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Cooling of portable hand-held electronic devices using phase change materials in finned heat sinks

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ABSTRACT

An experimental study was conducted on the cooling of portable hand-held electronic devices using n-eicosane as the phase change material (PCM) placed inside heat sinks with and without internal fins. The effects of the PCM, number of fins, orientation of the device, and the power level (ranging from 3 to 5 W), on the transient thermal performances were investigated under frequent, heavy and light usage conditions. The results indicated that PCM-based heat sinks with internal fins are viable options for cooling mobile devices but the effectiveness of the approach may require optimization with respect to the amount of PCM used, the number of fins, the power level of the heat source, and the usage mode of the device.

1. Introduction

Portable hand-held electronic devices such as mobile phones, personal digital assistants (PDAs), iPods, digital cameras, electronic game consoles, etc. are widely used items in everyday life. With the advancement in technology, the functionalities of these electronic devices (particularly in mobile phones) have significantly increased while their sizes and weights have decreased. For example, the latest models of mobile phones are smaller and packaged with additional features including cameras (with video recording and playback capabilities), digital music players and full web browsing facility. These advanced functions require more sophisticated electronics, which will generate extra heat. Without proper thermal management, the heat generation and temperature rise may lead to deterioration in performance, failure of critical components, and user-device interaction discomfort. As the physical space available for heat management is reduced, the cooling of these devices has become increasingly challenging [1].

Thermal management of portable hand-held electronic devices relies on a judicious combination of materials and heat transfer techniques to stabilize the component temperature at an acceptable level. Forced convection cooling requires bulky and massive equipment, such as a fan, and is thus not suitable for use in many hand-held portable devices. In recent years, phase change materials (PCMs) have been widely investigated as an alternative passive thermal management solution [2–10]. The main advantage of a PCM is its high latent heat of melting which provides good energy storage density. When a solid PCM melts, phase change occurs. The solid to liquid transition allows large amounts of energy to be absorbed. As latent heat is stored inside the PCM, the temperature remains fairly constant with very small volume changes. After the phase change is completed, the temperature will rise as heat is applied.

Besides the ease of controlling the melting temperature stability, PCMs are relatively light, chemically stable and non-corrosive to many materials. These are desirable features in the thermal management of mobile devices. In PCM-based cooling strategies, heat is removed from the component during the melting phase. Molten PCM can then be re-solidified by releasing heat to the surroundings when the electronic device is not in use. This process is suitable for mobile devices as they are seldom used continuously at peak load for more than a few hours and their idle times are usually long enough for the molten PCM to re-solidify. Nevertheless to achieve effective cooling, the duration of operating the portable electronic devices should not exceed the time needed for phase transformation. The maximum operation time of portable devices is often dictated by the battery and usage conditions.

All portable consumer electronics share common power related functions, which include battery management, voltage regulation and load switching. The battery is a critical component as its life between charges will dictate the maximum allowable operating

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time. The power of a typical Li-ion cell with a capacity of 1.5 Ah (nominal voltage 3.7 V) is about 5.5 W. Power management circuits are designed to extend the battery life by optimizing the efficiency. The power MOSFET is usually used for switching operations in battery operated systems. Depending on the chip set, the maximum power dissipation from these components can range from 2 to 5 W [11]. Practical devices seldom dissipate the peak amount of heat continuously. For example in mobile phones the maximum power in GSM 900 cell phones allowed to be transmitted by the present standards is 2 W and the average power is about 250 mW [12]. Luo et al. [13] analyzed the Samsung SPH E2500 mobile phone thermal characteristics and determined that the power amplifier dissipates the most heat, which was estimated to range from 0.5 to 2.2 W. In view of these power related functions, this paper will focus on PCM cooling of portable hand-held devices with input power ranging from 3 to 5 W under different usage conditions.

There are many recent investigations of PCMs for the thermal management of portable electronic devices. For example, the use of PCM-based thermal management system in mobile devices for power levels ranging from 6 to 12 W was investigated by Kandasamy et al. [7]. They concluded that a PCM is a viable thermal solution at higher heat source power levels. Their cooling scheme was successfully applied to the transient cooling of a printed circuit board [8]. Their findings indicated that the inclusion of a PCM in the cavities of the heat sinks can improve the cooling of the printed circuit board. Tan and Tso [5] also discovered similar findings in the PCM cooling of mobile electronic devices subjected to uniform and non-uniform heat distribution from 4 W to 16 W. Unfortunately, the cooling performances under different usage conditions were not investigated.

The heat storing capacity of PCMs is mainly due to the latent heat of melting. The main drawback is that PCMs generally have very low thermal conductivities. In order to utilize the heat storing capacity effectively, it is necessary to enhance the heat transfer rate into and out of the PCMs. Many techniques have been suggested to overcome this problem [14–17]. Among these techniques, the use of an internal fin in the heat sink is a popular solution.

This paper is an extension of the work of Tan and Tso [5]. The objective is to determine experimentally the effects of a PCM in heat sinks (with and without internal fins) in the cooling of portable hand-held electronic devices with input power ranging from 3 to 5 W. The transient thermal performances of the heat sinks are investigated under frequent, heavy and light usage conditions.

2. Experimental setup and procedures

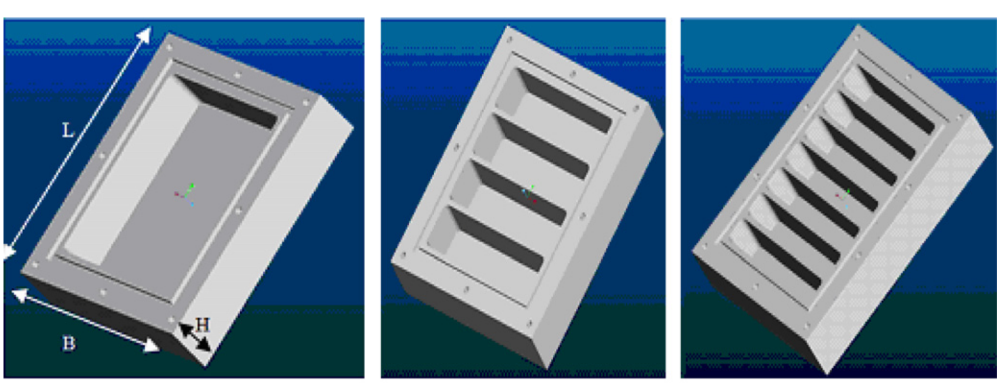
2.1. Setup

The experimental setup was designed based on the average dimensions of typical portable hand-held electronic devices. Four heat sinks were fabricated using Aluminum T6-6061. Fig. 1 shows the heat sinks, which are of different sizes with no fins, three fins, and six fins respectively. Their dimensions are 85 × 72 × 21 mm for heat sinks A and B, 91 × 72 × 21 mm for heat sink C and 97 × 72 × 21 mm for heat sink D. Heat sink A is a solid aluminum block that contains no PCM. Heat sink B is of the same dimensions as heat sink A but it has a cavity that contains the PCM. Heat sink C has three equally-spaced fins within the cavity. Heat sink D has six equally-spaced fins within the cavity. The thickness of each fin is 2 mm.

