Experimental Analysis of Heat Sinks incorporating Phase Change Materials and Thermal Conductivity Enhancers

Srivatsan Sampath[1], J. B Anand[2], S Deepak[3], D Senthil Kumar[4]
Department of Mechanical Engineering
Amrita School of Engineering
Coimbatore, India
[4] Assistant Professor, Department of Mechanical Engineering

***Abstract*—The transient thermal response of a heat sink for thermal management of portable electronic devices without phase change materials was simulated with ANSYS Fluent. The maximum temperature of the heat sink reached 85 °C after 720 seconds of usage at a power draw of 22 Watts. This is the maximum recommended operating temperature for most electronic devices. Thus the heat sink was redesigned to incorporate a passive thermal management system consisting of phase change materials. The redesigned heat sink was similarly modeled, showing a decrease in the maximum temperature to 72° C in the same time period. The inability of the system to handles higher powers lead to the inclusion of thermal conductivity enhancers to increase the overall thermal conductivity of the system. Application of the novel PCM package with thermal Conductivity enhancers was investigated experimentally for effects of various parameters e.g. power input, fin thickness, fin height and various numbers of fins. Also, an experimental analysis was conducted and compared the numerical results. Thus, the proposed passive thermal management system kept the heat sinks within their recommended operating temperature range.**

Keywords*—Phase Change Materials, Heat Sink, Passive Thermal Management System, Thermal Conductivity Enhancers

I. INTRODUCTION

Thermal management within the overall design of electronic products is increasingly important since each new generation of electronic devices squeezes more power and performance into ever smaller packages [1]. Techniques for heat dissipation include air cooling, immersion cooling, thermoelectric cooling, and heat pipes and so on [2][3][4]. Application of active cooling techniques is limited because of additional design and power requirements resulting in higher operating costs. Increased device size and weight are also matters of concern. The limited capability of the traditional air cooling techniques in the arising complex thermal management scenario has necessitated the development of new technologies.

There are two types of heat sinks that can be used, namely active or passive heat sinks [5]. Active heat sinks utilize power for operation of a fan or other cooling devices. Passive heat sinks , on the other hand do not need power and thus they have a higher reliability when compared to active heat sinks. This is owed to the absence of moving parts. Passive thermal management using Phase Change Materials are best suited when the heat dissipation is intermittent or transient. Therefore, in recent years, PCMs have been widely examined as alternative cooling methods for such transient electronic cooling applications as personal computing, wearable computers, mobile phones, digital video cameras etc. Among the advantages of PCM are: high latent heat of fusion giving high energy density, high specific heat, controllable temperature stability, and small volume change on phase change. Heat is stored (withdrawn from the hot component) during melting and is released to the ambient during the freezing period.

Paraffins and non-Paraffins are organic PCMs, while salt hydrates and Metallics are inorganic phase change materials[6]. PCMs can be used in industrial waste heat recovery, solar thermal applications, air conditioning systems, passive heating of buildings, textile industry, etc. PCMs can withstand a large number of cycles and are thus ideally suited for repeated use. PCMs are selected based on their heat of fusion and melting temperatures for different applications. The PCM melting temperature should be below the maximum operating temperature of the equipment [1]. Even so, phase change materials usually have a very low thermal conductivity, which makes charging and discharging slow during PCM melting. Using high thermal conductivity materials with fins of different geometry in conjunction with PCMs can tackle this challenge [8]. Heat sinks can be made from extrusion, casting or other sheet metal operations. Usually these are fabricated from copper or Aluminum [6].

