THERMAL MANAGEMENT OF MOBILE DEVICES

by

Weijan SHEN and Fock-Lai TAN *

School of Mechanical and Aerospace Engineering,
Nanyang Technological University, Singapore

Original scientific paper
UDC: 621.395.721.5:678.072
DOI: 10.2298/TSCI1001115S

This paper presents the experimental study of using phase change material in the cooling of the mobile devices. It investigates the thermal performance of transient charging and discharging of mobile devices in three different situations; making phone calls frequently, making long duration calls, and making occasional calls. The results show that mobile devices are heated up fastest during the long duration usage. Experiments are also conducted to determine the effect of fins and effect of orientation of the mobile device on its thermal performance.

Key words: *thermal management, mobile devices, phase change material, heat sink*

Introduction

With the advancement in technology, more functions are packed into smaller mobile devices. Moore [1] states that the objective of the future will be to miniaturize electronics equipment and to include increasingly complex electronic functions in limited space with minimum weight. The shrinking in size reduced the area available for heat dissipation. Enhanced and added power consuming features worsen the thermal management challenges. The end result is that the power density continues to increase despite the employment of power management strategies emerging in both hardware and software [2]. Agonafer [3] reported that as multiple components are stacked inside the package producing higher sustainable power, effective thermal management is a key.

Forced convection cooling requires bulky and massive equipment, such as fan, and is thus not suitable for use in mobile devices [4]. In recent years, PCM has been widely examined as a thermal management that is suitable for dissipating heat from mobile devices. PCM has a high latent heat of melting [5] which provides high energy storage density [6]. It absorbs huge amount of energy during the phase change from solid to liquid state with little increase in temperature and volume. Heat will be stored in the phase change material (PCM) and it cools the mobile devices by reducing the temperature increase during operation. Leoni *et al*. [7] assumed

* Corresponding author; e-mail: mfltan@ntu.edu.sg

that humans can comfortably hold plastic objects up to 45 °C. This criterion influences the thermal control design of mobile devices [8] and sets the benchmark for this experiment study.

This paper is to investigate the feasibility of using phase change material inside a heat sink to cool a mobile phone in terms of the differences in the usage habit of the mobile phone, the effect of fins inside the heat sink, and the effect of orientation of the heat sink on the cooling performance of the mobile device.

Experimental setup and procedures

Setup

The n-eicosane is chosen as the PCM as its melting temperature of 36 °C lies in the operating temperature of mobile devices. It has a high latent heat of melting of 247300 J/kg. Four aluminum T6-601 heat sinks as shown in fig. 1 are fabricated. The first two heat sinks (Case A and Case B) have the same dimensions while the third (Case C) and fourth (Case D) heat sink have three and six fins of 2 mm inside the heat sinks, respectively.

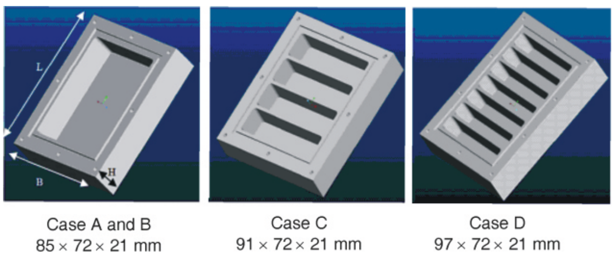

Figure 1. Heat sinks: Case A and B (no fins), Case C (3 fins), Case D (6 fins)

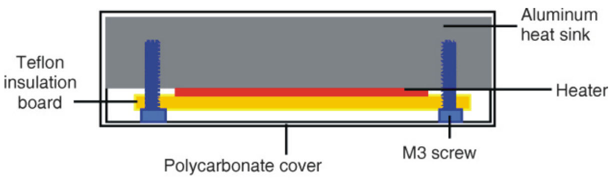

Figure 2. Schematic of the experimental setup

The volume of 44 mL of liquid n-eicosane is filled into each of the heat sink (Case B, C, and D). The rubber O rings are placed on the side of the heat sinks before being tightened and sealed up with the screws and epoxy, respectively. A 50 50 mm plate heater is placed behind the heat sink to simulate the heat dissipation of a main heat source inside the mobile phone [9]. A layer of thermal conducting paste (Omegatherm 201) is applied between the surface of the heater and the aluminum heat sink to provide better conduction by reducing the contact resistance between the surfaces. The power is being supplied by an adjustable DC power supply. A Teflon insulation board is placed behind the heater to prevent heat loss from the heater to the polycarbonate plastic case which encloses the entire experimental setup. The schematic diagram of the experimental setup is shown in fig. 2. The properties of the selected materials are given in tab. 1.

