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Experimental Investigations of Phase Change Material (PCM) Based Pin Finned Heat Sinks for Cooling Electronic Equipment

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ABSTRACT
This experimental investigation is carried out to study the passive cooling of electronic component using Phase Change Material (PCM). This study emphasis to find out the effect of square pin fin in the performance of the heat sink of different power input. Paraffin Wax, classified as organic phase change material, has been highly recommended in the energy storage system due to its excellent thermal combination of high latent heat, chemical stability and nontoxicity. A constant volume fraction of 10 % of square pin-fins is selected and the input heat was provided from 8 watts, 16 watts and 24 watts. Three volume fractions of PCM ψ = 0, ψ = 0.5, ψ = 1 are poured for fined and without fin configuration. A heat sink with no fin is chosen as a reference heat sink to find the effect of PCM and square fin. It concludes that volume faction has an effect on performance, volume fraction ψ = 1 is better than ψ = 0.5 and combine effect of paraffin wax and fin is more effective than only paraffin wax at ψ = 1. Effect of fin is more effective for heat input 16 watt and less effective for high heat input 24 watt and also enhancement ratio is more for 16 watt power input of this study.

Keywords: Phase change material (PCM); Thermal conductivity enhancer (TCE); Paraffin wax; Heat sink.

1. Introduction

In modern days effective thermal management becomes a major concern for designers and manufacturer as the miniaturization of electronic components, increasing functionality as a result high heat dissipation from electronic products. As reliability and longevity of electronic components highly depends upon to keep temperatures below its maximum allowable operating temperature which is 80°C to 110°C for most electronic devices. If this heat is not wiped out properly from the devices breakdown of the component will be occluded very fast. Many active heat transfer augmentation techniques such air cooling using centrifugal fan may not very useful as an addition of noise, space and power consumptions. Some conventional cooling method such as loop heat pipe, liquid cooling, piezoelectric pump are effective for cooling such products [1]. Several experimental investigations show the effect of temperature on the performance of electronic component. The result concludes that failure rate can be reduced up to 4% by decreasing component temperature only 1°C [2]. Above that thermal failure of components can be decreased by 50% for each and every 10 °C reduce in component temperature [3]. Therefore temperature is a major reason of failure of electronic elements and affects the reliability of operation. In recent times, the traditional cooling techniques such as natural and forced convection have been insufficient to fulfill the cooling needs of today's high performance devices. The selections of cooling techniques are influenced by a range of factors like material cost, maintenance, heat dissipation rate, operating environment, available space etc. [4]. Counting all of these factors passive cooling techniques using phase change materials (PCMs) is gaining attention among researchers as it can play promising roles to increase the operations time and equipment's functional performance. The inalienable properties of PCMs especially organic PCMs are high latent heat of fusion per unit volume, high specific heat, chemical stability under repeated melting and cooling modes, non-toxic, non-explosive and non-flammable and little volume change during phase change. This implies that excessive quantities of electricity can be saved in a constant amount of PCM for the duration of phase change period. Although most of the PCMs satisfy these criteria which are used in electronics cooling, however unfortunately, almost all PCMs possess undesirable low thermal conductivity, which can be result over heating of heating components and making heating and cooling slower throughout PCM melting and solidification [5]. As a result, to make PCMs appropriate for cooling applications, it is necessary to add materials with high thermal Conductivity into PCM which will assist to heat conduction throughout the PCMs .These materials are regarded as thermal conductivity enhancers (TCE). Both experimental and numerical investigations have been carried by several authors for a huge variety of PCMs and sets standards that govern the resolution of PCM is discussed by Agyeni et al. [6]. Fan and Tso [7] experimentally investigated the cooling of electronic devices by using use of a heat storage unit (HSU) filled with n-eicosane inside the device. It was found that the performance depends upon the amount of PCMs used. A similar finding out about was carried out numerically by Tan and Fok [8] for the thermal management of mobile phone by the usage of PCM. Numerical simulation was carried out in heat storage unit filled with PCM. Eight cases were considered at a variety of energy tiers (2–4 W) and it was concluded for low power, temperature is low and for high power temperature is high. Kandasamy et al. [9] investigated

