Thermal Management of Electronics Devices with PCMs filled Pin-fin Heat Sinks: A Comparison

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Abstract

The present paper covers the comparison of two different configurations (square and circular) *pin-fin* heat sinks embedded with two different phase change materials (PCMs) namely *paraffin wax* and *n-eicosane* having different thermo-physical properties were carried out for passive cooling of electronic devices. The *pin-fins*, acting as thermal conductivity enhancers (TCEs), of $2mm$ square and $3mm$ circular fin thickness of constant volume fraction of 9% are chosen and input heat fluxes from $1.2kW/m^2$ to $3.2kW/m^2$ with an increment of $0.4kW/m^2$ are provided. Two different critical set point temperatures (SPTs) $45℃$ and $65℃$ are chosen to explore the thermal performance in terms of enhancement ratios, enhancement in operation time, latent heating phase duration, thermal capacity and conductance. The results show that $3mm$ diameter of circular *pin-fins* has the best thermal performance in passive thermal management of electronic devices.

Keywords:

Phase Change Materials (PCMs), Thermal Conductivity Enhancers (TCEs), *pin-fin* Heat Sinks, *paraffin wax*, *n-eicosane,* Set Point Temperatures (SPTs)

Nomenclature

SPT	Set Point Temperature
TCE	Thermal Conductivity Enhancer
PCMs	Phase Change Materials
LHSU	latent heat storage unit
G	Thermal conductance (W/K)
T_m	Melting Temperature (℃)

Greek Symbols

γ	Volume fraction of the TCE
k_{PCM}	Thermal Conductivity of PCMs (W/mK)
C_{PCM}	Specific Heat of PCMs (kJ/kgK)
ρ_{PCM}	Density of PCMs (kg/m^3)
q	Heat Flux (kW/m^2)
λ_{PCM}	Latent Heat of PCMs (kJ/kg)
β	Thermal Capacity (kJ/K)

1-Introduction

So far, several technologies, active and passive, have been introduced for thermal management (TM) of portable electronic devices [1-4]. Previously, active TM techniques had limitations of bulky volume, noisy, more power consuming, more maintenance cost and time which eventually leads towards the inefficiency and unreliability of operation of electronic devices [5, 6]. In last few years, invention of passive cooling technologies introduced a new direction of TM of electronics using phase change materials (PCMs) and various thermal conductivity enhancers (TCEs) [1, 7-9]. Currently, Li et, al. [10] carried out the numerical study of a PCM filled double glazing to determine the thermophysical properties of PCM for the application of thermal energy storage. These passive cooling techniques although have taken a remarkable interest in the sight of researcher and as well as industrialist which have the tendency to compensate of all the limitations of active cooling technologies with increase in operation duration of electronic devices under user comfortable operating conditions [11-13]. However, there is the need of an optimum passive cooling device which will operate on critical design limits and enhance the operation time. In continuation of this, several studies of latent heat storage unit (LHSU) comprises of finned heat sinks as TCEs and PCMs have been reported yet [14-16]. Till yet, various configuration of fins such as square, circular, rectangular, plate, elliptical, triangular have been investigated both experimentally and numerically, however, the mostly commonly investigated *pin-fin* configuration was square [17-21].

Soodphakdee et, al. [17] conducted numerical study of inline and staggered circular, inline and staggered square, staggered elliptical, staggered and parallel plate-fins heat sinks. Authors concluded that staggered *plate-fin* showed the best heat transfer performance for provided pressure gradient and air flow rate. Nayak et, al. [22] presented the numerical model of matrix -type, plate-type, rod-type thermal storage unit and found that rod-type fins performed better than in the rest of all. Jaworski [23] performed numerical study of a heat spreader made of pipes for electronics cooling. Author concluded that heat spreader had the capability to keep the temperature below 50℃ of the microchips and protected the microprocessor from overheating while overloading of input power. Further, inclusion of heat spreader with PCM showed the excellent distribution of heat transfer in phase transition of PCM. Saha et, al. [24] carried out an optimum study for plate-fins and pin-fins TCEs of varying volume fractions of 0%, 2%, 8%, 18% and 27%. The authors concluded that 8% *pin-fin* heat sink with *n-eicosane* has the best thermal performance. Tan and his co-authors [25-28] conducted the experimental studies of *plate-fin* PCM filled heat sinks of no fin, three number and six number of fins under power input of 3W to 5W and found that six numbers of *plate-fin* heat sink had efficient heat transfer performance from heat sink base. Baby and Balaji [29] firstly conducted experimental study between plate fin and square fin PCM based heat sinks and found square *pin-fin* heat sink dominated than *plate-fin*, further the same author in [30], they conducted an optimization study using GA-ANN and concluded that a 9% of square *pin-fin* configuration performed better in the rest of 4% and 15%.

