TRANSIENT AND CYCLIC EFFECTS ON A PCM-COOLED MOBILE DEVICE

by

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A mock handset with heat storage unit has been designed, fabricated, and experimented under various conditions to examine the effect of external heat sink on the handset's transient temperature distribution, performance of the individual heat storage unit under different power level and orientation, as well as under the more realistic cyclic heating. The cooling of the handset is through using a phase change material, n-eicosane, stored in the external heat storage unit connected to the handset through a miniature heat pipe. The heat pipe channels the internal heat dissipation to the heat storage unit where it is absorbed by the phase change material. Results show that the temperature is significantly lowered with the phase change material based heat storage unit.

Key words: *heat storage, PCM cooling, mobile device cooling*

Introduction

Heat generation on newer mobile phones is rising rapidly due to continual demand for inclusion of more features within an increasingly compact package size. According to Walsh *et al.* [1], the trend of heat dissipation level of mobile devices is bound for 5 W and beyond. A recent analysis by Pentikousis [2] concurred, showing an average power consumption of 3 W by a typical 3G (third generation) phone with video playback ability. Woh *et al.* [3] predicted the next generation of 4G phones would demand processing power that is 10 to 1000 times more than their predecessors. As the dimensions of these devices are shrinking to enhance their aesthetics and portability, the surface area available for heat dissipation is reducing.

Many researchers in mobile phone thermal management believe that alternatives to case-cooling are needed in the further progress of cell phone technology. Luo *et al.* [4] performed both experimental and numerical thermal analysis for mobile phone for power consumption range of 0.5-2.2 W in order to establish appropriate thermal resistance network. The response of the phone to a single heat source was analysed and it was concluded that rise in temperature is directly proportional to power consumption. The maximum power permitted was found to be restricted by the small surface area of the phone, necessitating additional dissipation mechanism for higher power levels.

A thermal control technique at the chip level is the use of a heat spreader, typically made of high thermal conductivity material, applied onto the chip, as for instance in Moon *et al.* [5]. In Cher and Veatch [6], chip scale package design was optimized for thermal per-

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formance of mobile handsets. In an example of active cooling the performance of forced convection cooling on mobile phones was evaluated [1]. A custom-made centrifugal fan measuring 24 × 23 × 7 mm was incorporated into a Nokia 3120 casing, with a 2 W heater positioned at the original location of the battery. Perforated plates were placed in between the fan and the heater to simulate blockage of flow due to components. The set-up was able to sustain a maximum increase of 75% in heat generation, though in the actual setting, the sustainable increase is expected to reduce to around 40-60%. The result translates to a maximum heat rate of 3.5 W, beyond which a stronger fan would be required but noise could be a problem.

The consideration of phase change material (PCM) for cooling of mobile phone was studied as early as 2002 [7, 8]. Hodes *et al.* [7] tested the use n-alkane tricosane and Thermsorb-122, filling a volume of 12.1 cm^3 each in an aluminum heat sink unit (HSU) in direct contact with the heater. Experiments were only carried out for a single cycle of charging and discharging of the PCM under power setting of 2, 3, and 4 W and the heating portion was analyzed for transient response. It was found that, PCM could significantly extend mobile phone operation time under transient heating condition. By assuming that the safe temperature difference between handset and ambient to be 40 °C, it was observed that the phone's temperature could be sustained for 50 and 30 minutes under 3 W and 4 W, respectively, as compared to operating without PCM where the handset would exceed the temperature limit in approximately 12 minutes at 3 W setting. For power level of 2 W and below, the sustainability extends indefinitely. This finding was further supported by Tan and Tso [9] in a separate study later which concluded that the congruent melting nature of PCM allows for longer period of energy transfer without exceeding the temperature limit.

One of the main concerns about using PCM for thermal cooling is their poor thermal conductivity. Shatikian *et al.* [10] recommended the addition of extended surface such as fins to reduce the heat-up time required to reach the melting point of PCM. Wang *et al.* [11] reported benefits of using multiple-PCM configuration, through proper selection and placement of multiple types of PCM in a series arrangement a perfectly homogenous phase change could take place across the entire set-up thus improving heat transfer efficiency. Hawlader *et al.* [12] proposed the method of containing tiny amount of PCM within small microcapsules made of high thermal conductivity material, thus increasing heat dissipation area and improving conduction. Recently, Weng *et al.* [13] studied the use of heat pipe for cooling of electronics evaluating the thermal performance using different amount and kinds of PCM, and different heating powers.

