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Experimental performance investigation of PCM based heat sinks of various configurations for cooling of electronic components

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Abstract

The thermal control of electronic components is aimed at ensuring their use in a temperature range compatible with their performances. This paper presents an experimental study of the behavior of phase change materials (PCMs) as the cooling system for electronic devices. Four configurations are used to control the increase in the system temperature: pure PCM, PCM in a silicone matrix, PCM in a graphite matrix and pure PCM in a system of fins. Thermo-physical properties of different PCMs are determined and found to be desirable for application in this study. Solid liquid interface visualization and temperature evolution are employed to understand the mechanism of heat transfer during the different stages. Results indicated that the inclusion of PCM, can lower component increase temperature and extend twice the critical time of the heat sink. The use of Graphite matrix filled by PCM showed more improvement on system thermal performance than silicon matrix. Also, for the same fraction of copper, it was found by incorporating long copper fins with suitable spacing into PCM, can enhance heat distribution into PCM leading to longer remain component temperature below the critical limit. This work therefore shows that the combination of PCM and long. Well -spaced fins presents an effective means for thermal control of electronic device.

1.Introduction

With ever increasing in advancement in technology, the rise in demand for the important work of data centers has created a noticeable impact on the power grid. Moreover data centre dominates in almost every field these days. Data center is a facility that contains various computer related equipments most commonly known as IT equipments. In fact, data centers can be 40 times more energy intensive than a standard office building and require higher levels of power and cooling. At the same time the reliability of an electronic component is defined as its ability to satisfy its desired purpose. An electronic component fails to satisfy its desired purpose when the environmental condition or its application exceeds its application limit. Investigations show that 55% of failures in electronic devices are related to high temperature. Several methods exist which can be used to eliminate the heat generated from an electronic device during operation. To accomplish a device's cooling requirements, natural convection is the most commonly used method for low power electronic devices; but on the other hand, forced convection is necessary for higher power applications.

Cooling fans are needed and an extended surface can be used to improve the effectiveness of heat removal. Portable electronic devices such as tablets are needed to be light in weight, compact and completely sealed. Extended surfaces raise the weight and device size. Because of the noise and additional energy consumption from the battery, cooling fans are not preferred. In this situation, the cooling requirements of portable electronic devices with a limited duration of operation to a few hours can be satisfied by a thermal control unit (TCU). The TCU is composed of phase change material (PCM). The main aim of a TCU is absorbing the extreme heat generated in the electronic component by allowing the PCM to melt at near constant temperature, which corresponds to the phase transition temperature of the material.

Energy storage not only reduces the mismatch between feed and need but also improves the performance and reliability of energy systems and plays an important role in conserving the energy. It leads to saving of premium fuels and makes the system more cost effective by reducing the wastage of energy and capital cost. For example, storage would improve the performance of a power generation plant by load leveling and higher efficiency would lead to energy conservation and lesser generation cost. One of prospective techniques of storing thermal energy is the application of Phase Change Materials (PCMs). The use of a latent heat storage system using phase change materials (PCMs) is an effective way of storing thermal energy and has the advantages of high-energy storage density and the isothermal nature of the storage process.

Literature review

High heat storage capacity and isothermal behavior during melting and solidification, phase change materials are increasingly attractive in recent years. These materials can be employed in many applications such as thermal regulation of building, cooling electronic devices, heat storage and textile. For this purpose, many authors focused attention on their behavior in last decades.

C. Y.Zhao et al [1] analyzed the effect of natural convection on interface transition and heat transfer during melting from below and solidification from above for a pure PCM in a rectangular enclosure. Benard convection cells were observed during melting. Also, it was found that the presence of natural convection increases the melting rate.

More recently, **Siahpush et al [2]** explored experimentally the melting process in a rectangular thermal storage unit heated from one side. They visualized the front evolution during solid–liquid phase change process. The dominance of heat conduction during early stage of melting, followed by dominance of convection heat transfer at later times were observed.

H.Ryu et al. [3] studied the dynamic thermal behavior of phase change material (PCM) melting in a rectangular enclosure heated isothermally from one side at various inclination angles. It was found that the horizontal enclosure had more enhancement heat transfer than vertical enclosure.

