EXPERIMENTAL STUDY OF PCM BASED HYBRID HEAT SINK FOR ELECTRONIC COOLING

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Original Manuscript Submitted: 8/31/2021; Final Draft Received: 12/10/2021

The present experimental study reports the thermal performance analysis of a phase change material (PCM)-based finned heat sink placed on a silicone rubber heater which mimics the CPU chip and is cooled by natural and forced convection. The heat sink is subjected to constant and cyclic loading for five input power values (4, 6, 8, 10, and 12 W). Paraffin wax and 1-hexadecanol are selected as PCM for this study, which have melting points in the ranges of 58°C–60°C and 48°C–50°C, respectively. The steady-state and transient base temperature behavior of the heat sink indicated that the heat sink with PCM performed better than the heat sink without PCM under natural convection subjected to a constant load. With the increase in input power, the melting time of the PCM is reduced. Between the two PCMs, the heat sink filled with 1-hexadecanol performed better in transient operation. It was observed that cyclic loading offers better insight into the thermal behavior of the heat sinks at different power inputs. The total operation time of heat sink filled with 1-hexadecanol takes less time than paraffin-filled heat sink during cyclic loading when subjected to natural convection. For cyclic loading, the total operation time of the heat sink is reduced by a factor of 0.41 and 0.43 times when cooled by forced convection as compared to natural convection for heat sink filled with paraffin wax and 1-hexadecanol, respectively.

KEY WORDS: heat sink, thermal performance, phase change material, electronic cooling, constant and cyclic loading

1. INTRODUCTION

The continuous innovation and development of electronic devices have led to the miniaturization of computers, mobile phones, and other gadgets. Since the number of transistors installed on the integrated circuits has increased, heat generation has also increased, so the operating temperature of electronic devices has increased. High temperature deteriorates the reliability of electronic components, and it leads to failure/damage Lakshminarayanan and Sriraam (2014). In this context, many cooling techniques have surfaced over time, such as microchannel (Ansari and Kim, 2019; Deng et al., 2020; Robinson et al., 2018; Yang et al., 2020), impingement jet (Barrau et al., 2011; Sung and Mudawar, 2006; Zhang et al., 2017), heat pipe (Tran et al., 2014), phase change material (PCM) (Sahoo et al., 2016a,b), liquid cooling (Nguyen et al., 2007), etc. PCM-based finned heat sinks (FHS) can serve as a better alternative for cooling electronic devices (Khandelwal et al., 2020; Pavithran et al., 2020, 2021), owing to their high latent heat.
capacity and low volumetric change during phase change. PCM-based FHS is an example of a passive cooling technique; they can minimize the energy consumption required for cooling.

PCM can be divided into three categories (Socaciu et al., 2014): organic, inorganic, and eutectic compounds, which are made by combining organic and inorganic PCMs. Organic PCMs are chemically stable, less corrosive, inexpensive, and nontoxic. Organic PCMs are further categorized into paraffin- and nonparaffin-based PCMs. Inorganic PCMs have (1) high latent heat, (2) thermal conductivity, and (3) negligible change in volume during phase change. But due to inorganic PCMs’ corrosive and toxic characteristics, organic PCMs are preferred.

Despite all the advantages, the major drawback of paraffin-based PCM is its low thermal conductivity. This leads to a low heat transfer rate, and the time taken by the PCM to reach its melting point increases. Various techniques have surfaced over time to minimize this problem. Use of PCM with metal foam (Li et al., 2020; Qu et al., 2012; Tseng et al., 2019), adding nanoparticles or fibers in PCM (Choi et al., 2014; Frusteri et al., 2005; Yu et al., 2014), using fins integrated with PCM (Kandasamy et al., 2008) are a few techniques that are being used as solutions. The disadvantage of metal foam and nanoparticles is that the former increases the heat sink weight and, in the latter, there is a problem of settling down of nanoparticles. Out of the available solutions, the use of fins integrated with PCM is preferable. A hybrid heat sink can be designed to overcome heating caused in electronic devices by optimizing the area of fin and volume of PCM used. Therefore, the investigation of PCM-based FHS is significant.