Since previous studies mainly involved direct application of PCM onto the heat source which was more often than not restricted due to the small confined space of the phone interior. This paper reports an experimental study on the performance of PCM cooling method using three different detachable models of PCM-filled external HSU, connected to the combined source in the phone through a heat pipe to channel all the heat dissipated into a single external heat sink. Assessments include effectiveness of each HSU model, sustainability of the chosen model in terms of different level of heat dissipation as well as the effect of orientation of the PCM on the cooling performance of the sink. Cyclic performance is also investigated.

Experimental set-up and procedure

The experimental set-up illustrated in fig. 1 comprises a perspex mock handset and three detachable HSU (aluminium T-6061) with n-eicosane as the PCM. A flat flexible heater placed between the location of battery and chip acts as single heat source replicating the overall heat generated by various components in the phone. The heat pipe then connects the source to the external HSU which is filled with PCM. The heat pipe has a 3 mm diameter, 60 mm length, an effective thermal conductivity of 10,000 W/mK, and can dissipate heat up to 5 W with a temperature difference of about 5 °C between its ends. The fluid used inside the heat pipe is ethanol. The function of the heat pipe is to transfer the heat from the heater to the PCM in the HSU with a minimal temperature drop.

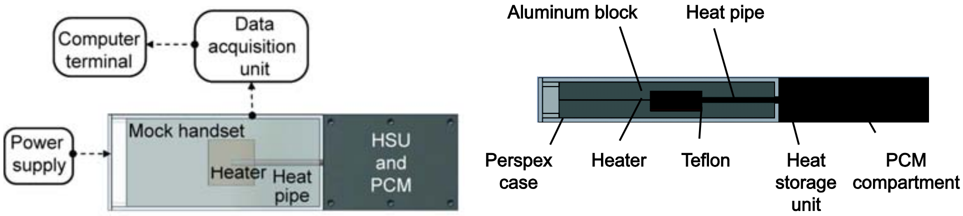

Figure 1. Schematic of mock handset and experimental set-up

Both the heater and heat pipe inside the handset are encased in a mold of teflon to minimize heat loss by convection as well as to simulate the packed internal configuration of actual cell phone. The heater was powered by a variable AC supply.

Type-K thermocouples are placed on the heater, at the top surface of the handset, at the condenser end of heat pipe, and at top left and right surfaces of the HSU. Agilent 34970A data acquisition unit monitors real-time temperature readings periodically throughout the experiment and saves them in the computer. The thermocouples have an uncertainty of ±1 °C. Figure 2 shows the three models of HSU. The dimensions of the three models of HSU are given in tab. 1. The amount of PCM inside the HSU was sized to sustain 5 W of continuous heating for 30 minutes. Table 2 shows the properties of n-eicosane, the PCM.

Table 1. Dimensions of heat storage units

Heat sinks	Dimensions	
	External [mm] $L \times W \times H$	Internal volume [mm^3]
Model A (no fin)	125 × 52 × 20	47,736
Model B (3 internal fins)	145 × 52 × 20	47,736
Model C (3 internal fins)	73 × 52 × 20	19,500

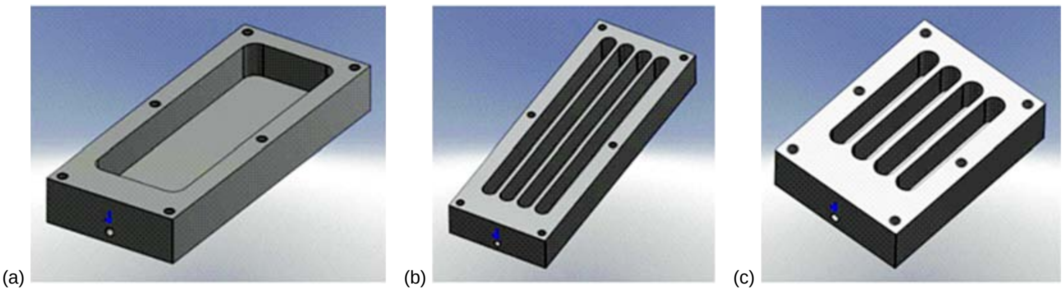

Figure 2. HSU units: (a) model A without fin, (b) model B with 3 fins, and (c) model C with 3 fins and reduced internal volume

The experimental procedure begins by attaching one of the three HSU models to the mock handset, with all the thermocouples pre-secured onto their respective spots on both the handset and HSU, as well as to the heater and heat pipe. For steady state simulation, the