TABLE I. NOMENCLATURE

F	External Body Forces (N)
g	Gravitational Acceleration (m/s^2)
h	Enthalpy (W/m^2 K)
k	Thermal conductivity (W/m K)
S_m	Source term
x_i	Cartesian coordinate direction
T	temperature (° C)
t	time (s)
u	velocity (m/s)
S	Solid

TABLE II. GREEK SYMBOLS

α	Fluid Volume Fraction
β	Thermal Expansion coefficient (K^{-1})
δ_{ij}	Kronecker delta
μ	Dynamic Viscosity (kg/m s)
ρ	Density (kg/m^3)

TABLE III. SUBSCRIPTS

f	Fin
i	Component
l	Liquid
s	Solid

II. REVIEW OF LITERATURE

There exists a functional temperature range for microprocessors and operation outside this range can degrade the system performance and can cause logic errors or component damage [1]. Mithal studied the effect of temperature on electronic component reliability. Different microprocessors have different maximum operating temperatures, with the maximum allowable temperature between 80°C and 115°C. The results indicated that there is a maximum temperature of optimal performance and a 1 °C decrease in a component temperature would lower its failure rate by as much as 4%.

Application of a novel PCM package for thermal management of portable electronic devices was investigated experimentally for effects of various parameters e.g. power input, orientation of package, and various melting/freezing times under cyclic steady conditions [25]. Also, a two-dimensional numerical study was made and compared with experimental results. Results of the paper show that increased power inputs increase the melting rate, while orientation of the package to gravity has negligible effect on the thermal performance of the PCM pack-age. Comparison with numerical results confirmed that PCM-based design is an excellent candidate design for transient electronic cooling applications.

Krishnan et al proposed a hybrid heat sink concept which combines the new passive and existing active cooling approaches [2]. The hybrid heat sink is essentially a plate fin heat sink with the tip immersed in a phase change material (PCM). The exposed area of the fins dissipates heat during periods when high convective cooling is available. The article quantified the improved performance with the performance of a finned heat sink (without a PCM) under identical conditions.

In order to reduce the computational time and aid in preliminary design, a one-dimensional fin equation is formulated which accounts for the simultaneous convective heat transfer from the finned surface and melting of the PCM at the tip. The influence of the location, amount, and type of PCM, as well as the fin thickness on the thermal performance of the hybrid heat sink is investigated.

In the dissertation,a computational methodology based on a front tracking/finite difference method is developed for the direct simulation of two-dimensional, time-dependent phase change processes involving: (1) pure material solidification, (2) alloy solidification and (3) liquid-vapor phase change with fluid flow [21]. The method is general in the sense that large interface deformations, topology change, latent heat, interfacial anisotropy and discontinuities in material properties between the phases are directly incorporated into the problem formulation and solution technique.

Convergence under grid refinement is demonstrated for unstable solidification problems. Experimentally observed complex dendritic structures such as liquid trapping, tip-splitting, side branching and coarsening are reproduced. It is also shown that a small increase in the liquid to solid volumetric heat capacity ratio markedly increases the solid growth rate and interface instability. The method is validated through comparison with an exact one-dimensional solution and by grid resolution studies.

III. COMPUTATIONAL DOMAIN

The flow of the molten PCM and air in heat sink assumed to be laminar, incompressible and unsteady. During the phase change process, the solid PCM will melt and change into its molten (liquid) state. The PCM in its solid state has a density of 920 kg/m^3 while the liquid state has a density of 770 kg/m^3 [10]. This change in density should be accounted while designing the heat sink and thus the heat sink is filled to up to 90 % of its capacity and the rest would be air.

A density temperature relation is used for air. The model PCM is based on the properties of commercially available paraffin wax. The density of PCM in solid phase is kept constant but after the melting period conservation equations associated with this type of flow. They are the mass conservation equation (continuity equation): at temperatures between 59 °C and 60 °C, the density of liquid PCM is shown in (1).

$$\frac{\partial \rho}{\partial t} + \frac{\partial \rho}{\partial x_i}(\rho u_i) = S_m \quad (1)$$

And the momentum conservation equation:

$$\frac{\partial}{\partial t}(\rho u_i) + \frac{\partial}{\partial x_j}(\rho u_i u_j) = \frac{\partial \rho}{\partial x_i} + \frac{\partial \rho}{\partial x_j} + \rho g_i + F_i \quad (2)$$