K. R.Ismali et al. [4] analyzed the impact of different enclosure geometries filled with thermal conductivity enhanced PCM. It was observed that the configuration with a portion of PCM placed above the cooled surface provided the best efficiency. In electronic applications, using PCMs for thermal control of electronic devices can offer a great advantage by stabilizing the temperature for a long period and improving device longevity. Several studies have been conducted to investigate the use of PCM in cooling of electronic devices.

I. M. Bugaje et al. [5] investigated experimentally a heat storage unit filled by PCM for cooling of portable hand held electronic devices. It was revealed that the use of PCM can stabilize the system temperature under allowable temperature of 50 °C for 2h of transient operations of the device.

R. Kandasamy et al. [6] studied numerically and experimentally the use of PCM based heat sink. They evaluated the effect of power input, orientation of package, and various melting/solidification times under cyclic steady conditions. It was concluded that using PCM-based heat sinks improve the thermal performance of electronic component during intermittent use. However, PCMs suffer from a low thermal conductivity which limits their efficiency. To overcome this problem, some heat transfer enhancement techniques were employed, such as micro-encapsulation of PCM, dispersed high thermal conductivity particles, incorporating porous matrix and extending fins inside the PCM.

Extensive research has been carried out to improve the thermal response of PCM by adding different high thermal conductivity enhancers. In this section a summary of the relevant research regarding PCM‟s is presented. The use of finned tubes with different configurations has been proposed by various researchers.

Lacroix and Benmadda [7] studied the behaviour of a vertical rectangular cavity filled with PCM. They found that both solidification and melting rates were improved by long fins. **Velraj et al [8]** studied the impact of internal longitudinal fins on a cylindrical vertical tube filled with paraffin wax. They concluded that adding fins reduces the solidification time by a factor of 1/n, where n is the number of fins. They also pointed out that for lower Biot numbers, addition of fins makes the surface heat flux more uniform, whereas for higher Biot numbers the addition of fins improves the magnitude of surface heat flux and appreciably reduces the solidification time.

Stritih et al [9] studied the heat transfer characteristics of a latent-heat storage unit with and without a finned surface. They developed a correlation giving the dimensionless Nusselt number as a function of Rayleigh number. A comparison of the equations for melting and freezing shows that natural convection is present during melting and increases heat transfer, whereas during solidification conduction is the dominant form of heat transfer. They concluded that heat transfer during solidification is greater if fins are included and a 40% reduction in solidification time is observed with fins.

Mettawee and Assassa [10] placed aluminum powder in the PCM for a compact PCM solar collector. Solar energy was stored in the PCM and was discharged to cold water flowing in pipes located inside the PCM. The propagation of melting and freezing fronts was studied during the charging and discharging process. It was found that the addition of aluminum powder in wax reduced the charging time by 60%. In the discharging process, it was found that the useful heat gained was increased by adding aluminum powder in the wax.

Bugaje et al. [11] found that the thermal response of paraffin wax was enhanced by the use of metal matrices embedded within the body of wax. Significant reductions in melting and freezing times were obtained by the use of aluminum sheet metal. Melting times were reduced by factors of up to 2.2 and freezing times reduced by factors of up to 4.2. It was also found that thermal response enhancement is greater during freezing than melting as conduction plays a greater role in freezing while natural convection becomes significant during melting.

Py et al [12] did some research on a new supported PCM made of paraffin impregnated in a compressed expanded natural graphite (CENG) matrix and found thermal conductivities in the range of 4 to 70 W/mK while that of paraffin wax is 0.24 W/mK. It was also found that CENG induced a decrease in overall melting and solidification time.

Zhong et al [13] used CENG matrices with different densities to see the increase in thermal response of paraffin wax. To predict the experiment of paraffin wax/CENG composites as a thermal energy storage system, their structure, thermal conductivity and latent heat were characterized. Results indicated that the thermal conductivity of the composites can be 28-180 times that of pure paraffin wax.

Mesalhy et al [14] studied numerically and experimentally the effect of porosity and thermal properties of a porous medium filled with PCM. In their model, the governing partial differential equations describing the melting of phase-change material inside porous matrix were obtained from volume averaging of the main conservation equation of mass, momentum and energy. From their model it was observed that the best method to enhance the response of PCM is to use a solid matrix with high porosity and high thermal conductivity. Model results indicate that estimated value of the average output power using carbon foam of porosity 97% is about five times greater than that for using pure PCM‟s. One intrinsic problem of a graphite matrix is its anisotropy in which the thermal conductivity depends on direction .To solve this problem, some metal materials with high thermal conductivities were used by several researchers to enhance the heat transfer performance of the PCM‟s.