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both experimentally and numerically of a novel PCM package with respect to various input parameters (e.g. power levels, orientation, and charging/discharging cycles). The results show that melting rate is increased with a corresponding increase in power input, it also concluded that the effect of orientation of gravity had no significant effects on the performance of the PCM package and could be neglected. A model of the novel hybrid heat sink was proposed for the transient thermal management of electronics using plate fin which is immerged in PCM by Krishnan et al. [10] combining the effect of both active and passive cooling approach in the hybrid heat sink . It concluded that metallic PCMs performed better than organic PCMs but not suitable for low weight heat sink design. As the thickness of a pin and the amount of PCMs is increasing heat transfer rate is also increase and decrease melting temperature of PCMs. Many researchers have investigated different techniques to increase the thermal conductivity of PCMs. An experimental investigation was performed by Baby and Baliji [11] using n- eicosane as phase change material and placed it inside different aluminum fin geometry for thermal management of portable electronic devices. Results showed that use of fin is very effective to stretch operation time and pin fin is more effective than the plate fin. Heat transfer mechanism based on composite phase change material was carried experimental by Yin et al. [12] for rapid thermal response. Paraffin wax was absorbed into expanded graphite, as it has excellent absorbability. It was concluded that the composite PCM had high thermal conductivity and excellent absorbability than that of paraffin wax. Experimental investigation was carried out by Setoh et al. [13] using n- eicosane for mobile phone cooling for both steady and intermittent heating. Experimental findings showed that internal fin is helpful to increase time to reach maximum operating temperature and it is more effective for intermitted moderate condition. Many authors have investigated the effect the composite PCM with a combination of nano-particles (using nanoparticle as a thermal conductivity enhancer). Alshaer et al. [14] investigated hybrid composite system for thermal management (TM) of electronics devices using different model of carbon nano composite and paraffin wax. It was concluded that the model is capable of controlling higher loads. Arshad et al. [15] explore the effect of round fin thickness at different heat flux and configurations experimentally. Its findings showed that fin thickness has significant effect in lowering the base temperature. Effect of cupper foam in the performance of PCM based heat sink was investigated by Rehman and Ali [16] at different porosity and volume fraction. Findings showed copper foams have significant effect on the performance of heat sink. In this study the effect of 6 mm square fin is investigated for different volume fractions and power level to evaluate fin effect at three different power levels (8 watt, 16 watt and 24 watt) at different set point temperatures (SPTs) and find the power at which the effect of fin is most significant.

2. Methodology

2.1 Experimental setup

At first a suitable setup is developed for the experimental investigation of the performance of the heat sink as shown in Fig.1.

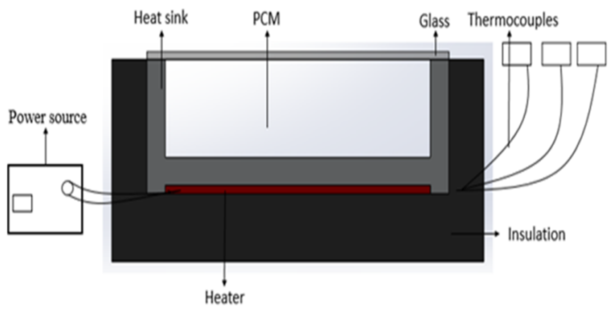


Fig.1 Schematic diagram of the experimental setup.

The setup consists of different heat sink configurations. A plate heater is used to mimic the heat generation in electronic chips in the base of the heat sink as a heating source. Power is used from an AC source of 220 volts and it is regulated by using voltage regulator. This type of heater is very useful to generate uniform heating. An insulating box is used to minimize heat loss from the heater so that all the time the condition remains the same.

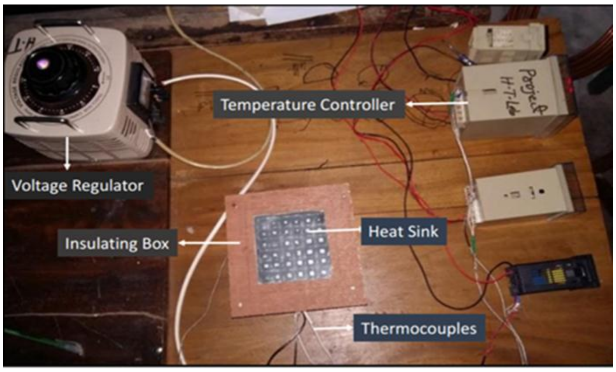


Fig.2 The experimental setup.