Where stress vector is given by

$$\tau_{ij} = \left[\mu\left(\frac{\partial u_i}{\partial x_i} + \frac{\partial u_j}{\partial x_i}\right)\right] - \frac{2}{3}\mu\frac{\partial u_l}{\partial x_l}\delta_{ij} \quad (3)$$

$$\delta_{ij} = \begin{cases} 0 \; for \; i \neq j \\ 1 \; for \; i = j \end{cases} \quad (4)$$

Momentum equations are shared by the fluids, and the volume fraction of each of the fluids in each computational cell is tracked throughout the domain. In each control volume, the volume fraction of all phases sum up to unity. The fields for all variables and properties are shared by the phases and represent volume-averaged values. Thus, the variables and properties in any given cell are either purely representative of one of the phases, or a mixture of the phases. The α^{th} fluid's volume fraction in the cell is denoted as a_{α}, then the following three conditions are possible.

α_q=0	the cell is empty
α_q =1	the cell is full
0<α_q<1	the cell contains the interface between the fluids

Based on the local value of a_α, the appropriate properties and variables will be assigned to each control volume within the domain.

The tracking of the interface(s) between the phases is accomplished by the solution of a continuity equation for the volume fraction of one (or more) of the phases. For the αth phase, this equation has the following form:

$$\frac{\partial \alpha_q}{\partial t} + u_i \frac{\partial \alpha_q}{\partial x_i} = S\alpha_q \quad (5)$$

In this simulation study, the two phases are defined as follows:

- Primary phase: Air.
- Secondary phase: PCM.

The volume fraction equation will not be solved for the primary phase. The primary-phase volume fraction will be computed based on the following constraint:

$$\sum_{q=1}^{n} \alpha_q = 1 \quad (6)$$

In this technique, the melt interface is not tracked explicitly. Instead, a quantity called the liquid fraction is associated with each control volume in the domain. The liquid fraction is computed for each iteration. This liquid fraction allows us to track the melting of the PCM.

IV. EXPERIMENTAL SETUP

The principal parts of the experimental setup are described below.

A. Temperature Indicator

A Digital Temperature indicator compatible with K-Type Ni-Cr thermocouples was used for measuring the temperatures in the heat sink. The indicator is capable of displaying the temperature at 10 different points and has an accuracy of order of one degree. The temperature indicator was calibrated using the freezing and boiling points of water and the zero error was found to be -1 Degree Celsius.

B. Thermocouples

K type thermocouples are made of Nickel and Chromium and used for measuring the temperature at various points in the heat sink assembly.

C. Single Phase Continuously Varying Auto Transformer

The continuously varying auto transformer is used to provide and vary the power to the heater coil. By connecting the Transformer to a voltmeter and ammeter, the voltage difference and the current are measured. The transformer is connected in parallel to an AC Voltmeter and in series with an AC Ammeter.

D. Heating Coil

The Resistance Heating coil by virtue of its high resistance converts the input electrical energy into heat energy thus acting as a substitute for a microprocessor.

E. The Heat Sink Assembly

1. Phase Change Material

The material used for the experimental analysis is Paraffin wax C22-45 commercially known as Paraffin wax 58-60.

2. The Heat Sink Casing

The walls of the heat sink casings and the fins are made of Aluminum 1100 Alloy.

3. Thermal Insulation

The heat sink is insulated on the four walls to make sure that heat transfer occurs only in one direction. The temperatures across the insulation were noted to determine the heat loss. This insulation is done with acrylic and heat insulation cloth. The insulating material (Styrofoam) is wrapped around the PCM heat sink using masking tape. The acrylic has a thermal conductivity of 0.2 W/m K while the Styrofoam has a thermal conductivity of 0.054 W/m K[15]. It is found that the largest heat loss under 45 W input to the heater is about 12.4%.

