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Thermal management of electronics using phase change material based pin fin heat sinks

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Abstract. This paper reports the results of an experimental study carried out to explore the thermal characteristics of phase change material based heat sinks for electronic equipment cooling. The phase change material (PCM) used in this study is n - eicosane. All heat sinks used in the present study are made of aluminium with dimensions of 80 x 62 mm² base with a height of 25 mm. Pin fins acts as the thermal conductivity enhancer (TCE) to improve the distribution of heat more uniformly as the thermal conductivity of the PCM is very low. A total of three different pin fin heat sink geometries with 33, 72 and 120 pin fins filled with phase change materials giving rise to 4%, 9% and 15% volume fractions of the TCE respectively were experimentally investigated. Baseline comparisons are done with a heat sink filled with PCM, without any fin. Studies are conducted for heat sinks on which a uniform heat load is applied at the bottom for the finned and unfinned cases. The effect of pin fins of different volume fractions with power levels ranging from 4 to 8 W corresponding to a heat flux range of 1.59 to 3.17 kW/m², was explored in this paper. The volume fraction of the PCM (PCM volume / (Total volume - fin volume)) is also varied as 0.3, 0.6 and 1 to determine the effect of PCM volume on the overall performance of the electronic equipment.

1. Introduction

Sustained growth of the electronics industry arising from the rapid miniaturization of the electronic equipment continues to open up new vistas and challenges to researchers working on thermal management solutions. The reliability of electronic equipment depends on several factors like temperature, humidity, vibration and shock, electromagnetic interference (EMI) and so on. Even so, the most critical of them is temperature [1]. As air cooling technologies are incapable of meeting the growing demands of the electronics industry, many new technologies are emerging and PCM based heat sinks is an excellent passive cooling strategy for thermal management, in cases where the application is transient or intermittent.

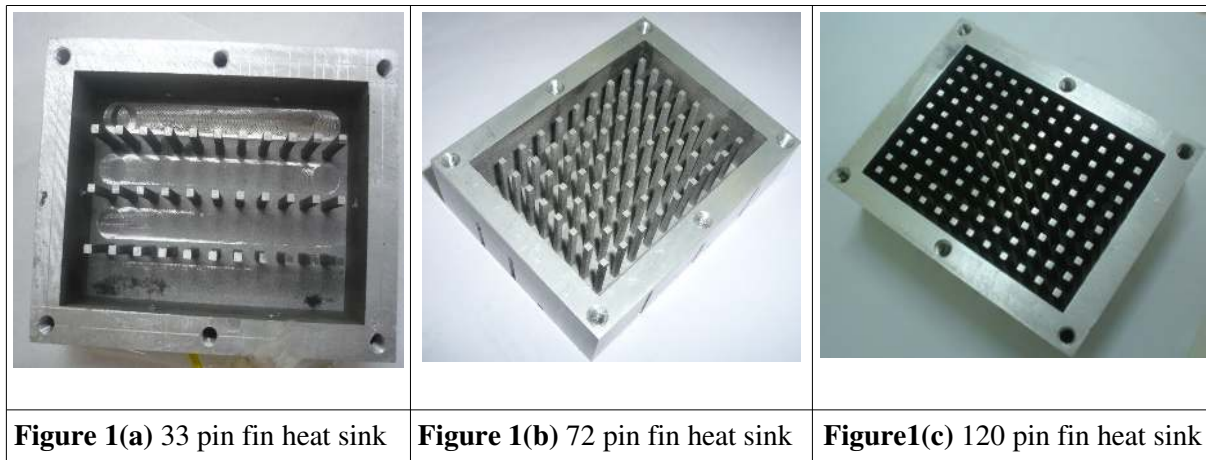
Phase change materials have a wide variety of applications like solar thermal storage, building temperature control, temperature controlled shipping, thermal management of space electronics and so on. PCMs can be broadly classified as organic, inorganic and eutectic [2]. Paraffin and non – paraffin compounds come under the organic category. The stability of the paraffin compounds below 500°C, makes these suitable for repeated use for normal applications. Congruent melting, non – corrosiveness and high heat of fusion are some of the desirable features of organic compounds which have made them popular for various applications. Salt hydrates and metallics fall under the inorganic category. Incongruent melting is a main concern for the use of salt hydrates. Metallics are rarely considered for applications due to their higher weight, even though they have high thermal conductivity among different types of PCMs.

