Thermal performance enhancement of PCM based cross finned heat sink for electronic cooling.

A project report

Submitted in partial fulfillment of the

requirements for the award of the degree

Of

BACHELOR OF TECHNOLOGY

IN

MECHANICAL ENGINEERING

Submitted by

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Indian Institute of Technology Indore

November 2019

CANDIDATE'S DECLARATION

We hereby declare that the project entitled **"Thermal performance enhancement of PCM based cross finned heat sink for electronic cooling"** submitted in partial fulfillment for the award of the degree of Bachelor of Technology in 'Mechanical Engineering' completed under the supervision of **Dr. Santosh K. Sahu, Associate Professor, IIT Indore** is an authentic work.

Further, we declare that we have not submitted this work for the award of any other degree elsewhere.

Pawankumar Singh (160003052) **Date:**

Rushikesh Vaidya (160003056)

CERTIFICATE by BTP Guide

It is certified that the above statement made by the students is correct to the best of my knowledge.

Signature

Dr. Santosh K. Sahu
Associate Professor,
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Preface

This report on "Thermal performance enhancement of PCM based cross finned heat sink for electronic cooling" is prepared under the guidance of Dr. Santosh K. Sahu.

The effect of different crossed fin configurations on the thermal performance of heat sinks containing phase change material (PCM) has been analyzed at three different heat fluxes. Numerical and Experimental analysis were carried out for various crossed fin heat sinks.

The results obtained from the present numerical and experimental study are presented in the tabular and graphical form.

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Abstract

Thermal management of electronic components has become a major concern in recent years due to their decrease in size and increase in functionality. Therefore, an efficient thermal management technique is required to prevent the failure rate of electronic devices due to overheating and to improve long term reliability. In the present study, a novel thermal management technique, phase change material (PCM) based cross finned heat sink is developed to enhance the thermal performance and increase the long term reliability of electronic devices. PCM based heat sink cooling is considered as very promising passive cooling technique because of high latent heat storage capacity. This study deals with numerical investigation of PCM based cross finned heat sink to enhance the performance of electronic devices. Here, four different configurations of heat sink such as heat sink without fins, 2×2 fin, 3×3 fin and 4×4 heat sink filled with paraffin wax as PCM is investigated numerically. The volume fraction of fins is kept constant (6.60 %) for all configuration of the heat sink. Various parameters such as effect of heat sink configuration, effect of heat flux, effect of fin thickness, and enhancement in operating time to reach critical set point temperature are reported. The comparison of different configuration of heat sink shows that increasing the number of fins, increase the thermal performance. However after a certain number of fins, further increment in fins does not improve thermal performance significantly. On increasing the heat flux, the melting rate of PCM in each heat sink increased as expected. Conduction was the primary mode of heat transfer before the melting starts however; convection heat transfer was dominant after melting started.

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Chapter 1

Introduction

1.1 Introduction:

Thermal management of electronic components has become a major concern in recent years due to their decrease in size and increase in functionality. Past studies have shown that failures of these components are primarily due to thermal reasons. Therefore, an efficient thermal management technique is required to prevent the failure rate of electronic devices due to overheating and to improve their long term reliability. To regulate the temperature of the system using technology based thermodynamics and heat transfer is known as Thermal management of the system. This technique is divided mainly into two types:

(1) Active cooling techniques (2) Passive cooling techniques.

An active cooling technique requires an external power for functioning. There are various types of active cooling techniques, e.g., a) Forced air cooling, b) Cold plates, c) Synthetic jet air cooling and d) Heat pipe, etc.

Passive cooling technique doesn't use any external power for its functioning. Change in geometry of the fins (finned heat sink) or using phase changing materials(PCM) are some of the techniques used for passive cooling. Its been realized that energy absorbed during phase change (latent heat) is more than the sensible heat for less temperature rise. Hence, in our present study PCM is used to absorb the waste heat to avoid any external power consumption.

Phase changing materials have relatively high latent heat of fusion and specific heat with a capacity to store and release high amounts of energy in a suitable temperature range. They also have various other advantages such as chemical stability , non corrosiveness, also their thermo-physical properties remain the same after numerous heating and cooling cycles.