Baby and Balaji [31] then carried out experimental optimization study of varying volume fraction of plate-fins PCM filled heat sinks. The authors concluded a fin thickness of 1.42mm having 15% volume fraction of *plate-fin* had the best thermal performance.

Suresh et, al.[32] conducted experimentally the comparison of four different configurations of heat sinks (empty, rectangular, square and circular) filled with paraffin wax. It was found that circular *pin-fins* performed better heat transfer characteristics. Similarly, Mahmoud et, al.[33] carried out experimental study of parallel and cross *plate-fin* of six different cavities and compared with honey comb structure heat sink and found honey comb structure gave more efficient thermal performance. Gharbi et, al. [34] conducted experimental comparison of four configuration of pure PCM, PCM in silicon matrix, PCM in graphite and PCM with plate-fins. It was found that graphite matrix with PCM had more heat transfer capability than the silicon matrix with PCM, moreover, long copper plate-fins showed the better enhancement of heat transfer from the heat sink base resulting lowering the heat sink temperature for a longer duration. Pakrouh et, al. [35, 36] performed a numerical parametric study PCM based square configuration *pin-fin* heat sinks. Taguchi method was adopted and parameters of number of fins, fins height, fin thickness and base thickness. Currently, the parametric investigations of square pin-fins and circular pin-fins heat sinks were presented by Arshad et, al. [37] and Ali and Arshad [38] respectively. The authors concluded that $2 \times 2mm^2$ and $3mm$ diameter had the best thermal performance individually.

From above aforementioned studies, present experimental study presents a combined comparison between $2mm$ square and $3mm$ circular configurations pin-fins, acting as a TCEs, heat sinks of volume fraction of 9% resulting different number of fins, filled with two different PCMs namely *n-eicosane* and *paraffin wax* having different thermo-physical properties under a range of input heat fluxes to quantify the thermal performance of passive cooling LHSU. This comparison will ultimately provide the better picture to the industrialist for the selection of manufacturing process and cost estimation for the mass production of novel passive technology for electronic gadgets.

2-Experimental Facility

The schematic and line diagram of experimental facility, used for current study makes up of different components, are shown in Figure 1a and 1b, respectively. There are four major parts include DC power supply [39] (Keysight Technologies 6675A, 120V/18A) with voltage and current accuracy of 0.04% + 120 mV and of 0.1% + 12 mA respectively, latent heat storage unit (LHSU) containing high thermal conductive finned heat sinks filled with PCMs having *pin-fins* configuration of square and circular, Data Acquisition System (Agilent 34972A, USA) and laptop to get analog data through data acquisition system software copy righted by Agilent Technologies, Inc. Pin-fins which are acting as TCEs, have fin size of $2 \times 2mm^2$ (square cross-section) and $3mm$ diameter (circular cross-section) are used having constant volume fraction of $\gamma = 9\%$ to the overall dimension of heat sink. The volume of TCE is denoted by γ, which is the *ratio of volume of fins to the total employed volume of the heat sink*. Earlier, Baby and Balaji [30] carried out the optimization and found that a *pin-fin* heat sink of $\gamma = 9\%$ has the best thermal performance. Additionally, Arshad et, al. [37] and Ali and Arshad [38] carried the experimental studies and concluded that a *pin-fin* heat sink with $\gamma = 9\%$ has the best heat transfer characteristics filled with PCMs. The current study is the next step of previous experimental studies [37, 38], which further focuses on the comparison of obtained optimum configuration of square and circular *pin-fins* heat sink. The PCMs used in current study are *n-eicosane* [40] and *paraffin wax* [41], having melting temperatures of $36.5℃$ and $56 - 58℃$ respectively. The material of *pin-fins* is Aluminum (Al-T6-6061) and overall dimensions of heat sink are $114 \times 114 \times 25mm^3$. To record the temperature variations at different points on the heat sinks, highly precision K-type (Omega, $0.5mm$ wire diameter) thermocouples are used and discrepancy error is obtained $\pm 1℃$. Calibration is carried out using ASTM standard [42] from a range of $0 - 100℃$. To mimic the heat generation, a silicon rubber plate heater of dimension $100 \times 100 \times 1.14mm^3$ by OMEGALUX (SRFG-404/10-P-230) is adhered to the heat sinks base. A range of input constant heat densities from $1.2kW/m^2$ to $3.2kW/m^2$ with an increment of $0.4kW/m^2$ is supplied through plate heater. A details description of experimental facilities, thermos-physical properties of PCMs, see Table 1, TCEs and date reduction can been found from the previous studies of same authors [37, 38].