The assembly of heat sink consists of wooden frame the gap between heat sink and box is filled with glass wool since the glass wool is very a good insulator. A glass plate is placed above the sink for monitoring the melting phase of paraffin wax time to time for better understanding of phase change phenomena during heating and cooling. A voltage regulator is used to regulate voltage so that required power can be supplied to the heater. Effect of different types of fins for different power level (8 watts to 24 watts with equal interval of 8) in enhancing the operating time for different SPTs and on the duration of latent heating phase is exploding in this study. Experimental setup consists of heat sinks having pin-fin configurations filled with PCM, insulated with glass wool & rubber which prevents the heat loss to the environment, thermocouples, power supply. To realize the melting and solidification of paraffin wax calibrated K-type thermocouples is used at different position. Two thermocouples are placed at the base of the heat sink between plate heater and the base of the heat sink in a groove of 2 mm depth at a distance of 40 mm of equal distance. Thermocouples are inserted 15 mm inside the vertical direction at different positions. They are placed at a distance 9 mm from each other from the base of the heat sink.

2.2 Heat sink configuration

Two configurations of heat sink filled with PCM are used. Heat sink of 6 mm square fin having a constant volume fraction of 10% of TCE as shown in Fig. 3 (a). Aluminum is used as thermal conductivity enhancers due to its high thermal conductivity and light weight. Heat sink with fin and without fin filled with PCM (paraffin wax) is used. A heat sink with no pin-fin at ψ = 0.00 and ψ = 1.00 (ψ = volumetric fraction of PCM) is tested to perform the base line comparison. Heat sink having constant volume fraction of 10% of TCE, is used. Aluminum is selected as the TCE due the good thermal conductivity and light weight. Paraffin wax is used as a PCM and three different volume fractions (ψ = 0, ψ = 0.5, and ψ = 1.0) are used for each heat sink by using by using Eq. (1).

$$\psi = \frac{\upsilon_{PCM}}{V_s - V_f} \tag{1}$$

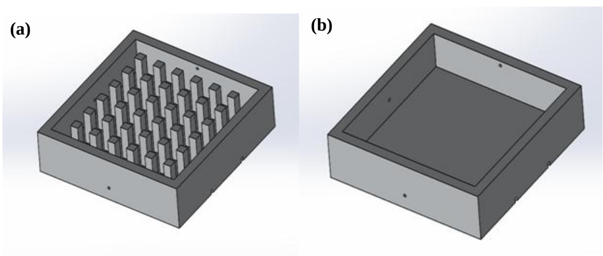


Fig.3 Isometric view of various heat sinks (a) 6 mm heat sink (b) No fin heat sink used in this study.

Overall dimension of the heat sink is 120 mm ×120mm. and height is 30mm, dimension of fin is 6mm×6mm as shown in Fig. 4.

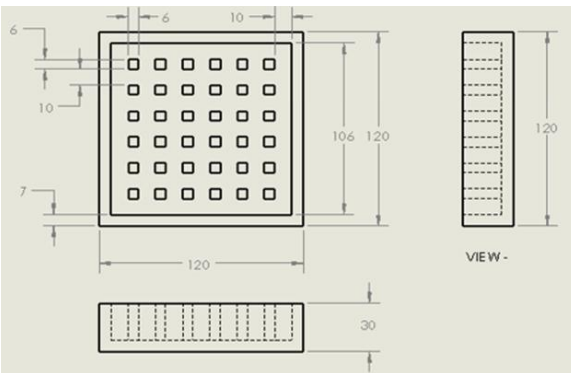


Fig. 4 Dimension of 6 mm heat sink.