A number of experimental and numerical studies have been reported to improve the PCM-based FHS in the past few decades. Kandasamy et al. (2008) investigated the transient thermal management of PCM-based FHS experimentally and numerically. The results indicated that the increase in input power improved the performance of the heat sink until the PCM was melted. Arshad et al. (2020) numerically solved the PCM-based FHS and found that the melting time increases with an increase in fin thickness. Kalbasi (2021) compared PCM-based finned heat sinks in different arrangements (filling PCM in alternative slots, not filling PCM in any slot, filling PCM in all slots). He found that with alternate slots filled with PCM, the heat sink performed better than the rest. Debich et al. (2020) simulated PCM-based FHS by optimizing between safety and cost for nonlinear materials. Srivatsa et al. (2014) numerically studied the behavior of metal foam in PCM-based FHS. An enhancement ratio of 7–8 was obtained due to increased surface area between PCM and heat sink. Qu et al. (2012) experimentally investigated the effect of metal foam on PCM-based FHS. The results inferred that the copper metal foam reduced the base temperature of the heat sink and the time required to melt the paraffin wax. Bondareva and Sheremet (2020) performed a numerical analysis to investigate the effects of paraffin wax mixed with Al2O3 nanoparticles in a PCM-based FHS. The results indicated that the performance depends on the convective heat transfer. Furthermore, adding more than 3% nanoparticles reduced PCM circulation, decreasing the heat transfer rate. Existing references indicate that PCM-based heat sink can be further improved by proper selection of fin geometry (Arshad et al., 2018; Ashraf et al., 2017; Li et al., 2014), orientation (Wang et al., 2007; Baby and Balaji, 2013), PCM (Fan et al., 2013, 2015; Qu et al., 2012; Wang et al., 2016; Yang et al., 2017), and increasing the surface contact between the heat sink and PCM (Akula et al., 2021; Hu and Gong, 2021). Among these listed factors, the selection of PCM is important for better thermal performance because the PCM is selected depending upon the operating temperature reached in the system.

For a detailed study of thermal performance based on the base temperature of the heat sink, a parallel plates heat sink is designed for this study. The thermal performance of a PCM-based FHS...
for cooling a CPU chip is evaluated by experimentation. A comparative study of the effect of two different PCMs has been done. Moreover, the thermal behavior of heat sink base temperature for constant and cyclic power input has been studied. Furthermore, the effect of fan has been included in the study and compared with the other cases. A study on PCM-air hybrid heat sinks for cooling CPU chips for different PCMs integrated with fans subjected to constant and cyclic loading has not been presented so as far as per the authors’ knowledge.

2. EXPERIMENTATION

The schematic representation of the experimental setup for this study is illustrated in Fig. 1.

The setup for experimentation mainly consists of heat sink assembly, data acquisition mechanism, and DC source unit. Thermocouples are inserted into the fin base to record the temperature. Moreover, the solidification and melting patterns are recorded by photographing from the top with a camera.

The heat sink assembly consists of a Teflon base, silicone rubber heater, fin, and heat flux sensor, as shown in Fig. 2(a). The silicone rubber heater is sandwiched between the heat sink and Teflon base, as shown in Fig. 2(b). The Teflon base has a thermal conductivity of 0.25 W m\(^{-1}\)K\(^{-1}\) because of which it serves as an insulator to prevent the leakage of heat. Only the top surface of the heat sink is exposed to ambient temperatures. Moreover, the PCMs containing slots/cavities are sealed with a polyethylene terephthalate (PET) sheet cut-out.

