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THERMAL PERFORMANCE OF PCM-BASED HEAT SINKS

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ABSTRACT

Thermal management of portable electronic devices plays a crucial role with regards to their reliability, increased installed functions, and user comfort. Using Phase Change Material (PCM) based heat sinks can offer a great advantage in such applications. However, poor thermal conductivity of the PCMs urges for a solution to improve their cooling performance. This work presents an experimental investigation into the effects of heat sink configuration on PCM thermal performance for the purpose of cooling of electronic devices. Based on fins arrangement and corresponding number of cavities, six heat sink designs having similar dimensions were tested. Heat sinks were partially filled with paraffin wax type PCM and experimentally investigated for their heating and cooling down performances. Results showed that using PCM reduces heating rates and consequently the peak temperature of heat sinks. In addition, the level of PCM in the heat sink showed a significant effect on the peak temperature. Besides, increasing the number of fins was shown to enhance the heat distribution to PCM and, thus, leads to lower heating rates of heat sinks. The lower heating rates obtained with the use of PCM-based finned heat sinks were shown to be at the expense of cooling down rates.

KEYWORDS: Heat Sinks, Phase Change Material, Cooling of Electronic Devices

INTRODUCTION

Producers of portable electronic devices are constantly striving to strike a balance between performance and scale to gain a competitive advantage in the market. The lifetime of electronic devices depends to a large extent on temperature swings and peak operating temperatures they are subjected to during their lifecycle. Higher demand for more installed functions, which requires higher power, urges the producers for greater need for efficient thermal management in electronic devices. Based on the used materials, portable device cases of temperatures higher than 45°C could cause discomfort to users [1]. Conventionally, micro chips are designed to operate at a maximum temperature of 85 - 120°C to prevent overheating [2]. A number of factors influence the choice of cooling methodology used in electronic devices including: space, operating environment, heat dissipated, cost of materials, and maintenance required [3]. The use of active thermal cooling methods such as miniature centrifugal fans proved to be inefficient due to space limitation, noise levels, high maintenance, and additional power consumption [4].

Thermal cooling by Phase Change Material (PCM) utilises a high latent heat of fusion that is absorbed and released during phase transition nearly at a constant temperature. PCM-based heat sinks can be employed to reduce peak operating temperatures but only for a limited duration. PCMs are best suited for applications that involve high peak loads but with low duty cycles [2]. The use of PCMs is therefore beneficial to applications where the power pulse is so long with a period of tens of minutes to provide adequate time for solidification [5]. It is critical to choose a PCM based on its melting range as melting of PCM only lowers the heat sink temperature during the melting time. Once the PCM is completely melted, the temperature thereafter increases in a similar way like that of a conventional heat sink [2]. Also to be considered is the latent heat of fusion of a PCM that specifies the amount of heat absorbed during the phase change process.

Several studies were conducted to investigate the use of PCM in transient cooling of electronic devices. Pal and Joshi [6] performed a comprehensive study on thermal control of plastic quad package and found that PCM could prevent chip temperature rise for a significant period. Leland et al. [7] and Shatikian et al. [8] conducted detailed numerical investigations into the phase change process of PCM which depends on thermal and geometrical parameters of the heat sink. Tan et al. [9] employed an organic PCM in Personal Digital Assistants (PDA) and reported the success of PCM in absorbing heat dissipated from chip and maintaining chip temperatures below the allowable operating temperature. Krishnan et al. [10] proposed a hybrid heat sink that combines a plate fin heat sink with its tip immersed in a PCM.

Recent findings looked into implementing fins of different dimensions and shape to improve the thermal conductivity of PCM. Saha et al. [11] found that a large number of small cross-sectional area fins is ideal in enhancing the thermal conductivity of PCM. The effects of power levels and heat sink configurations on the thermal performances of PCM for mobile devices were investigated by Setoh et al. [12].

The potential of using honeycomb inserts to replace machined fins to improve the thermal conductivity of PCM was investigated by Mahmoud et al. [13]. This research presents an experimental investigation into the benefits of introducing PCM material to enhance the thermal performance of finned heat sinks. Six heat sink designs having similar dimensions were tested: one with a single cavity, four with parallel fin arrangement, and one with crossed fin arrangement.