N-eicosane was the selected PCM as its melting temperature of 36 °C is within the operating temperature of general portable hand-held electronic devices. This melting temperature is also significantly higher than the ambient temperature so that no melting would occur at room temperature. N-eicosane has a high latent heat of melting of 247,300 J/kg. The volume of PCM used in each casing was kept constant. Heat sinks B, C and D were each filled with 44 mL of liquid n-eicosane and left to solidify for 24 h. Heat sink A, which contained no PCM, was used as a control in the experiment for comparison purposes.

A 50 mm × 50 mm plate heater was attached below each heat sink using a thin layer of thermal conducting paste Omegatherm 201. This attachment reduced the contact resistance and air gap between the surfaces, thus enhancing thermal conductivity during heat transfer. The heater can provide input powers ranging from 2 W to 7 W to simulate the heat source. An adjustable DC power supply (model Philips-1693) was connected to the heaters. The maximum voltage across each heater was 24 V DC.

Each heat sink with attached heater was enclosed in a plastic casing made of 2 mm thick polycarbonate, which has a melting temperature of 135 °C and a thermal conductivity of 0.21 W/mK. The heater was insulated from the casing using a 3 mm Teflon board. This prevents heat loss from the heater to the polycarbonate plastic casing. No insulation was provided on the top surface in order to allow natural convection to take place. Rubber O rings were placed on the side of the heat sinks before the device was sealed with M3 screws and epoxy. The metal screws hold the heat-transferring blocks tightly to the aluminum heat sink to prevent any leakage. Each setup was



Case A and B
85 x 72 x 21

Case C
91 x 72 x 21
(All dimensions in mm)

Case D
97 x 72 x 21

Fig. 1. Heat sinks used in the experiment: heat sinks A and B (no fins), heat sink C (3 fins), heat sink D (6 fins).

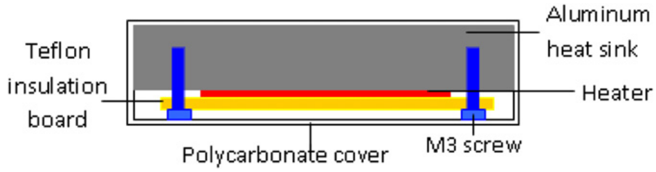


Fig. 2. Schematic diagram of the model.

Table 2
Locations of thermocouples on the heat sinks.

Heat sink types	Length in mm	
	x	*y*
Heat sink A	24	28.3
Heat sink B	24	28.3
Heat sink C	24	30.3
Heat sink D	24	32.3

Table 1
Properties of the selected materials.

Material	Thermal conductivity (W/mK)	Specific heat (J/kg K)	Melting temperature (°C)
N-eicosane	0.15	2460	36.0
Aluminum	202.4	871	660.4
Teflon	0.20	1172	335.0
Polycarbonate	0.21	1170	135.0

placed inside a black box to reduce environmental effects due to lights, flows from air-conditioning fans and other disturbances. The schematic diagram of the model is shown in Fig. 2. The properties of the selected materials are summarized in Table 1.

Eight K-type thermocouples were used to measure the temperatures of the heater and the heat sink in each setup. Each thermocouple has uniform uncertainty of ±0.5 °C over the range of 0–100 °C. The thermocouples were calibrated to within ±0.75 °C (between 0 and 100 °C) according to ASTM standards [18] and attached to different points on the heat sink by epoxy (i.e. West System 105 epoxy resin and 205 super slow hardener). The thermocouples are designated by symbols to distinguish the temperatures that they are measuring (Fig. 3). Six of the calibrated thermocouples (i.e. T1, T2, L1, L2, R1 and R2 in Fig. 3) were attached to the external surfaces along the perimeter of the aluminum heat sink. The thermocouple (H1) was attached between the heater and the aluminum heat sink and the thermocouple (H2) was placed between the underside of the heater and the insulation board. The exact positions of the thermocouples on the heat sink are given in Table 2. Random noise was estimated at ±0.1 °C. The thermocouple temperature measurement uncertainty is estimated to be ±0.5 °C [19].

The K-type thermocouples were connected to a PC-based temperature data acquisition system. The data acquisition unit (i.e. Agilent 34970A Data Acquisition Unit) with two multiplexers (34908A 40-Channel Multiplexer and 34901A 20-channel multiplexer) was linked to a computer to record the real time temperature of each thermocouple. Temperatures were automatically recorded at 5 min intervals. A thermal imaging system (i.e. TVS-2000 MkII Series Compact Thermo) was used to capture the thermal images and surface temperature of the plastic cover. The plastic cover has a higher emissivity which helps to reduce the error due to the reflection of spurious heat sources from the surroundings to the thermal imager. The thermal images were automatically captured every 10 min. The system has a measurement range of −40–500 °C and a temperature resolution of less than 0.05 °C at 60 Hz and 30 °C with accuracy of 0.5% full scale (typical). The resulting uncertainty for thermal imager measured temperature was estimated to be within ±0.3 °C.

2.2. Procedures

The experiments can be separated into two series. The first series of experiments was conducted at three different constant power levels (i.e., 3 W or, 4 W and 5 W) for three different orientation angles: 0° (i.e. horizontal), 45°, and 90° (i.e. vertical). The three orientations are shown in Fig. 4. Each experiment lasted 150 min. This first series of experiments was designed to investigate the effects of using a PCM in the heat sinks, the effect of the heating power level on a PCM-based heat sink without a fin, the effect of fins in a PCM-based heat sink on the heat dissipating performances, and the effect of the setup orientations on the cooling strategy.