2.3 Properties of materials employed in present study.

In this experiment paraffin wax is used as Phase Change Material (PCM), which is used as heat storage medium in the heat sink. Paraffin wax is a soft colorless solid, derived from petroleum. That consists of a mixture of hydrocarbon molecules containing between twenty and forty carbon atoms. Its physical properties are: thermal conductivity 0.167 (liquid) 0.212 (Solid) W/m-K; specific heat 2.8 kJ/kg-K; latent heat 173.6 kJ/kg-K; melting point 55-60 ^{o}C; density 790 (liquid) 880 (solid) kg/m^3. Heat sink is fabricated by using Aluminum because of its excellent properties such as is remarkable for its low density and its ability to resist corrosion through the phenomenon of passivation. Its properties are: Thermal conductivity 202 W/m-K; specific heat 0.871 kJ/kg-K; melting point 660^{o}C; density 2719 kg/m^3.

3 Results and discussion

3.1 Base line comparison

To find out the all other parameter finding the base level temperature is very important as with respect to these values all other parameters are compared. For base line compression temperatures of the base of the heat sink is taken without PCM and without fin is taken for 16 watt power input as shown in Fig. 5(b). The average of the base temperature is taken for the base temperature of the heat sink. For reaching base temperature 55°C and 65°C it takes 23 minutes and 33 minutes for heat sink without PCM on the other hand it is 42 minutes and 92 minutes with PCM respectively as shown in Fig. 5.

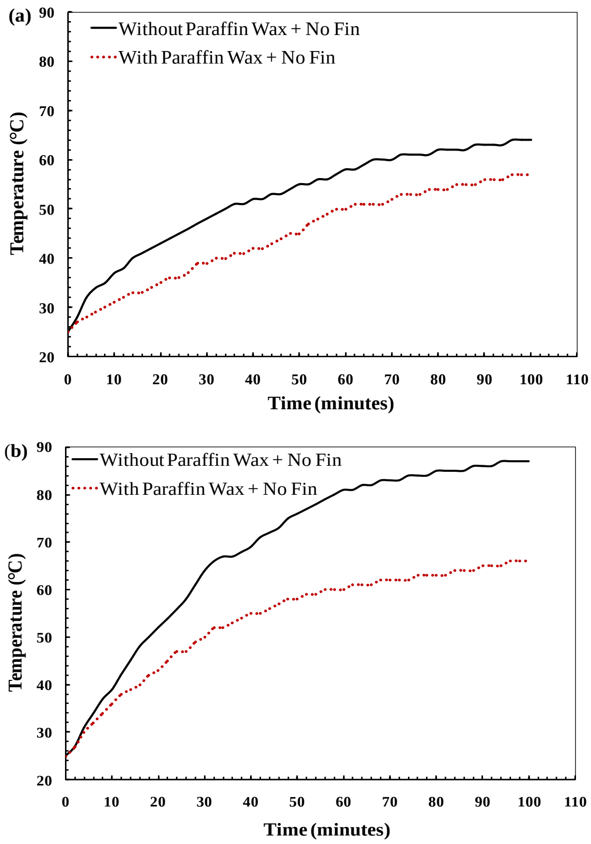
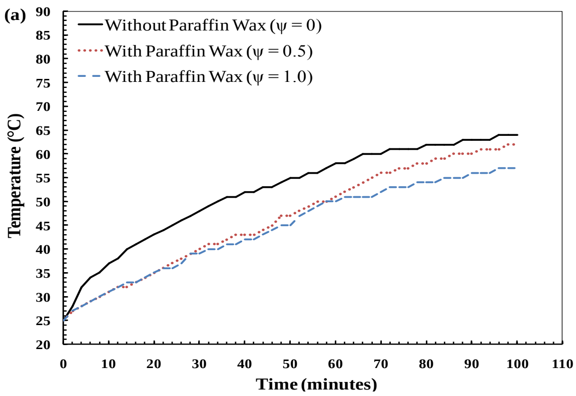


Fig. 5 Heat sinks base temperature at various power input (a) 8 watt input (b) 16 watt input.

To reach temperature 50°C and 60°C its takes 20 minutes and 31 minutes for heat sink without PCM, whereas it takes 32 minutes and 82 minutes for with PCM. Without PCM the temperature is increasing rapidly for, it is not expected of any electronic device it could easily damage the device. As the temperature reaches so fast operating time is also decreased and reached critical operating temperatures very quickly.