Table 2. Properties of n-eicosane

PCM	Thermal conductivity [$Wm^{-1}K^{-1}$]	Specific heat capacity [$Jkg^{-1}K^{-1}$]	Density [kgm^{-3}]	Latent heat of fusion [Jkg^{-1}]	Melting temperature [°C]
n-eicosane	0.1505	2,460	769	247,300	36.5

Table 3. Summary of experiments conducted

No.	Heating condition	HSU	Setting
1	Steady-state (continuous heating for 120 minutes)	None	5 W, 0° orientation
2		Model A (47,736 mm^3 of PCM without fin)	4 W, 0° orientation
3			5 W, 0° orientation
4		Model B (47,736 mm^3 of PCM with 3 fins)	4 W, 0° orientation
5			5 W, 0° orientation
6		Model C (19,500 mm^3 of PCM with 3 fins)	1 W, 0° orientation
7			2 W, 0° orientation
8			3 W, 0° orientation
9			4 W, 0° orientation
10			5 W, 0° orientation
11			4 W, –90° orientation
12			4 W, 45° orientation
13			4 W, 90° orientation
14			5 W, 90° orientation
15	Transient heating 25 minutes ON 10 minutes OFF (for 6 cycles)	Model B (47,736 mm^3 of PCM with 3 fins)	4 W, 0° orientation
16		Model C (19,500 mm^3 of PCM with 3 fins)	3 W, 0° orientation
17			4 W, 0° orientation
18			4 W, 90° orientation
19			4 W, 90° orientation with external fins

power of the heater is set to a specified value and maintained for 120 minutes, data acquisition units automatically register scan readings set at frequency of 2 minutes. As for transient simulation, the power of the heater is again tuned to a specified value but is turned on and off intermittently for 6 cycles at 25 minutes on, and 10 minutes off.

All three models are tested under steady-state heating of 4 W and 5 W at 0° orientation, model C is further tested under power levels 1 W, 2 W, and 3 W, and also tested for the effects of heat sink orientation at –90°, 45°, and 90°. Figure 3 shows the orientation of the heat sink with the heat sink above the mock handset. Only model B and C are experimented under transient heating, model B is tested at 4 W heat level and orientation at 0°. Model C is tested for 3 W and 4 W at 0° and 90° orientation. Table 3 summarizes the experiments conducted.

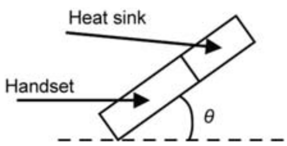

Figure 3. Orientation of heat sink

The surface areas of the models A, B, and C are 0.01358 m^2, 0.01542 m^2, and 0.008798 m^2, respectively. Based on the average surface temperature of 45 °C and a heat transfer coefficient of 5 W/m^2K, the estimated heat losses from the side wall of the three models ranged from 0.8 W to 1.5 W. Thus, not all the heat supplied by the heater is stored in the PCM inside the HSU, for example only about 3.5 W for 5 W heater input is stored in the HSU.

Results

Effect of PCM

To evaluate the effectiveness of PCM on cooling of the mobile phone, the temperature distribution of the chip and surface casing temperature are compared for the run with (model A) and without heat sink. Figure 4 shows the temperature profile for both settings.

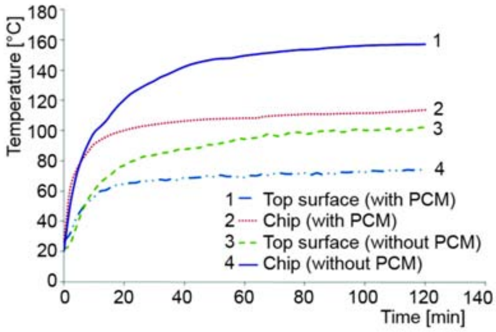

Figure 4. Steady-state 5 W temperature profile of the handset with and without PCM-based HSU

It can be observed from fig. 4 that the absence of PCM leads to a higher temperature outcome in both the chip and the surface compared to those with PCM. With PCM-based HSU installed, temperature of the chip was brought down by about 50 °C and the surface temperature by an average of 20 °C. Thus, PCM plays an effective role in thermal cooling of the unit.

The initial temperature gradients are identical for both settings, probably due to the heat-up time required to bring the PCM to its melting temperature. However, even in the setting with PCM, the temperature rise of the chip only begins to even out at around 90 °C, which is more than double the melting temperature of the PCM. This suggests that the heat pipe was probably not dissipating heat away as efficiently. Another comparison was done to verify this by measuring the temperature distribution when using the heat pipe against that when using a copper rod.