Zhao et al. [15] did performance investigation on the solid/liquid phase change in which paraffin wax was embedded in high porosity (> 85%) open cell copper metal foams. The test samples were electrically heated on the bottom surface with a constant heat flux. They observed that the addition of metal foam increases the overall heat transfer by 3-10 times during the melting process. They also found that the temperature gradient in metal foam sample is significantly reduced compared to pure PCM.

2.Experimentation

The PCM used in this study was a commercial product, paraffin wax 60. The two composite PCMs (PCM/silicone matrix and PCM/graphite matrix) is mentioned in Table 1. It was observed that these materials are suitable for application due to their melting temperature, which is below critical temperature (60°C) & it is cheap cost material. Furthermore, these materials are suitable because of their favorable characteristics such as non-toxicity and chemical stability even after 3,000 cycles. Thermal properties of all PCMs are described.

Thermal conductivity measurements were made by FP2C based on the hot wire method. Thermal measurements were performed at two temperature levels, at 30°C (the solid phase) and at 70°C (the liquid phase). Table 3 shows the value of thermal conductivity at each temperature. The accuracy of thermal conductivity measurements is 5%.

The latent heat and the melting and crystallization temperature measurements were also determined by differential scanning calorimetry (DSC). During the first heating, an endothermic phenomenon occurred at 53°C and repeated at 51°C during second heating. Du ring cooling, an exothermic phenomenon occurred at 48°C

A schematic diagram of the apparatus used in this study is shown in Figure 5. It consists mainly of a PCM container, a heater, a power supply, a temperature data logger, a personal computer.

Five thermocouples with a calibrated accuracy of ±0.5°C were placed in different locations to measure the transient temperature distribution. Thermocouple locations included three units at the inner copper slab face, one unit between the heater and copper slab and a final unit outside to measure the ambient temperature. All thermocouples are connected to the computer through a data logger to record temperature.

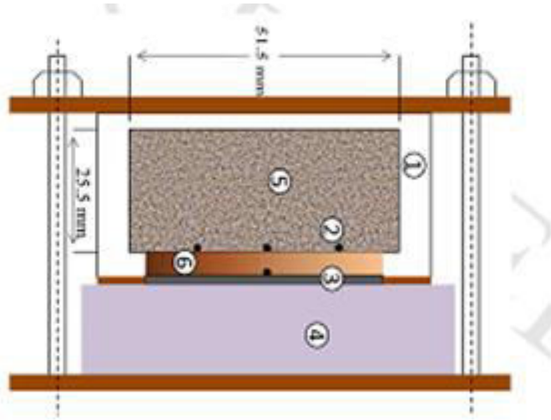

Fig.No.1*:-Schematic layout of proposed setup*

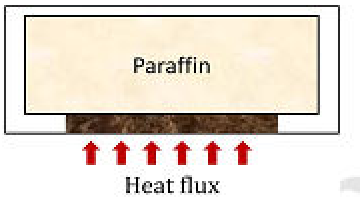

Fig.No.2:-Schematic layout of proposed Copper slab + Paraffin

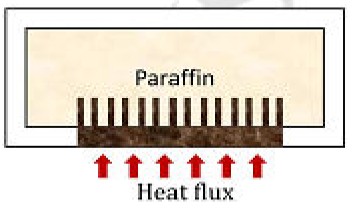

Fig.No.3*:-Schematic layout of proposed Copper slab with fins+ Paraffin*

Each experiment was composed of two phases: the temperature rise and melting of the PCM phase followed by the phase of solidification of the PCM by removing the heater until the temperature returns to its initial value. To visualize the melting front evolution, photographs are taken every 5 min. The temperatures of the PCM at the specified locations were logged some interval of time. Every experiment was performed twice to verify their repeatability.