V. PROCEDURE

A. *Preparation of Heat Sink Assembly*

A. *Heat Sink Casing*

The casing and the fins were manufactured using sheet metal and the fins were fitted into the casing by pressure fitting and relative motion is arrested by the interference fit between the fin and the casing.

B. *Positioning of Thermocouples*

Each heat sink has eight to 10 strategically located thermocouples. These thermocouples are meant to record the temperature distribution on the heat sink for the duration of the heating process. The thermocouples are located on the outside sink wall, inner vertical fin surface, between the fins, and at the inner and outer base of the heat sink. A thermocouple is also positioned outside the insulation to study the effectiveness. Ideally the temperature recorded by this thermocouple should be the same as the atmospheric temperature. But since there is some heat loss, there is a variation in temperature and this variation is used to find the amount of heat loss. A schematic of the thermocouple positioning is shown in Fig. 1.

C. *Addition of Phase Change Material*

The PCM is melted on a heating plate. Upon reaching its melting point, the PCM melts. The molten PCM is then transferred to a measurement beaker, and poured into the heat sink.

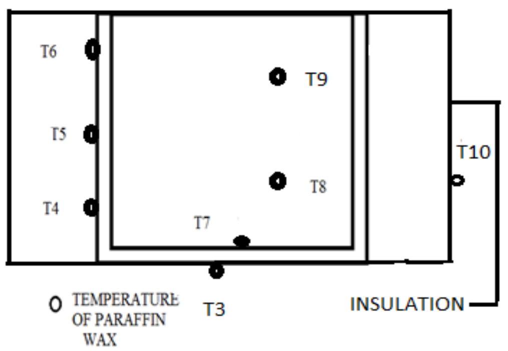

Fig. 1 Thermocouple Positioning for a heat sink without Fins

TABLE I. PLACEMENT OF THERMOCOUPLES

THERMOCOUPLE	LOCATION	FUNCTION
T3	Heater Base	Heater Temperature
T4	Side Wall Outer	Outer Side Wall 10 mm from inner base
T5	Side Wall Outer	Outer Wall Temperature 30mm From inner Base
T6	Side Wall Outer	Outer wall Temperature 50mm from inner base
T7	Base Inner	Inner Base Temperature
T8	PCM	20mm above inner base
T9	PCM	40 mm above inner base
T10	Insulation outer	Outer Insulator temperature

The PCM is poured until it fills the beaker up to 2mm from the top wall. This heat sink is then exposed to natural convection at room temperature for about 3 to 4 hours. The contraction induced by the solidification of the PCM results in the beaker being filled up to 4 t 5mm from the brim.

D. *Circuit Assembly*

The circuit assembly is shown in figure 2.

E. *Heating and Temperature Measurement*

Because a microprocessor cannot provide a constant supply of heat, a heating coil is used to supply a stipulated amount of heat. If the heat sink is able to sustain stable operation in this temperature range, then it can withstand any heat flux that a microprocessor can dissipate. The presence of a heating coil prevents us from treating the circuit as a constant resistance circuit because the change in temperature causes a consequent increase in voltage. Thus to find required power level the voltage is increased and the corresponding current is noted. This is used to find the power and many trials are conducted to arrive at the desired power levels. Following which heating is done to check the effect of the following parameters.

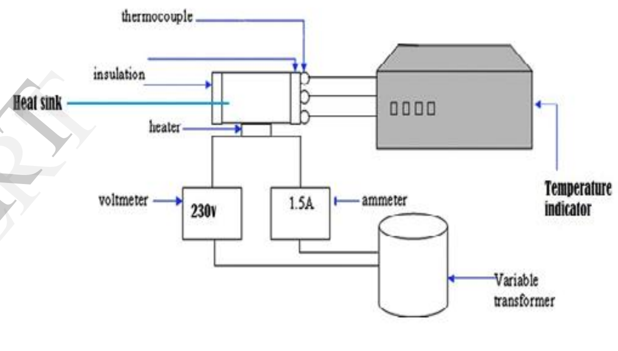

Fig. 2 Experimental Setup

A. *Effect of PCM*

In this case, a power of 22W is supplied to a Heat sink without PCM and the temperature distribution is recorded. Then the experiment is carried out with a PCM and the results are noted. Both the heat sinks are finless. The schematic of the heat sink without and with PCM are shown in the figures 3 and 4.