The silicone rubber heater is connected to a DC power supply unit (Make: APLAB, Maharashtra, India, Model number: L8025). The rating of the power supply unit is 80 V and 2.5 A with a least count of 0.1 V and 0.1 A, respectively. The silicone heater used in this experiment has a power rating of 50 W, which is 20 kW m\(^{-2}\) in terms of heat flux, and the power input is regulated by varying the voltage and current magnitude. The base temperature is measured through a T-type thermocouple (transient nature). The thermocouples are inserted into the base through holes of diameter 1.5 mm. A 16-channel data acquisition system (Make: NI Systems [India] Pvt Ltd.) integrated with the setup for data acquisition. The least count of the temperature measurement is 0.01.

![FIG. 1: Schematic representation of the experimental setup](image-url)
FIG. 2: Experimental setup: (a) setup and (b) schematic diagram of heat sink assembly

3. HEAT SINK DESIGN AND PCM SELECTION

The design of the heat sink used in the experiment is illustrated in Fig. 3. The heat sink material is aluminum alloy 6063 with 98% purity, which is light in weight, has good thermal conductivity, and is economically viable. It is manufactured from the aluminum block by electrical discharge machining (EDM).

The base of the heat sink is 5 mm deep and has 12 holes for accommodating thermocouples. The three rectangular slots amount to a total volume of 18,900 mm$^3$, which is the volume of PCM that is being filled. The volume of PCM is constant for all cases. For this study, two PCMs are selected: (1) paraffin wax and (2) 1-hexadecanol. The selected PCMs are noncorrosive with aluminum and have sufficient latent heat. The detailed thermophysical properties of the used PCMs are presented in Table 1.

FIG. 3: Heat sink dimensions: (a) front view and (b) side view
<table>
<thead>
<tr>
<th>Materials</th>
<th>Melting point (°C)</th>
<th>Specific heat (J/kg K)</th>
<th>Density (kg/m³)</th>
<th>Latent heat (kJ/kg)</th>
<th>Thermal conductivity (W/m K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Paraffin</td>
<td>58–60</td>
<td>2,540</td>
<td>920</td>
<td>189</td>
<td>0.21</td>
</tr>
<tr>
<td>1-hexadecanol</td>
<td>48–50</td>
<td>2,120</td>
<td>811</td>
<td>226.1</td>
<td>0.3</td>
</tr>
</tbody>
</table>

4. RESULTS AND DISCUSSION

Initially, the base temperature was kept at ambient temperature, which is 33°C for all the cases. In this study, heating and cooling phases were analyzed in natural and forced convection conditions. The base temperature was defined by the average of all the thermocouple readings. The PCM temperature was recorded by dipping a thermocouple into it through a hole made in a PET cap. $T_f$ is the average base temperature of the heat sink which is found out by averaging the temperature reading obtained by $m$ number of the thermocouples.

$$T_f = \frac{\sum_{n=1}^{m} T_n}{m}.$$  

4.1 Evolution of Melting Front

The melting behavior of both PCMs was observed by recording the melting front evolution at different time intervals, as shown in Fig. 4. The power input is set to 12 W under natural convection as boundary conditions. Because the thermal conductivity of the aluminum is higher than that of PCM, the walls get heated first. So the melting of the PCM starts from the wall of the fin.

**FIG. 4:** Melting front evolution and propagation within PCM: (a) paraffin wax and (b) 1-hexadecanol
4.2 For Constant Loading

4.2.1 Without PCM

The input heat load was varied from 4 to 12 W to consider various intermediate power dissipation levels starting from 1371.74 to 4115.22 W/m². The thermal behavior of heat sink without PCM can be seen in Fig. 5(a). Theoretically, for heat sinks without PCM, the variation of temperature with time is exponential in nature, which becomes constant when time is infinite. A similar trend is obtained with the experimental results. The steady-state base temperature increases as the input heat load increases. The steady-state base temperatures for 4, 6, 8, 10, and 12 W are 61.6°C, 75.7°C, 88.01°C, 97.9°C, and 107°C, respectively.

