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Effects of melting temperature and the presence of internal fins on the performance of a phase change material (PCM)-based heat sink

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ABSTRACT

Experiments were conducted to investigate the effects of melting temperature and the presence of internal fins on the performance of a phase change material (PCM)-based heat sink for thermal management of electronics. At various intensive pulsed heat loads, comparisons were made between two PCMs with close thermophysical properties but different melting temperatures. The performance of an unfinned heat sink was also compared with its finned version. It was found that the use of a PCM with a higher melting temperature can extend a longer time of protection of the target devices from overheating, and that it also facilitates cooling for recovering the heat sink for subsequent operations. A lower melting temperature, however, is possibly favored because it may enable a prompt protection of the target devices. Selection of the PCM with an appropriate melting temperature depends strongly on the thermal conditions exerted. In contrast, employment of internal fins was shown to be always preferred as the performance of the heat sink can be improved, regardless of the PCM adopted. In the cases studied, the maximum temperature rise was lowered by up to 10 °C for the finned heat sink.

1. Introduction

The operation of devices involving heat generation requires a means by which the excess heat can be removed, as their performance, reliability, and safety depend significantly on temperature. This demand creates a need for efficient thermal management technologies. Of the several mesoscale technologies that have long been explored and practiced, the use of phase change materials (PCMs) is a passive cooling option [1]. PCMs are often incorporated into traditional active cooling heat sinks to improve their performance by taking advantage of the thermal energy stored as latent heat (of fusion) upon melting. The narrow temperature variations (nearly isothermal) during melting can also protect the target devices from overheating. In such *hybrid* heat sinks, the PCMs serve as an energy buffer that is capable of extracting heat from the hot spots on the devices before it can be dissipated efficiently to the surroundings.

The PCM-based thermal management technology was first proposed and tested for thermal control of avionics equipment [2]. Such technology is also suitable for cooling a variety of commercial electronic devices subject to periodic and pulsed heat loads, such as portable electronics, mobile phones, and power electronics. Of the concerns regarding design, operation, and optimization of PCM-based heat sinks that have been addressed extensively in the literature [3–36], one of the essential limitations on their performance has been identified to be the low thermal conductivity associated with common PCM candidates. Paraffins, for example, possess a thermal conductivity of the order of only 0.1 W/mK, which is much lower than that of the materials composing the devices such as metals, semiconductors, and ceramics. Efficient enhancement of the apparent thermal conductivity of PCMs has been realized successfully by introducing highly-conductive extended surfaces or fillers, metal fins/foams for example, into the PCM containers [37]. Performance of PCM-based heat sinks is able to be improved by accelerating their thermal responses (i.e., enhanced heat conduction) to heat loads of the target devices under protection. The presence of internal fins and their geometric optimization have been investigated both experimentally and

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Nomenclature

c_p	specific heat capacity (kJ/kg K)
k	thermal conductivity (W/mK)
L	latent heat of fusion (kJ/kg)
Q	heating power (W)
q''	heat flux (W/cm^2)
R	effective thermal resistance (°C/W)
T	temperature (°C)

Subscripts

cal	calculated
meas	measured
onset	onset of melting
pred	predicted
tar	target
∞	ambient

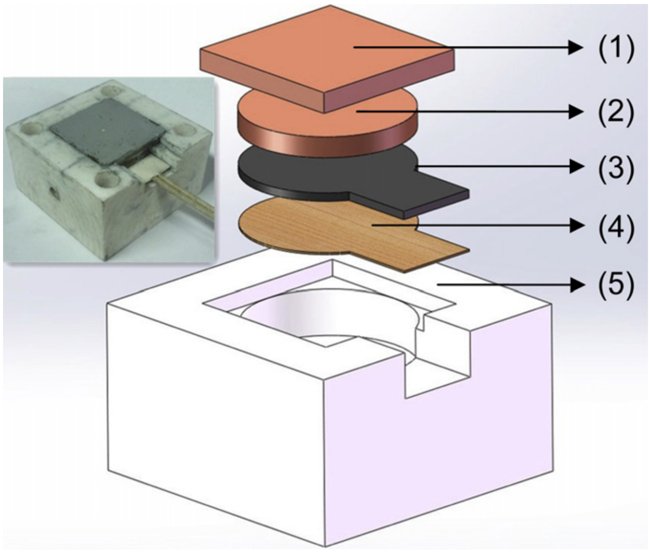

Fig. 1. Schematic diagram of the components of the heating unit with the inset photograph showing the assembly. The components are: (1) heat spreader, (2) round copper plate, (3) mica heater, (4) insulation pad, and (5) packaging.

numerically [20–22,24,25,27,30,31,33,36]. On the other hand, during operation of PCM-based heat sinks, melting (energy charging) is often dominated by natural convection. Strengthening natural convection, which accelerates the melting processes, can also improve the performance of PCM-based heat sinks. Hence, orientation of the heat sinks has been studied parametrically to identify its effect [18,19,32].