In order to investigate the thermal performance of PCM heat sink, the heat sink charged with heater as heat source on hot side of heat sink. After reaching the temperature of the PCM above transition temperature, the supply of heater is stopped thus again after some time charging and discharging characteristics of a PCM heat sink has been evaluated. Two types of tests have been carried out on the PCM air heat exchanger:

- Charging of the PCM, which changes the state of the PCM from solid state to liquid state.
- Discharging of the PCM, which changes the state of the PCM from liquid state to solid state.

The wattage to heater is changed from 500W to 1000 W in step of 250W. It has been taken in to consideration that the at a particular wattage the same velocity is maintained for hot air and cold air during charging and discharging process of heat exchanger. The changes of the PCM temperature has been recorded at a various time interval during charging and discharging process of heat exchanger. The temperatures are measured with temperature sensors (RTD) which are inserted in the PCM tubes on hot side and cold side of heat exchanger. Then average temperatures of PCM have been evaluated from warm side during charging and cold side between discharging. Air velocity is measured with the help of air vane anemometer on hot side and cold side of PCM air heat exchanger.

Table 1.Test parameters

Parameter	Description
Heat load (W)	250 W to 1000 W
Source temperature(0C)	70 to 120 0C

2.3 Performance Parameters:

The changes of PCM air heat exchanger have been calculated in terms of the time required for charging and discharging of the PCM air heat exchanger by supplying the heat exchanger with different source temperature for charging and cold air for discharging at constant velocity. Additionally the variation of the PCM temperature during charging and discharging process has been recorded. The variation of the charging and discharging time with variation in the warm air flow velocity and cold air flow velocity has also been noted.

3. Results and Discussions

The variation of the PCM temperature during charging and discharging of the PCM air heat exchanger and charging and discharging time at different wattage and different air velocities are as shown below.

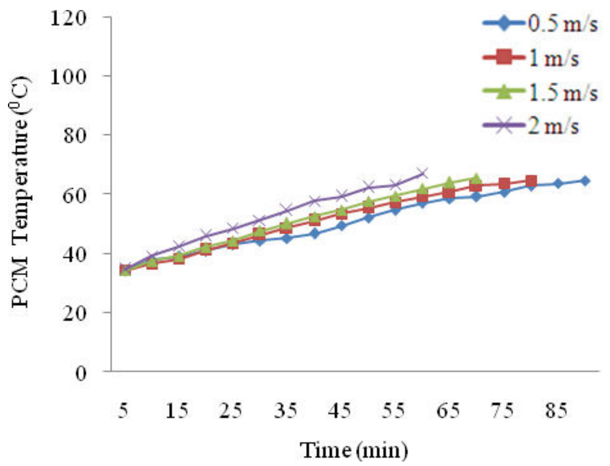

Fig. 4. Variation of PCM Temperature with time during Charging at heat input 500 W

Fig. 4 shows the variation of the PCM temperature with time during charging the PCM air heat exchanger at different air velocities at 500 W. The graph shows that with increase in the air velocities, time required to reach the predetermined temperature reduces. At a given time the higher velocity gives the maximum temperature of the PCM during charging of the PCM.

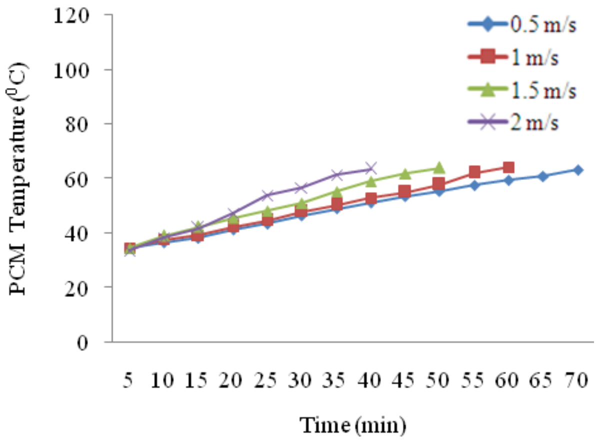

Fig. 5. Variation of PCM Temperature with time during Charging at heat input 750 W