EXPERIMENTAL SETUP

Figure 1 shows a schematic diagram of the experimental setup used to study the effect of fins configuration on the thermal performance of PCM-based heat sinks. It consists of a heat sink having the dimensions of (40mm x 40mm x 30mm) and of 1mm wall thickness. The heat sink is partially filled with PCM and is enclosed by an insulation material to minimise thermal losses. A paraffin type PCM was partially included in the heat sinks used in this investigation. An electric heater was attached to the base of the heat sink and is also covered by the insulation material at the bottom. The heater was connected to an adjustable AC power supply. The power input was measured and found as 4.84W.

A set of thermocouples were used to measure the average base surface temperatures of the heat sink. To ensure good contact between the thermocouple tips and the metal, the thermocouples tips were embedded in grooves milled in the base of the heat sink. Also a thermally conductive epoxy resin was used to secure the thermocouples in their locations. The thermocouples were calibrated in the range of temperature measurements with a maximum uncertainty of ±0.5^{o}C. They were connected to a digital multimeter to read out the average heat sink base temperature in ^{o}C. Temperatures were recorded at time intervals of 30 seconds throughout the length of experiment.

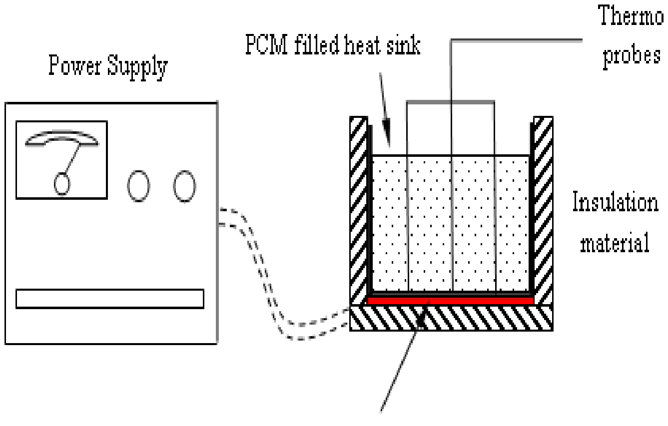


Figure 1: Schematic of the Experimental Setup

HEAT SINKS CONFIGURATION

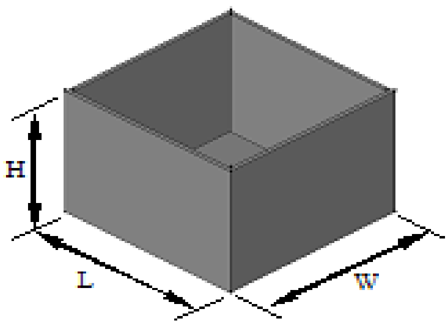
Six configurations of heat sinks were experimentally tested to study the effects of fins configuration and PCM on the thermal performance of heat sink. Figure 2 shows the tested designs of heat sinks used while Table 1 lists their dimensions. The base heat sinks were: one single cavity, four with parallel fin arrangement, and one heat sink with crossed fin arrangement. All heat sinks were made from Aluminium and have equal dimensions of 40mm in length, 40mm in width, and 30mm in height. The single cavity heat sink (SC) has one large cavity. In the parallel fin arrangement, three designs were used; 2-Cavity, 3-Cavity, and 4-Cavity (with either uniform or non-uniform fins) heat sinks, while in the crossed fins heat sink, a 16-Cavity design was used. In all tested heat sink designs, a fin thickness of 1mm was used. Taking into consideration the volume expansion of PCM when melts, the heat sinks were partially filled with a constant height of liquid PCM and so the volume of PCM could vary as the dimensions of the heat sink cavities are different.

RESULTS AND DISCUSSIONS

Two sets of experiments were carried out to study the effects of different factors on the heat sink thermal performance. This includes the effect of PCM height and the effect of heat sink configuration. The duration of each experiment was chosen such that the first 60-minute was for the heating and melting phase of the PCM, while the remaining time was for the cooling and solidification phase of the PCM to the ambient temperature.

