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Thermal Management of Electrical and Electronic Systems Using PCM

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Abstract— The present experimental research investigates transient thermal performance of a PCM-based thermal management system for cooling electronics components. The proposed system consists of a heatsink that is submerged into Rubitherm (RT-18) for melting experiments. The heat sink has a total length of 10cm, a width of 5cm and a height of 13cm. The heat sink contains 4 vertical copper heat pipes and 34 horizontal aluminum fins. The proposed system is insulated from all sides except the front wall for periodic visualization pictures, and it is exposed to a constant heat flux boundary condition from the top with a 1-inch^2 Omega heat flux heater with a wattage density of 10 W/in^2 at 100V. The PCM is heated from 0°C to about 51°C. The visualization results as well as the temperature distribution are discussed. Primarily, the results show that the melting process of the PCM manages the temperature of the heatsink and the base at which the heater is attached due to the high heat storage capacity of the PCM.

Keywords_latent heat thermal energy storage system; PCM, electronics thermal managemen;, rectangular cavity; experimental measurement.

I. INTRODUCTION

Sensible heat Thermal Energy Storage (TES) systems are not as efficient as latent heat TES systems for extensive thermal discharge or high climate temperatures [1]. There are many advantages of incorporating PCM in TES systems. PCM-based TES systems can store energy for various periods of time (e.g., from minutes to seasons), which diversifies its applicability and scalability. PCM-based TES systems are used in many applications such as solar engineering, building energy consumption, greenhouse thermal control, food protection, occupant thermal comfort systems, and aircrafts thermal management. Latent heat storage is an efficient way of storing thermal energy for most applications since it can store high amount of energy at nearly constant temperature. Thus, PCM-based TES technologies have been used in electronics and electrical applications for thermal management. Electrical and electronics applications produce a massive amount of heat that minimizes the operation duration and the efficiency of the overall system. PCMs can maintain the optimal operation temperature limits of such delicate systems. However, such applications require PCMs with high thermal conductivity for more responsive thermal management. Unfortunately, PCMs have low thermal conductivities. In the literature, various methods have been utilized to increase the thermal conductivities of PCMs.

In automobile industry, for instance, a significant amount of carbon dioxide (CO_2) and other greenhouse gas emissions are produced by traditional transportation vehicles (by means of fossil fuel combustion process). Therefore, researchers have been investigating on how to overcome the major limitations and to grow the potential of electric vehicles in the automobile market. The electric energy storage system (electric battery) is a substantial component of an electric vehicle. Electric batteries necessitate an appropriate thermal management for more effective operation and longer life span at different operation conditions. The common key challenges with these electrical batteries are the small range of their optimal operational temperature, the intensive undesired power consumption associated with their excessive heat generation, the practicality in different climate conditions. Luckily, PCM-based thermal management technology addresses all these issues.

For instance, an improvement of 50% of an electric battery life span was accomplished for a small electric vehicle by combining TES technology and wax as a PCM with an electric scooter bike [2]. The wax was incorporated with graphite to enhance the thermal conductivity of the wax by up to 70 Wm-1K-1. This graphite-wax-based-TES system significantly increased the maximum driving distance of the small electric vehicle from 30Km to 55Km [2]. Moreover, Wang et al. performed an experimental study on electric automobiles battery safety and thermal management using heat pipes. Two battery cells producing 2.5-40W of heat have been built and tested by a thermal camera at off-normal conditions. It was found that incorporating heat pipes helped to maintain the temperature below 40°C when the battery generates a maximum of 10W/cell; when the battery cell generates 20–40 W/cell (uncommon thermal abuse), the proposed system could decrease the temperature of the battery to 70°C [3].