Table 1. Properties of the selected materials

Material	Thermal conductivity [$Wm^{-1}K^{-1}$]	Specific heat [$Jkg^{-1}K^{-1}$]	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

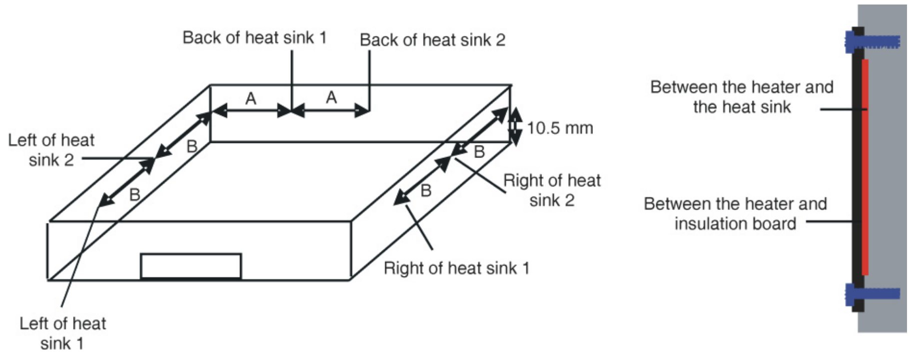

Figure 3. Location of the thermocouples (color image see on our web site)

Eight thermocouples are calibrated and attached to different points on the heat sink by epoxy as shown in fig. 3. The locations of the thermocouples on the heat sink are shown in tab. 2. The data acquisition unit with two multiplexers is linked to a computer to record the real time temperature of each thermocouple. A thermal imager is used to capture the thermal images and the surface temperature of the plastic cover. The upper and lower ranges of the thermal imager are set at 20 and 60 °C, respectively.

Table 2. Location of thermocouples on heat sink

Heat sinks	Length in [mm]	
	A	B
Case A	24	28.3
Case B	24	28.3
Case C	24	30.3
Case D	24	32.3

Procedures

During the charging phase, the heater is switched on and off to simulate three different situations of using the mobile phone (frequent usage, heavy usage, and light usage). The operation sequences of the heater to simulate the three different usages are shown in tab. 3. Under the heavy and frequent usages, the heater is mostly switched on for 60 minutes over the 70 minutes duration call. The heater is switched on for the most 10 minutes for the light usage. The input power to the heater is maintained at 5 W for all calls. The experimental setup is left to cool by natural convection to the ambient with no power supplied to the heater during the discharging phase.

Table 3. Operation sequences of the heater

Situation	Operation sequences of the heater
Frequent usage of making many calls within 70 minutes [on: 60 minutes, off: 10 minutes]	– on for 15 minutes – off for 2 minutes – on for 20 minutes – off for 5 minutes – on for 10 minutes – off for 3 minutes – on for 15 minutes
Heavy usage of making long duration calls within 70 minutes [on: 60 minutes, off: 10 minutes]	– on for 30 minutes – off for 10 minutes – on for 30 minutes
Light usage making occasional call within 70 minutes [on: 10 minutes, off: 60 minutes]	– on for 5 minutes – off for 30 minutes – on for 2 minutes – off for 30 minutes – on for 3 minutes

Figure 4. Different orientations of the heat sink

Table 4. Summary of the experiments of the heat sink

No.	Case	Situation	Orientation
1	A (without PCM)	Frequent	0°
2	A (without PCM)	Heavy	0°
3	A (without PCM)	Light	0°
4	B (with PCM)	Frequent	0°
5	B (with PCM)	Heavy	0°
6	B (with PCM)	Light	0°
7	C (with PCM and 3 fins)	Heavy	0°
8	D (with PCM and 6 fins)	Heavy	0°
9	C (with PCM and 3 fins)	Heavy	30°
10	C (with PCM and 3 fins)	Heavy	60°
11	C (with PCM and 3 fins)	Heavy	90°