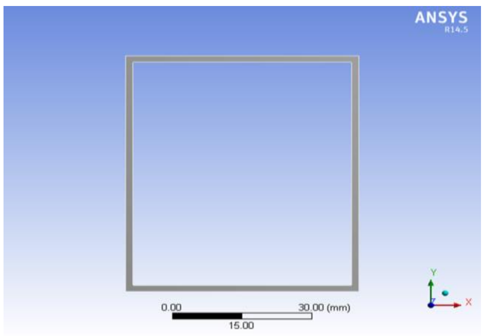

Fig.3 Heat Sink without PCM

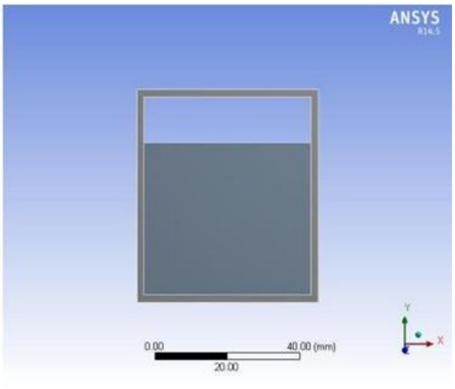

Fig. 4 Heat Sink with PCM

B. Effect of Power Input Levels

The experiment is conducted with varying power levels and the corresponding temperature distributions are noted. The two power levels tested are 22W and 45W respectively.

C. Effect of Fin Thickness

Heat sinks with fin thickness 2mm and 4mm are heated with 63W of power and the corresponding temperature distributions are noted. The sectional views of the heat sinks with different thickness are shown in figures 5 and 6.

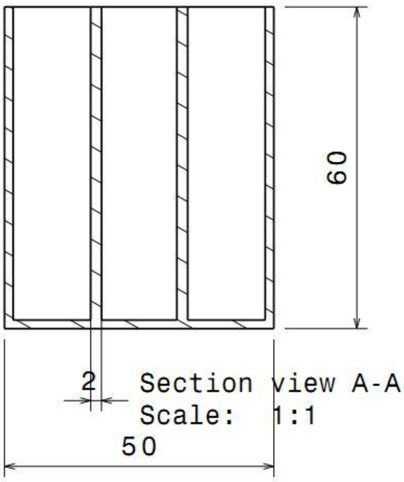

Fig.5 Sectional View of Heat Sink with 2 fins of Fin Thickness 2 mm.

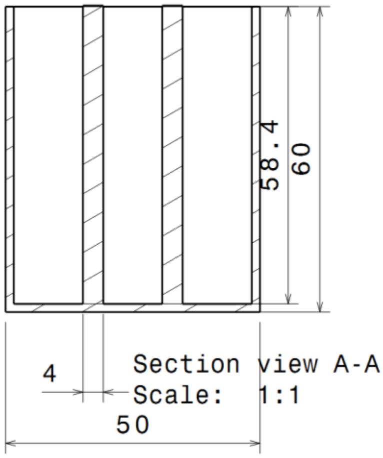

Fig. 6 Sectional View of Heat Sink with 2 fins of Fin Thickness 4 mm and Fin Height 60mm.

D. Effect of Fin Height

Heat sinks with fin heights of 30mm, 45mm and 60mm are given 63W of power and the results were noted. The sectional views of the heat sinks are shown in figures 6,7 and 8 .