Based on the temperature profiles in figs. 5 and 6, it is evident that the heat pipe shares similar performance to the solid copper rod at best. The heat pipe has an effective thermal conductivity of 10,000 W/mK compared to 400 W/mK for copper rod and should theoretically perform much better. If a copper rod of the same dimension as the heat pipe is to be used, the temperature between the two ends of the copper rod will be about 106 °C if 5 W is to be dissipated, according to the Fourier's law of heat conduction. Taking into account the heat loss by natural convection of about 1.5 W from the sides of the mock handset, only about 3.5 W is transferred through the copper rod and that will give a temperature difference of about 70 °C as seen in fig. 5. But as seen in fig. 6, there is a large temperature difference of about 70 °C between the chip and the heat pipe, when it should have been within 15 °C. This explains that the heat pipe may have malfunctioned. If the heat pipe is working well, the temperature difference of the heat pipe between the heater end and the HSU end should be much lower than the 70 °C.

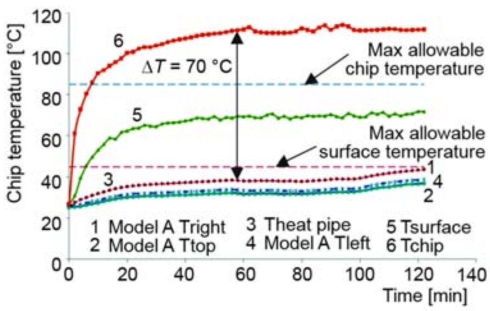

Figure 5. Temperature of model A at 5 W with copper rod

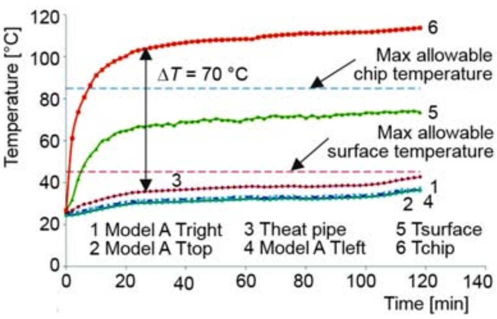

Figure 6. Temperature of model A at 5 W with heat pipe

Effectiveness of the different HSU design

While the heat pipe may not be performing up to par, the external PCM-based HSU proves to be successful in keeping the handset at lower temperature. As such, further investigations are done to verify the effectiveness of the three different HSU designs as per fig. 7.

Referring to fig. 7, both models B and C maintain a lower chip temperature profile compared to model A throughout the entire experiment. This is most likely due to the absence of internal fin within model A, contributing to poorer thermal conductivity; the HSU is less effective in dissipating heat to the PCM within, thus resulting in a higher temperature before the phase change begins. Although sharing the same amount of PCM as model A, model B is further installed with three internal fins. This brings about a significant effect as the chip temperature of model B is about 20 °C lower than model A during phase change (the flat portion). With the enhancement effect from internal fins, the PCM was able to function better and maintain a constant temperature.

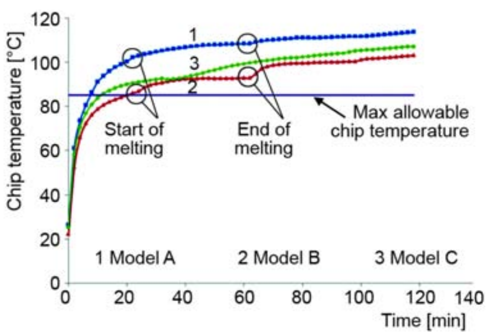

Figure 7. Comparison of chip temperature for all three HSU at 5 W

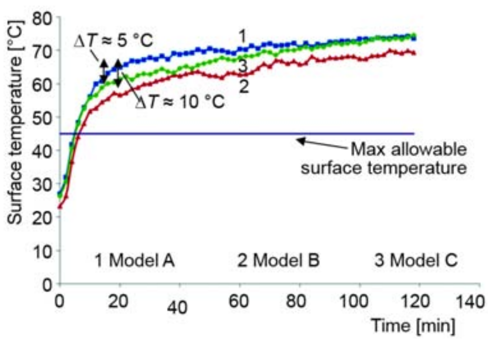

Figure 8. Comparison surface temperature for all three HSU at 5 W

A slight "jump" can be seen around the 20th and 62nd minute, indicating the start and end of melting for model A. This coincides closely with that of model B which contains the same amount of n-eicosane, indicating that fins' effect on phase change duration is trivial at best, and it only affects how fast the HSU gets heated. The sooner the HSU is heated, the earlier the phase change takes place thus the higher the chance of preventing device temperature from overshooting critical point. This is especially crucial because during the initial phase, temperature gradient is very high; a slight delay could cause a big spike in temperature.

