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Copper foam/PCMs based heat sinks: An experimental study for electronic cooling systems

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ABSTRACT

Copper foam (with porosity 97% and pore density 35 pores per inch) based heat sink without phase change material (PCM) and copper foam/PCM composites heat sinks are investigated to observe the behavior of operational time of heat sinks with respect to specific temperature both for charging and discharging. Paraffin wax, RT-35HC, RT-44HC and RT-54HC are used as PCM. Investigations are performed at heat flux of 0.8–2.4 KW/m^2 with a gap of 0.4 KW/m^2 uniformly distributed. PCM volume fractions of 0.68 and 0.83 are used in composites. Results indicated that at the end of 90 min charging, maximum temperature reduction of 25% is noted for RT-35HC/Copper foam at 0.8 KW/m^2 for PCM volume fraction 0.83. Afterwards, RT-44HC/Copper foam reveals maximum temperature reduction of 24% for 1.6 KW/m^2. RT-35HC/Copper foam is least efficient at 2.4 KW/m^2 which reduces the base temperature only by 5–7%. Maximum enhancement ratio in operation time is noticed as 8 and 7.7 for RT-35HC/Copper foam and RT-44HC/Copper foam respectively at set point temperature (SPT) of 40 °C and 60 °C for respective composites.

1. Introduction

In the present lifestyle, the use of electronic devices such as mobiles, laptops, iPad, computers and robotics has become integrated with our life. Without compromising on the performance of electronic devices, miniaturization of these devices ensued in large amount of heat generation. Safe limit of operating temperature varies depending upon circuit complexity. Anyhow, heat generation always reduces the life of electronic equipment. According to USA air force survey, 55% of electronic failures are caused by exceeded safe temperature limits [1]. Hosseineizadeh et al. [2] reported the increase in failure rate of electronic devices by 100% for the temperature rise of 10–20 °C. While for 1 °C temperature reduction results in decrease of failure rate by 4%.

Therefore, researcher have been focusing on cooling of these devices for many years. In this respect, both active and passive cooling has worked out. Generally, active cooling calls for direct contact of heat sink with lot of metallic fins with a fan arrangement so as to dissipate maximum heat. It also involves cooling through fluidic motion particularly nano-fluid in mini channel heat sink [3] with the help of some kind of pump arrangement thereby enhancing coefficient of heat transfer. In case of failure in pump or fan, system runs out of working for longer time. So, limitations exist in using active cooling technique.

Passive cooling technique like heat pipes [4] has no moving mechanism so there are less limitations to use it for cooling applications. In recent years, phase change material (PCM) is examined to be promising source used for passive cooling. Owing to its high heat of fusion, it can absorb huge amount of energy maintaining the constant temperature of the heat sink. PCMs have wide range with respect to its melting range, latent heat, volume expansion, density and thermal conductivity as profusion of literature is available on this [5–7]. Suitability of various PCMs depends on temperature control requirement of electronic equipment. Sharma et al. [8] distinguished PCMs as organic, inorganic and eutectic in many temperature ranges. PCMs with high latent heat (120–250 kJ/kg), high thermal conductivity (≥20 W/m K), high density (Above 1000 kg/m^3), corrosion resistant low cost and most importantly abundant are considered to be ideal. Previous research studies using same organic PCMs used in the present experimental study are depicted in Table 1.

Organic PCMs are most suitable due to their ease of availability, low cost, good compatibility with other materials [9,10], chemical inertness, recyclability and thermal stability [11]. Thermal stability of suitable PCM is very important as PCM has to undergo huge number of cycles during its continuous operation. Shukla et al.

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Nomenclature

C_P	heat capacity
I	current
K	thermal conductivity
L	length of heating surface
m_{PCM}	mass of PCM
q	heat flu
ΔT	temperature difference
T_C	congealing temperature
T_f	flash point
T_m	melting temperature
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
SPT	set point temperature
TCE	thermal conductivity enhancer

Greek symbols

ε	porosity
δ	pore density
ρ_{PCM}	density of PCM
ρ_{app}	apparent density
β	coefficient of expansion
ψ_{PCM}	volume fraction of PCM

[12] performed thermal cycling of few inorganic and organic PCMs and revealed that organic PCMs have better thermal stability than inorganic PCMs. Similarly, Sharma et al. [13] performed thermal analysis of Acetamide and paraffin wax for 300 cycles and found that paraffin wax is more stable PCM.