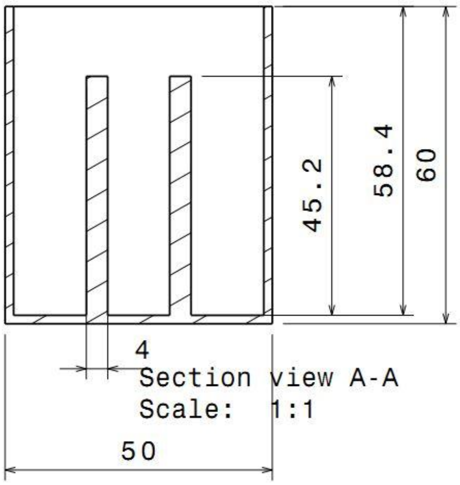

Fig. 7 Sectional View of Heat Sink with 2 fins of Fin Thickness 4 mm and Fin Height 45 mm.

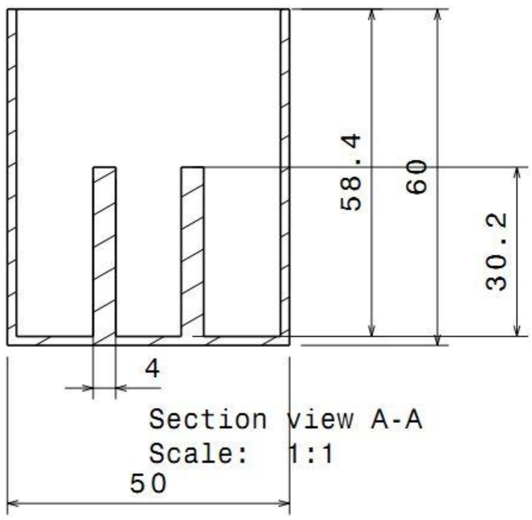

Fig. 8 Sectional View of Heat Sink with 2 fins of Fin Thickness 4 mm and Fin Height 30mm.

VI. EXPERIMENTAL RESULTS

A. *Effect of PCM*

The thermal performance of two heat sinks, one filled with PCM and one without PCM are showed in Fig. 8. We can notice that for the case of heat sink without PCM there is a steady temperature rise. The case temperature rises to 104 °C in six minutes. However, for the heat sink with PCM, the temperature rise is lower throughout. In fact the case doesn't reach 100°C and attains steady state at 60°C. This is because the power input of 22W is too low to make the PCM melt completely and the rate of convection heat loss in the vertical direction from the top face is equal to the heat flux provided at the bottom. There is also a period between 10 and 20 min where the temperature rise seems to be low. When a larger amount of heat flux is given, this period coincides with the melting of the PCM in the heat sink. The difference between the two cases is due to the fact that for the heat sink without PCM there is no effective latent energy storage to maintain the temperature. For the heat sink with PCM, when a sufficient amount of power is given, the PCM stores the heat during melting as latent heat, thus keeping the temperature at around the melting temperature of the PCM. The PCM-based heat sink does lower the base temperature of the heat sink through the absorption of heat by the PCM compared to the heat sink without PCM. However, for high power inputs, once the solid PCM is fully melted, the base temperature of the PCM-based heat sink can rise to the same temperature value of about 150 ˚C as the heat sink without PCM within a same duration of 30 min. Thus, the PCM-based heat sink cannot operate continuously. It can only be used in application intermittently where there is a need for the molten PCM to release its heat to the surrounding for re-solidification.

One interesting thing to note is that even though the melting only starts at 7 min, the heat sink with PCM seems to be able to maintain a lower temperature compared to the heat sink without PCM from the 1st minute. This is due to the fact that besides having a large latent heat absorption capability, the PCM also has a larger specific heat compared to air. For the case of paraffin C22-45, it has a specific heat of 2100 J/kg K.

As such, the PCM continually absorbs this amount of sensible heat per unit kg and 1K of temperature rise as the base of the heat sink is heated. The numerical simulations for the 2D compared reasonably well with the experimental data.