The second series of experiments was conducted to investigate the transient thermal performances of the heat sinks in three usage modes, i.e. frequent, heavy and light usages. The charging stages of these three modes are different. The operation sequences of the heaters for these three modes are given in Table 3. The total time for

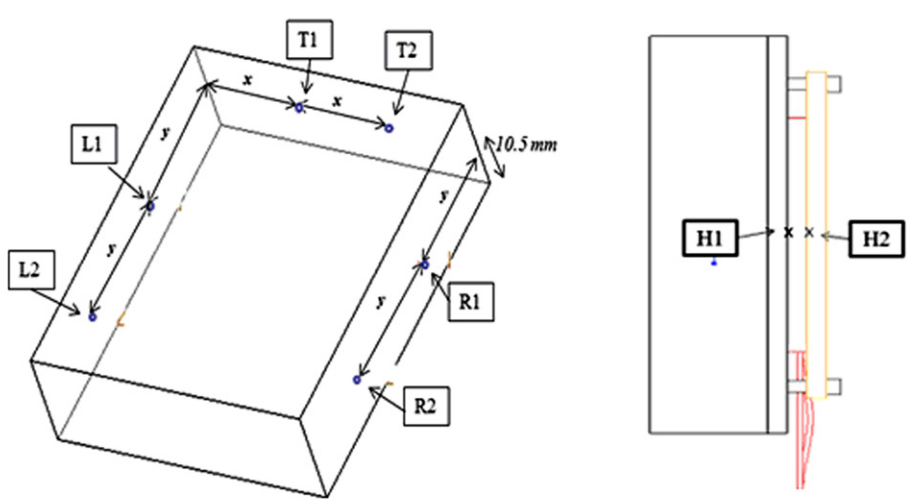


Fig. 3. Location of thermocouples.

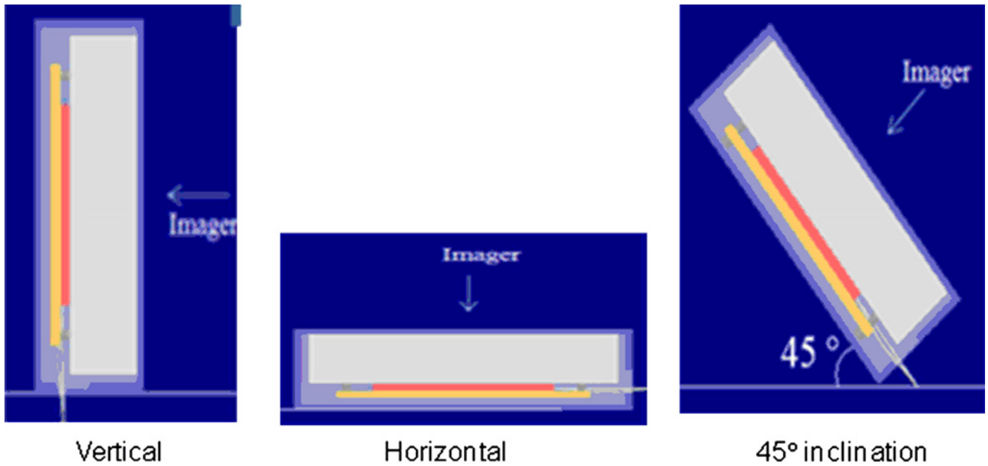


Fig. 4. Three different orientations of heat sink.

all operation sequences was fixed at 70 min and the heating power was maintained at 5 W for all cases. All models were left to cool during the discharging stage (i.e. with the heater turned off).

3. Results and discussions

3.1. Effect of PCM in heat sink without fin

The effect of using a PCM in the heat sink with no fin was first investigated. The investigation simulates the cooling of a hand-held electronic device under natural convection with and without the use of a PCM inside the aluminum heat sink. Table 4 summarizes the thermocouple temperatures of heat sink A (without a PCM) and heat sink B (filled with a PCM) at 4 W in the vertical position. The heat dissipations from the heaters were quite uniformly distributed over both setups. Due to symmetry, the thermocouple temperatures of T1 were similar to that of T2, L1 with L2, and R1 with R2, thus only temperatures of thermocouples T1, L1 and R1 are shown in Table 4. The temperature of the thermocouple at the heater side H1 is also shown in Table 4. The temperatures of heat sink B in Table 4 are generally lower than that of the heat sink A. The results indicated that the use of a PCM in a heat sink can help to maintain the device at a lower temperature.

Fig. 5 compares the surface temperatures of heat sinks A and B. When there is no PCM in the heat sink, the surface temperatures would increase steeply until the end of the experiment. It is undesirable to have conditions like this to occur in a hand-held device as the service temperature of the electronic components would be quickly exceeded. The allowable temperatures of the chips and other electronic components are important considerations in the thermal management of mobile phones or PDAs. Another equally important factor is the temperature limit at which the average user can comfortably interact with the hand-held device. The thermosensory system was evaluated psychophysically by Greenspan et al. [20] and their findings indicated that 45 °C is the average threshold for heat. Story [21] suggested that Transient Receptor Potential (TRP) ion channels activated by temperature are important molecular players in acute inflammatory and chronic

Table 3
Operation sequence of the heater in three operational modes.

Situation	Operation sequence of the heater
Frequent usage [Heater on for 60 min. and off for 10 min.]	- On for 15 min. - Off for 2 min. - On for 20 min. - Off for 5 min. - On for 10 min. - Off for 3 min. - On for 15 min.
Heavy usage [Heater on for 60 min. and off for 10 min.]	- On for 30 min. - Off for 10 min. - On for 30 min.
Light usage. [Heater on for 10 min. and off for 60 min.]	- On for 5 min. - Off for 30 min. - On for 2 min. - Off for 30 min. - On for 3 min.

Table 4
Thermocouple temperatures of heat sinks A and B.