1.2 Classification of phase change materials (PCM)

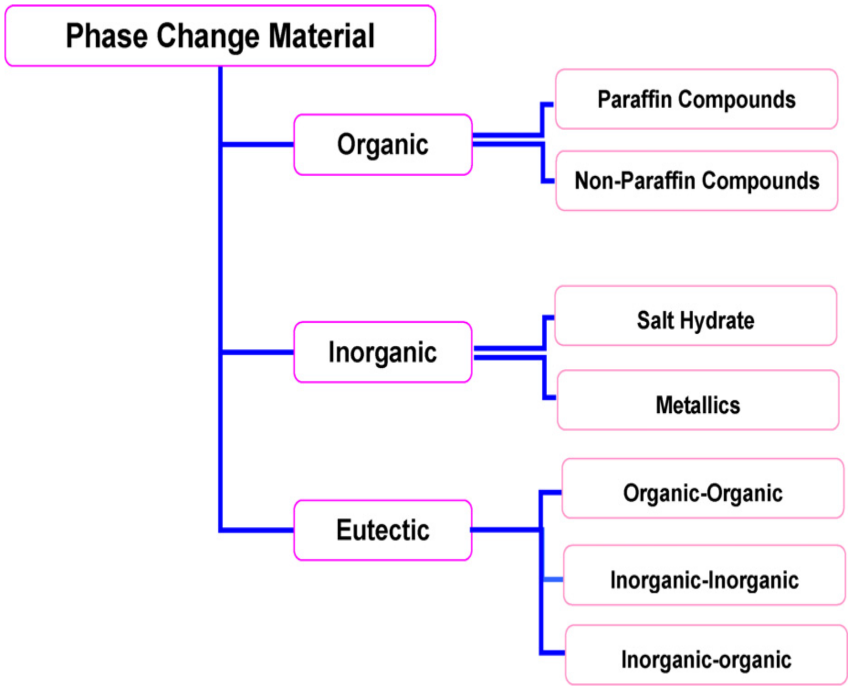


Fig 1: Classification of phase change materials

1.2.1. *Organic PCM*

Organic PCMs are based on Hydrocarbons .They are further classified as paraffin and non-paraffin .Paraffin consists of a mixture of hydrocarbon molecules containing between twenty and forty carbon atoms. It is mostly available as a white, odorless, tasteless waxy solid. It has a typical melting point between about 46 and 68°C. Various paraffins are available with different melting temperatures. Due their high latent heat they can be effectively used for energy storage over a large temperature range.

Non-paraffin compounds are the PCMs consisting mainly of carbohydrates and fatty acids. Compared to inorganic PCMs, organic PCMs are generally more stable, and due to the following characteristics, they are generally preferred over inorganic PCMs:

1. Self nucleating properties
2. Freeze without much supercooling
3. Ability to melt congruently (melting and freezing can be done repeatedly without any consequences such as phase segregation and reduction of latent heat)
4. Chemically stable

1.2.2. *Inorganic PCM*

Salt hydrates and Metallics together form inorganic PCMs. Salt hydrates contains water of crystallization with a general formula of$(M_x\,N_y H_2 O)$. Metals and metal-eutectics that melt at very low temperature are included in Metallics. Following are the advantages of using inorganic PCM:

1. Easy availability and cheap
2. High heat of fusion
3. Non-flammable

Apart from above mentioned advantages, it also has some disadvantages such as its corrosive nature and supercooling.

1.2.3. *Eutectics*

Eutectics are the mixture of two or more constituents. They solidify simultaneously out of the liquid at a minimum freezing point. Water-salt solutions are chemically very stable, but can cause corrosion in metals. Most of the solutions are safe, but should not be leaked in large amounts. Since they are cheap, they can be commercially used for large-scale applications.

1.3 Selection criteria for PCM

High latent heat of fusion and a suitable melting temperature are the obvious requirements of a phase change material. However there are more other criteria that need to be fulfilled.

1. Suitable phase change temperature
2. High latent heat of fusion per unit volume and high specific heat
3. Reproducible phase change (cycle stability)
4. Non-toxic and non-corrosive nature
5. Low price and easy availability
6. Chemically stable
7. High thermal conductivity
8. Small volume change on phase change

Apart from high thermal conductivity, paraffin satisfies all the above criteria.

1.4 Applications of PCM

1. For cooling of electronic devices. PCM with effective heat sinks can be used for better thermal management.
2. It can also be used to delay the ice and frost formation on surfaces.
3. Solar power plants, spacecraft thermal systems use PCMs for their thermal management.
4. PCMs are also used in Textile industries in clothing
5. Various PCMs are used in Medical applications like transportation of blood, operating tables, hot-cold therapies, treatment of asphyxia, where the temperature is to be kept constant
6. It is used to protect the high-value equipment in the shelters in tropical regions by keeping the indoor air temperature below the maximum permissible limit, thereby reducing the use of diesel generators.
7. Its medical applications include transportation of blood, operating tables, hot-cold therapies, treatment of birth asphyxia.

1.5 Literature Review:

For the past few years, thermal management of electronic components using PCM is in vogue. During phase change, the materials undergo a very small volume change and they also possess a large latent heat of fusion. They have a large number of desirable characteristics. The only concern found in almost all PCMs is their low thermal conductivity. Thus numerous studies have been conducted to enhance their thermal conductivity using different kinds of TCEs (Thermal Conductivity Enhancers). Metallic fins, foams, nanoparticles are the different kinds of TCEs. Several different fin configurations have been previously studied to determine their impact on the thermal conductivity of PCM.

S.F. Hosseinizadeh et al. [5] studied the performance of PCM based heat sink with different arrangements of internal fins. They determined the effect of fins by varying fin dimensions in various cases. In the first case the height of the internal fins was varied. In the second case the thickness of fins was varied. In the third case, the number of plate fins was varied. In all the three cases the PCM used was Rubitherm RT-80 and the fins used were plate fins. The results in the first case showed that as the fin height increases the thermal performance improves. The results in the second case show only a slight improvement in thermal performance as the thickness of the fins is increased. For the third case as the number of plate fins increase the thermal performance improves to a great extent.