4.2.2 With PCM

In Fig. 5(b), the transient behavior of the heat sink filled with paraffin wax is plotted. At \( t = 0 \) s, the temperature varies exponentially because the melting point of the PCM has not been reached yet. As the base temperature gets close to the melting point of the PCM, the slope of the temperature variation is reduced, meaning that the rate at which the temperature increases has been retarded. This is because the PCM has started to melt by absorbing the generated

![FIG. 5: Base temperature variation with time at different power input values: (a) heat sink without PCM, (b) heat sink with paraffin wax, (c) heat sink with 1-hexadecanol, and (d) comparison between thermal performance natural convection and both PCM-based heat sinks for input power of 8 W](image)
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heat, which leads to a comparatively lower base temperature. After the PCM has melted, the temperature again increases exponentially and achieves a steady state after a certain time.

The lower temperature region starts near 58°C–60°C due to the melting of paraffin wax. The steady-state base temperatures for 4, 6, 8, 10, and 12 W are 62.5°C, 73.1°C, 86°C, 96.9°C, and 107.5°C, respectively. The base temperatures for 4, 6, 8, 10, and 12 W are 53.1°C, 58.8°C, 69.6°C, 80°C, and 90°C, respectively at \( t = 2000 \) s.

The thermophysical properties of 1-hexadecanol are different from paraffin wax. It has a higher latent heat capacity and lower melting point. In Fig. 5(c), the base temperature variation of the heat sink with time is plotted. The lower temperature region starts near 48°C–50°C due to the melting of 1-hexadecanol. The steady-state base temperatures for 4, 6, 8, 10, and 12 W are 62.5°C, 74.3°C, 85.2°C, 97.2°C, and 106.9°C, respectively. The base temperatures for 4, 6, 8, 10, and 12 W are 49.4°C, 54.9°C, 66.1°C, 78.5°C, and 86.1°C, respectively, at \( t = 2000 \) s.

The base temperatures of the heat sink without PCM, heat sink filled with paraffin wax, and heat sink filled with 1-hexadecanol are compared in Fig. 5(d). The steady-state temperatures of heat sink without PCM, heat sink filled with paraffin wax, and heat sink filled with 1-hexadecanol are 87°C, 83°C, 82°C, respectively. Because the thermal conductivity of 1-hexadecanol is higher compared to paraffin wax, it dissipates more heat, which leads to a lower steady-state base temperature of the heat sink filled with 1-hexadecanol than the heat sink filled with paraffin wax. The base temperatures of the heat sink without PCM, the heat sink filled with paraffin wax, and the heat sink filled with 1-hexadecanol are 77.6°C, 69.6°C, and 66.1°C, respectively at \( t = 2000 \) s. The base temperature of the 1-hexadecanol is lower owing to its high latent value.

4.2.3 Effect of Fan

The forced convection environment was induced by using a DC fan (12 V) with an air velocity of 7.88 m/s, which was measured using a pitot tube placed at a distance of 2 mm from the fan blades. Figure 6(a) presents the input power required to reach a 60°C base temperature at varying fan heights. It can be concluded that a fan held at 0 mm apart from the heat sink will give the best cooling effect. Hence, the experiment for forced convection is conducted only for 0 mm height.
of DC fan from the heat sink. Figure 6(b) shows the variation of base temperature with time in forced convection conditions.

For forced convection, the steady-state base temperatures for 4, 6, 8, 10, and 12 W are 35.9°C, 38.44°C, 40.7°C, 42.4°C, and 44.8°C, respectively. The steady-state temperatures obtained are lower than the melting point of both the PCMs. Hence the melting phase does not occur. The performance of the heat sink with forced convection is best when compared with the performance of heat sinks with and without PCM under natural convection. Sahoo et al. (2017) numerically investigated PCM-based heat for natural and forced convection and found similar results.