Time (min)	Heat sink A (°C)				Heat sink B (°C)			
	L1	T1	R1	H1	L1	T1	R1	H1
0	25.8	25.9	25.9	26.3	26.1	25.8	25.9	26.2
5	27.5	27.9	27.9	42.3	28.5	28.7	28.9	36.3
10	29.3	30.1	30.1	47.6	30.8	31.2	31.4	40.2
15	31.1	32.1	32.2	50.8	32.8	33.3	33.6	43.5
20	32.8	34.1	34.1	53.1	34.5	35.2	35.6	45.9
25	34.3	35.8	35.9	55.0	35.7	36.6	36.9	49.2
30	35.8	37.4	37.5	56.5	36.2	37.2	37.4	51.0
35	37.0	38.8	38.9	57.8	36.4	37.3	37.5	51.8
40	38.2	40.1	40.2	58.9	36.4	37.2	37.5	52.1
45	39.2	41.2	41.3	60.0	36.4	37.3	37.6	52.4
50	40.1	42.2	42.2	60.9	36.5	37.4	37.7	52.6
55	40.8	43.1	43.1	61.7	36.7	37.7	37.9	53.0
60	41.5	43.9	43.9	62.4	37.1	38.2	38.5	53.4
65	42.2	44.6	44.6	63.0	37.5	38.9	39.1	54.0
70	42.7	45.1	45.2	63.5	37.9	39.3	39.6	54.5
75	43.2	45.7	45.8	64.0	38.3	39.8	40.0	54.9
80	43.6	46.2	46.2	64.5	38.7	40.3	40.5	55.3
85	44.0	46.6	46.7	64.8	39.2	40.7	40.9	55.8
90	44.3	47.0	47.0	65.2	40.0	41.6	41.9	56.4
95	44.6	47.3	47.3	65.5	40.9	42.5	42.8	56.8
100	44.9	47.6	47.6	65.7	41.8	43.5	43.9	57.9
105	45.1	47.8	47.9	65.9	42.6	44.4	44.8	58.9
110	45.3	48.0	48.1	66.1	43.3	45.3	45.6	59.7
115	45.4	48.2	48.3	66.3	43.9	46.0	46.2	60.4
120	45.6	48.4	48.4	66.4	44.4	46.5	46.8	61.1
125	45.7	48.6	48.6	66.6	44.8	47.0	47.3	61.6
130	45.9	48.7	48.7	66.7	45.1	47.4	47.7	62.0
135	45.9	48.8	48.8	66.8	45.5	47.7	48.0	62.4
140	46.0	48.8	48.9	66.8	45.7	48.0	48.3	62.7
145	46.1	48.9	49.0	66.9	45.9	48.2	48.6	62.9
150	46.2	49.0	49.0	67.0	46.1	48.5	48.8	63.2

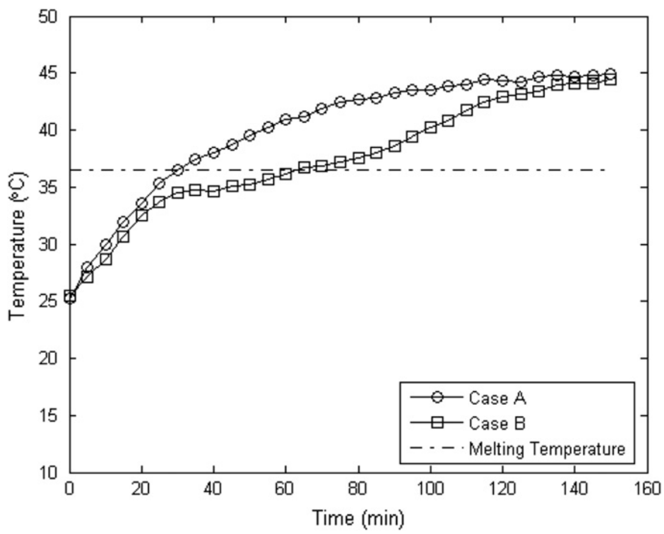


Fig. 5. Temperature distributions in heat sinks A and B at 4 W.

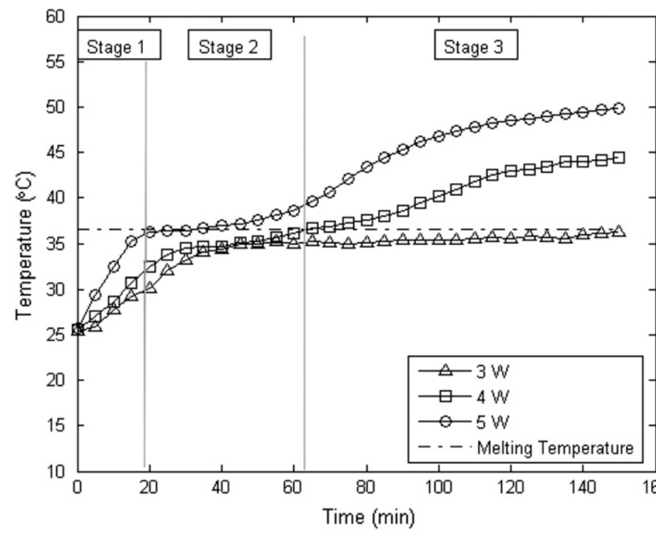


Fig. 7. Comparison of three different powers in heat sink B.

pain states. A cloned TRP Vanilloid 1 channel exhibited a thermal threshold of ≥42 °C when activated by heat. Based on these works, it can be assumed that users should start to feel uncomfortable when the device temperature reaches about 45 °C.

The temperature profile of heat sink B in Fig. 5 can be classified into three stages. In stage 1, the temperature of the solid PCM will increase to its melting temperature. In stage 2, phase change occurs as the solid PCM melts under constant temperature. Latent heat is stored in this phase. In stage 3, the PCM has fully melted and can no longer maintain the constant temperature. This resulted in the temperature rise in stage 3. It took about 27 min to complete stage 1 and 63 min to complete stage 2.

Fig. 5 shows that without a PCM in the heat sink, the surface temperature increases rapidly. Adding the PCM stabilizes the surface temperature for the duration of stage 2. The maximum surface temperature difference between the two cases is 5.2 °C. The temperatures rise more slowly in the device with the heat sink B. This is desirable as it extends the usage time of the portable device. The extension of the usage time is dependent on the amount of PCM used. This is because more energy can be stored as latent heat with more PCM and extra time will be needed for the phase transition. Fig. 6 shows the thermal images of heat sinks A and B at 4 W for the vertical position. Heat sink B (with a PCM) has a lower temperature than heat sink A (without a PCM) after 90 minutes. The results indicated that a heat sink with a PCM can help to limit a rapid temperature rise in mobile devices.

