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Experimental investigation of Phase Change Materials for thermal management of handheld devices

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ABSTRACT

The trend of enhanced functionality and reducing size of mobile devices has led to a rapid increase in power density and a potential thermal bottleneck since thermal limits of components remain unchanged. Active cooling mechanisms are not feasible due to size, weight, and cost constraints. This work explores the feasibility of a passive cooling system based on Phase Change Materials (PCMs) for thermal management of mobile devices. The PCMs stabilize device temperatures due to the latent heat of phase change, thus increasing the operating time of the device before threshold temperatures are exceeded. The primary contribution of this work is the experimental evaluation of key parameters which influence the design of a PCM based thermal management system. *In situ* measurements with PCMs as a passive thermal management solution demonstrate that a significant extension in the time that the processor can run at full power before the processing power would need to be throttled to prevent damage.

1. Introduction

The development and rapid progress in computing over the last century ushered in an era of unprecedented scientific and technological advancements. The pervasive use of computers and other electronic devices is due, in part, to cost reduction and mobility brought about by the miniaturization of the circuit components, in accordance with the Moore's Law. To highlight the manifold growth in processing performance in the last 20 years, the peak performance (measured in floating point operations per second) of a Samsung Galaxy S6 smartphone (launched in 2015) is 5 times greater than a Sony Playstation 2 (launched in 2000), and the power density has in turn increased due to an increase in power dissipation coupled with a reduction in form factor. This results in an increase in processor temperatures which poses serious reliability concerns. Thermal issues have been long standing, and a 1989 survey by US Air Force [1] demonstrated that more than half the failures in electronic components were due to thermal issues. The thermal limits, which include the processor, Random access memory (RAM), Multi-Media card, and the surface (or skin) temperature of the device, remain unchanged. The maximum operating temperatures of electronic components range from 70 °C to 120 °C. The surface temperature of handheld consumer electronics is limited to 40 °C due to ergonomic constraints [2].

Thermal Energy Storage (TES) systems for passive thermal management are promising due to their ability to absorb heat (during solid to liquid or liquid to vapor phase transitions), which dampens temperature fluctuations in response to power variations, thus reducing the susceptibility to thermal fatigue. Consequently, surface temperatures are maintained within ergonomic requirements. Phase change materials (PCMs) represent a type of TES system which exploits the latent heat of melting during the solid to liquid transition to dampen the temperature spikes, thus increasing the operating time of the device before the threshold safe operating temperatures are reached.

Over the past several decades, many different combinations of PCMSs properties and configurations have been evaluated. For example, Amon et al. [3] experimentally studied the influence of adding foams or nanofibers to enhance the thermal conductivity of paraffin wax and found that the graphite nanofiber - PCM composite showed the greatest delay in the time to melt. However, at higher heat fluxes, the temperatures at the baseplate were as high as for pure paraffin wax. The graphite foam (with higher thermal conductivity) had the lowest baseplate temperatures at these heat fluxes. This study clearly indicated the importance of thermal conductivity in design of PCM infiltrated heat sinks.

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Acronyms

DSC	Differential Scanning Calorimetry
GPU	Graphics Processing Unit
I/O	Input/Output
IR	Infrared
PCB	Printed Circuit Board.
PCM	Phase Change Material
RAM	Random access memory
SBC	Single Board Computer
TES	Thermal Energy Storage
TIM	Thermal Interface Material

Many applications in mobile devices require short bursts of high computational demand interspersed with periods of lower demand, therefore it is often effective to design for responsiveness rather than sustained performance. To ensure that the temperatures remain within prescribed limits, Shao et al. [4] integrated the PCM on the chip. Specifically, the PCM was filled in cavities etched on the opposite side of a heater (which mimicked a processor on a silicon chip). This package was exposed to ambient air and mounted in a smartphone. There was a drop in peak temperatures due to the PCM. Also, the melting process was completed within a second and the solidification process completed within few seconds when the package was placed in the smartphone due to high thermal conductivity of integrated heat spreaders.

Much past work has demonstrated that PCMs can be effective in reducing the operating temperature in consumer electronic devices through investigation of different power profiles, boundary conditions, device geometries, and PCMs [4–8]. To integrate PCMs in consumer electronics (especially in mobile devices), it is imperative to develop a set of design guidelines. These guidelines require understanding the influence of not only the material properties of the PCM, but also the interplay of material properties and geometry of the structure containing the PCM for real-time power profiles.