Besides the above-mentioned heat transfer enhancement attempts on system level, attention has also been paid to the effects of PCMs. Appropriate PCM candidates for thermal management of electronics should possess a melting point ranging from room temperature to below 100 °C. Selection of PCMs seems to be somewhat flexible because a variety of organic PCMs are available within this temperature range, which all have similar thermophysical properties (e.g., density, thermal conductivity, latent heat of fusion, etc.) except for the melting temperature. By fixing the other conditions, the effect of melting temperature on the performance of a PCM-based heat sink has been examined numerically [5,9,10,15]. Leoni and Amon [5] proposed a design criterion stating that a higher melting temperature, within the rational range, is preferred in considering the advantages of longer protection (melting) time and shorter energy discharging (re-solidification) time for cyclic operation. This simple conclusion, however, lacks of direct experimental verification.

Hence, this paper aims at examining experimentally the effect of melting temperature on the transient performance of a PCM-based heat sink for thermal management of electronics under pulsed heat loads. Two organic PCMs with different melting temperatures are tested. Experiments are performed on prototype heat sinks that are designed and constructed to also allow for examination on the effect of the presence of internal fins.

2. Experimental

2.1. Design of the heating unit and PCM-based heat sinks

In the present work, a heating unit resembling commercial CPUs for modern personal computers was designed and assembled. As shown in Fig. 1, the core component of the unit was a round mica-insulated electric heater (Minco HM6807, USA) having a diameter of 38.1 mm and a resistance of 2.0 Ω. One side of the mica heater was attached to a round copper plate (5.0 mm thick) with an identical size, while another side was attached to a pre-trimmed insulate pad made of ceramic fabric paper (3.2 mm thick, provided by Minco, USA), having a thermal conductivity of approximately 0.08 W/mK. This sandwich assembly was tightly bolted together by a screw through pre-reserved central holes of the three components, and was packaged in the cut out area of a bulk rectangular base made of Teflon®, having a thermal conductivity of approximately 0.25 W/mK. A square copper plate having a side of 40 mm and a thickness of 5 mm was also fabricated to serve as the heat spreader, which was attached to the round copper plate. A high-temperature (up to 240 °C) thermal grease (Cooler Master PTK-L01, TAIWAN) was applied to reduce thermal contact resistance between the two copper plates.

Such an integrated design of the heating unit allows for convenient installation and replacement of heat sinks. However, the thermal inertia of the heating unit is much higher than that of the real electronic devices, CPUs for example. In this study, a prototype heat sink was fabricated from a rectangular bulk of aluminum. As shown in Fig. 2a, the bulk material was machined to an uncovered container for accommodating PCMs. In addition to this unfinned one, another heat sink of identical dimensions but with internal cross-shaped straight fins was also machined by cutting from the bulk aluminum along with the outer frames of the heat sink, as shown in Fig. 2b. The dimensions of the heat sinks including the fins are also given in Fig. 2. It is noted that although sharp edges are shown in the design drawings of the heat sinks, the corners of the heat sinks were actually rounded off. The maximum volume of the unfinned heat sink was approximately 110 mL, whereas the effective volume of the finned heat sink was somewhat smaller due to the presence of the internal fins.

2.2. Experimental setup

The experimental setup was arranged by mounting a heat sink on top of the heating unit that was always horizontally placed, as shown in Fig. 3. The thermal grease, serving as the thermal interface material, was again applied in the gap between the heat sink and heat spreader. A total number of 18 thermocouples (TCs) were positioned at various places of the experimental setup. Sheathed type-K TCs (Omega TJ36-CASS, USA) with a diameter of 1.0 mm were utilized. Holes of a diameter of 1.2 mm were drilled on the round copper plate, heat spreader, and the heat sinks for accommodating the TCs. The arrangement of the TC installation is