Generally, the thermal conductivity of the PCMs is very low. Using high thermal conductivity materials along with PCM is a method to circumvent the problem of low thermal conductivity of PCMs. As high thermal conductivity materials like aluminium or copper are helpful in enhancing the thermal conductivity of the PCM based heat sink, these materials are known as thermal conductivity enhancers (TCE). Saha et al. [3] used different volumetric fractions of aluminium plate and pin fins to determine the optimum distribution of fins in heat sinks filled with PCMs. They found that fins with small cross sectional areas in large numbers are preferable for better thermal performance. Hatakeyama et al. [4] experimentally and analytically studied the performance of pin studded PCM for thermal management of electronic equipment. They used Paraffin (Nippon Seiro's 155) with a melting point ranging from 40°C to 70°C as the PCM. A design procedure to improve the geometry of PCM composite heat sink in order to enhance the heat transfer rate was proposed by Akhilesh et al. [5]. Fok et al. [6] carried out experimental investigations using plate fin heat sinks. They experimentally showed that the effect of orientations on the change in phase is small and can be ignored. Weng et al. [7] integrated PCM with a heat pipe for electronic cooling. They reported a power saving of 46% when PCM is used in a heat pipe.

From the preceding review, it is clear that a lot of studies have been conducted on the performance of finned heat sinks for thermal management of electronic equipment. However, there is a need to quantify the superior performance of the PCM filled heat sinks in terms of an enhancement ratio from a view point of the time to reach a set point temperature. The present experimental study is an attempt in this direction. From the experimental investigations on PCM based finned heat sinks, *viz* plate and pin fins, by the same authors [8], it is found that pin fins are preferred over plate fins for better heat transfer performance. Hence, in the present experimental study the authors consider only heat sinks with pin fin geometry.

2. Experimental Setup

The average dimensions of a typical portable hand held electronic equipment are taken for designing the heat sink. The test section considered in all the cases is an 80 x 62 mm² base with a height of 25 mm. The heat sink made of aluminium having dimensions 80 × 62 mm² base with a height of 25mm, when completely filled with PCM, but without fins is used for baseline comparisons. All the sides of the heat sink, except the top, are insulated with cork. The top surface is covered with a perspex sheet. To prevent air leak from the top, the perspex sheet is placed over a rubber packing. The pin fins 2 x 2 x 20 mm³ are made by Electrical Discharge Machining. A 60 x 42 mm² plate heater of 2 mm thickness, made up of a standard coil-type nichrome wire wound over a mica sheet is used to mimic the heat generation in electronic chips. Before inserting the plate heater into the slot provided at the base of the heat sink, a thermal paste is employed, in order to avoid contact resistance. Photographs of the heat sinks with 33, 72 and 120 pin fins are given in figures 1(a), (b), (c) respectively.



The dimensions of the 120 pin fin heat sink used in this study are given in figure 2.