Single Cavity Heat Sink with Variable PCM Height

To investigate the effect of PCM height on the thermal performance of heat sink, the single cavity heat sink was heated first without the PCM. The experiment was then repeated with the same setup but this time with different heights of liquid PCM added into the cavity. Figure 3 illustrates the difference in temperature variation with time between the single cavity with and without PCM at a constant input power of 4.84W. In the case without PCM, the heat sink base temperature increases rapidly to reach a peak value of 78°C at the end of heating stage, while that with PCM it increases at a slower rate to reach a lower value than that of the case without PCM. This shows the clear advantage of using PCM where after reaching the melting point of the PCM, the heat sink is significantly cooler during the heating phase than the case without PCM. This is owing to the fact that the PCM absorbing large amount of heat (the latent heat) when it melts at the melting point resulting in better cooling of the heat sink. The solid PCM begins to melt at about 54°C where latent heat is stored during this phase change process, but the heat sink temperature is not constant as anticipated and increased at a slow rate, which is caused by the poor thermal conductivity of PCM. By removing the heat source, i.e. right after 60mins, the heat sink with PCM cools down at a slower rate than that without PCM. This is due to the PCM having to release the stored heat (i.e. solidification process) back to the surroundings including the heat sink. Since PCM-based heat sinks heat up at a slower rate, when implemented in a portable electronic device, longer usage lifetime of the device with low thermal stresses can be achieved.



Single Cavity (SC)