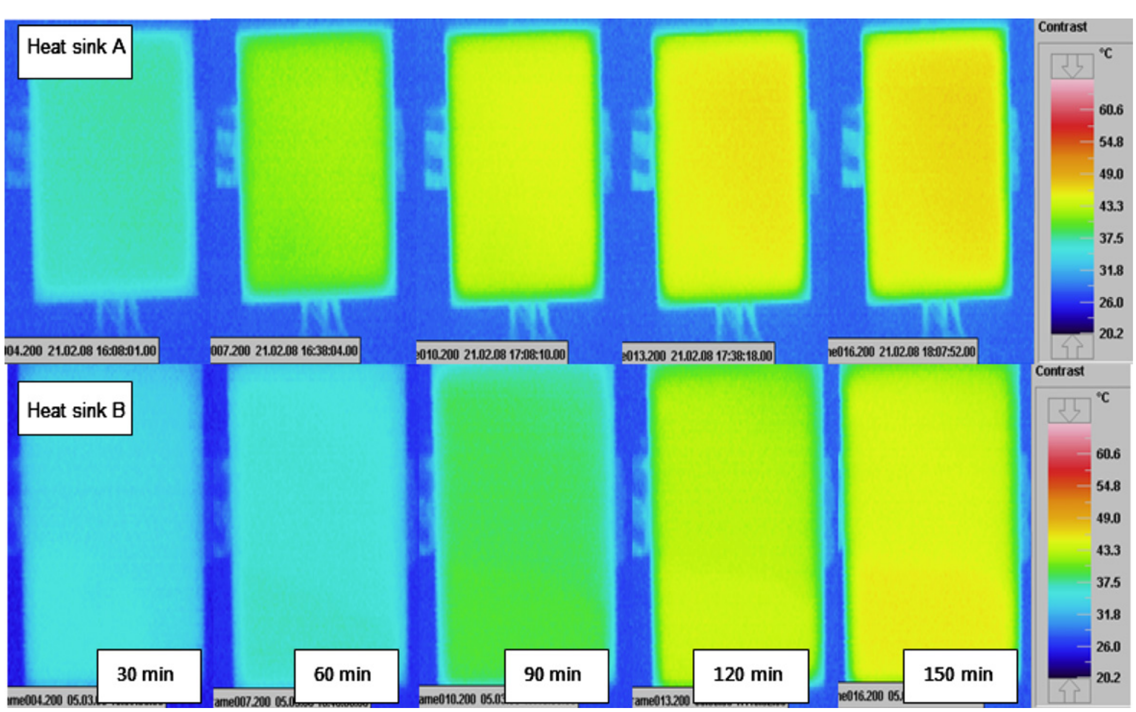


Fig. 6. Thermal images of heat sinks A and B at 4 W.

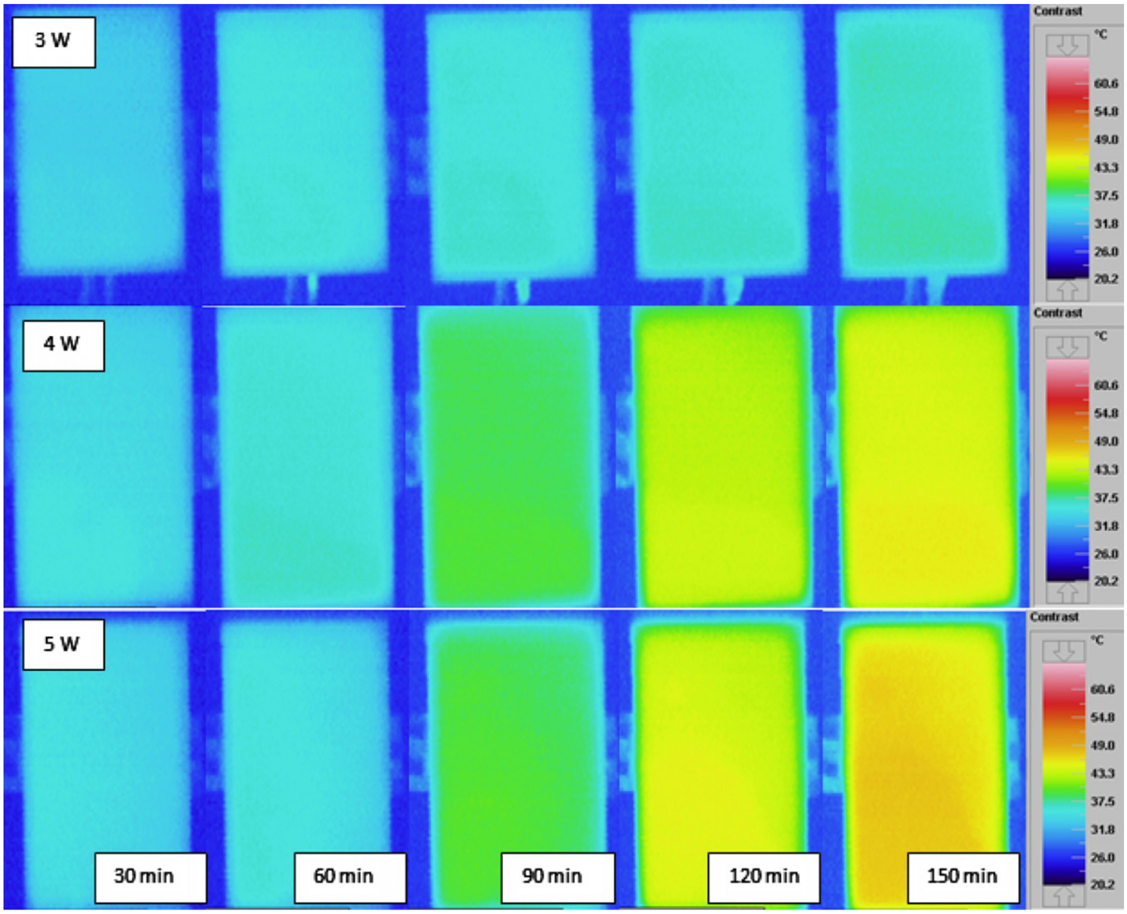


Fig. 8. Thermal images of heat sink B at 3, 4 and 5 W.