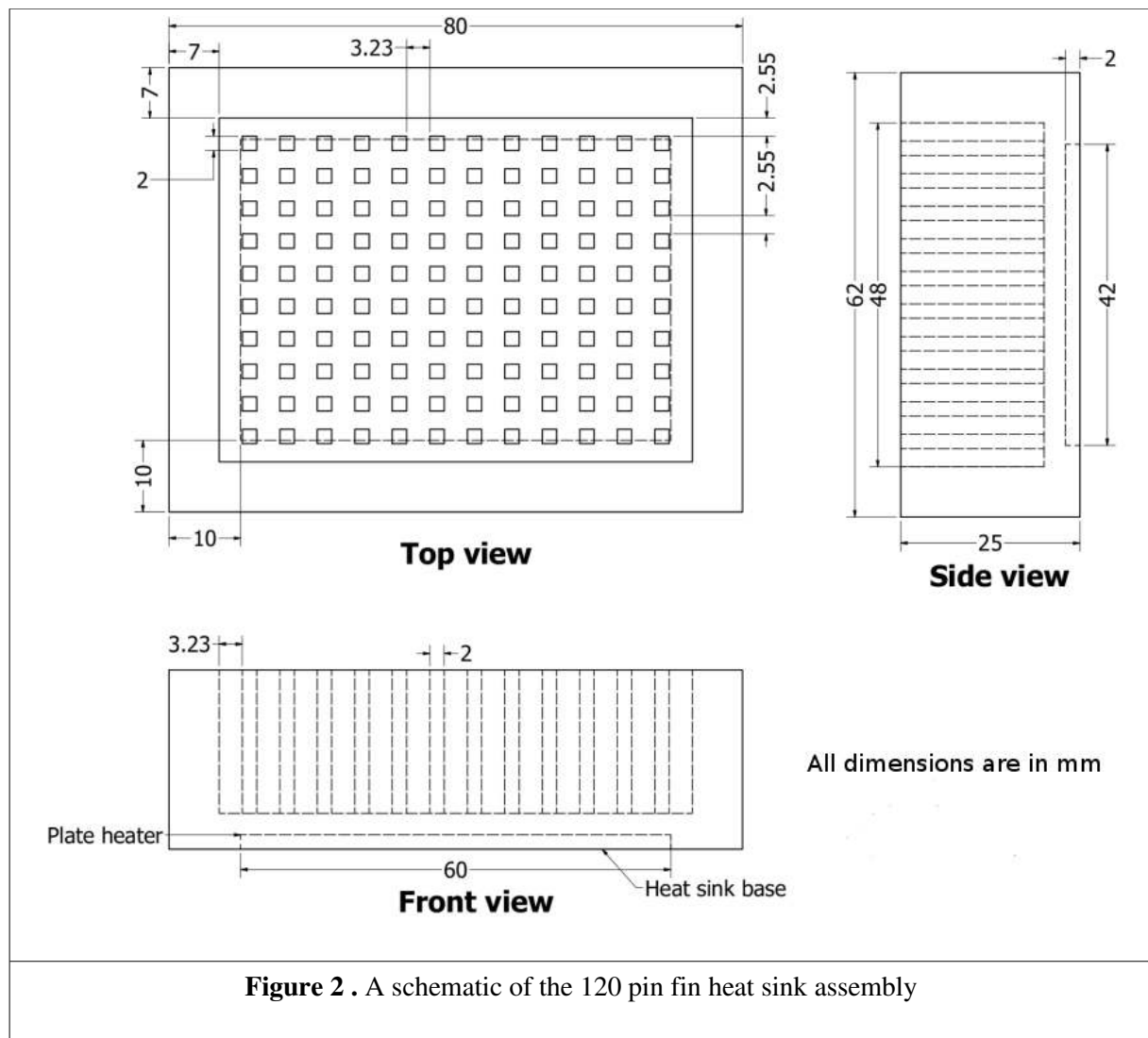


Figure 2 . A schematic of the 120 pin fin heat sink assembly

A total of thirteen calibrated thermocouples are used. All the thermocouples are fixed in position using araldite™ epoxy and their locations are detailed in figure 3. The ambient temperature is

measured by keeping one thermocouple outside. H1 and H2 are the thermocouples kept at the heat sink base to measure the base temperature. The thermocouples are connected to a PC- based data acquisition system. An independently controlled DC power unit which has a voltage range of 0 - 30 V and a current range of 0 - 2 A is used for providing power input to the plate heater. Throughout the experiment, the entire heat sink assembly is kept in the horizontal position.