Heat generation in a great deal of engineering applications is nonuniform with time. This unstable behavior of heat generation is associated with undesired spikes of temperature increase [4]. The sudden increase of temperature could damage or decrease the efficiency of the electrical circuits. Thermal management systems that absorb the undesired heat by means of sensible and latent heat can maintain a nearly constant desired temperature. Number of researchers have investigated the improvements of thermal management performance considering many thermal enhancement methods. Hosseinizadeh et al. [5] conducted a numerical and experimental study on the performance of PCM incorporated with different configurations of fins for thermal management applications. This study considers different number, height, and thickness of fins at different power intensity. The outcomes show that the higher the number of fins and the higher the height of fins, the higher the overall thermal performance. However, increasing the fins thickness does not increase the overall thermal performance as significantly. Furthermore, Peleg et al. [6] conducted a numerical study to optimize the geometry, quantity the number of internal fins, and to optimize the amount of PCM for thermal management of electronics. The results show that at fewer fins, the temperature range increases, which decreases the PCM quantity to keep the electronics at operation temperature range. Rajesh, and Balaji [7] carried out an experimental study on the performance of PCM based thermal management storage systems using several numbers of pin fins (0, 33, 27, and 120 pin fins) for two different PCMs (n-eicosane and paraffin wax). The authors also performed an Artificial Neural Network and Genetic Algorithm optimization techniques to extend the operation time of the system to reach the set point and increase the thermal performance. The results show an improvement factor of 24 was achieved by using 72 pin fins combined with n-eicosane. Li-Wu et al. [8] experimentally investigated the thermal performance of heatsink combined with high aspect-ratio carbon nanofillers at different loads. The results show that for heating cases, the use of high aspect-ratio carbon nanofillers is less effective in removing heat due to the weak natural convection to the environment. Thus, the authors have combined carbon nanotubes and graphene nanoplatelets, which increases the thermal recovery due to their high thermal conductivity. Yoram et al. [4] studied a combination of PCM and heat sink experimentally and numerically. The prototype is meant to absorb the undesired heat by the PCM (eicosane $C_{2}0H_{42}$) and to reject the heat to the surroundings by aluminum heat sinks with a fan. A two-dimensional thermal model was developed and analyzed for estimation of thermal field. The experimental and numerical results of the base temperature and PCM melting behavior have some agreement. It was observed that as the heat input increases, the sensible-heat-based accumulation rate increases. Fok et al. [9] targeted cooling gadgets with power input of 3 to 5W using PCM (neicosane) with and without fins. In this experimental study, the considered variables are the device orientation (vertical, horizontal, and 45° incline), power input level (3-5W), number of fins (3, 6 fins), and the usage intensity (light to heavy). The main objective of this study is to investigate the thermal performance of small handheld devices when cooled using PCM with and without fins. It has been observed that cooling mobile devices using PCM with fins is feasible; however, an optimization on the device is required considering the amount of PCM used and all previously mentioned parameters.

In this experimental study, a PCM-based thermal management system is examined. The thermal management system contains of a heatsink with 34 horizontal aluminum fins integrated with 4 vertical copper heat pipes to increase the thermal conductivity of RT-18 PCM in a rectangular shaped cavity for electrical and electronics applications. The prototype is examined under transient thermal condition on the top side with maximum power input. All other walls of the enclosure are thermally insulated. This study investigates the thermal performance by means of visualization and the temperature distribution of the PCM during melting.

II. METHODOLIGY

A. *Components Details and Description*

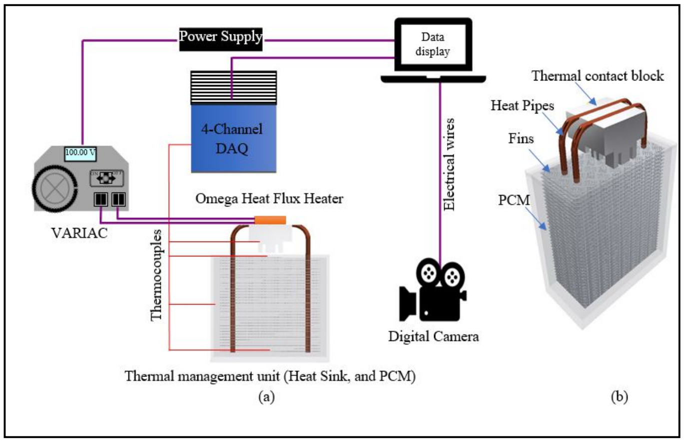

Figure 1: Schematic diagram of the (a) experimental setup and (b) components of thermal management system.