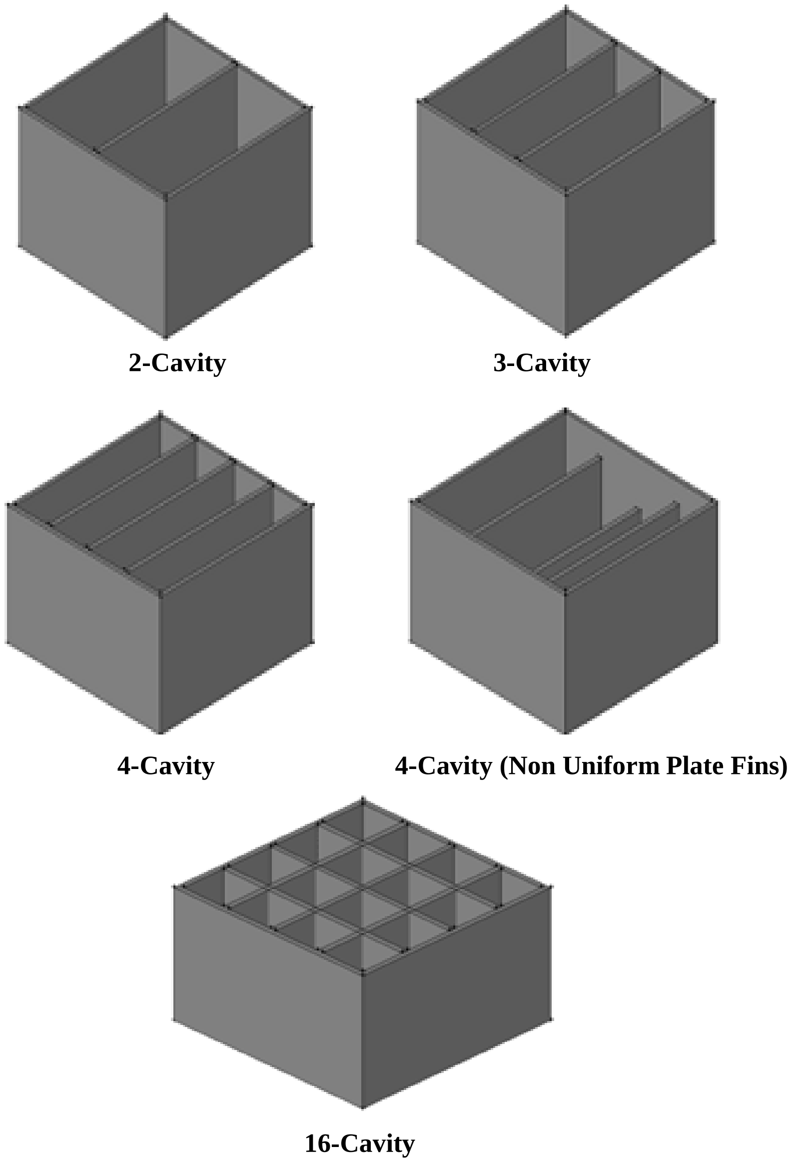


Figure 2: Models of Tested Heat Sinks

Table 1: Dimensions of Heat Sinks and Cavities

Heat Sink	Dimensions (L x W x H) mm	Dimensions of One Cavity
Single Cavity (SC)	40 x 40 x 30	38 x 38 x 29
2-Cavity (parallel fins)	40 x 40 x 30	18.5 x 38 x 29
3-Cavity (parallel fins)	40 x 40 x 30	12 x 38 x 29
4-Cavity (parallel fins)	40 x 40 x 30	8.75 x 38 x 29
16-Cavity (crossed fins)	40 x 40 x 30	8.75 x 8.75 x 29

It is apparent from Figure 3 that increasing the PCM height inside the single cavity heat sink considerably reduces the maximum heat sink temperature. The increase in the PCM height increases the contact area between the heat sink and the PCM, and therefore increases the heat transfer to the PCM. The increase in contact area between walls of the heat sink and PCM results in a good distribution of heat through the PCM. Increasing the volume of PCM due to the increase in PCM height would always increase the heat capacity of PCM. Increasing the height of PCM from 6mm to 13mm, for example, reduces the maximum heat sink temperature by 12^{o}C (16.7%), see Figure 4. It has to be elucidated that incomplete melting of PCM may take place at higher levels of PCM. This is obvious in the case of 18mm thickness PCM.

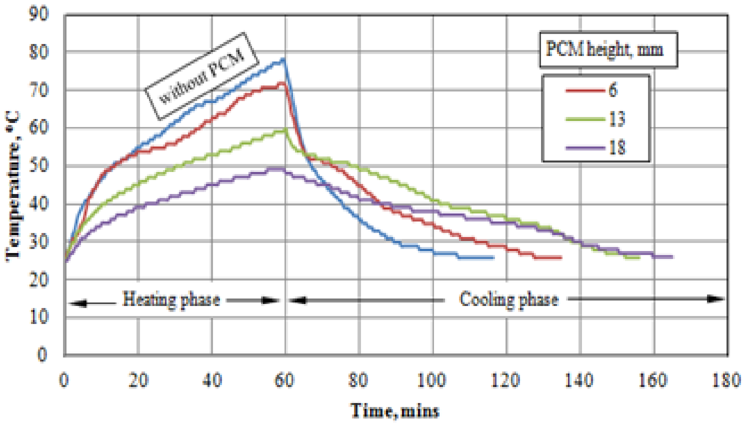


Figure 3: Temporal Temperature Distribution of the SC Heat Sink with Variable PCM Height