Figure 7 shows a comparison between the base temperature of the heat sink without PCM, Heat sink filled with paraffin wax, heat sink filled with 1-hexadecanol, and heat sink cooled by forced convection. The steady-state base temperature obtained for cooling through forced convection is 44.8°C at 12 W power input, which is comparatively lower than the steady-state base temperature of the heat sink with and without PCM cooled by natural convection. The power required to run the DC fan is 1.8 W, but on the contrary, the PCM-based FHS is a passive cooling technique; hence, no power input is required. For intermediate cooling, PCM-based FHS is more suitable. Among the two PCMs used in this study, 1-hexadecanol shows relatively better performance than paraffin wax. A similar type of observation has been obtained by Sahoo et al. (2018) for use PCM-based heat sinks in power surge operation.

4.3 Influence of Cyclic Loading

After the PCM is melted, the generated heat is not absorbed as latent heat. The temperature of the heat sink base again rises exponentially afterward. The advantage of PCM-based heat sink is negated once the PCM is melted. Hence, in order to extract maximum benefit out of a PCM-based heat sink, it should be used in a cyclic order, i.e., after the PCM is melted, it should be allowed to cool to a certain temperature. Therefore, the behavior of the PCM-based heat sink in cyclic loading must be studied.

The cyclic loading was applied in the following way: (1) the heating phase was continued till the entire PCM is melted, and (2) the cooling phase was continued till the base temperature reached a certain value, which is 36°C. The PCM temperature is monitored by dipping a thermocouple into it.

![FIG. 7: Comparison of the thermal performance of natural convection, both PCMs, and fan for input power of 8 W](image-url)
4.3.1 Effect on PCM Based Heat Sink without Fan

The time taken for completion of four cycles of heating followed by cooling of paraffin filled heat sink under natural convection is longest for 4 W and decreases as the input power increases, as shown in Fig. 8(b). But in the case of 8 W power input, the trend doesn’t follow. The time taken to complete four cycles for 8 W power input is lower than the time taken to complete four cycles for 10 W power input. This is due to the peak base temperature attained while the PCM is being melted. The PCM takes a certain amount of time to melt completely. The peak temperature reached during the melting of the PCM is higher for the 10 W input power as compared to 8 W. So, when cooling starts for the 8 W and 10 W input power, the cooling time to reach 36°C for the 8 W is lower because its peak temperature is also lower as compared to 10 W input power. Moreover, cooling doesn’t start immediately because the input power is cut off as the heat available at the base of the heat sink keeps dissipating into the PCM. The dissipation of heat from the base to PCM becomes significant at higher power levels, which delays the start of cooling. Hence, the cooling time for 8 W was less than for 10 W. Although the difference in cooling time of 8 W and 10 W is not significant in the first cycle, it became more visible in the subsequent cycles as the difference stacked up. Even though the heating time of 10 W is lower than 8 W, it is compensated by higher peak temperature and delay in the start of cooling, which is reflected in its cooling time in a given cycle. Figure 8(a) shows the variation of base temperature of heat sink filled with paraffin wax at different power inputs ranging from 4 to 12 W. At the time when PCM is completely melted, the base temperatures of the paraffin wax filled heat sink for 4, 6, 8, 10, and 12 W are 58.4°C, 62.3°C, 68.2°C, 69.7°C, and 70.9°C, respectively.

Figure 9(b) shows the time taken to complete the four cycles of heating followed by cooling of 1-hexadecanol filled heat sink under natural convection, showing similar behavior for 8 W power input. The time taken to complete four cycles is lower than that taken by 10 and 12 W power input. Figure 9(a) shows the variation of base temperature of heat sink filled with 1-hexadecanol at different power inputs ranging from 4 to 12 W. At the time when PCM is

![Figure 8](image_url)

**FIG. 8:** Thermal performance of heat sink filled with paraffin wax with natural convection for various power inputs: (a) base temperature variation of the heat sink filled with paraffin wax at different power inputs and (b) time required to complete four cycles of heating followed by cooling for heat sink filled with paraffin wax for different power inputs
completely melted, the base temperatures of the paraffin wax filled heat sink for 4, 6, 8, 10, and 12 W are 54.1°C, 57.1°C, 57.5°C, 60.2°C, and 63.9°C, respectively.

