International Communications in Heat and Mass Transfer 98 (2018) 155–162

Contents lists available at ScienceDirect

International Communications in Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ichmt

Experimental investigation on paraffin wax integrated with copper foam based heat sinks for electronic components thermal cooling

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ARTICLE INFO

Keywords:
Heat sink
Thermal performance
Electronic cooling
Thermal management
Metal foams

ABSTRACT

Owing to enormously high surface area and high thermal conductivity, copper foam based heat sinks for electronic cooling are investigated in this paper. Copper foam1 with porosity 0.95 and pore density 15 pores per inch and copper foam2 with 0.97 porosity and pore density 35 pores per inch are used to investigate the performance of heat sinks filled with phase change material (PCM). Various configurations of heat sink with PCM volume fractions 0.0, 0.6, 0.7 and 0.8 are investigated under heat load of 8–24 W to figure out the optimum performance of the heat sink. Experimental results revealed that base temperature of the heat sink is reduced as the volume fraction of PCM is increased. Anyhow, discharging process is not affected significantly. Furthermore, copper foam1 (0.95 porosity) exhibited better heat transfer both in charging and discharging as compared to that of copper foam2 (0.97 porosity). Maximum temperature reduction of 9.81% was found for copper foam1/PCM at 8 W and PCM volume fraction of 0.8 when it is compared with copper foam2/PCM composite. For the same porosity, maximum reduction in base temperature was observed for 0.8 volume fraction of PCM at 16 W heat input. Finally, it is concluded that copper foam1/PCM composite impregnated with 0.8 volume fraction is an optimized configuration of heat sink.

1. Introduction

In the past few years with the development of technology, electronic circuits attained more complexity due to compactness of the systems. As a result, these devices pose to high heat generation which declines the performance of equipment significantly. Moreover, the life of electronic equipment is adversely affected by over heat generation if not wiped out properly. According to US defense research, it was revealed that after temperature rise of 75 °C, failure rate of electronic component becomes exponential [1]. Similar kind of study also reported that 50% of the failures regarding integrated circuits are due to thermal concerns [2]. So, thermal failures can be reduced by 50% for every 10 °C decrease in temperature [3]. In the recent years, computers and robotics have gone through reasonable miniaturization while keeping its enhanced work load. Amount of heat generation depends on the number of applications running on computer and complexity of running program.

Many research studies have been carried out to address the huge heat generation in electronic components. In this respect, Harmand et al. [4] developed a complex and precise transient model for flat heat pipe (FHP) to predict the cooling of electronic devices. It was observed that FHP is more suitable as compared to solid plate for prolonged thermal cycling. Naphon et al. [5] performed experimentation for heat removal of central processing unit (CPU) against various working loads of CPU and observed the cooling effect of different coolant fluids. Pin fin geometries were used for higher heat transfer through heat sink. Behi et al. [6] investigated both numerically and experimentally the cooling effect of heat pipe assisted with phase change material (PCM) on electronic devices. It was noticed that cooling system provided 86.7% of required cooling. PCM contributed 11.7% of the produced cooling. Detailed review for electronic cooling using small heat pipes is carried out by Chen et al. [7]. It was revealed that heat pipes were proven to be good media for electronic cooling. Flat heat pipes were considered best among small heat pipes due to their geometric flexibility, high thermal conductivity and being light weight. Nanofluids due to their high thermal conductivity contributed well in electronic cooling [8–10]. Anyhow, because of continuous moving components and usage of electrical energy for fan and pump make it inefficient both technically and economically.

Thus, there is strong need to focus on passive methods of cooling. In this regard, phase change materials (PCMs) serve role of primary importance owing to high heat absorbing capacity. In the past decade, a lot of research studies have been conducted to sort out efficient usage and optimization of PCM based heat sinks. Major drawback of using

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https://doi.org/10.1016/j.icheatmasstransfer.2018.08.003

Nomenclature

I	Current
L	Length of heating surface
m_{PCM}	Mass of PCM
q	Heat flux
V	Voltage
V_S	Volume of heat sink
W	Width of heating surface

Abbreviations

PCM	Phase change material
PPI	Pores per inch
SEM	Scanning electron microscope

Greek symbols

ε	Porosity
ψ_{PCM}	Volume fraction of PCM

PCM based heat sinks is that it can absorb and release thermal energy at very slow rate due to very low thermal conductivity. Therefore, different techniques are employed to increase the thermal conductivity of PCMs thereby enhancing the heat transfer rate. Ashraf et al. [11] and Ali et al. [12] worked on optimization of various PCM based pin fin geometries for electronic cooling. Heat sinks were investigated at different heat loads ranging from 4 to 8 W with or without any PCM. Keeping the same geometry, inline and staggered arrangement of pin fins were experimentally studied. Staggered arrangement was observed to be more promising regarding cooling of electronic components. Similar type of study was also conducted by Srikanth and Balaji [13]. Study revealed the optimization of pin fin heat sink using discrete heating followed by Non-dominated sorting genetic algorithm technique. Results were validated by conducting experimentation which agreed good with theoretical values.