The temperatures of the thermocouples are recorded every 5 minutes and plotted *vs*. time to observe the thermal performance during the transient charging and discharging phases of the PCM-based heat sink. The thermal images of the surface are captured every 10 minutes. Case C and D are used to compare with Case B to investigate the effect of fins on the cooling performance. Case C is placed in four different orientations; 0°, 30°, 60°, and 90° as shown in fig. 4 to determine the effect of orientation of the heat sink on the thermal performance. According to Ozen *et al.* [10], the thermal conductivity of human inner tissue is 0.5 W/mK. Thus, a 15 mm thick high density polyethylene of the same thermal conductivity is stuck behind the polycarbonate cover to model a human hand holding the mobile phone. The number and type of experiments conducted are given in tab. 4.

Results and discussions

Effect of usage of mobile phone

Frequent usage

The temperatures at several locations of the heat sink, heater temperature, and surface temperature for Case A and B (frequent usage) are shown in figs. 5 and 6. It is observed that the temperatures at different locations of the heat sink and the surface temperature on the cover are about the same. The heater side is at the highest temperature as expected. However, using heat sink that contains phase change material (Case B) on the mobile phone, the temperatures are generally lower compared to the heat sink without using phase change material (Case A). From

90 minutes onwards in figs. 5 and 6, all the temperatures are about the same during the discharging phase as the heat sink is being cooled by natural convection to the ambient. The heat stored in the phase change material inside the heat sink is dissipating slowly to the ambient. It takes a longer time to discharge the heat stored inside the heat sink and to bring the temperature down to the ambient compared to the charging phase.

Comparing the surface temperatures of Case A and B (frequent usage) as shown in fig. 7, there is maximum difference of 6.4 °C at the 65th minute during the charging phase. Case A reaches a highest temperature of 42.1 °C while Case B reaches the highest temperature of 36.3 °C at the 70th minute. For the discharging phase, Case A is cooled to 30.7 °C and Case B is cooled to 32.5 °C at the 170th minutes. Thus, the results show that the phase change material contains inside the heat sink can help to lower the surface temperatures of the mobile phone by absorbing the heat during the charging phase when the phone call is made.

Comparing the thermal images of Case A and B (frequent usage) as shown in fig. 8, the images change from blue to yellowish green to orange for Case A while the images change from blue to dark green for Case B. This indicates a higher temperature for Case A than Case B.

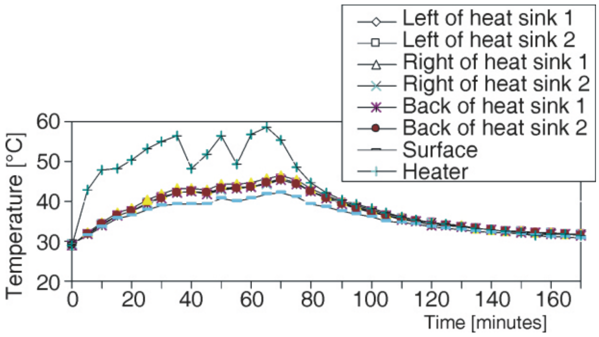

Figure 5. Temperature of heat sink, heater, and surface *vs.* time (case A – frequent usage) (color image see on our web site)

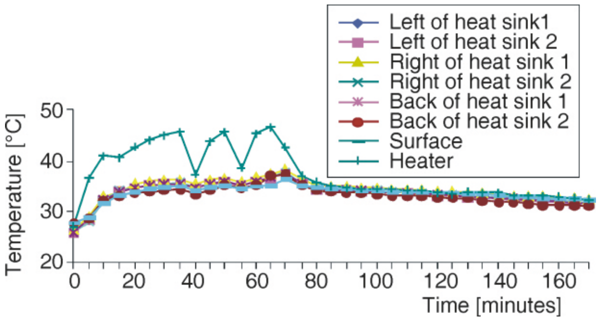

Figure 6. Temperature of heat sink, heater, and surface *vs.* time (case B – frequent usage) (color image see on our web site)