3.2 Effect of volume fractions of PCM for different configurations of heat sinks

Effects of volume fraction of paraffin wax are investigated by taking three different volume fraction of paraffin wax (ψ = 0, ψ = 0.5, ψ = 1) and taking the corresponding base temperature for 8 watts, 16 watts and 24 watts power input represented in Fig. 6. By comparing the corresponding values, the effect of volume fraction can be found. From the Fig. 6 (a), it is clearly seen for 8 watt power input that the volume fraction ψ = 1 is more effective to keep the base temperature lower than the other two. At the end of 100 minute temperatures reaches 64°C, 62°C and 57°C for volume fraction of ψ = 0, ψ = 0.5 and ψ = 1 respectively. Similar results have been found for 16 watt represented in Fig. 6 (b). For 16 watt power input, effect of volume fraction is more visible. After reaching melting temperature for volume fraction ψ = 0.5, temperature increases faster than volume fraction ψ = 1. This is because of more amount of paraffin wax is capable of storing more heat so that temperature increases slowly for large volume fraction. Similar effects are also found for 24 watt power input.



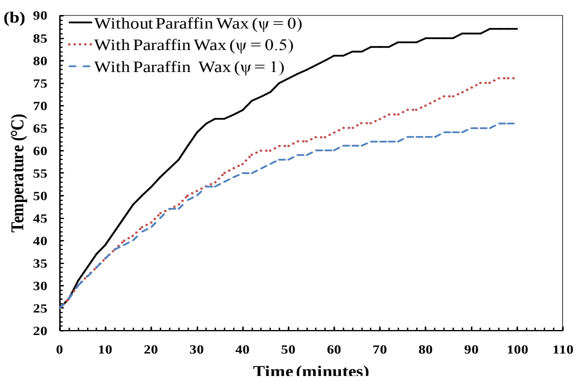


Fig. 6 Effect of different volume fraction at different power input (a) 8 watt (b) 16 watt.

Therefore, it is clear that volume fraction of PCM has a significant effect in the performance of PCM based heat sink. In this experimental investigation volume fraction of ψ = 1 is more effective than the others.

3.3 Temperature variation within heated fin sink filled with PCM

For better understanding of temperature distribution in vertical direction inside the heat sink three thermocouples are placed at a height of 8 mm, 16 mm and 24 mm from the bottom of the heat sink into the PCM from the side wall. Temperature is taken against 16 watt power input. Fig. 7 represents the temperature after three different time 20 minutes, 60 minutes and 100 minutes for better observation. It showed that temperature variations inside the heat sink is insignificant.

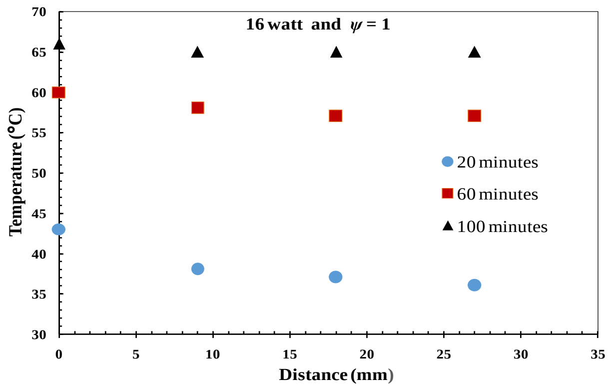


Fig.7 Spatial distribution of temperature inside the PCM at 16 watt.

3.4 Enhancement in operation time for different configurations of the heat sink

Operation time of various configurations of heat sink is taken at assorted set point temperature (SPTs) such as 55°C, 60°C and 65°C which are analysed for volume fraction of ψ = 1 for different power inputs (8 watt, 16 watt, 24 watt) presented in Fig. 8. The summary are plotted for better understanding of operation time for different configurations. The critical SPT may be defined as the maximum operating temperature for any electronic component which can withstand without damage or breakdown. Time is measured with respect to reach heat sink base temperature 55°C, 60°C and 65°C of different configurations of heat sink for three different power input**.** It is seen from Fig. 8 that time to reach SPT, heat sink with paraffin wax and fin takes more time than other heat sink configuration since large thermal conductivity of fin helps to absorb heat simultaneously throughout the sink. From Fig. 8 it is very clear that pin fin is very effective for better performance of PCM based heat sink as in every configuration and different power input time taken by with paraffin wax and fin configuration always more than other configurations. Among other power levels for 8 watt power input, effect of fin is more visible and effective since time taken to reach melting point of the paraffin wax is moderate and also heat stored throughout the sink is more uniform than others.