With the recent development in enhancing the thermal conductivity of the PCMs, metallic foams worked out efficiently due to their large surface area. Tian and Zhao et al. [14] numerically investigated the heat transfer in copper foam/paraffin composites and concluded that heat transfer rate was raised 3–10 times that of pure paraffin depending on porosity of foam. Zhao et al. [15] investigated the copper foam/PCM composites with low melting point organic PCMs and high temperature hydrated salts of Calcium and Sodium and revealed that heat transfer rate was enhanced 4 times that of pure PCMs. Zang et al. [16] performed numerical and experimental investigations to determine the thermal properties of aluminum foam/paraffin composites with porosity of aluminum foam 0.9. Investigations revealed the 1.16 times reduction in temperature. Results demonstrated that there was reasonable agreement between numerical and experimental results. Ji et al. [17] experimentally investigated the thermal properties of paraffin and Erythritol composites with graphite foams. Results revealed that thermal conductivity of the composite PCMs was enhanced 18 times that of pristine PCM. Laser flash technique was used to measure the thermal conductivity of the PCM/foam composite. Wang et al. [18] studied the PCM/foam based heat sinks with different porosity of foams to investigate the porosity effect of foams on thermophysical properties of PCMs for electronic cooling. Results illustrated that heat transfer rate was enhanced up to 2.88 times for composite PCMs. While thermal conductivity of the composite PCMs was enhanced to 26.78 W/m-K. Which was several times that of pure paraffin.

Expanded graphite is highly conductive low density and highly porous ($\varepsilon \geq 99\%$) material and is promising media used for composite PCMs [19]. Zhao et al. [20] performed experimental investigation to sort out the effect of expanded graphite on thermal properties of PCM. Charging and discharging spans were diminished by 4–6 times as compared to that of pure paraffin against 5–35 wt% expanded graphite. In another experimental study for passive electronic cooling, Nada and Alshaer et al. [21] revealed that base temperature for carbon foam/paraffin composite declined by 2.2 times. Karaipekli et al. [22] used 10 wt% expanded graphite to improve the heat transfer through PCM (Stearic acid). Results showed that thermal conductivity of the Stearic acid was raised 2.8 times thereby enhancing heat transfer rate. Furthermore, melting temperature of the PCM was also reduced.

Keeping in mind the above literature review, it comes into notice that a lot of research studies have been carried out to single out the performance of heat sinks. Anyhow, studies presented in the literature did not adequately describe the optimization of PCM/foam based heat sinks regarding fraction of PCMs which lead to cost inefficiencies. In this research article copper foams with porosity 0.95 and 0.97 are used to make its composites with paraffin wax for 0.6–0.8 volume fractions of PCM to investigate the optimum configuration of the composite. As electronic components at different operating load generate respective amount of heat so three heating levels are studied to discuss the various circumstances of heat generation.

2. Experimental setup

Heat sink with overall internal dimensions 100 × 100 × 25 mm^3 is used to perform experimental investigations with little dimensional tolerance. Walls of aluminum heat sink is provided with 3 mm thick acrylic sheets to make the walls insulated and to ensure one dimensional heat flow. Silicon plate heater (100 × 100 × 1.2 mm^3, 337 Ω, OMEGA) is pasted at the rear groove of heat sink with thermal grease to minimize the thermal resistance. Although thermal conductivity of thermal paste is of the order 9 W/mK but thickness of the thermal paste is kept $<$ 0.1 mm so thermal resistance is negligible according to $R = x/KA$. If thermal paste is not applied, air trapped may offer large thermal resistance. Heater is pretended to be heat generating electronic chip. Highly calibrated K-type thermocouples (0.5 mm diameter and 1 m length) are placed at different positions of heat sink to measure the temperatures. Data logger (Agilent 34972A) is used to record the measurements of thermocouples at interval of 5 s. Voltage to the heater is supplied through power supply (Keysight Technologies 6675A) with voltage range 0-120 V and 0-18A. To analyze the different heat generation rates, heater is supplied with three power levels i.e. 8 W, 16 W and 24 W using their respective voltages estimated via Ohm's law. Schematic diagram and actual experimental setup is illustrated in Figs. 1 and 2 respectively. While schematic diagram of heat sink is presented in Fig. 3.

2.1. Materials

Paraffin wax with melting temperature range 47–57 °C and two copper foams with porosity 0.95 (15 PPI) and 0.97 (35 PPI) are used to analyze the performance of the heat sink. SEM analysis reveals that purity of copper foams is > 99%. Paraffin wax is comparatively more viscous than others thereby reducing leakage problems. Actual image of copper foam1 and copper foam2 are shown in Fig. 4 and structure of the copper foam1 and copper foam2 by SEM is shown in Fig. 5.

To investigate the true properties of paraffin wax, DSC analysis is performed in an inert environment to avoid any chemical contaminations. Paraffin is heated and cooled at constant rate of 5 °C/min from 30 °C to 70 °C. Latent heat of paraffin is found to be 167 J/g while peak melting, onset and end set temperatures are noticed to be 53.5 °C, 46.4 °C and 56.9 °C respectively. DSC curve for paraffin wax is shown in Fig. 6. Thermophysical properties of paraffin and copper foams are