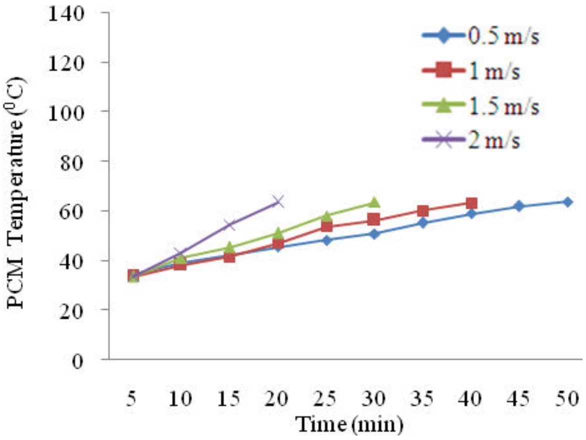

Fig. 6. Variation of PCM Temperature with time during Charging at heat input 1000 W

Fig. 5 & 6 shows the changes of the PCM temperature with time during charging the PCM air heat exchanger at different air velocities at 750 W and 1000 W respectively. The graph shows that with increase in the air velocities, time required to reach the predetermined temperature reduces. At a given time the higher velocity gives the highest temperature of the PCM during charging of the PCM. With increase in wattage, time required to reach the certain temperature is reduced.

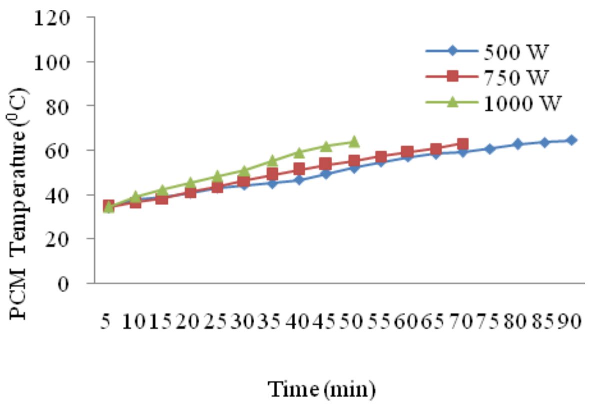

Fig. 7. Variation of PCM Temperature with time during Charging at air velocity 0.5 m/s

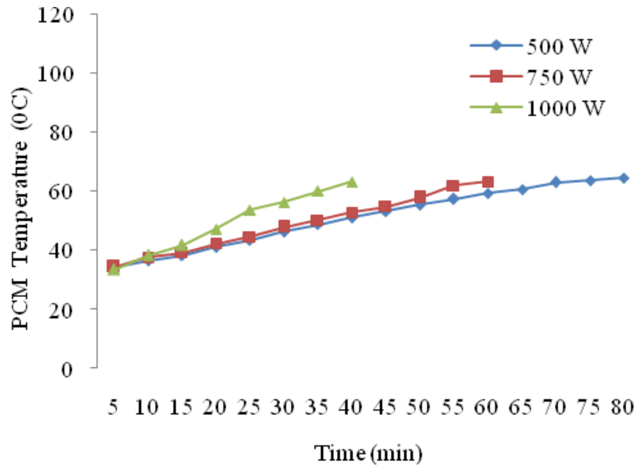

Fig.8. Variation of PCM Temperature with time during Charging at air velocity 1 m/s

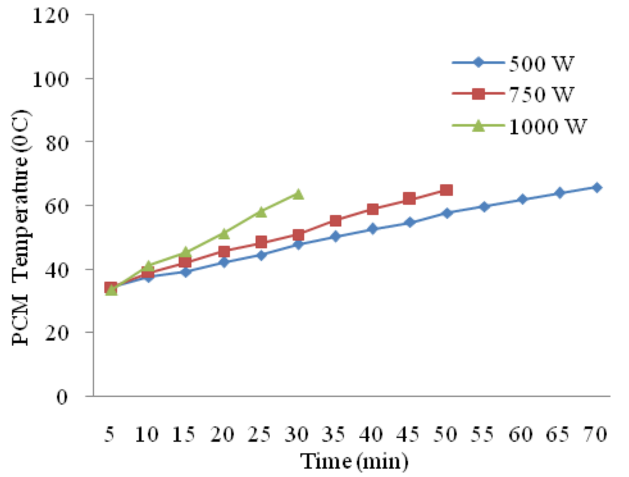

Fig. 9.Variation of PCM Temperature with time during Charging at air velocity 1.5 m/s