3.2. Effect of heating power level on a PCM-based heat sink without fin

The effect of heating power level on the performance of a heat sink with no fin and filled with a PCM is next examined. Fig. 7 shows the effects of different input powers on the setup with heat sink B in the vertical position. The PCM starts to melt earlier as the power is increased. The maximum temperature attained at 3 W was 36.3 °C and the PCM was still undergoing phase change after 150 min. At 4 W and 5 W the phase changes were completed after about 60 min and their maximum temperatures attained after 150 min were 44.4 °C and 49.8 °C respectively. These results suggested that the user might feel uncomfortable (i.e. temperature wise) after 150 min when operating a 5 W device that is cooled using heat sink B. Fig. 8 shows the thermal images of the three different power levels associated with heat sink B in the vertical position. At 3 W, the heat sink is at a much lower temperature compared to the powers at 4 W and 5 W. The temperature of the mobile device at 5 W is much higher after 150 min when the PCM in the heat sink has completely melted.

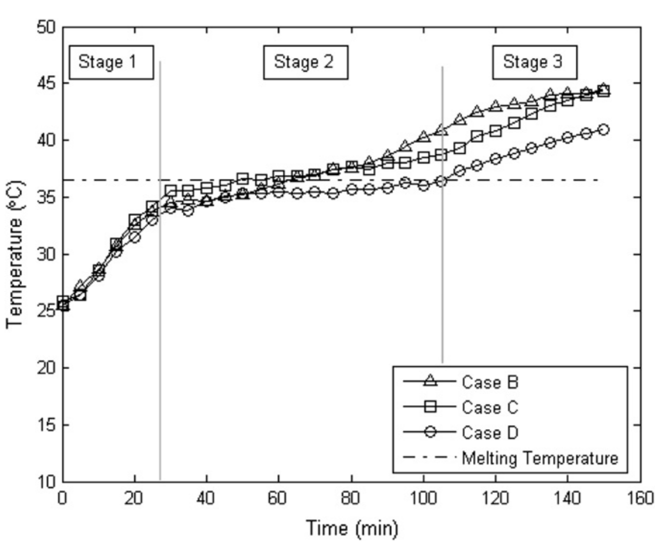


Fig. 9. Surface temperatures for heat sinks B, C and D at 4 W.

3.3. Effect of fin in PCM-based heat sink

The previous results indicated that adding a PCM in a heat sink can increase the usage time of the device. The usage time is affected by both the heat source power and the amount of PCM used. This section examines the effect of adding fins in the PCM-based heat sinks. Fig. 9 shows the temperatures associated with heat sinks B, C and D at 4 W for the setups placed in the vertical position. All the three cases took about 27 min to complete stage 1. In stage 2, slight differences begin to occur. The temperature in heat sink B increases slightly faster than that of heat sinks C and D in stage 2. Heat sink B took 63 min for the PCM to melt completely. After 150 min, heat sink D had the lowest temperature of 40.9 °C. Both heat sinks B and

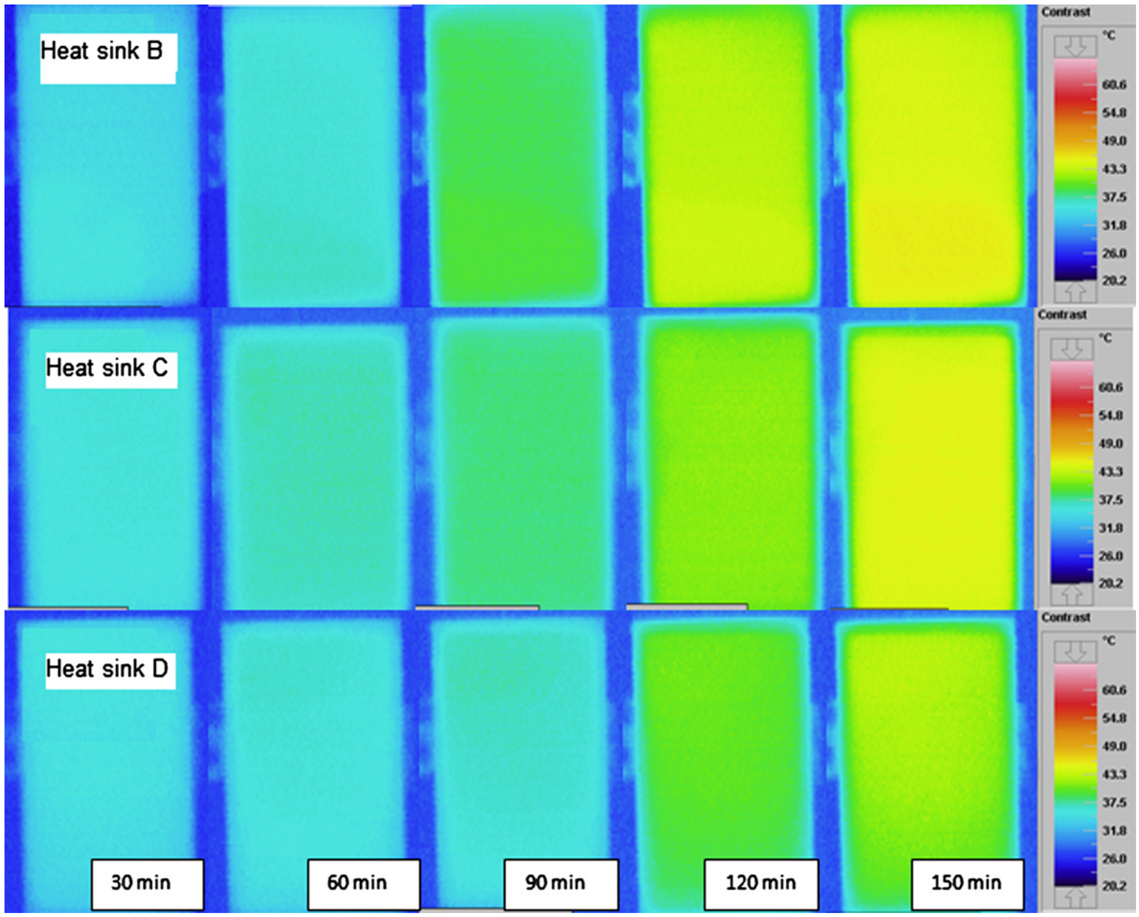


Fig. 10. Thermal images of heat sinks B, C and D at 4 W.

C reach 44.3 °C after 150 min. The results indicate that increasing the number of internal fins in the PCM-based heat sink can help to lower the device temperature. This finding is not unexpected as more fins can better distribute the heat to the PCM and for dissipation to the ambient. Similar trends were also found at 5 W for heat sinks B, C and D in different orientations. The results suggest that the proper design of the heat sink with internal fins could enhance the thermal performance. Fig. 10 shows the thermal images for heat sinks B, C and D at 4 W and placed in the vertical position. Heat sink D, with most number of internal fins in the heat sink, has the slowest rise in temperature compared to heat sinks B and C.