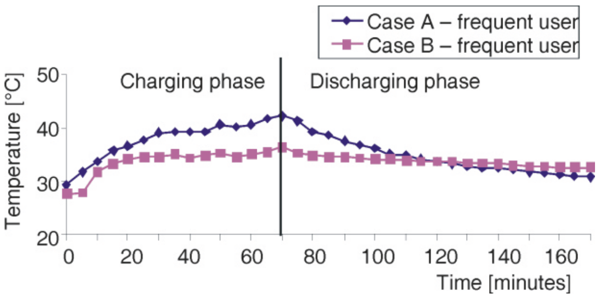

Figure 7. Surface temperature *vs.* time for case A and B (frequent usage)

Heavy usage

The surface temperatures of Case A and B are shown in fig. 9. During the charging phase, Case A and B reach a highest temperature of 43.0 °C and 36.8 °C, respectively. The highest temperature of Case A is undesirable as it is near to the human uncomfortable temperature of holding plastic at 45 °C. For Case B, the heat from the heater is absorbed by the PCM and the surface temperature is maintained at around 35 °C despite constant power supplied. During the

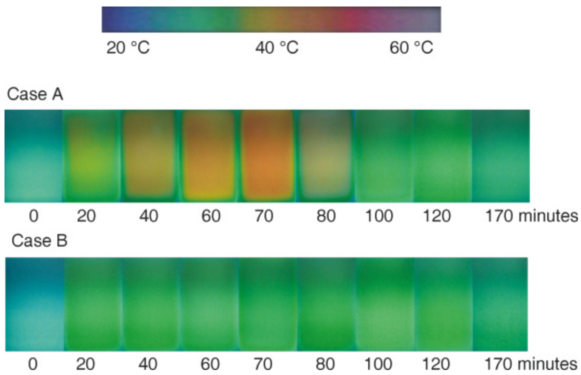

Figure 8. Thermal images of frequent usage (color image see on our web site)

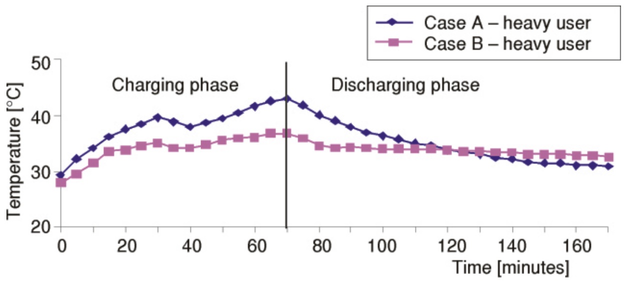

Figure 9. Surface temperature *vs.* time for case A and B (heavy usage)

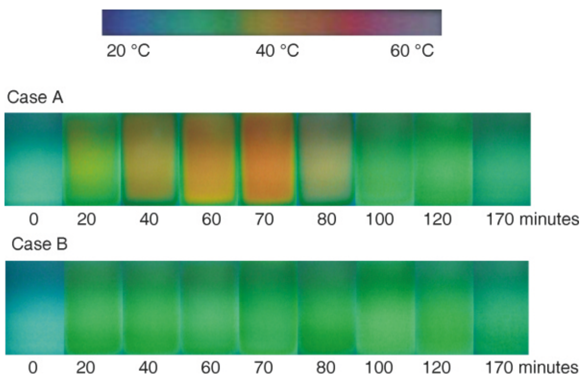

Figure 10. Thermal images of heavy usage (color image see on our web site)

discharging phase, Case A is cooled to 30.9 °C and Case B is cooled to 32.7 °C at 170th minute. The heats sink with PCM show a slower cooling rate.

The result of Case A having a higher temperature than Case B during the charging phase is verified with the thermal images (heavy usage) as shown in fig. 10. From the images, it is observed that the image is orange for Case A and green for Case B at the 70th minute.

Light usage

With reference to the surface temperature for Case A and B (light usage) as shown in fig. 11, there is little temperature difference between the two cases during the charging phase. The temperature for Case B is slightly higher than Case A for the discharging phase. Thus, it seems that the use of phase change material in heat sink for Case B may not be useful for light usage of mobile phone. The use of heat sink without phase change material in Case A is sufficient enough to cool the mobile phone. There is no advantage in using PCM inside heat sink under light usage condition.