Model C contains only about 40% of PCM as those in models A and B, and also has three internal fins similar to model B. A similar profile to that of model B can be seen due to the same boost from internal fins. Model C could only sustain a constant temperature up to the 40th minute compared to model B which lasted till 62nd minute. However, considering the amount of PCM to the length of time sustained, model C proved to be the more efficient design. The length of model B became an added "resistance" causing the far-end PCM to heat up slower thus its lowering efficiency.

Figure 8 describes the surface temperature distribution for all three designs. Correspondingly, model B gives the lowest temperature followed by models C and A, respectively. Temperature difference between models B and C is approximately 5 °C and between models B and A about 10°C. It can be deduced that the dominating factor affecting surface temperature is not the amount of PCM, because model C has significantly lesser PCM than model A, yet manages to maintain a lower surface temperature than model A. Thermal conductive aid from the internal fin seems to play a more effective role in keeping the surface temperature low. Lastly, both the chip and surface temperature for all three cases rise rapidly above their respective allowable temperature, again attributable to the poor performance of the heat pipe.

Effect of power level

Model C is chosen to be studied further. Figure 9 shows its performance when subjected to heat dissipation, ranging from 1 W to 5 W. As indicated, model C is able to maintain chip temperature below the critical temperature of 85 °C for the power level 1-4 W. The phase change of model C for 5 W setting occurs above chip temperature of 85 °C, again due to the poor performance of the miniature heat pipe. From the result, model C could sustain heat dissipation indefinitely for power levels of 3 W and below. In the instance of 4 W, the phone can continuously operate for 60 minutes before exceeding its critical temperature.

This shows potential because even with the poor performance in the heat pipe, the unit shows capability to handle up to 4 W of heat generation. In the event that the heat pipe performed as it should, the phase change could begin earlier and would effectively go through constant temperature phase beginning at a lower temperature below the critical chip temperature.

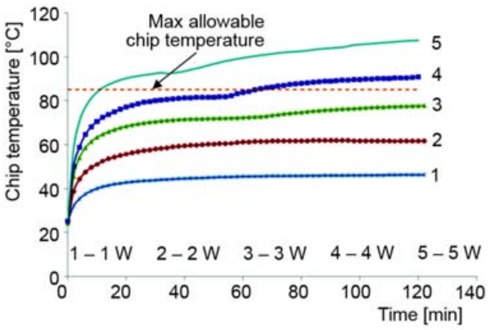

Figure 9. Comparison of chip temperature profiles of model C at different power levels

Effect of orientation

Four orientations of HSU are investigated and the results are shown in fig. 10, where the orientation angle is with respect to the horizontal, at 0°, 45°, 90°, and –90°.

The temperature profile indicates that for optimal cooling, positive 90° orientation is preferred. Cooling performance of the HSU is also found to improve with the increase in the angle of orientation as evident in the decrease in chip temperature following increase in angle. If we assume the evaporator section of heat pipe to be a heat source, convection flow within the HSU can be promoted by placing the HSU to an upright position directly above the source. At 90°, model C was able to maintain the temperature of the chip below 80 °C throughout the entire duration of testing. On the other hand, a negative angle configuration would see the HSU directly below the source. This is not ideal for convection as the heated part will remain on top due to buoyancy, and the colder portion at the bottom remains, as evident in the comparison between –90° and the neutral horizontal position. Based on the observation, the ideal position of HSU is at the head of the handset, since most of the time the phone would be in almost vertical orientation during phone calls and approximately angled 45° during texting and other applications.