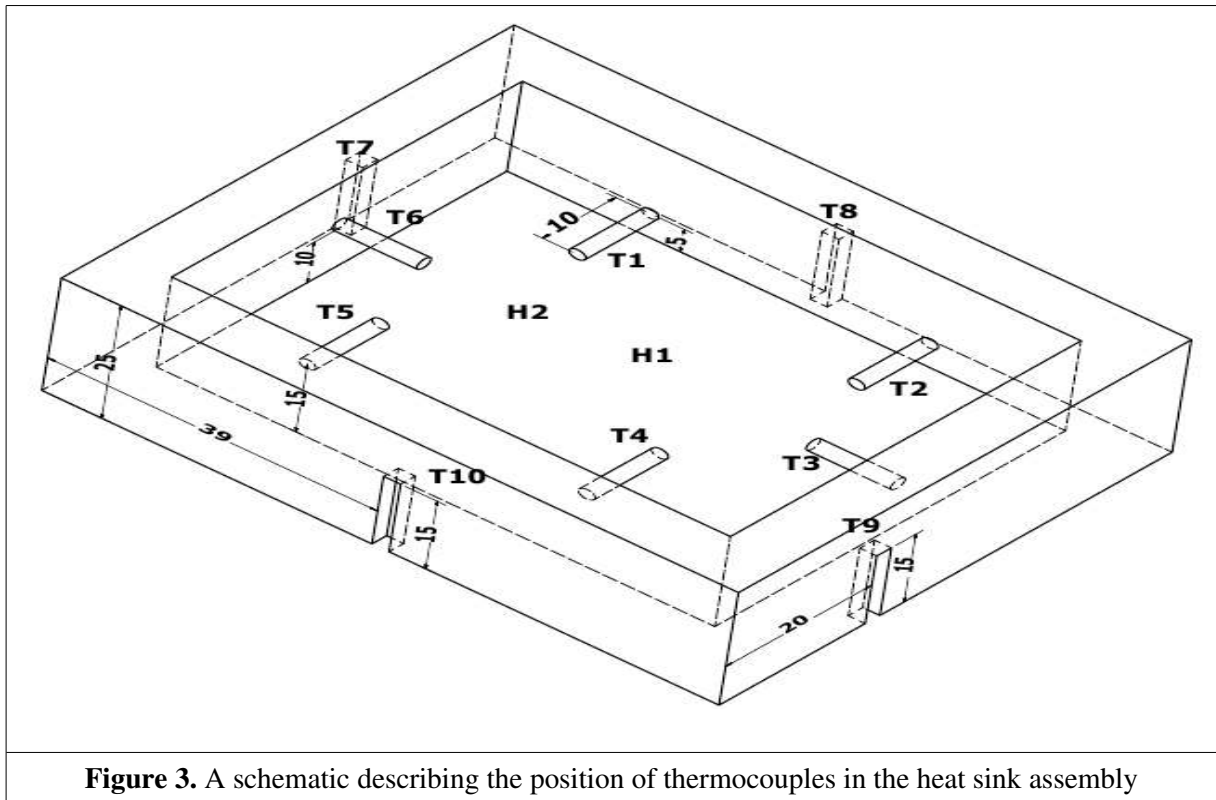


Figure 3. A schematic describing the position of thermocouples in the heat sink assembly

The uncertainties in the temperature measurement are determined by calibrating the thermocouples with a standard thermometer having a resolution of 0.1°C. The voltage and current indicated by the DC power supply are verified with a standard calibrated multi-meter. The uncertainties in the voltage and current are ± 0.1 V and ± 0.01 A respectively and so the resulting uncertainty in the measurement of power input is ± 3.2 %. A detailed discussion on the design and fabrication of the heat sink assembly, uncertainty in measurement, characterization of PCM and TCE based on Modulated differential scanning calorimetry of n-eicosane and Scanning electron microscope analysis for the TCE is given in ref [8] and is not repeated here for the sake of brevity. The properties of the materials employed in the present study are given in Table 1. The masses of the completely filled heat sink with no fin, 33 pin fins, 72 pin fins and 120 pin fins are 49.32, 47.46, 43.87 and 39.75 g respectively. The density of the PCM is 776 kg/m³.

Table 1. Properties of the materials employed in the present study

Material	Thermal conductivity (W/mK)	Specific heat (kJ/ kgK)	Latent heat (kJ/ kg)	Melting point (°C)
n eicosne	0.39(solid), 0.16 (liquid)	1.9(solid), 2.2 (liquid)	237.4	36.5
Aluminium	202.4	0.87	-	660.4
Cork	0.05	2.05	-	-

3. Results and Discussion

For all the experiments in the present study, the power levels varied from 4 to 8 W in steps of 0.5 W. The heat flux corresponding to 4W is 1.59 kW/m² while that corresponding to 8W is 3.17 kW/m².

3.1. Baseline Comparison.

A comparison of the side wall temperature of the heat sink with and without PCM at a heat input of 5W (corresponding to a heat flux of 1.98 kW/m²) is given in figure 4. In this figure, the dotted line represents the temperature variation in the heat sink filled with PCM. An average value of the thermocouples T 7 to T 10 is used to record the transient variation in temperature at every 5s. From figure 4, it is clear that to reach a temperature of 53°C, a heat sink without PCM takes 1800 seconds, whereas for the one with PCM it is 7500 seconds. As the phase change process takes place at constant temperature by absorbing latent heat, the side wall temperature does not increase rapidly. But, this is not the case with heat sink without PCM, for which the temperature rise is rapid.