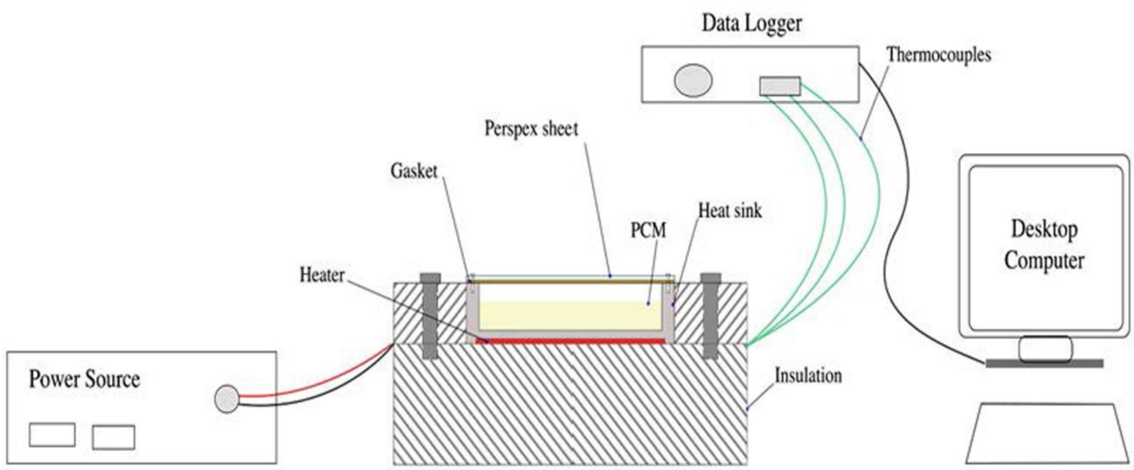

Figure 1a-Shematic diagram of experimental setup.

Table 1-Material Properties used in present study.

Material	k_{PCM} (W/mK)	C_{PCM} (kJ/kgK)	λ_{PCM} (kJ/kg)	T_m (°C)	ρ_{PCM} (kg/m^3)
Paraffin Wax	0.167 (Liquid)	2.8	173.6	56-58	790(Liquid)
	0.212(Solid)				880(Solid)
n-Eicosane	0.160 (Liquid)	2.2(Liquid)	237.4	36.5	780(Liquid)
	0.40(Solid)	1.9(Solid)			820(Solid)
Aluminum	202.37	0.871		660.37	2719
Rubber Pad	0.043	1.23		-	2500