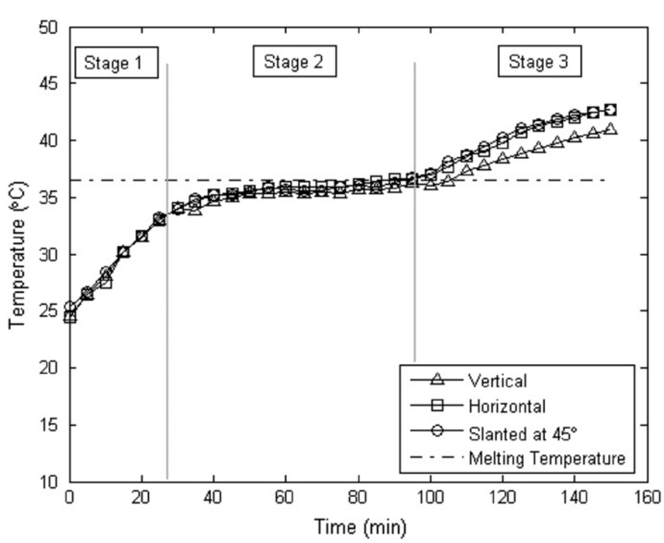


Fig. 11. Three orientations of heat sink D at 4 W.

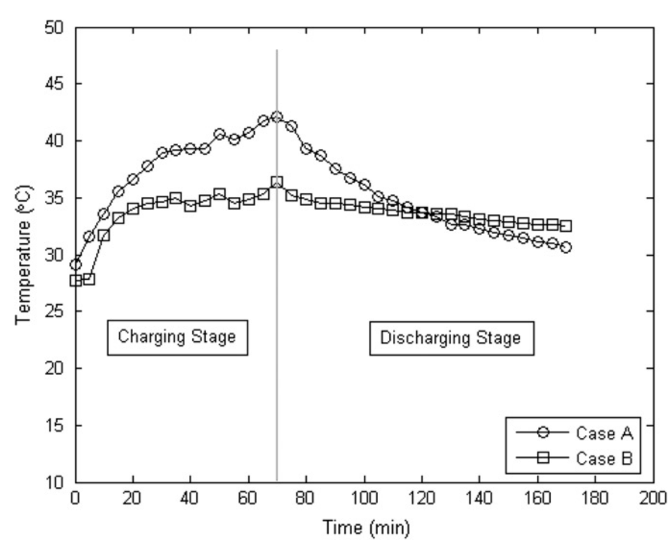


Fig. 12. Surface temperatures for heat sinks A and B (frequent usage).

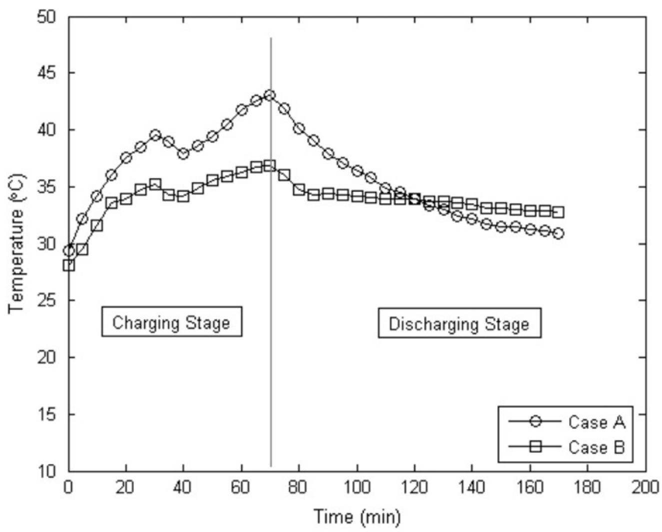


Fig. 13. Surface temperatures for heat sinks A and B (heavy usage).

3.4. *Effect of orientation on PCM-based heat sink performance*

The position and orientation of portable electronic devices such as mobile phones or PDAs may be subjected to random changes during normal usage. Fig. 11 shows the average temperature profiles of heat sink D at 4 W for the three different orientations given in Fig. 4. The results show that the effect of the device orientations on the phase changes is negligible and can be ignored. This finding indicates that the phase changes would not be seriously affected by the random position/orientation of the portable device during normal usage. Similar findings were reported by Wang et al. [9] and Kandasamy et al. [7] for electronic devices of up to 12 W. After phase change has completed, it may be advisable to operate the device in the vertical position to maximize heat convection to the ambient.

3.5. *Transient thermal performance – effect of PCM in heat sink without fin*

The second series of experiments investigate the transient thermal performances of the heat sinks in the frequent, heavy and light usage modes. The effect of a PCM in the heat sink without fins on the transient thermal performances was first examined.

Fig. 12 compares the surface temperatures of heat sinks A and B under frequent usage conditions. A maximum temperature difference of 6.4 °C occurred at the 65th minute during the charging stage. At the 70th minute the highest temperatures reached by heat sinks A and B were 42.1 °C and 36.3 °C respectively. During the discharging stage, heat sinks A and B were cooled to 30.7 °C and 32.5 °C respectively after 170 min. The heat sink with a PCM showed a slower cooling rate.

Fig. 13 compares the surface temperatures of heat sinks A and B under heavy usage conditions. During the charging stage, heat sinks A and B reached peak temperatures of 43.0 °C and 36.8 °C respectively. For heat sink B, the surface temperature was maintained approximately constant. During the discharging stage, heat sinks A and B were cooled to 30.9 °C and 32.7 °C respectively after 170 min. The heat sink with a PCM again showed a slower cooling rate.

Fig. 14 compares the surface temperatures of heat sinks A and B under light usage conditions. There was little temperature difference between the 2 cases during the charging stage. The temperature for heat sink B was slightly higher than heat sink A during the discharging stage. This result shows that the use of a PCM may not have a significant advantage under light usage conditions.