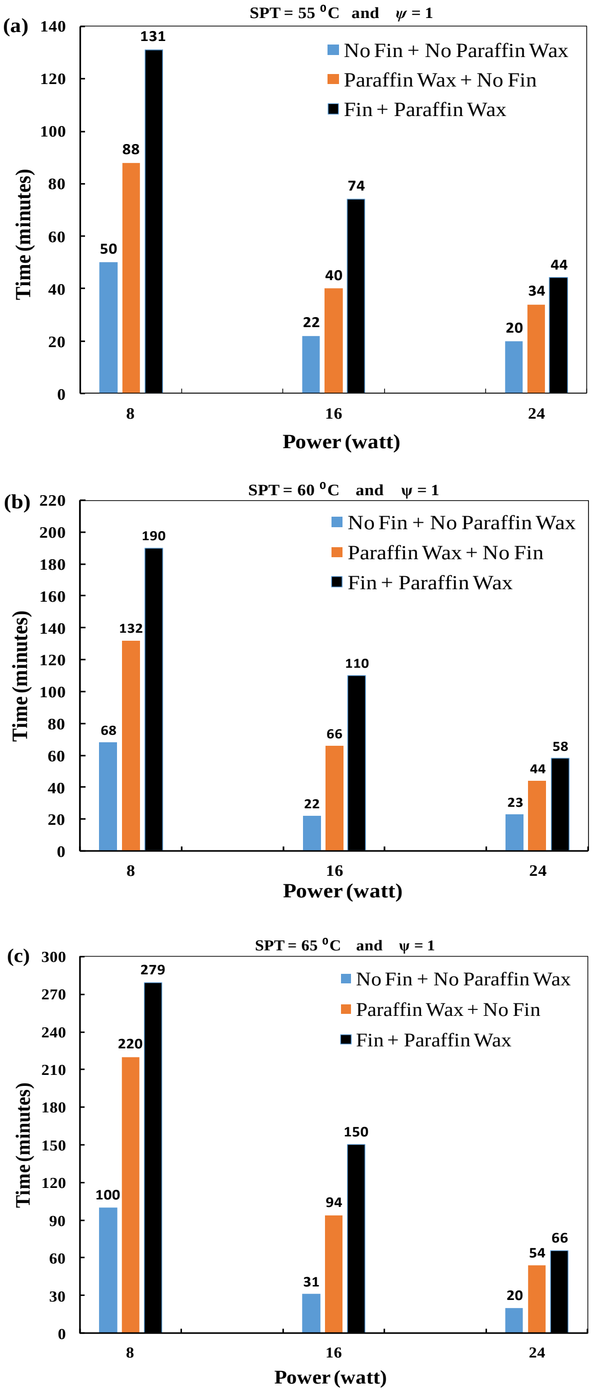


Fig. 8 Time to reach SPTs (a) 55°C (b) 60°C & (c) 65°C at 8 watt, 16 watt & 24 watt power input.

At 24 watt power input, time taken to teach melting point is short and therefore, temperature increases very rapidly in the base of the heat sink and heat sink has less time to absorb the heat throughout the sink.