The components of the experimental setup are presented in Figure 1, (a), while Figure 1, (b) shows the components of thermal management system. The main components used in this experiment are: a variac, a DAQ system, an Omega flexible heater, a thermal management unit (heat sink, and PCM), 4 K-type thermocouples, a computer with LabVIEW software installed, and a digital camera. The variac feeds the omega heater with a series of different voltages that vary from 0-100V. 4 thermocouples are instrumented in the thermal management system at four locations (heat source, top fin, bottom fin, and PCM). The thermocouples are measuring the temperature across the heat sink using a DAQ system (NI USB-9162) from National Instruments. The LabVIEW software monitors and saves the thermocouples readings. The Omega heater (SRFG-101/10) is 1-inch^2 with a wattage density of 10 W/in^2. The maximum operating temperature of the heater is 232°C, and the maximum rated voltage is 115VAC. The heater is in a direct contact with the heatsink from the top base as illustrated in Figure 1, (a). The heat sink has a total length of 10cm, a width of 5cm and a height of

13cm. The heat sink contains four vertical copper heat pipes and 34 horizontal aluminum fins. The heat sink is submerged into a phase change material to assist the heat sink to dissipate heat coming from the electronic component (Omega heater). Therefore, this helps to maintain the operational average temperature for the electronic component. Rubitherm (RT-18) whose melting point ranges from 17-19°C was selected as thermal storage medium. The heat storage capacity of RT-18 is 250 kJ/kg, and the maximum operation temperature is 48°C. The container is made of a clear acrylic with a thickness of 0.24-inch. The outer shell of the container is insulated by 1-inch thick Styrofoam. A high definition Canon camera "EOS Rebel T2i" is used to capture the images periodically during the melting process. The laptop monitor is used to display and save visualization pictures and the thermocouples readings.

B. *Experimental Procedure*

The experimental setup of the electronics thermal management system is presented in Figure 2. Initially, the thermal management system is placed in a refrigerator at about (0°C) for 24 hours to ensure a uniform temperature across the PCM at a solid state. Then, the thermal management system is connected to the DAQ system and the heater is connected to the variac power supply. The digital camera starts taking pictures, and the LabVIEW software starts running to take the readings. The variac is turned on immediately at maximum voltage to feed omega heater with (100V). Once the PCM is in a liquid form, the experiment is done.

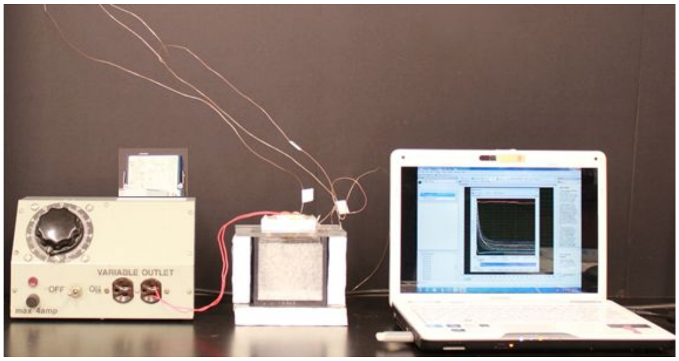

Figure 2: Experimental setup of the electronics thermal management system.