The temperature – time history of the heat sink without fin (but with PCM) at a power level of 8W is given in figure 5. The plate heater is on for the first 160 minutes and this phase is the heating phase. The cooling phase corresponds to the phase when the heater is switched off. As the four side walls are insulated with cork, the time taken for cooling is much more than that required for the heating phase. The average value of the temperature recorded by the thermocouples T1 and T2 is used in figure 5 for analyzing the temperature pattern inside the PCM. Studies are conducted for the three volume fractions of the PCM namely 0.3, 0.6 and 1. The volume fraction, ϕ as defined in this study, is the ratio of the volume of the PCM to the difference between the total empty volume of the heat sink and the volume occupied by the fins. When the PCM temperature changes from the room temperature of 28°C to 36.5°C in the heating region, sensible heating takes place. This is followed by latent heating phase without a change in temperature which is then followed by the temperature rise due to the sensible heating in the post melting scenario. From figure 5, it is to be noted that the latent heating phase, which is the region of interest from the view point of thermal management of electronic equipment, is strongly dependent on the amount of the PCM. The latent heating phase is least in the case of the heat sink without fin having $\phi = 0.3$. It is found from the experiments that the temperature variation within the liquid PCM is not significant, mainly due to the influence of natural convection. Natural convection aids in maintaining the chip temperature close to the melting temperature of the PCM.

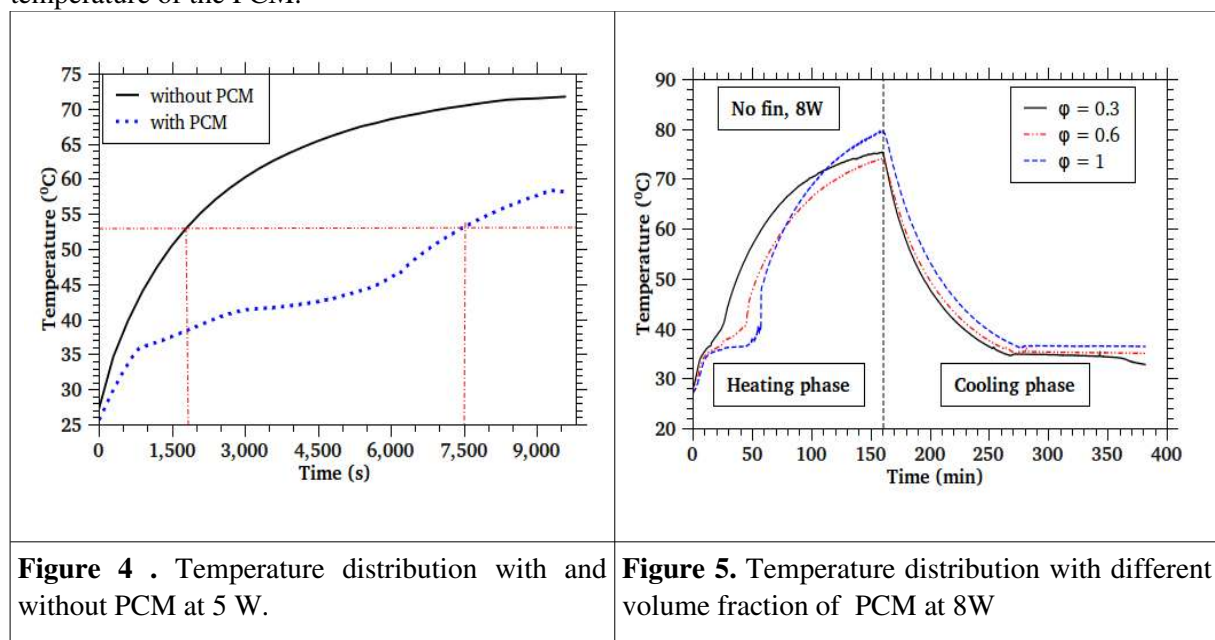


Figure 4 . Temperature distribution with and without PCM at 5 W.

Figure 5. Temperature distribution with different volume fraction of PCM at 8W

3.2. Effect of PCM volumetric fractions

Figures 6 – 8 present the results of a parametric study for a power level of 7 W corresponding to a heat flux of 2.78 kW/m^2 . It is seen that the thermal performance of different pin fin heat sinks is better than the heat sink without any fin in all cases considered for the present study. It is also seen that 72 pin fin case gives the best thermal performance. Figure 9 shows the effect of volume fraction of PCM on the thermal performance of the 72 pin fin case at a power level of 7 W.