This work experimentally studies the feasibility of using a PCM in consumer electronic devices by placing the PCM filled in an enclosure (open from the top to allow for infrared thermal imaging) used as a passive heat sink for a smartphone processor. Different enclosure sizes and PCMs are used to identify key parameters that influence the effective integration of the PCM. Ultimately, the results are analyzed to provide design guidelines for integrating PCMs into thermal management systems.

2. Methodology

2.1. Selected phase change materials

This work investigates the effect of PCMs with transition temperatures between 42 °C and 62 °C. This transition temperature range is selected because it is below the maximum operating temperature limits of the processor. Specifically, three commercially-available wax-based PCMs are obtained: pure paraffin wax from Sigma-Aldrich®, PureTemp® PCM from Entropy Solutions, and AllCell PCC® from AllCell Technologies. The latent heat is measured using Differential Scanning Calorimetry (DSC) 2000 (TA Instruments, New Castle, DE, USA) with a liquid nitrogen cooling system. The temperature range used for the DSC is from 0 °C to 100 °C, with heating and cooling rate of 5 °C min^{-1}. Table 1 shows selected material properties for the tested phase change materials.

2.2. In situ thermal measurements

Here, we measure the impact of PCM-based thermal management solution on the thermal performance of an android processor. Specifically, the setup consists of an enclosure filled with PCM, which acts as a heat sink, placed directly on the smartphone processor. To allow access to the processor for integration of this heat sink, we use a Single Board Computer (SBC) (see Fig. 1), which is a development board containing the essential components in a smartphone - the processor, Graphics Processing Unit (GPU), memory, and Input/Output (I/O) laid out on a single Printed Circuit Board (PCB), instead of a true smartphone.

The SBC runs Android based benchmarking applications, which are configured to stress the processor, thus representing worst case realtime usage scenario for a mobile device. Furthermore, since the components are laid out laterally, this geometry enables non-contact surface thermal measurements using Infrared (IR) imaging. The SBC (model IFC 6410, Inforce Computing Inc. Fremont, CA) runs an Android 4.0 operating system and has a Qualcomm Snapdragon APQ 8064 processor. The SBC is connected to I/O using USB ports, to a display via micro-HDMI port, and to a computer for data acquisition via micro-USB port. Processor temperatures and clock frequencies are monitored using a custom script and sampled at 60 Hz. The resolution of the temperature sensors is 1 °C. One temperature sensor is active before core 0 reaches 70 °C, then multiple sensors on the die are monitored. Here, we use 70 °C as a "cutoff" temperature in our thermal comparisons. In addition to the die temperatures, the top surface temperature is measured with an infrared microscope (Quantum Focus Instruments Corporation).

PCMs are contained in enclosures of size 10 mm × 10 mm × 3 mm, 10 mm × 10 mm × 5 mm, and 15 mm × 15 mm × 5 mm fabricated from 0.3 mm thick copper sheets. The enclosures are handmade from metal sheets and the edges are sealed to prevent leakage (The Gorilla Glue Company, Cincinnati, OH). Target dimensions for the enclosure are presented as $X \times Y \times Z$, but given the manual nature of the fabrication the dimensions are accurate to within 0.5 mm. Since the enclosures are slightly flexible, the 10 mm × 10 mm × 3 mm and 10 mm × 10 mm × 5 mm volumes reported are approximate, which is

Table 1

Material properties of PCMs used for *in situ* tests. (*s*) and (*l*) denote the solid and liquid state properties where available. All other properties, unless indicated are for solid phase. Thermal conductivity *k*, specific heat C_p, and density ρ are from Sigma Aldrich® [9,10], PureTemp® [11] and AllCell PCC® [12]). The transition temperature T_m, transition temperature range ΔT_m, and latent heats ΔH are measured using DSC.

PCM	T_m (datasheet) (°C)	T_m (DSC heating) (°C)	T_m (DSC cooling) (°C)	ΔT_m (DSC heating) (°C)	ΔT_m (DSC cooling) (°C)	ΔH (datasheet) (J/kg)	ΔH (DSC major transition) (J/kg)	k (W/(mK))	C_p (J/(kg K))	ρ (kg/m^3)
Paraffin Wax	58	60.36	54.04	18	9	NA	194.2×10^3	0.21 (s) 0.12 (l)	2890	900(s) 750 (l)
PureTemp®	42	41.3	37.3	12	4.25	218×10^3	310.5×10^3	0.25 (s) 0.15 (l)	1850 (s) 1910 (l)	940(s) 850 (l)
AllCell PCC®	55	53.6	49.8	13	6	165×10^3	222.3×10^3	10 (in-plane) 6 (cross-plane)	1960 (s) 2200 (l)	875