There is little color deviations between the thermal images for Case A and B (light user) as shown in fig. 12. This indicates a small temperature difference.

The surface temperatures for three different usages of Case A and B are shown in figs. 13 and 14. For Case A, the maximum temperature is 43.0 °C for heavy usage and 42.1 °C for a frequent usage. For Case B, it takes about 55 minutes and 68 minutes for the temperature to rise to the melting temperature of 36 °C of the

PCM for heavy and frequent usages, respectively. Since the heater is switched on for 60 minutes and off for 10 minutes during the charging phase for both cases, this shows that mobile phone get heated up faster during long usage than frequent usage. The temperature remains at about 30 °C for light usage for both cases.

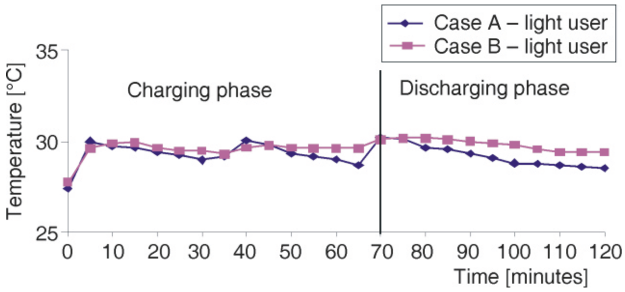

Figure 11. Surface temperature versus time for case A and B (light usage)

Effect of fins

The surface temperatures of Case B, C, and D are shown in fig. 15. For the charging phase, the temperature reaches the maximum of 36.8, 34.9, and 34.0 °C for Case B, C, and D, respectively, at 70th minute. This indicates that the heat transfer rate increases with the additional surface area provided by the fins. The heat supplied by the heater is conducted by the fins to the top surface of the heat sink and finally to the atmosphere through free convection. However, for the discharging phase, the temperature difference between the three cases is less than 1 °C after 100 minutes of cooling. This indicates that the fins have minimal effect on the cooling of the mobile phone during the discharging phase where free convection is the dominant heat transfer mode. This is due to the fact that the heat is stored in the PCM during the charging phase. Since PCM has a low thermal conductivity, the heat is conducted slowly from the PCM to the fins. Thus, the fins have limited effect on the cooling performance during the discharging phase.

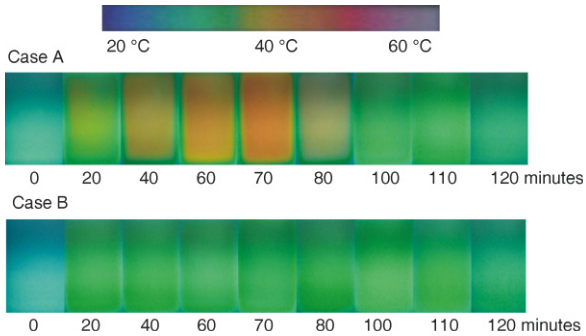

Figure 12. Thermal images of light usage (color image see on our web site)

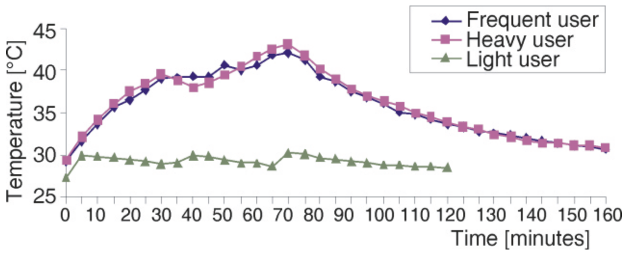

Figure 13. Surface temperature *vs.* time for case A for three different usages (color image see on our web site)

Effect of orientation

The surface temperature of Case C in different orientation is shown in fig. 16. The heat transfer rate is the highest for 90° orientation due to an increase in the surface area for free con-