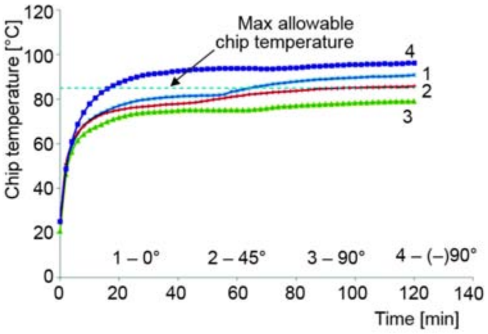

Figure 10. Comparison for different orientations of model C at 4 W

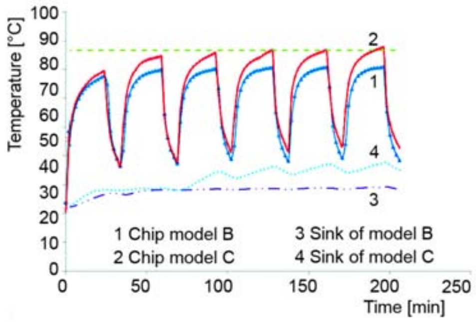

Figure 11. Temperature profile for a 4 W cyclic heating with models B and C

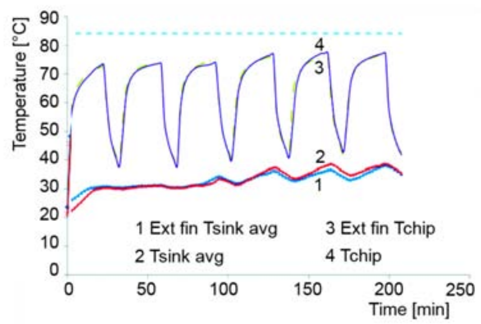

Figure 12. Comparison between temperature distributions with and without external fins for model C, 4 W at 90° orientation

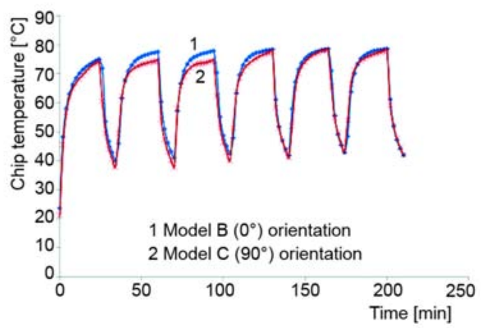

Figure 13. Comparison of cyclic temperature for model B (at 0°) and model C (at 90°), at 4 W

Cyclic heating

For a more realistic simulation of repeated unit use, cyclic heating are carried out, based on 4 W heating according to the cyclic pattern of 25 minutes ON and 10 min OFF. Figure 11 shows the results for both models B and C.

Model B is able to sustain the heavy usage condition for the whole duration of testing, and judging from the profile of its heat sink temperature, it could maintain the temperature below critical indefinitely. Model B, on the other hand, manages to prevent the chip temperature from overshooting its critical value for as long as 130 minutes after which the PCM fully melted as indicated by the temperature of the sink shooting above 36 °C, the melting point of n-eicosane. Although model B is more effective than model C in the cycles, it is more bulky, and as such further modification was made to model C in order to achieve the same performance.

A set of external fins are attached to model C and the results are shown in fig. 12. The plot indicates that the temperature profiles for model C with and without external fin are the same. Hence, external fins have no effect on the performance of the HSU. However, leaning on previous observations regarding the orientation, by setting model C in a vertical upright position, the temperature of the chip could be maintained below 80 °C throughout the experiment, almost achieving the same level of cooling as model B as shown in fig. 13.

Weight increase due to usage of PCM and HSU

The weight of PCM in models A and B is 36.4 gram each and in model C is 15 gram. The average weight of a mobile phone is between 200 g and 800 g. Thus the percentage increase of weight of the mobile unit ranges from 4% to 18% in our work. The weight of the HSU is not included in the calculations as it would be misleading as the mock handset using perspex in our work is heavier compared to the commercial mobile unit using thin polymer for the casing.

The inclusion of the PCM and HSU results in weight increase from 5 to 20% or more. That is a disadvantage of using PCM. There is further research work on using PCM on the cooling of mobile phone despite the weight increase. The authors are currently embarking on research using PCM fabric for mobile cooling. The PCM fabric is basically microencapsulated PCM that is woven inside fabric and is light. The research and application of PCM for mobile cooling is exciting for many years to come.

Conclusion

It is concluded that the PCM does play an effective role in managing the temperature rise of the handset. The incorporation of PCM-based HSU using only 19,500 mm^3 of n-eicosane could reduce the temperature by as much as half of that without PCM. However, for external HSU, it is important to design good heat transfer mechanism in order for the HSU to function well. The time to reach phase change temperature must be minimized and it can be achieved through thermal performance enhancement of PCM such as the present installation of internal fins, and proper placement of the HSU with respect to the source as adopted in this work. The current unit is able to support up to 4 W of heat dissipation despite the malfunctioning heat pipe. Thus, it can be certain that with a fully functional heat pipe, the performance of the sink would be further improved. In addition, adopting an external cooling sink allows for more freedom in design without compromising the need for a compact mobile phone.

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