is reached within a few minutes in the optimal metal volume fraction range. As expected, the time response of the copper-PCM heat spreader is faster than that of aluminum-PCM heat spreader. Figure 5 shows the mass of the metal-composite heat spreader and the maximum available storage capacity for the heat spreader dimensions under consideration. Based on the data in Figures 4 and 5, we conclude that while copper-PCM composites have better time response, aluminum-PCM composites are lighter for the same total storage capacity. Thus, the metal for matrix in these composite heat spreaders must be chosen based on the time response and weight requirements of the specific application.

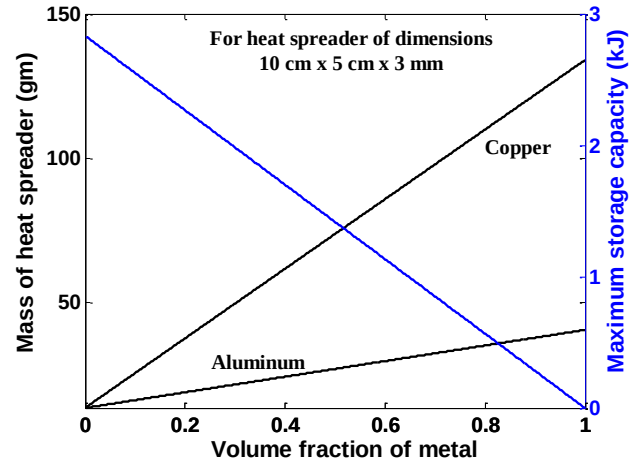


Figure 5. Variation of maximum available storage capacity (blue line) and mass (black lines) of the heat spreader with metal volume fraction.

A lumped capacitance assumption is made to evaluate the temperature responses of a solid copper heat spreader and a MCM-PCM composite heat spreader to a representative heat input from a tablet shown in Figure 6a, with the results plotted in Figure 6b. Predictions based on this assumption are valid for times greater than the diffusion time scales of the respective heat spreaders ($t > 25$ sec for the copper heat spreader and $t > 2$ min for the MCM-PCM heat spreader), and the condition is met adequately for the 25 min time scale considered. Heat dissipation from the heat spreader to its surroundings is neglected in this analysis. As seen in the Figure 6, use of the MMM-PCM composite heat

spreader limits the heat spreader temperature, and as a result, also limits the device skin temperature under the ergonomic limit for longer durations when compared to a heat spreader without phase change material. Additionally, the temperature of the MMM-PCM composite heat spreader after 25 min is 30 °C below the temperature of the copper heat spreader, which is substantial.

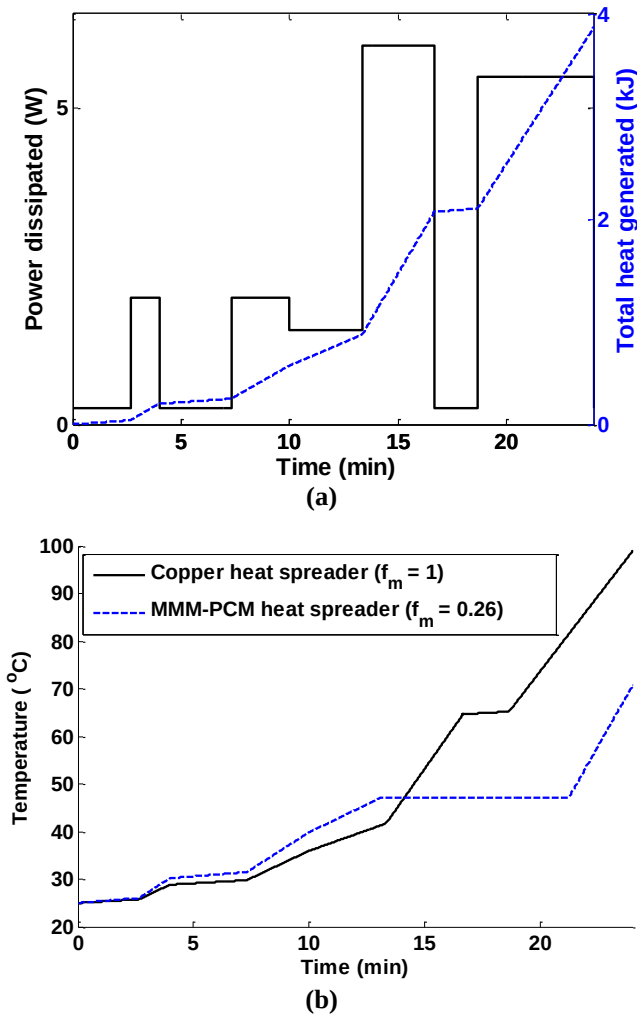


Figure 6. Temperature response of MCM-PCM heat spreader to a heat input. (a) Representative power profile of an electronic device while performing various actions and resulting heat generated during the prolonged usage. (b) Temperature response of a copper heat spreader and MCM-PCM heat spreader of dimensions 10 cm x 5 cm x 3 mm to the heat input in Figure 6a, calculated based on the lumped capacitance model.

5 CONCLUSIONS

A microporous metal matrix (MMM)-PCM composite heat spreader fabricated through electrodeposition of metal over a template of PCM microcapsules is proposed for transient cooling applications. An order of magnitude analysis is performed to understand the variation of time response and storage capacity utilization of metal-PCM composite heat spreaders with respect to metal volume fraction, and it is found that the MMM-PCM composition ($f_m = 0.26$) falls in

the optimal metal volume fraction range of 0.2-0.5. The MMM-PCM composite heat spreader temperature response to a heat input, predicted based on a lumped capacitance model, showed that it is very effective at maintaining the device skin temperature under the ergonomic limit during prolonged device usage. The thermal performance of MMM-PCM composite heat spreaders can be further improved through optimization of design parameters, including material choice and heat spreader geometry.

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