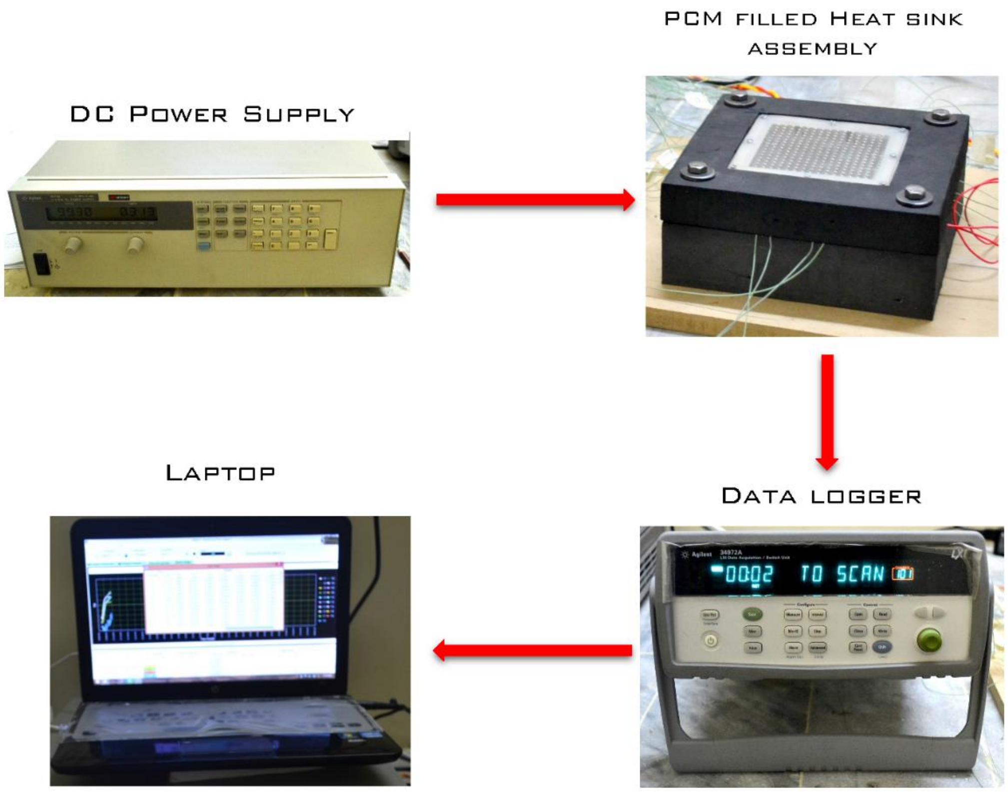

Figure 1b-Line flow of experimental facility.

3-Results and Discussions

The results are incorporating the geometrical and thermally comparison of $2mm$ and $3mm$ *pin-fins* heat sink embedded with PCMs *paraffin wax* and *n-eicosane*. The details are following in different sections to explore the thermal characteristics of both *pin-fins* geometries heat sinks.

3.1-Comparison of Heat Sinks base temperatures

The comparison of heat sinks base temperatures (recorded by the thermocouples H1, H2 and H3) for input heat fluxes of $2.0kW/m^2$ and $2.8kW/m^2$ are shown in Figure 2a-2b for PCMs *paraffin wax* and *n-eicosane*. In both figures, it can be seen ultimately that the $3mm$ circular configuration *pin-fin* heat sink leads to lower the base temperature significantly in comparison of $2mm$ square configuration *pin-fin* heat sink particularly in case of *paraffin wax* but closely for *n-eicosane*. However, the closer look at the peak temperatures reveals that $3mm$ *pin-fin* heat sink has maximum and best thermal performance for passive cooling of electronics embedded with PCMs. The temperature curves are overlapping initially for both PCMs, in both figures, however for *paraffin wax*, 3*mm* thick round *pin-fin* clearly manifests better heat transfer than 2*mm* fin thickness square *pin-fin*. The uniform temperature distribution from heat sink base to PCMs through fins is solely depends on number of fins and pitch of fins (the fin spacing in stream-wise, span-wise and diagonal directions).

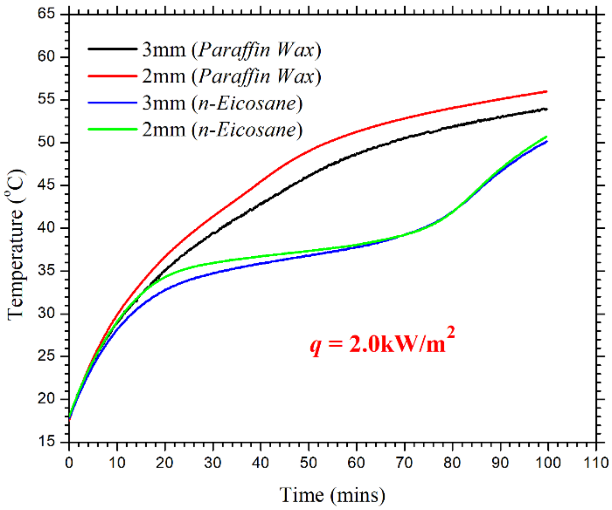

Figure 2-(a)