3.5 Enhancement ratios for different configuration of heat sink

Enhancement ration for various configurations of heat sink at SPTs of 55°C, 60°C and 65°C respectively taken from different power input**.** Enhancement duration operation of a heat sink for effect of paraffin wax can be denoted as ξ which is the ratio of time taken by heat sink with paraffin wax (ψ = 1) to that of a heat sink without paraffin wax (ψ = 0) as in Eq. 2. Since temperature increas in paraffin wax start to take heat from the base of the heat sink and helps to keep operating temperature low, it can be seen from the Fig.8 that the best enhancement occurs with enhancement of paraffin that was configured at 16 watt power input.

$$\xi = \frac{t_{with\ PCM}}{t_{without\ PCM}} \qquad (2)$$

$$\epsilon = \frac{t_{without\ TCE}}{t_{with\ TCE}} \qquad (3)$$

The effect of fin with respect to without fin can be denoted as ϵ which is the ratio of time taken to reach SPT without fin to that of with fin at ψ =1 as in Eq. 3. It can be seen from the above Fig. 9 that enhancement ratio is always more for 16 watt power input for all three SPT. This is because heat sink has more time to store heat uniformly throughout the paraffin wax as the power level is favorable for this heat sink. Also, as the SPT increases, enhancement ratio also increases since all the paraffin wax has to store heat to change its phase. However, temperature increases rapidly when phase change is complete beacause of the lower value of sensible heat.

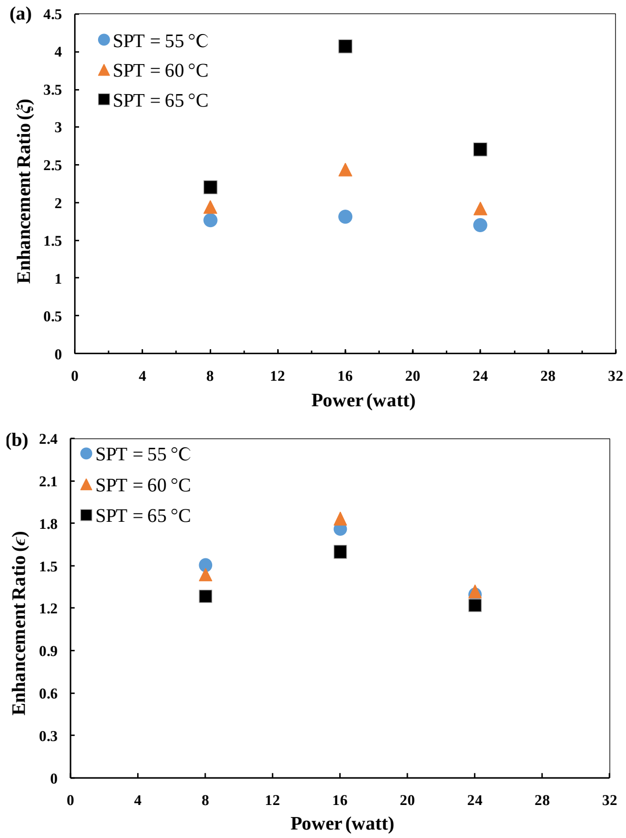


Fig. 9 Enhancement ratio at different power input (8 watt, 16 watt, 24 watt) (a) ξ (b) ϵ.

4. Conclusion

The experimental investigation performed aimed to investigate the effect of paraffin wax to evaluate the effect of volume fraction of paraffin wax and pin fin of PCM based heat sinks for power input of 8 watts,16 watts and 24 watts. Since the thermal conductivity of paraffin wax is low, this experimental study presents the effect of pin fin keeping the volume fraction constant at 10% as thermal conductivity enhancer for different heat sinks tested with volume fraction $\psi = 0$, $\psi = 0.5$, $\psi = 1.0$. Taking temperature with respect to time and evaluating the results of this study, the followings can be concluded.

- It is shown that inclusion of paraffin wax helps to keep the base temperature lower.
- It is also found that a heat sink with a volumetric fraction of $\psi = 1$ means fully filled with PCM is more effective to keep the base temperature lower than that of $\psi = 0$ and $\psi = 0.5$.
- The experiment proves that combine effect of paraffin wax and fin is more effective than only paraffin wax.
- Inclusion of fin is more effective for heat input 16 watt and 8 watt than higher heat input of 24 watt.
- Enhancement ratio is higher for 16 watt power input for different SPTs.

NOMENCLATURE

PCM : phase change material
TCE : thermal conductivity enhancer
TM : thermal management
V_s : total volume of heat sink
V_f : total volume of PCM

Greek Symbols

ψ : volume fraction of PCM
v_{PCM} : specific volume of PCM
ξ : enhancement ratio at PCM
ϵ : enhancement ratio at TC

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