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Experimental investigation of PCM based round pin-fin heat sinks for thermal management of electronics: Effect of pin-fin diameter

Adeel Arshad [a], Hafiz Muhammad Ali [b,*], Shahab Khushnood [b], Mark Jabbal [a]

[a] Fluids & Thermal Engineering (FLUTE) Research Group, Faculty of Engineering, University of Nottingham, Nottingham NG7 2RD, UK
[b] Mechanical Engineering Department, University of Engineering and Technology, Taxila, Pakistan

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ABSTRACT

This experimental study presents the parametric analysis for the round pin-finned heat sinks subjected to steady heat densities for effective and reliable cooling of mobile electronic devices. Phase change material (PCM) namely paraffin wax is adopted as energy storage material and aluminum made round pin-fins are selected as thermal conductivity enhancers (TCEs). A constant volume fraction of 9% of round pin-fins is selected with pin diameter of 2 mm, 3 mm and 4 mm and input heat flux was provided from 1.6 kW/m^2 to 3.2 kW/m^2 with an increment of 0.4 kW/m^2. Three volume fractions of $\psi = 0.0$, $\psi = 0.5$ and $\psi = 1.0$ of PCM amount are poured in each configuration of pin-finned heat sinks. A heat sink with no fin is chosen as a reference heat sink to quantify the effect of PCM and TCEs. The thermal performance of PCM filled heat sinks are analyzed to explore the effect of volumetric fractions of PCM, heat densities, pin diameter on latent heat phase, enhancement in operation time, heat capacity and thermal conductance. Three reference set point temperatures (SPTs) are chosen and results have evidenced that a 3 mm pin diameter heat sink has best thermal performance.

1. Introduction

Due to advancement of modern electronic packages, heat transfer augmentation technologies are needed to be improved for reliability of these modern packages. Consequently, various advance heat transfer techniques have been introduced for the cooling of electronic devices which may contain active and passive cooling. Heat, which is the main byproduct of any electronic device, generates inside the miniature and complex circuits of these devices. The key objective of a heat transfer augmentation technique is to enhance the thermal performance of system by enhancing the coefficient of heat transfer. Although, there are some typical cooling techniques like piezoelectric pump, air cooling, liquid cooling and heat pipes which remove heat efficiently [1,2]. However, latent heat thermal energy storage system (LHTESS) is now highly under research for passive cooling of electronic devices. A LHTESS has a capability to absorb large amount of heat inside it and to reject this heat in surrounding [3,4]. Phase change materials (PCMs), have the characteristics to absorb high amount of thermal energy during changing the solid-liquid interface [5]. PCMs have a large amount of latent heat of fusion, high specific heat, chemical stability under repeated melting and cooling modes, high volumetric density, little sub-cooling, small volume change, low vapor pressure and are non-toxic, non-explosive and non-flammable [6].

A fewer studies have been reported on parametric investigation of LHTESS. Wang et al. [7] carried out the numerical parametric investigation of PCM volume fraction, aspect ratio, temperature difference and PCM properties of PCM-based heat sink. The results concluded that a heat sink with PCM has better thermal performance and aspect ratio. Qu et al. [8] conducted the experimental work for passive cooling of electronics using parallel hybrid heat sink saturated with solid copper and pure paraffin wax. The results showed that lower base temperature of heat sink was achieved in case of metal foam-PCM then pure paraffin with a linear trend. Mahrous [9] carried out an experimental study based on PCM based sink and investigated the fins arrangement and number of fins. Heat sinks were partially filled with paraffin wax and effects of heating rates were observed. It was concluded that both heat rate and peak temperature reduced using PCM based heat sinks. The effect of thermal resistant for heat management of electronics using finite element analysis was reported by Grujicic et al. [10]. Authors explored the effect of surface roughness, applied pressure,

* Corresponding author.
E-mail address: h.m.ali@uettaxila.edu.pk (H.M. Ali).

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Nomenclature

TM	thermal management
TCE	thermal conductivity enhancer
SPT	set point temperature
T	thermocouples inside the PCM
W	thermocouples inside the side walls
H	thermocouples inside the base
HSU	heat storage unit
PCM	phase change material
V_S	total volume of heat sink
V_f	total volume of fins
t_{cr}	time to reach for a critical temperature
G	thermal conductance
Q	heat transferred
ΔT	temperature difference
T_{max}	maximum temperature after charging phase
T_{amb}	temperature at ambient condition
q	heat flux
c_{PCM}	specific heat
T_m	melting temperature of PCM

Greek symbols

γ	volume fraction of the TCE
ψ	volumetric fraction of PCM
υ_{PCM}	specific volume of PCM
ξ	enhancement ratio at TCE
ε	enhancement ratio at PCM
c	heat capacity
κ_{PCM}	thermal conductivity of PCM
λ_{PCM}	latent heat
ρ_{PCM}	density of PCM

mechanical and thermal properties for two PCMs and acrylic or silicon base tapes to cool the central processing unit. The results revealed that the use of thermal interface material lowered the overall base temperature.