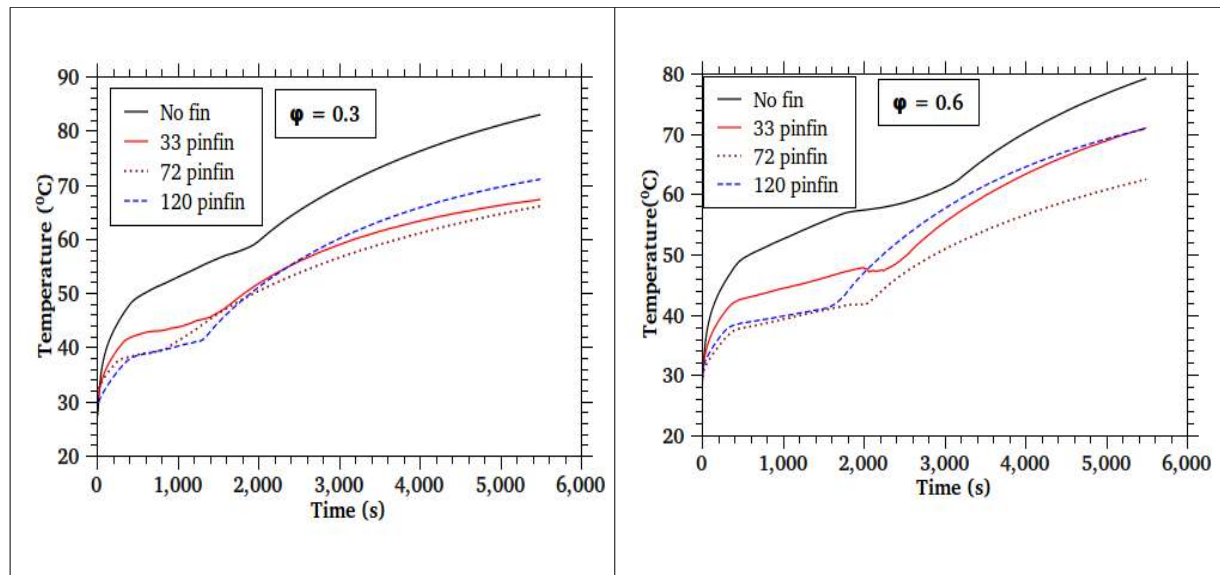


Figure 6. A Comparison of heat sink base temperature for $\phi = 0.3$ at 7W

Figure 7. A Comparison of heat sink base temperature for $\phi = 0.6$ at 7W

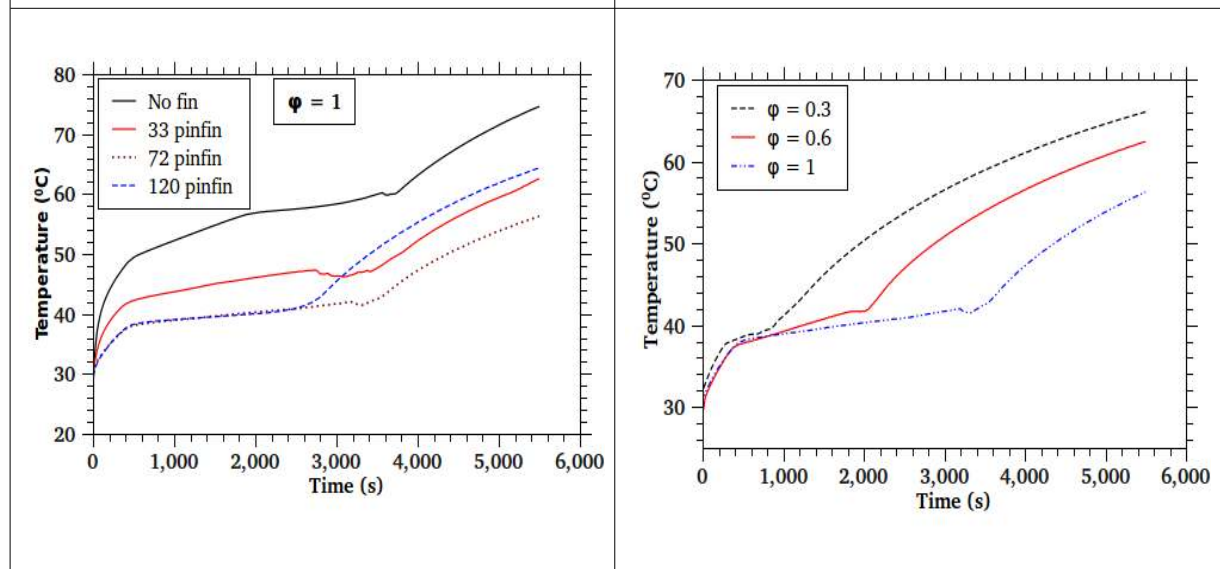


Figure 8. A Comparison of heat sink base temperature for $\phi = 1.0$ at 7W

Figure 9. Temperature distribution with different volume fraction of the PCM at 7W for heat sink with 72 pin fin