4.3.2 Effect on PCM Based Heat Sink with Fan (Hybrid Heat Sink)

The forced convection boundary condition was established by a DC fan operated at 6 V input power. Heating was performed under ambient conditions, whereas cooling was carried out by forced convection. The time taken by the heat sink filled with paraffin wax to complete four cycles of heating in ambient condition followed by cooling under forced convection is presented in Fig. 10(b). The time taken to complete four cycles of heating followed by cooling is maximum for the input power of 4 W and decreases as the input power increases. Figure 10(a) shows the variation of base temperature of heat sink filled with paraffin wax at different power inputs ranging from 4 to 12 W.

The time taken by the heat sink filled with 1-hexadecanol to complete four cycles of heating in ambient condition followed by cooling under forced convection is presented in Fig. 11(b). The trend obtained for the total time taken is similar to that of a heat sink filled with paraffin wax. But the heat sink filled with 1-hexadecanol takes less time than the heat sink filled with paraffin wax to complete four cycles of heating followed by cooling. Figure 11(a) shows the variation of base temperature of heat sink filled with 1-hexadecanol at different power inputs ranging from 4 to 12 W.

The heat sink cooled by natural convection and heat sink cooled by forced convection filled with paraffin wax and 1-hexadecanol are compared in Figs. 12(a) and 12(b), respectively. The heat sink cooled by natural convection takes 2.43 and 2.29 times the duration taken by the heat sink cooled by forced convection for paraffin-filled heat sink and 1-hexadecanol filled heat sink, respectively.

Even after thoroughly analyzing the heat sink designed for this study, various aspects are yet to be explored. The geometry considered in this study is simplistic. Hence, complex geometries integrated with PCM can be studied to get more insights into the heat sink design. Moreover,
the present experimental study has been designed according to the input heat flux ranging from 1000 W/m² to 4000 W/m² and a temperature up to 120°C. For higher heat flux, the present results may not be applicable, but the same methodology with different material selection will be applicable.

5. CONCLUSION

The experiment was designed to study the transient thermal behavior of PCM-based FHS for different power inputs (constant and cyclic loading), types of PCM, and boundary conditions.
The base temperature of the heat sink was recorded and analyzed. The melting front propagation of both PCMs was studied. Furthermore, all the cases were compared and discussed and can be summarized as follows:

1. For the heat sink subjected to natural convection, the steady-state temperatures of heat sink without PCM, heat sink filled with paraffin wax, and heat sink filled with 1-hexadecanol are 87°C, 83°C, and 82°C for 8 W power input, respectively. The base temperature of the heat sink without PCM, the heat sink filled with paraffin wax, and the heat sink filled with 1-hexadecanol are 77.6°C, 69.6°C, 66.1°C for 8 W power input, respectively at $t = 2000$ s. Similar trends were obtained for all power input values. This suggests that the PCM-based heat sink performs better than the heat sink without PCM. Among the two PCMs used in this study, 1-hexadecanol yields a better result for transient operation.

2. The heat dissipation by forced convection is always better than natural convection, irrespective of the presence of PCM, but it consumes energy (1.8 W). In contrast, PCM-based heat sinks under natural convection are passive cooling techniques and do not consume power.

3. For cyclic loading, when cooling is carried out by natural convection, the time taken by the heat sink filled with 1-hexadecanol to complete four cycles is less than the heat sink filled with paraffin wax for all power input.

4. For cyclic loading, the total operation time of the heat sink is reduced by a factor of 0.41 and 0.43 times when cooled by forced convection as compared to natural convection for heat sinks filled with paraffin wax and 1-hexadecanol, respectively.

ACKNOWLEDGMENT

The work reported in this paper is supported by a research Grant from the Department of Science and Technology, Government of India (Project No. SERB/F/12769/2018-2019).
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Volume 29, Issue 3, 2022


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*Journal of Enhanced Heat Transfer*