3.6. *Transient thermal performance – effect of fin in PCM-based heat sink*

The effect of fins in a PCM-based heat sink on the transient thermal performances in the heavy usage mode is examined next. The surface temperatures of devices using heat sinks B, C and D under heavy usage conditions are shown in Fig. 15. During the charging stage, heat sinks B, C and D reached the peak temperatures of 36.8 °C, 34.9 °C and 34.0 °C respectively after 70 min. This indicated that the heat transfer rate was increased with the additional surface area provided by the fins. The heat from the source was conducted by the fins to the surface of the heat sink and finally dissipated to the atmosphere through free convection. During the discharging stage, the temperature differences between the 3 heat sinks were less than 1 °C after 100 min of cooling. This indicated that the fins had minimum effect on the cooling of the mobile devices during the discharging stage where free convection was the main heat transfer mechanism.

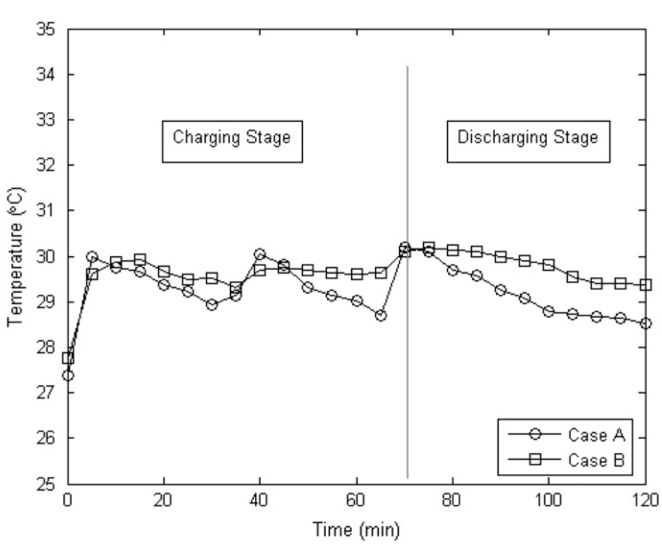


Fig. 14. Surface temperatures for heat sinks A and B (light usage).

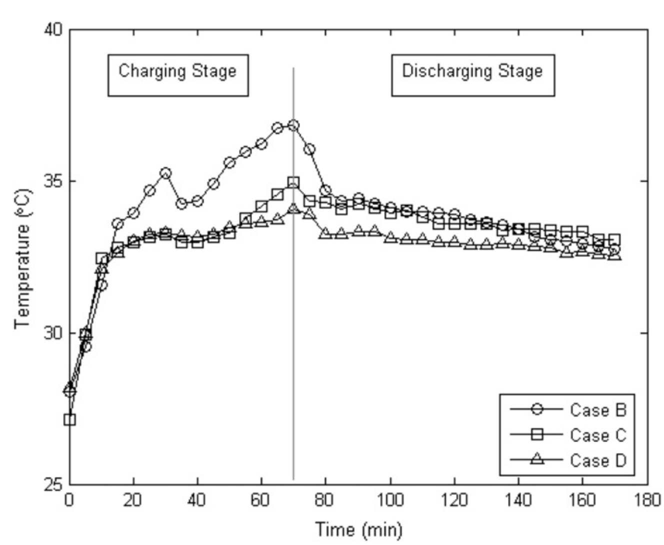


Fig. 15. Surface temperatures for heat sinks B, C and D (heavy usage).

4. Conclusion and future work

Experiments were carried out to observe the temperature variations in a typical size hand-held device cooled using different PCM-based heat sinks. The experimental findings indicated that the use of n-eicosane in the aluminum heat sink helps to stabilize the system temperature and extends the usage time. The usage time extension depends on the amount of PCM and the heat source power level. Internal fins aid in lowering the temperature of the device. Increasing the number of internal fins in the PCM-based heat sink can provide better heat dissipation. The orientations of the setups have limited effect on the phase change performance of the PCM-based heat sinks.

Power level and the thermal resistance of the PCM are two important design considerations in a PCM-based thermal management system. The current work investigates the effects of using n-eicosane in finned heat sinks for power levels ranging from 3 to 5 W. No attempts had been made to optimize the thickness of the heat sink and the number of the fins. It is envisaged that the optimization must take into consideration the type and amount of PCM used, the power level of the heat source and the geometry of the heat sink. At higher power levels, the heat flux will be higher if the device size is reduced. This could lead to higher temperatures and shorter operating time. In the presence of higher heat flux, the geometry as well as orientation of the fins during discharge may become significant. The orientation of the fin would have to be optimized based on the heat flux pattern within the device. Similarly, the fin geometry will have to be improved to enhance heat transfer. Various techniques have been suggested. For example, Akhilesh et al. [15] proposed the use of an elemental composite heat sink made of large latent heat capacity PCMs and highly conductive base material to improve the fin geometry. This could be explored in future work to improve the PCM cooling of mobile devices at higher power.

The optimization of finned PCM-based heat sinks for practical applications would require in depth understanding of the volumetric expansion due to phase change, convection in a melted PCM and air, and the motion of solids in the melt due to density differences. Furthermore, effects such as ambient temperature could affect the thermal performance. The higher ambient temperature would cause a higher temperature in the portable devices. The daily ambient temperature in Singapore, where the study was undertaken, varies consistently from 24 °C to 34 °C. This might not be the case in many other countries. For example, the temperature in the UAE can exceed 40 °C during the summer. Under such circumstances, n-eicosane might not be the appropriate PCM. The choice of a suitable PCM for the device would depend on the ambient temperature. In this aspect, organic and composite PCMs are still evolving. As mobile devices are used in countries where ambient temperatures can change considerably, more extensive research studies are needed to determine the effectiveness of the approach with respect to different types of PCMs. That would be another direction of our future work.

The results of the transient thermal performances indicated that the use of a PCM in a heat sink without fins may not result in better thermal performance if the device is operated in the light usage mode. The PCM-based heat sink can significantly cool the mobile device under frequent and heavy usage conditions during the charging stage. However, the cooling rate can be slower during the discharging stage. Adding fins to the PCM-based heat sink can improve the thermal performance. Increasing the number of fins can increase the heat transfer rate during the charging stage. The fins did not seem to have any significant effect in the device cooling during the discharging stage. These findings indicated that PCM-based heat sinks with internal fins could be viable for cooling hand-held electronic devices under intermittent-usage conditions such that the duration of operation does not exceed the time for full melting of the PCM. The effectiveness of a PCM-based heat sink depends on the number of fins, the amount of PCM that is being used, the heat source power level, and the usage mode of the device. Future work could explore the optimization of the thermal performance with respect to these parameters and the use of composite PCMs in the heat sink.

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