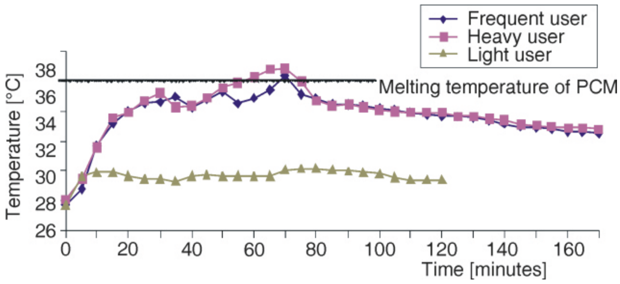

Figure 14. Surface temperatures *vs.* time for case A for three different usages (color image see on our web site)

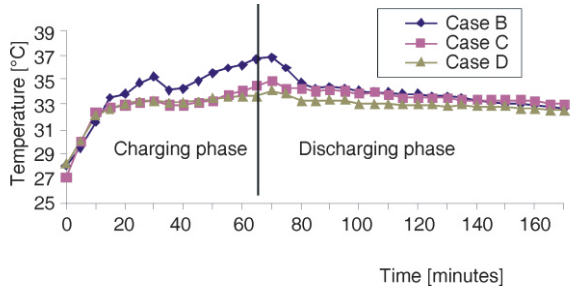

Figure 15. Surface temperature *vs.* time for case B for three different usages (color image see on our web site)

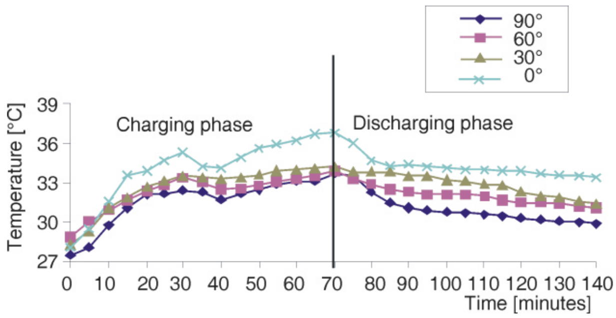

Figure 16. Surface temperature *vs.* time of case C at different orientation (color image see on our web site)

vection and lowest for 0° orientation. There is a maximum difference of 3.6 °C between 0° orientation and 90° orientation at the 65th minute during the charging phase and 3.6 °C at the 120th minute during the discharging phase. From fig. 16, it can be concluded that the orientation has a small influence on the cooling performance of the mobile phone.

From the thermal images for four different orientations shown in fig. 17, it can be seen that the thermal image at 70th minute for Case C at 0° orientation is a brighter green than the image for 90° orientation, which indicates a higher temperature. The Rayleigh number of 30° and 60° orientation is lower than the orientation at 90°. The lower the Rayleigh number, the smaller is the convection heat transfer coefficient according to the typical empirical Nusselt number correlation for free convection heat transfer. Thus, the natural convection heat transfer rates of 30° and 60° orientations are lower than the one at 90° orientation.

Conclusions

The experimental studies have proven feasible to use PCM for application in thermal control of mobile devices. It has significantly cooled down the mobile devices during the charging phase. However, the cooling rate is slower during discharging as heat is being stored during the charging phase. This leads to the point that using PCM cooling system is only applicable for intermittent-use mobile devices and not for continuous usage. It is important that the duration of operation does not exceed the time for full melting of the PCM. Mobile devices get heated up faster during long continuous operation than frequent usage. Incorporating fins inside the heat sink increase surface area for heat transfer during the charging phase. The greater the number of fins, the faster the heat transfer rate. However, the fins have no or little effect in cooling during discharging. Mobile device at 90° orientation provides better heat dissipation to the ambient