III. RESULTS AND DISCUSSION

A. *Experimental Temperature Distribution Analysis*

Figure 3 presents the experimental temperature profile in the thermal management system at 100V. The initial temperature of the PCM is 0°C. The thermal management system is insulated from all sides except the front wall for visualization. The PCM was heated up to 34.7°C. Four thermocouples are measuring temperatures at four locations in the thermal management system (heat spreader, top fin, bottom fin, and PCM). As can be seen from Figure 3 that once the heater is tuned on, most of the heat is absorbed by the aluminum heat spreader and top fin since they are close the heat source. It also can be seen from Figure 3 that once the heater is tuned on, the temperature of top fin increases rapidly from 0°C to 18°C by means of sensible heating. Then, the temperature of the top fin remains almost constant at the melting point temperature while the PCM was melting at the top. Once the melting of PCM is done at the top, the temperature of PCM increases due to sensible heating supplied by the heater. Note that temperature of PCM at the top and the heat source remains the same throughout the melting process. Further, it can be observed that the temperature of bottom fin increases less rapidly from 0°C to 15°C by means of sensible heating. The PCM temperature profile follows the same trend to that of the bottom fin. The melting of PCM occurs around 15°C and this is the reason the bottom fin and the PCM temperature remain nearly 15°C during the melting. The temperature of the PCM and the bottom fin increases due to sensible heating once melting of PCM is finished. Due to high thermal energy storage and low thermal conductivity of PCM, the temperature of PCM remains constant around melting point temperature for a longer period compared to bottom fin.

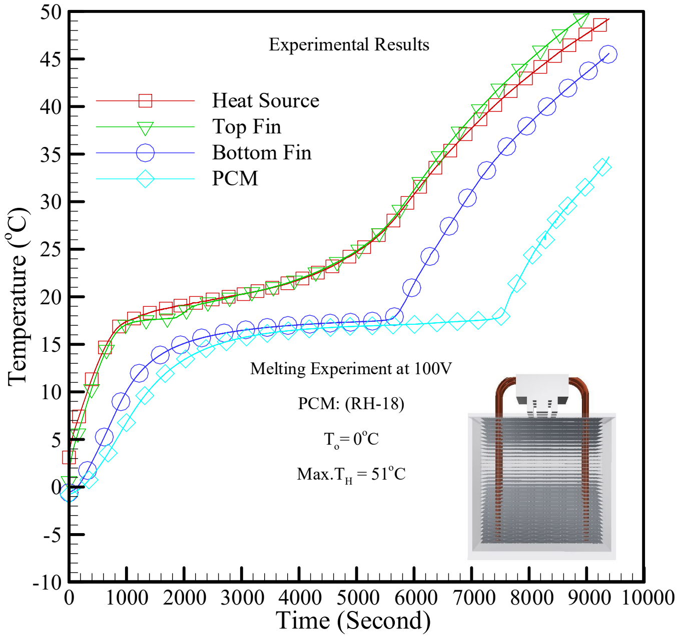

Figure 3: Temperature profile at different locations in the thermal management system at 100V.

B. *Experimental Visualization Results*

Since the heater is in direct contact with the top base of heat sink, the heat sink will absorb the heat through the base. Then, the heat will dissipate through the heat pipes and then to the fins. Therefore, the solid PCM starts absorbing the heat across the heatsink by conduction in a sensible form, as shown in Figure 4 (at time=0-16 minutes). The initial sensible heat storage takes about 1000 seconds (16 minutes). This sensible heat transfer keeps going until the PCM temperature reaches 17-19°C causing the PCM to start melting down, as shown in Figure 4 (at time=25 minutes). The melting starts from the right and left sides of the thermal storage system due to the vertical heat pipes that are transferring the heat from the top base. The melting process (latent heat storage process) takes about 4750 seconds (79 minutes) at nearly constant range of temperature (17-19°C). During the melting process, heat will transfer to the liquid PCM by conviction in a latent form until all PCM become liquid. As the temperature increases above 19°C, the heat will transfer by convection in a sensible form to the liquid PCM, as shown in Figure 4 (at time=126 minutes). This entire process helps to maintain the temperature of the attached electronic component at a desired temperature range.