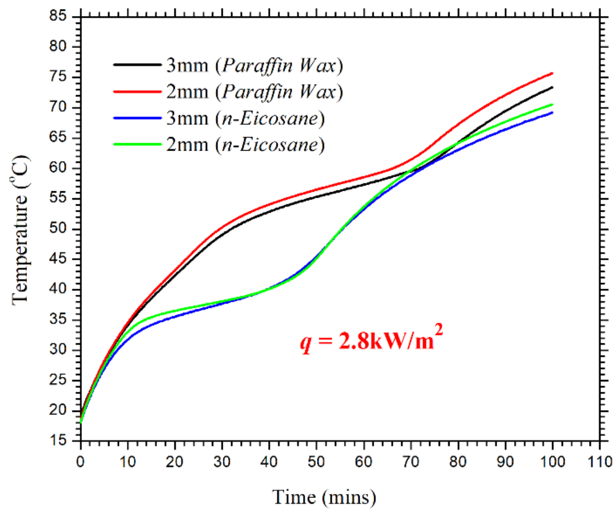

Figure 2-(b)

Figure 2-Comparison of heat sinks base temperature for paraffin wax and n-eicosane. (a) $q = 2.0kW/m^2$ *(b)* $q = 2.8kW/m^2$

3.2-Comparsion of Latent Heating Phase duration

The comparison of latent heat phase completion time is shown in Figure 3. The range of input heat fluxes are provided from $1.2kW/m^2$ to $2.8kW/m^2$ with an interval of $0.4kW/m^2$. The comparison of 3*mm* circular and 2*mm* square cross-sectional thick *pin-fin* heat sinks clearly evidences that the 3*mm* thick circular *pin-fin* heat sink leads from the 2*mm* thick square *pin-fin* configuration heat sink to enhancing the latent heat phase duration. The two extreme, maxima and minima, latent heating phase completion times of 141mins and 36mins are obtained at $1.2kW/m^2$ and $2.8kW/m^2$ input heat densities for 3*mm* thick circular *pin-fin* heat sink. The enhanced latent heating phase duration is because of optimum fins distribution which transfer the internal generated heat more uniformly through fins without causing local overheating the heat sink base.

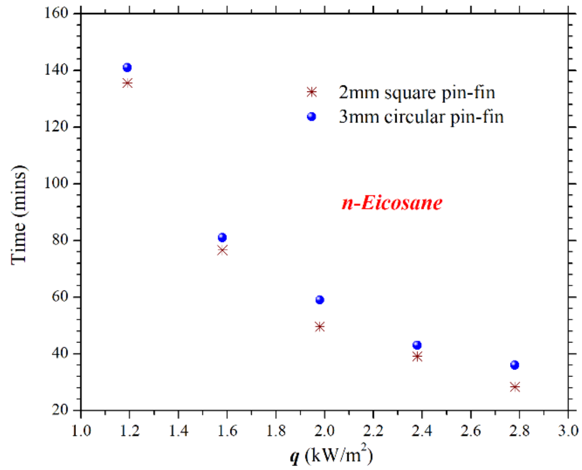

Figure 3-comparison of latent heating phase completion time.

3.3-Comparion of Enhancement in Operation time

The thermal performance of both tested *pin-fin* heat sinks is terms of enhancement in operation times is presented in Figure 4a-4b for employed PCMs, *paraffin wax* and *n-eicosane* respectively. Operation time, actually is the maximum operating duration at which the cooling device can sustain its work operation under reliable conditions without causing any harm and losing its efficiency. In current experimentation, two SPTs 65℃ and 45℃ are chosen as per melting temperatures of *paraffin wax* and *n-eicosane*, given in Table 1, to compare the time taken by $3mm$ circular and $2mm$ square fin thickness heat sinks to reach at these SPTs. The results shown in both Figures it can be clearly evidenced that the $3mm$ thick *pin-fin* heat sink of circular cross-section takes more time to reach for either of SPT = 65℃ or SPT = 45℃. This shows that a *pin-fin* heat sink of $3mm$ fin diameter has maximum tendency to store heat, generated inside the electronic device, and transfer it atmosphere which eventually leads to cool down the electronic device temperature in comfortable zone for end users.