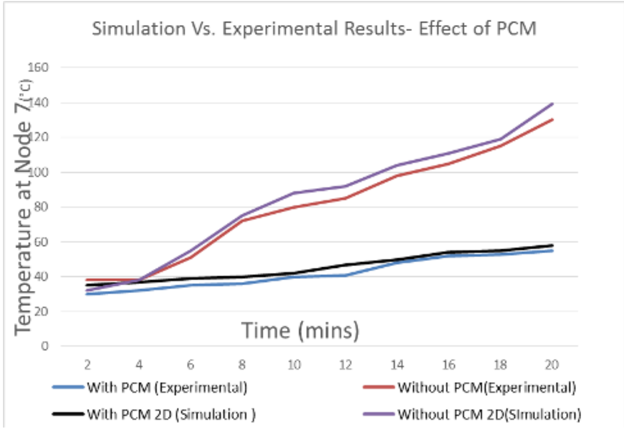

Fig. 8 Simulation and Experimental Results- Effect of PCM

B. *Effect of Power Input Levels*

Figure 9 shows the case temperature versus time for different power level. As expected, higher power levels results in a higher temperature for the base of the heat sink. Through visual inspection it is observed that the melting rate increases with higher power levels. In fact for the experiment at 22 W power input, the experiment extends beyond 30 min as the PCM has yet to melt completely. This is expected as a higher power input will result in a higher energy absorption rate by the PCM. One interesting observation is that there is two different melting durations are observed. The higher the power input, the shorter the melting duration. This is expected as the PCM has reached it melting point and any further increase in the power input simply increases the temperature of the heat sink. The numerical simulation results on case temperatures for 2D simulation models compare reasonably well with the experimental data.

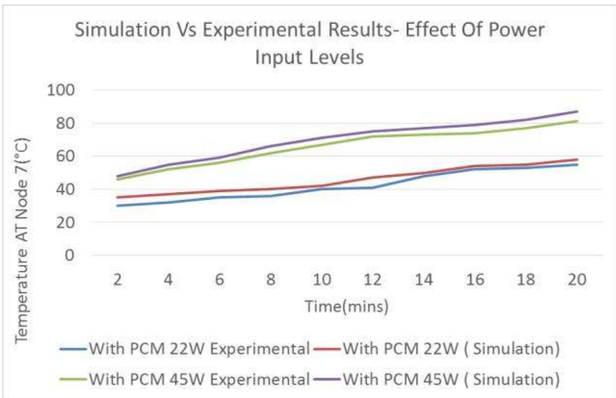

Fig. 9 Simulation vs. Experimental Results- Effects of Power Levels

C. *Effect of Fin Thickness:*

Fig. 10 shows the temperature evolution with time for various fin thicknesses. 4-mm give slightly better results than 2mm. This is because of the thermal resistance of fins reduces with

larger fin thickness. This causes an increase in temperature of fins and rate of heat releases to PCM and so the overall temperature of heat sink decreases. We should note that the heat sink with thicker fins have lesser PCM volume. We can also see that fins thicker than 4 mm do not further improve the performance of the heat sink. We can say that the heat sink reaches it maximum performance capability at a 4-mm fin thickness. Too thick a fin allows for only little volume of PCM, this limits its functioning as a latent heat storage material.
This is because when the PCM is in the solid phase, the main mode of heat transfer in the PCM is through heat conduction. Heat conduction requires a temperature gradient. So the larger the temperature gradient, the greater is the heat conduction. We can see that the thinner fins have a higher temperature gradient throughout as compared to the thicker fins. This will cause a higher heat conduction rate in the heat sink with thinner fins. Thus, the PCM will reach its melting temperature faster. Also we can observe that the thicker fins have a shorter melting period. This is due to the lower volume of PCM which means lower latent heat capacity.