It is seen from table 1 that the thermal conductivity of the PCM is very low and in the liquid state it is still lower. As the plate heater is attached to the heat sink base, the layer of PCM immediately adjacent to the heat sink base heats up initially and when the temperature reaches the

melting point, the solid PCM will change to liquid PCM. The initial liquid layer will act like an insulator, thus almost preventing further transfer of heat. This causes a sharp increase in the temperature for heat sinks without fins. The pin fins act as a medium for transfer of heat and this transfer of heat takes place at multiple locations. Thus the pin fin heat sinks ensure that the entire PCM changes its phase, thus keeping the electronic equipment below the allowable operating limit in the real applications. The time scale used here is based on the time to reach a set point temperature, t_{set}

3.3. Operation time enhancement with the addition of fins.

The major objective of the PCM based heat sink is to keep the temperature of the heat sink base below the allowable temperature limits. The enhancement in the operation time of the electronic

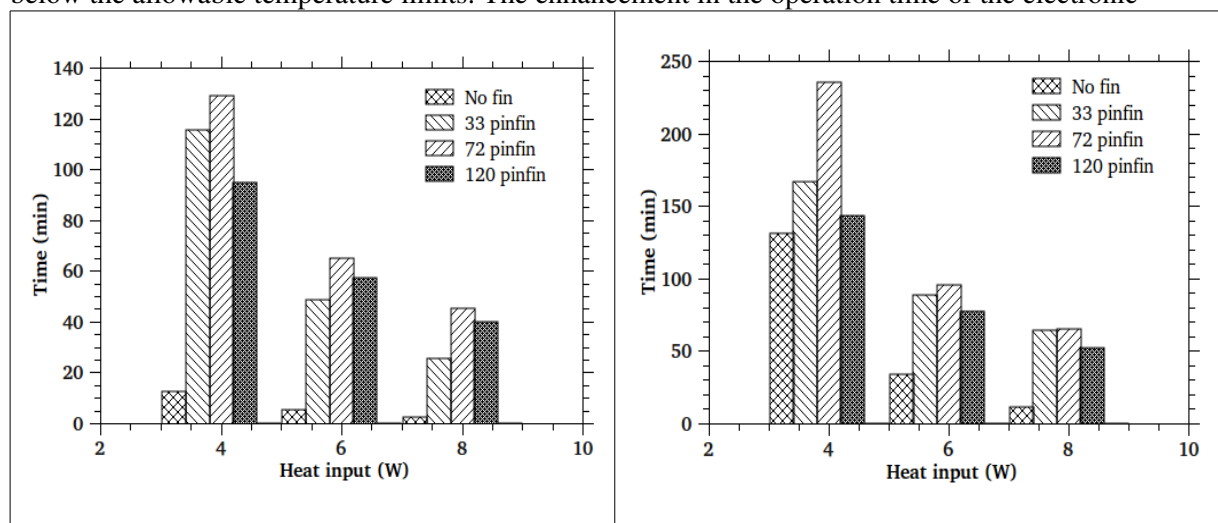


Figure 10. Time to reach a set point temperature of 43°C at power levels of 4, 6 and 8W ($\phi = 1.0$)

Figure 11. Time to reach a set point temperature of 53°C at power levels of 4, 6 and 8W ($\phi = 1.0$)