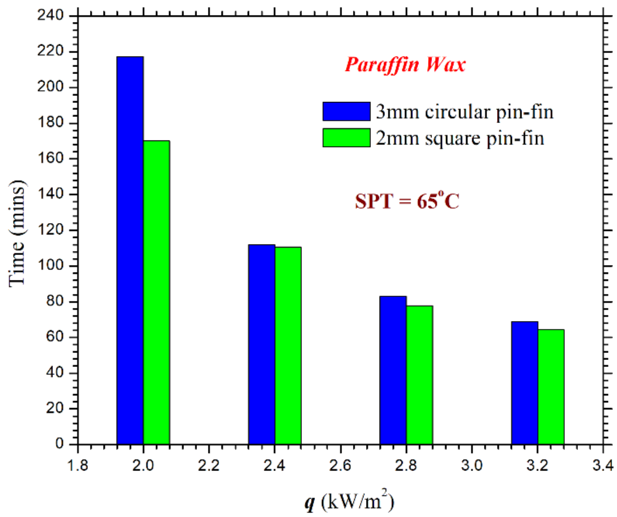

Figure 4-(a)

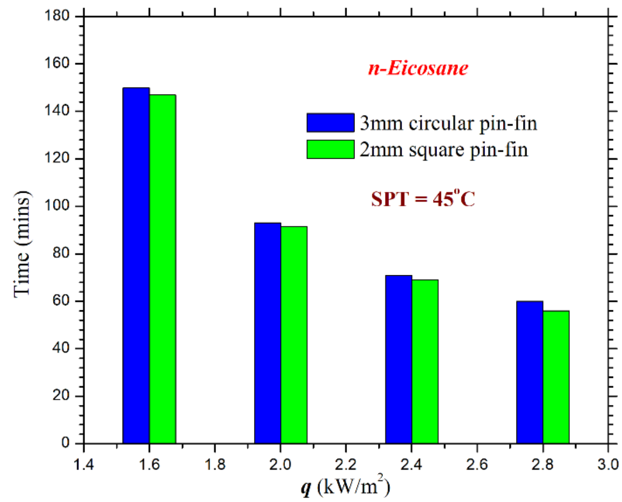

Figure 4-(b)

Figure 4-Comparison of enhancement in operation time. (a) $SPT = 65℃$ *(b)* $SPT = 45℃$.

3.4-Comparion of Thermal Capacity and Thermal Conductance

The comparisons of thermal properties (i.e. thermal capacity and thermal conductance) of $3mm$ and $2mm$, circular and square configuration respectively, *pin-fin* heat sinks are presented in Figures 5a-5b and Figure 6. A higher thermal capacity reflects that the system needs higher thermal energy to rise its temperature which eventually enhance the cooler time in operation mode. The maximum thermal capacities of $2.24kJ/K$ and $2.90kJ/K$ are obtained for $3mm$ thick circular *pin-fin* heat sink for *n-eicosane* as a PCM at input heat flux of $2.0kW/m^2$. However, for *paraffin wax* at $2.0kW/m^2$, a thermal capacity of $3.08kJ/K$ is found for $3mm$ thick circular *pin-fin* heat sink. Similarly, from Figure 6, the thermal conductance of $6.95 \times 10^{-1}W/K$ and 5.69×10^{-1} are obtained for *paraffin wax* and *n-eicosane* respectively in case of $3mm$ thick circular *pin-fin* heat sink. Thermal conductance which is heat transfer rate per unit temperature difference from the surface of PCM filled heat sink to the ambient conditions. From figures 5a-5ba and 6, it is revealed that the best thermal performance of $3mm$ circular *pin-fin* heat sink is because of optimum number of fins, fin thickness, fins pitch.