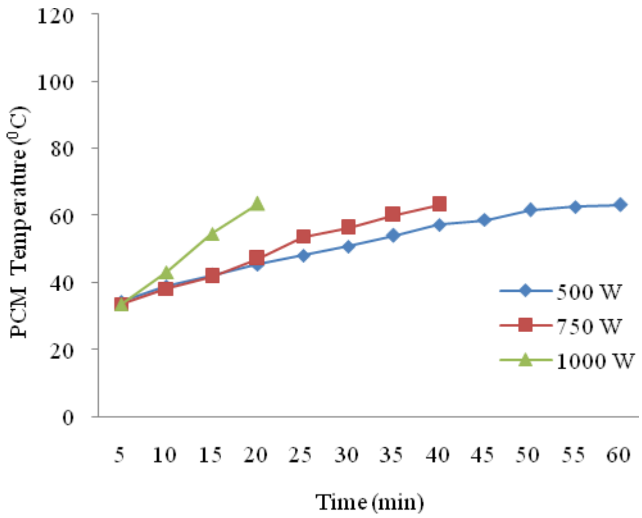

Fig. 10.Variation of PCM Temperature with time during Charging at air velocity 2 m/s

Fig. 7 to 10 shows the variation in the PCM temperature with time at different wattages during charging for air velocity ranges from 0.5 m/sec to 2 m/sec. The graph shows that with increase in the wattage time required to charge PCM air heat exchanger is reduced.

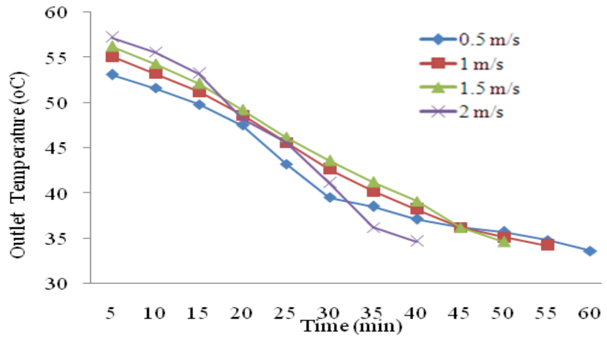

Fig. 11.Variation of cold air outlet temperature with time during Discharging at heat input 500 W

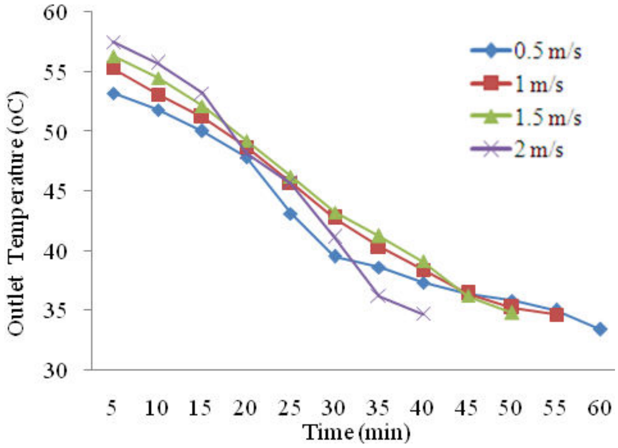

Fig 12.Variation of cold air outlet temperature with time during Discharging at heat input 750 W

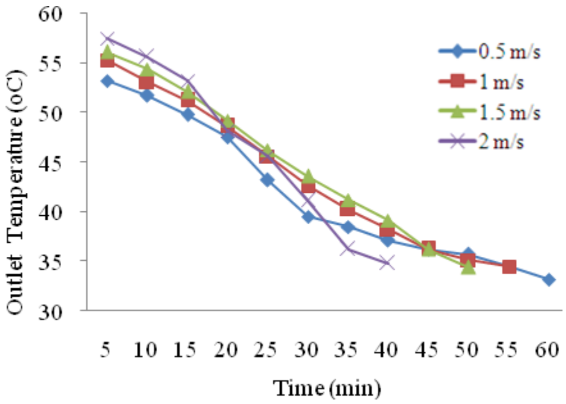

Fig. 13.Variation of cold air outlet temperature with time during Discharging at heat input 1000 W

Fig. 11 to 13 shows the variation of the PCM temperature with time during discharging the PCM air heat exchanger at different air velocities at 500 W to 1000 W respectively.. The graph shows that with increase in the air velocities, time required to reach the predetermined temperature reduces. At a given time the more velocity gives the minimum temperature of the PCM during discharging of the PCM.