Researchers used different PCM based passive techniques for electronic cooling. Melting temperature of PCM is selected depending on the range of safe temperature limit. Hetsroni et al. [14] considered 50–60 °C as safe temperature limit for electronic components. While, Jajja et al. [15] reported the normal operating temperature range 60–100 °C for computer chips. Kandasamy et al. [16] experimentally investigated the transient thermal management of electronic circuits using PCM based heat sinks and indicated that PCM based sinks have strong potential to store large amount of heat during intermittent use of such devices.

Li et al. [17] and Tiari et al. [18] experimentally investigated the cooling effect of combined heat pipe and liquid metal phase change materials for electronics cooling at different heating loads. Authors reported that Combined PCM and heat pipe revealed the maximum operating temperature below 45 °C for 3468 s at 3.65 W and 600 s for 7.65 W which lies in safe limits as reported by [14]. Chang et al. [19] also performed an experimental study for electronic cooling via heat pipe using thermal resistance model. It was concluded that thermal resistance of condenser and evaporator was increased when heat load got over 120 W. Huang et al. [20] determined the cooling performance of thermoelectric water cooling device for electronic cooling at different heating loads both experimentally and theoretically. An optimum condition of below 57 W was proposed along with water cooling after effective cooling. Similar type of study was conducted by Liu et al. [21] and Cai et al. [22] who developed the model to analyze heat transfer through CPU using mini thermoelectric cooler.

Joybari et al. [23] numerically investigated the effect of metallic fins on PCM's thermal behavior. Enhanced heat transfer rate was attained for increased number of fins and length. Ashraf et al. [9] experimentally investigated the effect of PCM based pin fin geometries at heating load ranging from 4 to 8 W for passive cooling of electronic devices. Maximum operation time enhancement was revealed to be 9.28 times at 5 W. Anyhow, at all power levels, enhancement in operation time was noticeable. Setoh et al. [24] experimentally analyzed the cooling of mobile phones via n-eicosane based finned heat sinks and observed the decrease in peak temperature of the device. Similar kind of study was carried out by Tomizawa et al. [25] who used encapsulated PCMs with copper sheet for mobile phone cooling. PCMs encapsulation clogged the leakage of PCM. Ali et al. [26] and Arshad et al. [27,28] performed experimentation to investigate the performance evaluation of pin-fin geometries filled with n-eicosane and paraffin wax as PCM for cooling of electronic devices. Authors explored that round pin-fin geometries were found to be more effective. Moreover, PCM volume fraction 1.0 was proven to be most beneficial to keep the base temperature constant for maximum time. Baby and Balaji [29,30] observed the enhancement in operation time 18 folds for fined geometry filled with n-eicosane PCM as compared to that of n-eicosane based heat sink without fins. In another experimental study, authors turned the system toward optimization using hybrid technique of optimization and noticed the operational time enhancement ratio of 24 for heating load of 7 W. Uniform distribution of fins throughout the sink caused this effective enhancement. Pakrouh et al. [31] numerically investigated the optimization of pin fin heat sinks approaching Taguchi method. Optimum PCM fraction was noticed to be 0.61 and 0.82 for critical temperature 50 °C and 60–80 °C respectively. Fok et al. [32] also used finned heat sinks filled with n-eicosane PCM for cooling of portable electronic devices and concluded that finned heat sinks with PCM showed better performance than that of heat sink without fins. Regarding electronic devices cooling, a detailed study has been carried out by Sahoo et al. [33]. Authors discussed various methods of thermal management of electronic devices including finned heat sinks, porous materials and nano enhanced PCMs, etc.

Table 1
Previous studies using organic PCMs.

Reference	PCM	Composite media	Findings
[9]	Paraffins (RT-35HC, n-eicosane, RT-54HC, SP-31, RT-44HC)	Pin fins	Operation time of sink was enhanced 9 times
[28]	Paraffin wax	Pin fins	Enhancement ratio was achieved 2.64 times
[42]	Paraffins	Carbon foam	Base temperature was lowered by 2.2 times
[46]	RT-44HC	Expanded graphite	Thermal conductivity enhancement was noticed 32 times
[47]	RT-35HC	Copper foam	Melting time was reduced 11 times