Hajmohammadi et al. [11] carried out the numerical study of V-shaped fins/inserts embedded in a square heat generating cavity. The authors performed the geometric optimization of fins and concluded that V-shaped inserts had the remarkable heat transfer performance and reduced the base temperature of heat generating cavity. Further, to improve the cooling performance, Hajmohammadi et al. [12,13] presented the numerical study of forced convection cooling and proposed the correlation between the thick plate and heat source. Authors concluded that at low Reynolds number and low Prandtl number, temperature was reduced with the interface of plate. Hajmohammadi and his co-authors [14,15] presented the numerical investigations of laminar forced convection cooling of plate and round pipe under the array of heat sources of varying size of spacing. Najafi et al. [16] carried out the optimization study of plate and fin heat exchanger using genetic algorithm using air as a working fluid at both end of heat exchanger.

For PCM-based finned heat sinks for thermal management of electronic devices with a constant volume fraction of 9% of fins, an experimental study was carried out by Baby and Balaji [17]. An enhancement ratio of 18 was obtained for *pin-fin* heat sink and it was concluded that *pin-fin* heat sink had better efficiency than plate-fin heat sink filled with PCM. In extension of phase change cooling of electronic devices, Baby and Balaji [18] performed an optimization study by choosing three different volume fractions (4%, 9% and 15%) of *pin-fins*. The authors concluded that a *pin-fin* heat sink of volume fraction of 9% had the best thermal performance for cooling of portable electronic devices.

Jaworski [19] reported a numerical study using round *pin-fin* heat spreader filled with PCM. Heat transfer rates and thermal resistance were investigated under steady state conditions. The conclusions revealed that the use of PCM was effective in heat transfer through fins. TM of microelectronics using a platform filled with PCMs was investigated using experimental, numerical and analytical approaches by Tigner et al. [20]. The authors concluded that thermal response increased due to the decrease in surface area which transferred heat. An transient heating and cooling phase change cooling of electronics was experimentally carried out by Baby and Balaji [21] using plate-finned PCM filled heat sink. Authors conducted a detailed experimentation on different constant and intermittent heating loads. The results claimed that a plate matrix PCM based heat sink reduced the base temperature in comfort and reliable temperature conditions in intermittent operation mode.

Sun et al. [22] proposed a natural cold source with PCMs for cooling of telecommunications base stations of China. Mathematical model and then prototype of a latent heat storage unit was developed. Authors reported that a significant amount of energy was saved by latent heat storage unit to cool the telecommunications base stations. Alshaer and his co-authors [23,24] carried out the numerical studies for phase change cooling of electronics using carbon form/PCM/carbon nano tubes composite. Authors tested three different modules of pure carbon foam (CF)-20, CF20+RT65 and CF-20+RT65/Nano carbon tubes. It was revealed that RT65 and multiwall carbon nanotubes lead to 11.5% reduction in surface temperature of carbon foam of porosity less than 75%. Thermal performance of composite PCMs were also under observation employing carbon nanofillers in PCM in transient mode by Fan et al. [25]. Carbon nanotubes and graphene nanoplatelets were used to make composite PCM. The results showed that carbon nanofillers had undesirable results but carbon tubes and graphene nanoplatelets had much better thermal performance in transient conditions.

Kalbasi and Salimpour [26] developed and optimized the PCM based rectangular enclosures by changing the geometric parameters. Results revealed that for a rectangular enclosure with vertical fins, it was better to use wider enclosure than a square and thin one. Furthermore, authors concluded that the ratio of vertical fin thickness to horizontal fin had no significant effect. Nada and Alshaer [27] presented a detail parametric numerical study using different carbon foam structures of different porosities and different PCMs. The results showed that with decreasing carbon foam and PCMs thermal conductivities, increasing porosity and module height increased the module temperature. Additionally, it was revealed that transient temperature of module was decreased and time to approach any steady state temperature was delayed of a higher heat of fusion of PCM.

In recent past, Srikanth et al. [28] presented an experimental and numerical study of *pin-fin* heat sink filled with n-eicosane as a PCM with an objective to increase the charging time during operation and to decrease the discharging time during idle conditions. At constant heat flux and PCM amount, 40 various geometrical configurations of heat sinks were taken. Authors carried out the multi objective optimization using artificial neural network and predicted the optimum configuration of heat sink. In extension of phase change of cooling, Ahmed et, al. [29] experimentally carried out the TM of tablet computers using two PCM (*n-eicosane* and PT-