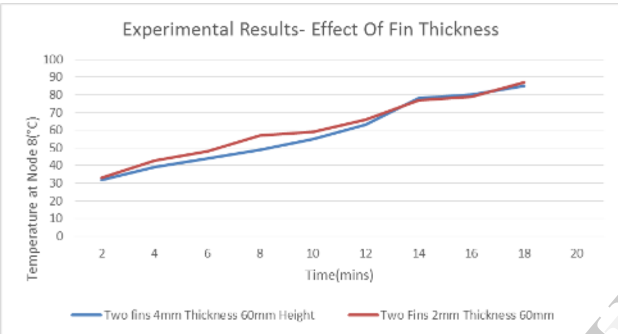

Fig. 10 Effect of Fin Thickness

D. Effect of Fin Height

From fig. 11, we can see that the performance of the heat sink increases with increasing fin height. This is expected because the heat transfer surface increases with increasing fin height. For the 10-mm fin height, heat is transferred from the base to the fins. The fins transfer heat only to a small portion of the PCM. As the thermal conductivity of the PCM is low, further heat transfer toward the upper regions of the PCM in inhibited. This causes local overheating at the fins and the base which increases the case or base temperature.

For the 40-mm fin height, heat from the fin is transferred to a larger portion of the PCM. Once the base and sides of the PCM are heated and melted, internal natural convection of the melted PCM takes place. This increases the rate of the heat transfer to the upper regions of the PCM.
We must bear in mind that all heat sink models have the same fin thickness. This lower heat capacity storage means a faster rate of temperature rise for a given heat input. This will cause the fins and PCM to reach the PCM melting temperature faster and thus begin to melt earlier. We also can notice that the melting period is reduced with an increase in fin height. This is due to the lower content of PCM in the heat sink with taller fins.

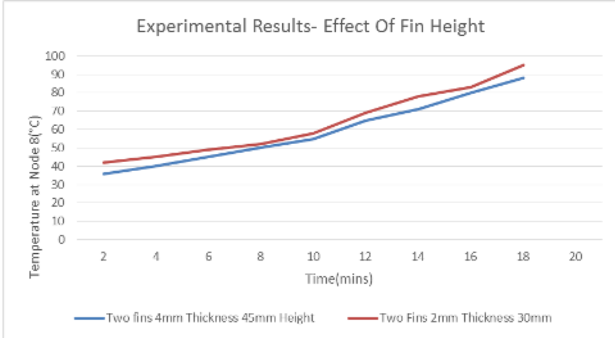

Fig. 11 Experimental Results- Effect of Fin Height

VI. CONCLUSION

Heat sinks with internal fins give better thermal performance (lower temperature) compared to one without internal fins. The greater the number of fins, the lower is the case temperature during melting. Also, a heat sink with more fins starts melting later as compared to a heat sink with lesser fins (of the same size). Also, the melt period is reduced with an increase in the number of fins. This is mainly due to the smaller PCM volume in the heat sink. It is observed that there is more convective fluid motion in the heat sink with more fins. This results in a higher melting rate.
An increase in fin thickness shows only a slight improvement in thermal performance. Also it is observed that there is an optimum point to which the fin thickness can be increased to. Increasing the fin thickness beyond this optimum point will yield no further improvement in thermal performance. The starting time for melting is delayed as the fin thickness is increased. The thicker fins also have a shorter melting period. For thicker fins, the melt front moves in parallel with the fin. For thin fins the melt front movement is not uniform. Also it is noticed that in earlier periods, the lower regions of the PCM for the thin fins seem to melt faster. This indicates that the primary heating is from the base of heat sink. For both cases however, in later periods of melting, the upper regions of the PCM seem to melt faster, indicating internal fluid convection. Internal fluid convection is a far more effective heat transfer mechanism compared to heat conduction within PCM. The performance of the heat sink increases with increasing fin height. The starting time for melting is delayed with an increase in fin height. Also the melting period is reduced with increasing fin height.

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