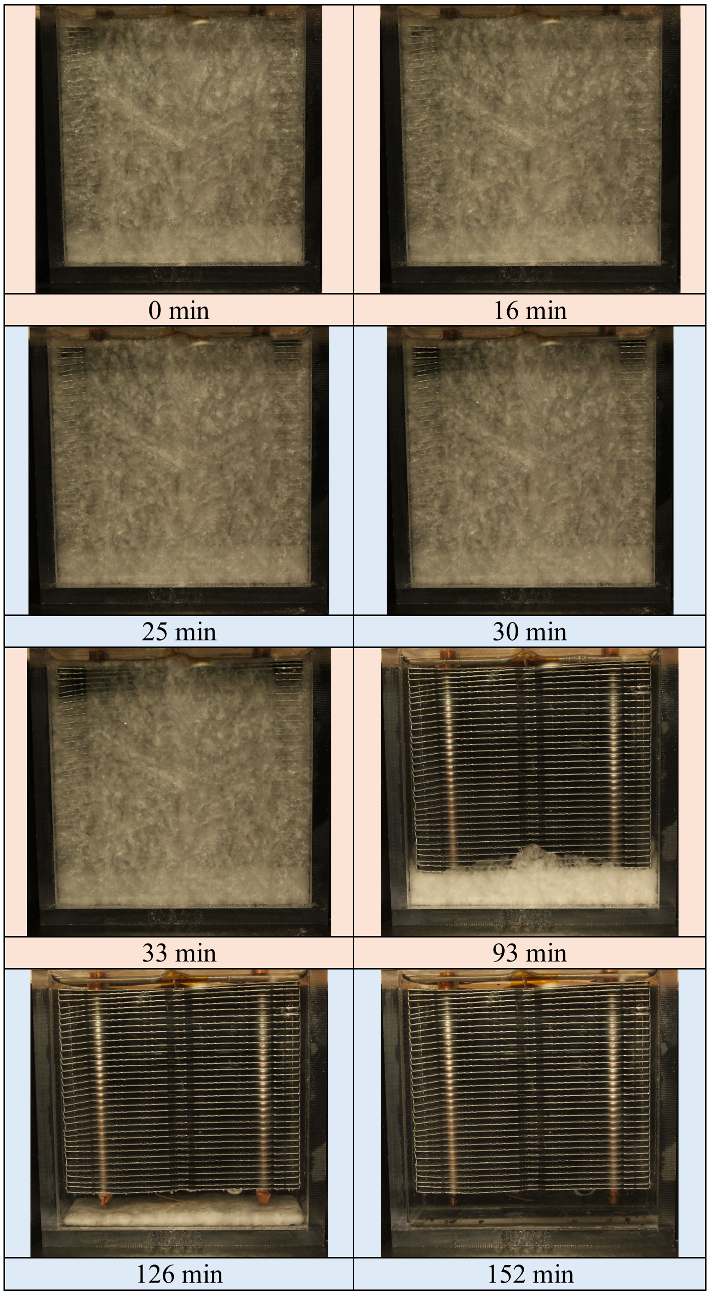
0 min
16 min
25 min
30 min
33 min
93 min
126 min
152 min

Figure 4: Visualization pictures of the PCM melting process in the thermal management system.

IV. CONCLUSION

In this research, an experimental investigation has been carried out to examine the thermal performance of a PCM-based thermal management system for cooling of electrical and electronics components. The thermal management system consists of a heat sink that is submerged into Rubitherm (RT-18) to assist the heat sink to dissipate the heat coming from the electronic component. The heat sink contains 34 horizontal aluminum fins and 4 vertical copper heat pipes. The thermal management system is insulated from all sides except the front wall for capturing periodic visualization pictures; the thermal management system is tested under a transient condition by a 1-inch^2 Omega heat flux heater. The PCM was heated from 0°C to about 51°C. To assess and analyze the performance of the cooling system, the camera records the visualization of the melting process of PCM, while the DAQ system records the temperature profile in different locations of the thermal energy storage system. The visualization results as well as the temperature profile are discussed. Mainly, the results show that the melting process of the PCM manages the temperature of the heat spreader of the heatsink, at which, the heater is attached. This thermal control is associated with the high heat storage capacity of the PCM.

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