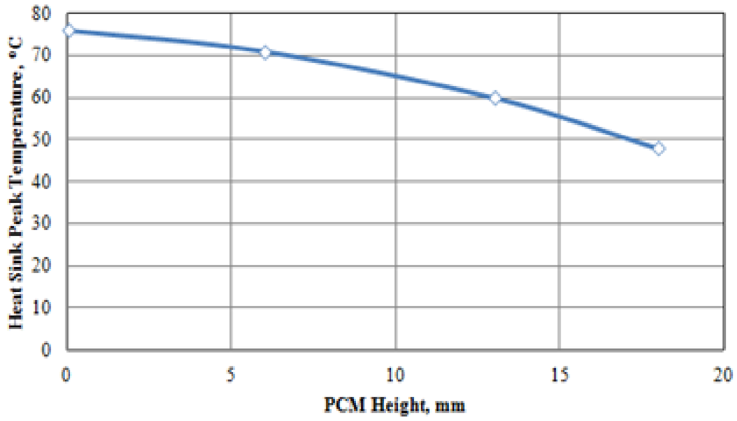


Figure 4: Variation of the SC Heat Sink Peak Temperature with PCM Height

Heat Sink with Different Fin Configurations

Figure 5 shows the variation of average base temperature during the heating and cooling phases for the all heat sink designs without PCM at 4.84W. As depicted in Figure 5, the presence of fins in both parallel and crossed fin configurations results in lower temperature variation during the heating process than that of the single cavity case. This is definitely due to the improved overall thermal conductivity of the heat sink as a result of the increased contact area with the ambient. The 4-cavity parallel fin configuration and the 16-cavity crossed fin configuration heat sinks show comparable thermal performance and superior to other heat sinks in terms of lower peak heat sink temperatures. This indicates that the 4-cavity parallel fin configuration is more cost effective than the 16-cavity crossed fin configuration due to ease of manufacturing and lower weight.

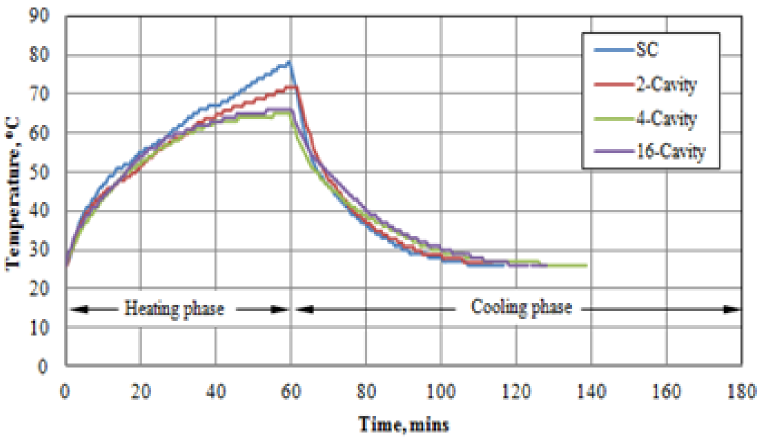


Figure 5: Temperature Profiles of the Parallel and Crossed Fins Heat Sinks without PCM

During the cooling phase for all heat sink designs, the SC heat sink achieved the best cool-down rates and rapidly arrived at the lowest temperature as compared to the parallel and crossed fins heat sinks. The cooling down performance of the 16-cavity crossed fins heat sink was poorer than that of the 2-cavity parallel fin configurations. Also, the performance of the 4-cavity parallel fins heat sink was poorer than that of the 2-cavity parallel fins heat sink.

Finned Heat Sinks with PCM

The effect of fin configuration on the thermal performance of heat sinks with PCM is shown in Figure 6. As can be seen, using the 4-cavity parallel fins heat sink with a PCM height of 6mm reduces the maximum heat sink temperature by about 17^{o}C than the SC case, compared to a reduction of 13^{o}C in the case without PCM (see Figure 7). The thermal conductivity of PCM-based heatsinks is thus improved when using finned configuration heat sinks.