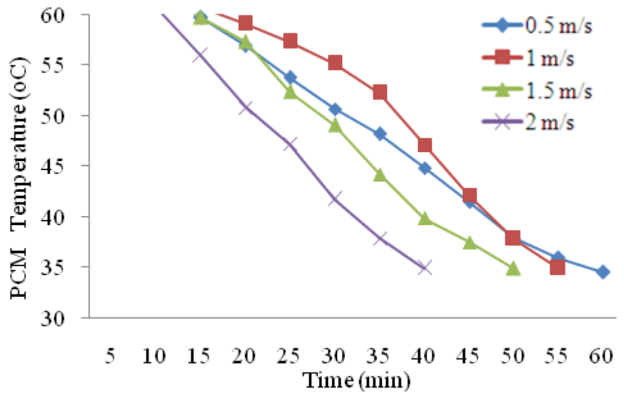

Fig. 14. Variation of PCM Temperature with time during Discharging at heat input 500 W

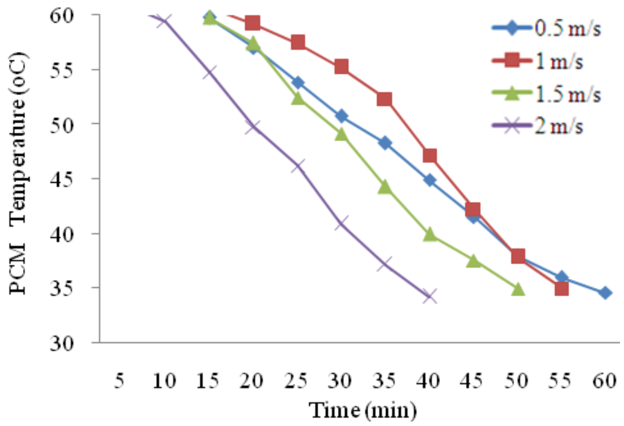

Fig. 15. Variation of PCM Temperature with time during Discharging at heat input 750 W

Fig. 14 to 16 shows the variation in the PCM temperature with respect to time at different watts during discharging for air velocity ranges from 0.5 m/sec to 2 m/sec. The graph shows that with increase in the wattage time required to discharge PCM air heat exchanger is reduced. Thus in general the fast charging or discharging can be achieved by blowing the hot or cold air through the PCM air heat exchanger at higher velocities or by increasing the source temperature.

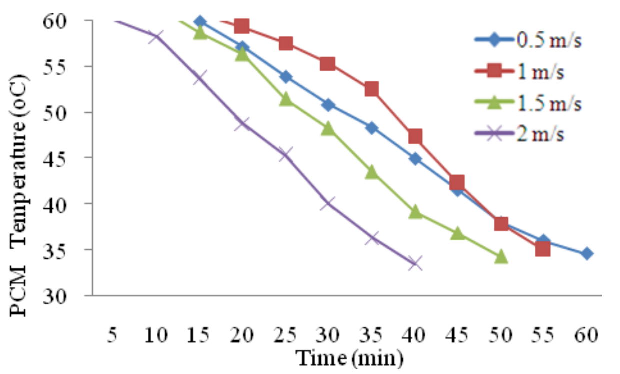

Fig. 16. Variation of PCM Temperature with time during Discharging at heat input 1000 W

CONCLUSIONS

Following conclusions can be drawn from the work carried out in context of the charging and discharging of PCM heat sink for electronic cooling of components.

1) The charging behavior of the PCM heat sink with variation in air flow velocity and electrical energy supplied to the heater is studied. The experiment shows that increase in the air velocity and electrical energy required to the heater leads to decrease the charging time and thus agitates the charging.

2) The discharging behavior of the PCM air heat exchanger with variation in air flow velocity and electrical energy supplied to the heater is studied. The results shows that increase in the air velocity and electrical energy required to the heater leads to decrease the discharging time and thus agitates the discharging.

3) At 1000 W, charging time reduces by 60 % with increase in air velocity from 0.5 m/sec to 2 m/sec and at same wattage the discharging time reduces by 30% with increase in air velocity from 0.5 m/sec to 2 m/sec. This leads to conclusion that for fast charging and discharging can be achieved by increasing the air velocity.

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