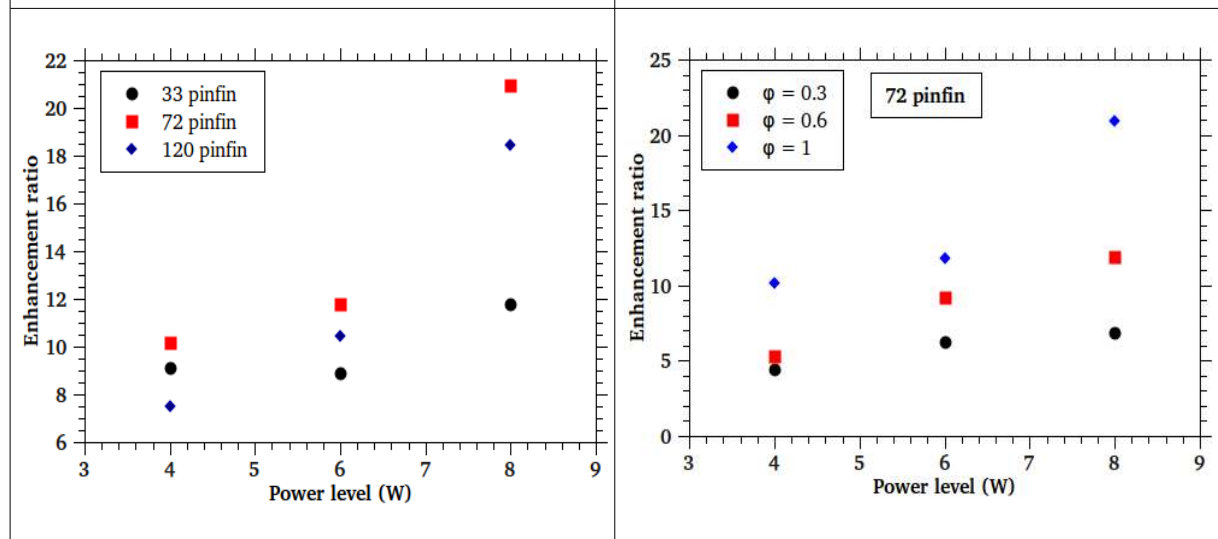


Figure 12. Enhancement in operating time due to presence of fins for a base temp. of 43°C ($\phi = 1$)

Figure 13. Enhancement in operating time at different ϕ for 72 pin fin case at 43°C

equipment as a result of the highly efficient PCM based pin fin heat sink can be quantified by the enhancement ratio. The enhancement ratio can be defined as the ratio of the time required for the PCM filled finned heat sink to reach a set point temperature to that without fins but filled with PCM.

Figures 10 and 11 show the time required for the different heat sinks considered, i.e., the heat sink with no fin, 33 pin fins, 72 pin fins and 120 pin fins to reach a set point temperature of 43°C and 53°C at the heat sink base. From these figures it is seen that the performance of the 120 pin fin heat sink is deteriorating when the set point temperature is on the increase. A decrease in the total volume of the PCM and the poor convection heat transfer due to a large number of fins result in an inferior heat transfer performance of the 120 pin fin heat sink. From this study, it is clear that further optimization is required to determine the optimized configuration of the heat sink in terms of the number of fins and the amount of PCM. The average of the temperature readings H1 and H2 is used for recording the heat sink base temperature. The power levels considered here are 4, 6 and 8 W with the heat sinks fully filled with PCM. Figure 12 describes enhancement in operation time due to the addition of fins at 43°C corresponding to a PCM volume fraction, $\phi = 1$. The heat sink with 72 pin fin is seen to have better heat transfer performance. An enhancement of 21 is achieved for the 72 pin fin heat sink which is operating at a power level of 8 W for a set point temperature of 43°C. This is very promising as the electronic equipment is to be operated at higher power levels with decreasing maximum allowable temperature. Figure 13 shows the enhancement in operating time due to the addition of fins with respect to the baseline case, at different volume fractions ($\phi = 0.3, 0.6$ and 1) of the PCM for the 72 pin fin case to reach a base temperature of 43°C. The enhancement is seen to be more at (i) higher power levels for a given ϕ and (ii) higher ϕ for a given power.

4. Conclusions

Parametric studies have been conducted by changing the number of fins, power density and the volume fraction of the PCM to evaluate the thermal performance of a composite heat sink made of aluminium, filled with n-eicosane and aluminium fins. Heat sinks with fins were found to be helpful in stretching the duration of operation of the electronic device. Effective transfer of heat due a large number of uniformly distributed fins is mainly responsible for higher enhancement ratios for the pin fin heat sinks. An enhancement factor of 21 is obtained in the operation time for the heat sink with 72 pin fins as opposed to heat sink without fin (used as a baseline comparisons) for a set point temperature of 43°C and a power level of 8W. Increasing the number of fins beyond 72 resulted in reduced heat transfer enhancement at higher set point temperatures. From the studies of different volume fractions of the PCM, it is clear that the heat transfer performance strongly depends on the amount of PCM used apart from the volume fraction of the fin. Optimization studies are also relevant as the performance of the heat sink depends on multiple factors.

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