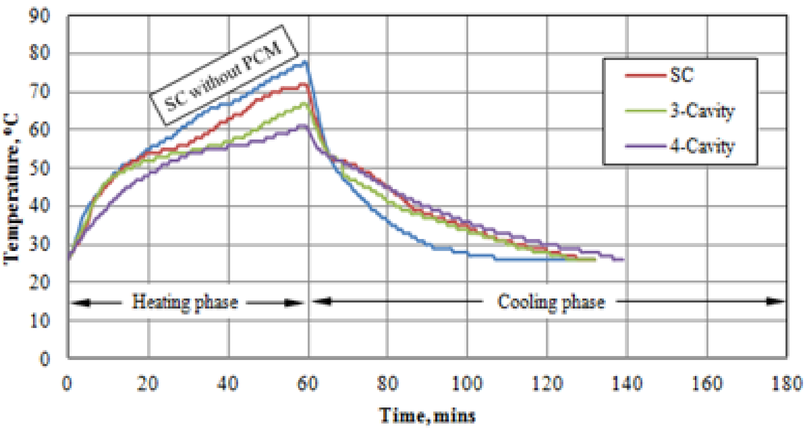


Figure 6: Temperature Profiles of Heat Sinks at 6mm PCM Height

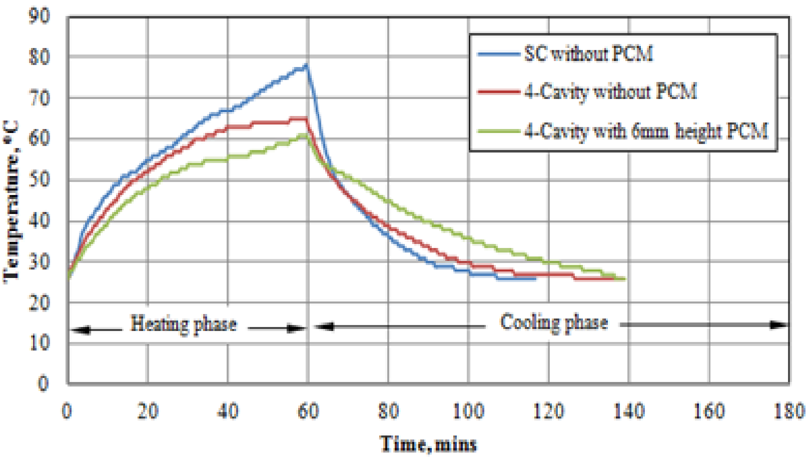


Figure 7: Thermal Performance of the 4-Cavity Heat Sink with and without PCM

As mentioned so far, a comparison between different heat sink designs is necessary to choose between alternatives with regards to best thermal performance. Having the same number of cavities, an attempt was made to study the effect of fin height on the thermal performance of heat sink. Figure 8 compares the thermal performance of a 4-cavity PCM-based heat sink with and without uniform fin height. The non uniformity in the height of the fins was expected to increase the degree of free circulation of air filling the heat sink cavities.

In the current case, however, this behaviour is minimal due mainly to small size of the heat sink used and also owing to the difference in temperature between heat sink walls and ambient air. As shown in Figure 8, the heat sink with uniform fin height showed better thermal performance than the one with non uniform fin height. This is actually due to the large contact area between heat sink walls and the ambient air in case of heat sink with uniform fin height.

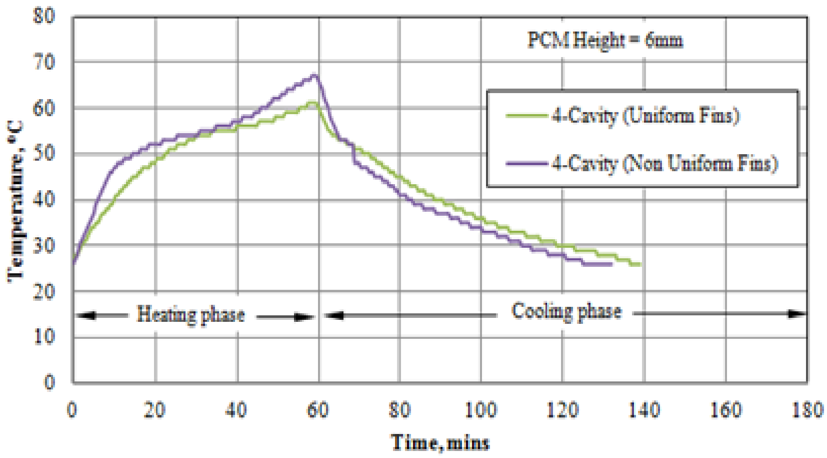


Figure 8: Effect of Fin Uniformity on Temperature Variation for the 4-Cavity PCM-Based Heat Sink

CONCLUSIONS

Using Phase Change Materials (PCMs) based heat sinks offers potential in cooling portable electronic devices. With the poor thermal conductivity of PCMs, this work presents an experimental investigation of using fins with different arrangements to enhance the thermal conductivity and to improve the cooling performance of PCM-based heat sinks. The results showed that including the PCM in the heat sinks reduces the heating rate and subsequently the peak temperatures. Increasing life span of electronic devices is therefore beneficial when using PCMs. Results also showed that the effect of PCM level on the heat sink thermal performance is more significant. It was further demonstrated that increasing the number of fins improves heat transfer to PCM leading to lower heating rates and peak temperatures of heat sinks. However, cool-down rates are being lower with PCM-based heat sinks.

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