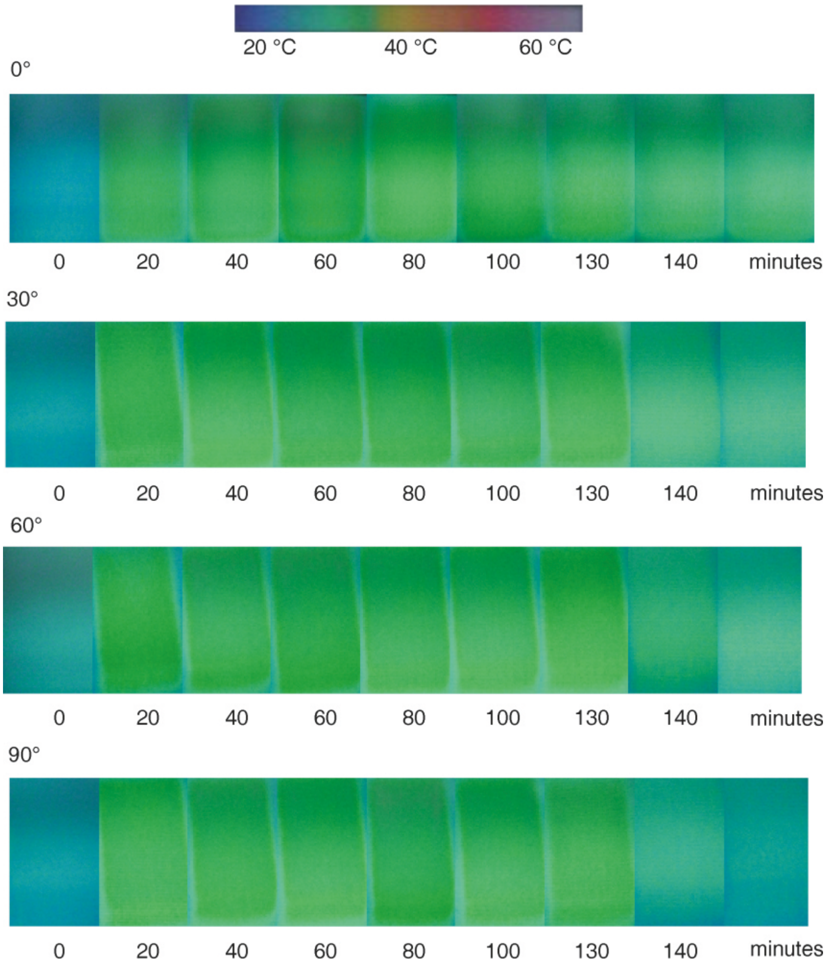

Figure 17. Thermal images of case C at different orientation (color image see on our web site)

than at 0° orientation, however, the orientation of mobile devices has a little effect on the cooling performance.

References

[1] Moore, E. G., Cramming More Components onto Integrated Circuits, *Electronics, 38* (1965), 8, pp. 114-117
[2] Hodes, M., *et al*., Transient Thermal Management of a Handset Using Phase Change Material, *Journal of Electronic Packaging*, *124* (2002), 4, pp. 419-426
[3] Agonafer, D., Four Challenges in Thermal Management in Communication Devices, *Proceedings*, Inter Society Conference on Thermal Phenomena, Las Vegas, Nev., USA, 2004, pp. 710-711

[4] Tan, F. L., Tso, C. P., Cooling of Mobile Electronic Devices Using Phase Change Materials, *Applied Thermal Engineering, 24* (2004), 2-3, pp. 159-169
[5] Tan, F. L., Fok, S. C., Thermal Management of Mobile Phone Using Phase Change Material, *Proceedings*, IEEE 9th Electronics Packaging Technology Conference, Singapore, 2007, pp. 836-842
[6] Zivkovic, B., Fuji, I., An Analysis of Isothermal Phase Change of Phase Change Material within Rectangular and Cylindrical Containers, *Solar Energy, 70* (2001), 1, pp. 51-61
[7] Leoni, N., Amon, C. H., Transient Thermal Design of Wearable Computers with Embedded Electronics Using Phase Change Materials, *ASME HTD, 343* (1997), 5, pp. 49-56
[8] Kandasamy, R., Wang, X. Q., Mujumdar, A. S., Application of Phase Change Materials in Thermal Management of Electronics, *Applied Thermal Engineering, 27* (2007), 17-18, pp. 2822-2832
[9] Michael, M. P., Energy Awareness for Mobile Devices, Paper for Research Seminar on Energy Awareness, Department of Computer Science, University of Helsinki, Finland, 2005
[10] Ozen, S., Helhel, S., Cerezci, O., Heat Analysis of Biological Tissue Exposed to Microwave by Using Thermal Wave Model of Bio-Heat Transfer, *Burns, 34* (2008), 1, pp. 45-49

Paper submitted: November 12, 2008
Paper revised: November 18, 2009
Paper accepted: December 2, 2009