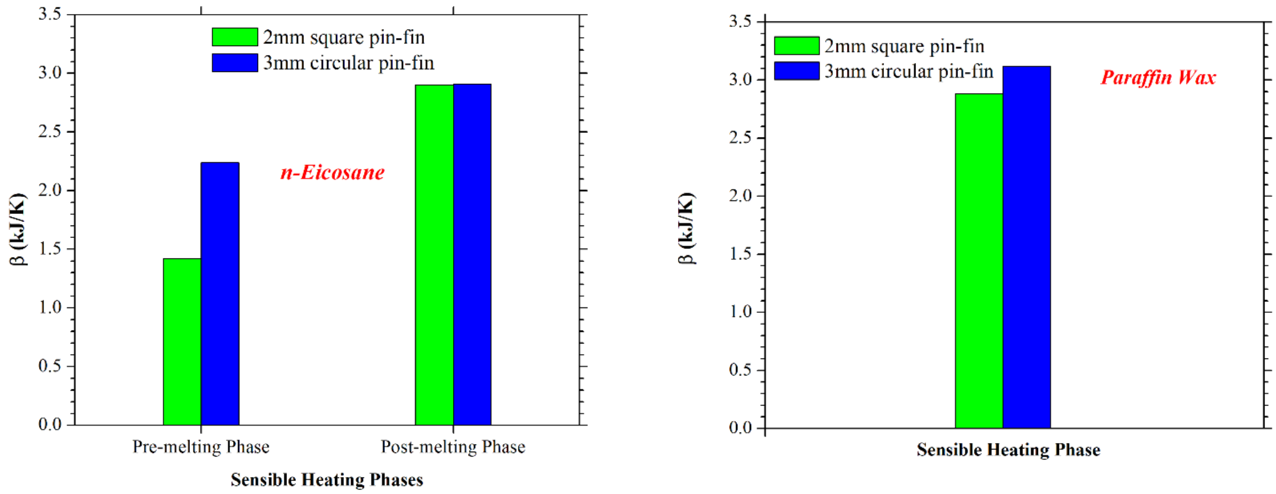

Figure 5-(a)

Figure 5-(b)

Figure 5-Comparison of thermal capacity of heat sinks (a) n-eicosane (b) paraffin wax

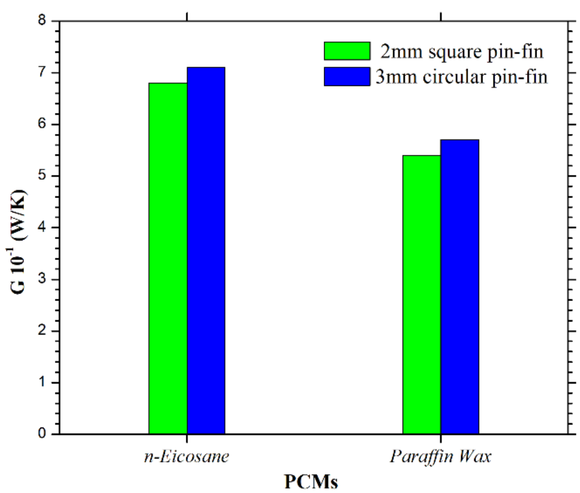

Figure 6-Comparison of thermal conductance of heat sinks for paraffin wax and n-eicosane.

Conclusion

A comparison of two different configurations (square and circular) *pin-fin* heat sinks embedded with two different PCMs namely *paraffin wax* and *n-eicosane* having different thermo-physical properties were carried out for passive cooling of electronic devices. The *pin-fins*, acting as TCEs, of $2mm$ square and $3mm$ circular fin thickness of constant volume fraction of 9% are chosen and input heat fluxes from $1.2kW/m^2$ to $3.2kW/m^2$ with an increment of $0.4kW/m^2$ are provided. The results found the following conclusions;

1. The comparison of heat sinks base temperature proves that $3mm$ diameter of *pin-fin* heat sink better than $2mm$ square *pin-fin* heat sink.
2. An enhancement in operation times of 210mins for *paraffin wax* and 150mins for *n-eicosane* are found at input heat flux of $2.0kW/m^2$ and $1.6kW/m^2$ respectively. Similarly, higher operations times to reach SPTs of $65℃$ and $45℃$ are found for $3mm$ circular configuration *pin-fin* heat sink in comparison of $2mm$ square configuration fin thickness *pin-fin* heat sink.
3. In continuation, of comparing both configurations *pin-fin* heat sinks filled with *n-eicosane* the maximum latent heat phase completion time are found for $3mm$ thick circular *pin-fin* heat sink for all provided input heat fluxes. The maximum and minimum latent heat phase completion duration are found of 141mins and 36mins at $1.2kW/m^2$ and $2.8kW/m^2$ input heat densities for $3mm$ diameter *pin-fin* heat sink.
4. The comparison of thermal capacities and thermal conductance further proves that $3mm$ diameter fin thickness *pin-fin* heat sink has maximum potential to absorb thermal energy and to transfer heat from the electronic devices.

To sum up, the above findings reveals that a $3mm$ fin diameter circular *pin-fin* heat sink filled with PCMs namely *paraffin wax* or *n-eicosane* has maximum tendency of an efficient and reliable passive thermal management technology for electronic devices.

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Figure 6-Comparison of thermal conductance of heat sinks for paraffin wax and n-eicosane.

List of Tables

Table 1-Material Properties used in present study.

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