



Transient performance of a thermal energy storage-based heat sink using a liquid metal as the phase change material



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HIGHLIGHTS

- A liquid metal is adopted as the PCM in a thermal energy storage-based heat sink.
- Transient performance of the heat sink is tested in comparison to an organic PCM.
- The liquid metal has a similar volumetric latent heat of fusion to the organic PCM.
- Outperformance of the liquid metal is found due to its higher thermal conductivity.
- Liquid metals are preferred when the system weight is less important than volume.

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ABSTRACT

In this Technical Note, the use of a liquid metal, i.e., a low melting point Pb–Sn–In–Bi alloy, as the phase change material (PCM) in thermal energy storage-based heat sinks is tested in comparison to an organic PCM (1-octadecanol) having a similar melting point of $\sim 60^\circ\text{C}$. The thermophysical properties of the two types of PCM are characterized, revealing that the liquid metal is much more conductive while both have nearly identical volumetric latent heat of fusion ($\sim 215\text{ MJ/m}^3$). By using at the same volume of 80 mL, i.e., the same energy storage capacity, the liquid metal is shown to outperform significantly over the organic PCM under the various heating powers up to 105.3 W/cm^2 . During the heating period, the use of the liquid metal leads to a remarkable extension of the effective protection time to nearly twice longer as well as a reduction of the highest overheating temperature by up to 50°C . The cool-down period can also be shortened significantly by taking advantage of the much higher thermal conductivity of the liquid metal. These findings suggest that liquid metals could serve as a promising PCM candidate for particular applications where the volume limit is very rigorous and the penalty in weight increment is acceptable.

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1. Introduction

The incorporation of phase change materials (PCM) in heat sinks, by taking advantage of the large amount of thermal energy absorbed during phase transitions, is one of the applicable mesoscale thermal management technologies for electronic devices [1]. The emergence of this technology dates back to the 1950s for the thermal management of aviation and spacecraft electronics [2], and has then been studied and implemented with application to

cooling of advanced microelectronics, Li-ion batteries and photovoltaic modules [3].

The system performance of PCM-based heat sinks has been extensively investigated for general-purpose or particular electronic devices, with the attention being paid to the variety of influencing factors, such as heating mode [4], geometric design [5], orientation [6], PCM selection [7], etc. Because of the temperature range of interest for cooling of electronics, the pertinent PCM candidates mostly belong to the organic family, e.g., paraffin wax. Despite a high latent heat storage capacity, an obvious shortcoming for such organic materials is the low thermal conductivity that significantly deteriorates transient heat transfer in PCM-based heat sinks. Thermal conductivity enhancement has been routinely sought for improving the performance of thermal energy storage

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systems with organic PCM. The use of highly-conductive extended surfaces (e.g., fins) is a natural solution to this issue [2]. Hence, parametric studies of fin configuration have been extensively performed to explore its effects on the system performance of finned PCM-based heat sinks [7,8]. An emerging solution is proposed by adding highly-conductive fine particles (e.g., carbon nanotubes and graphene) into the matrix PCM to form composite PCM with enhanced effective thermal conductivity [9]. However, since the loading of the additives, either in fixed form (e.g., fins) or free form (e.g., nanoparticles), should be reasonable, the relative thermal conductivity enhancement, and hence the system performance improvement, is limited.

In view of their inherently high thermal conductivity, the application of liquid metals, i.e., low melting point alloys [10], has been proposed as an emerging liquid coolant for the thermal management of electronic devices [11], which has been demonstrated for cooling of a computer chip [12]. In fact, the functionality of liquid metals has also been extended to serve as highly-conductive PCM for thermal management of electronic devices [13,14] within the temperature range comparable to organic PCM. In this Technical Note, in order to further prove this idea, the system performance of a PCM-based heat sink using a liquid metal will be tested in direct comparison to that with an organic PCM.

2. Experimental

2.1. Experimental setup and test conditions

A rectangular-shaped prototype heat sink, having outer dimensions of 80 mm × 80 mm × 30 mm and wall thickness of 3 mm, was fabricated with aluminum. As illustrated in Fig. 1, the design was greatly simplified from the existing heat sinks in the absence of any pin/fin structures. The PCM was enclosed in the rectangular cavity with a Plexiglas lid. The volume of the PCM applied was fixed at 80 mL. Another major component of the test setup was the heating unit, as shown in Fig. 1, which mimics the heat generation of electronics. A cylindrical rod made of copper, having a diameter of 40 mm and a height of 60 mm, was used as the heat source with four embedded heaters. The copper rod had an extended neck section with the diameter being only 20 mm. The height of this neck section was also 20 mm. The copper rod was wrapped up by a heavy insulation jacket made of glass fibers, while the whole unit was packaged in a cylindrical box made of Polytetrafluoroethylene (PTFE). The total power of the heating unit was controlled by selecting the number of heaters being powered. Each of these AC-powered heaters had a rated power of 120 W, and the

actual total power generated was measured by an AC power meter (see Fig. 1). By neglecting the heat losses through the lateral wall and bottom of the copper rod, the nominal heat flux through the round top end surface was estimated to be 28.8 W/cm², 56.1 W/cm², 83.6 W/cm² and 105.3 W/cm² with increasing the number of heaters from one to four.

The heat sink was directly mounted on top of the heating unit. A commercially-available thermal grease was applied between the bottom of the heat sink and the top end surface of the copper rod. Two T-type thermocouples (TC), as numbered in Fig. 1, were installed. The TC-1 was used to represent the surface temperature of the heat source, i.e., the cooling target temperature, while the TC-2 was mounted at the center of the PCM in the cavity. The TCs were calibrated to have an accuracy of ±0.2 °C prior to use, and the frequency for data acquisition was 2 Hz. A typical test run involved both heating and cool-down periods, corresponding to charging and discharging of the heat sink, respectively. The heating unit was turned on to provide a constant heat flux condition for a certain short time period, followed by a long enough free cool-down process after turning off the power. In order to have a reasonable total heat input, the heating time period was shortened accordingly with increasing the heating power. All experiments were carried out in an air-conditioned room with a temperature around 21 °C. Multiple test runs were performed for each case to ensure data reproducibility.

2.2. Thermophysical properties of the PCM

In view of the typical operation temperature of electronics (no greater 100 °C) [4,7], a liquid metal having a nominal melting point around 60 °C was adopted in this work. This melting temperature range was chosen by referring to the findings of a previous experimental study [7]. The liquid metal was a Pb–Sn–In–Bi alloy with the composition being Pb18%, Sn12%, In21% and Bi49%. A common organic PCM, 1-octadecanol (C₁₈H₃₈O), having a similar melting point was also adopted as a reference for comparison.

The thermophysical properties of the two types of PCM were characterized. The measurement results are presented in Table 1, where the averaged values with scattering were determined over at least three parallel tests for each case. First, the density in solid phase was measured via the Archimedes principle at 40 °C. Secondly, the melting point, latent heat of fusion and specific heat capacity were determined on a differential scanning calorimeter (DSC). The DSC tests were performed between 30 and 80 °C at a ramping/cooling rate of 5 °C/min. The typical DSC curves, both melting and crystallization, are compared in Fig. 2. The representative specific heat capacity in solid and liquid phases was obtained at 40 °C and 75 °C, respectively. Obviously, the melting peak for the liquid metal is much shorter than that for the organic PCM, which has an almost 10 times greater latent heat of fusion (per unit mass). However, because the density of the liquid metal is more than 10 times greater than that of octadecanol, its thermal energy

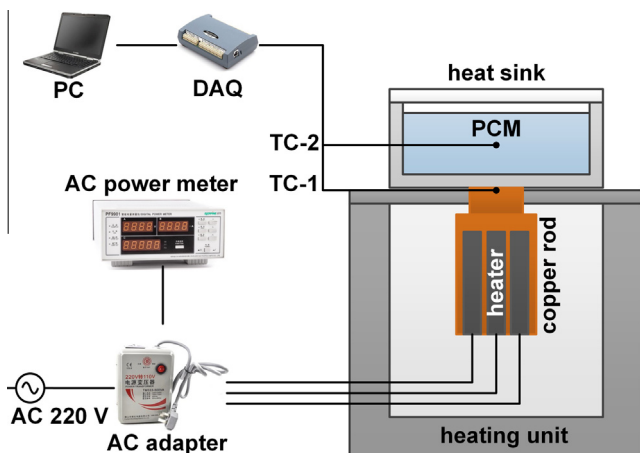


Fig. 1. Schematic diagram of the test setup of the PCM-based heat sink.

Table 1
The measured thermophysical properties of the liquid metal and organic PCM.

Property (unit)	Liquid metal	Octadecanol
Melting point (°C)	58.2 ± 0.2	55.6 ± 0.1
Density (kg/m ³)	9307 ± 16 (S)	894 ± 1 (S)
Specific heat capacity (kJ/kgK)	0.213 ± 0.007 (S)	2.053 ± 0.088 (S)
	0.211 ± 0.005 (L)	2.732 ± 0.084 (L)
Thermal conductivity (W/mK)	7.143 ± 0.028 (S)	0.273 ± 0.002 (S)
	10.095 ± 0.067 (L)	0.175 ± 0.002 (L)
Latent heat of fusion (kJ/kg)	23.4 ± 0.4	239.7 ± 2.5
Volumetric latent heat (MJ/m ³)	~217.8	~214.3

S and L in parentheses denote the solid and liquid phases, respectively.

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