Baby et al. [2] investigated the effect of PCM based finned heat sinks on its thermal performance experimentally. A rectangular matrix of 9X8 small pin fin of square cross-section is used to demonstrate the effect of fins. The PCM used was n-eicosane and the fins used in this study were pin fins. The results indicated an enhancement factor of 18 in the operation time for a pin fin heat sink as compared to the heat sink with no fins for a set point temperature of 45℃ and a power of 7W.

Saad Mahmoud et al. [7] investigate the effect of inserts configurations and PCM type on the thermal performance of PCM based heat sinks. The types of heat sinks they considered were parallel fin type, crossed fin type and honeycomb structure. During the heating phase 6 cavity and 36 cavity fins are standout performers followed by honeycomb structure. Whereas during the cooling phase, honeycomb structure was the best performer. Hence honeycomb structure was the best choice among them also considering its light weight and ease of manufacturing. The PCMs considered in this investigation are PCM-HS29P, PCM-HS34P, PCM-OM37P, PCM-OM46P, PCM-HS58P and Rubitherm RT-42. It is found that PCMS with lower melting points produced lower heat sink operating temperatures for longer durations than that of the paraffin wax.

Kozak et al. [6] investigated the performance of hybrid PCM-air heat sink experimentally. The base of the heat sink consisted of 14 compartments for PCM while the top surface consisted of extended fins to assist in cooling. PCM used in this investigation is 96%eicosane (C20H42). A fan is installed above the extended surfaces for better circulation of air. It is found that at 6 minutes after the process of cooling starts at 300W, the temperature drops are 11.7 and 8.2 centigrade and the base temperatures are 47.4 C and 49.4 C for the cases with and without the fan operating, respectively.

Hafiz Ali et al. [3] investigates the thermal performance of n-eicosane based circular pin-fin heat sinks for passive cooling of electronic devices. Enhancement ratios for various PCM-volume fractions are calculated to illustrate thermal performance for passive cooling. Three different diameters (2mm, 3mm, and 4mm) of circular pin fins were considered for the study. 3 mm diameter fins was found to be the best among all the different sized fins considered. The enhancement ratios of 4.78 and 1.90 against 2.0 kW/ m2 and 1.6 kW/ m2 heat densities respectively were obtained for 3 mm thick pin-fin heat sink. All the three pin fin heat sinks performed better than heat sink with no fins.

Santosh et al. [1] investigated experimentally the performance of hybrid cooling system during power surge operation for three different PCMs: Eicosane, 1-Hexadecanol, and Paraffin. Both active and passive cooling methods are taken into consideration. During power surge the heat gets considerably high. After melting, the PCM gets superheated and hence temperature rises, as hybrid heat sinks are used which provide enough space for better circulation of air, the peak temperature is reduced. It is concluded that for low power level hybrid PCM-based heat sink is better than conventional air based heat sink and for high power level that falls in the sensible heating region its performance deteriorates.

Chenzhen Ji et al. [4] conducted Numerical Simulation on PCM melting enhancement with double-fin length arrangements in a rectangular enclosure induced by natural convection. The PCM used was Rubitherm RT 42. Three cases were considered. In the first case the upper fin was shorter and lower fin was longer. In the second case both the fins were equal in length. In the third case the upper fin was longer in length than the lower fin. Among all the three cases the first case with short upper fin and long lower fin performed the best followed by the second and third cases respectively. For a ratio of 0.25 in the first case, the melting time was saved by 25% than the equal fin length scheme.

1.6 Objectives

The current investigation focuses on the use of various arrangements of crossed fins as TCE for a heat sink filled with Paraffin wax as the PCM. The various arrangements considered for comparison are heat sink with no fins, with 2×2 fins, with 3×3 fins and with 4×4 fins. The dimensions of the heat sink are 100mm×100mm×25mm. A heat plate is incorporated under a heat sink providing three different heat fluxes (1000 W/m^2, 1500 W/m^2, and 2000 W/m2). Initially keeping the heat flux constant the effect of different arrangements is studied for all three heat fluxes and is then compared. Then by keeping the arrangement constant, the effect of different heat fluxes is studied and then compared for all the four arrangements.

The specific objectives are as follows:

- To determine an optimum number of crossed fins in the heat sink assembly.
- Development of a numerical scheme to study the effect of different fin configurations on temperature distributions, melt fraction profiles, spatial temperature distributions and velocity contours for varied range of input heat fluxes.
- Compare the thermal performance of various heat sink assemblies, each with same mass and same amount of PCM.
- Development of a test facility to study the thermal performance of various heat sink assemblies.

Chapter 2

Numerical analysis

2.1 Mathematical modeling

2.1.1 *Problem model*

The PCM-based thermal energy storage (TES) system is simplified to a three-dimensional geometric model for the numerical simulation. The heat sink and the internal crossed fins are made up of Aluminium. The thickness of the walls of the heat sink is t_w=2mm for all cases. The overall mass of the heat sink is kept constant by carefully adjusting the thickness of the internal fins. The thickness of the fins in 2×2, 3×3 and 4×4 configurations is kept as 3mm, 1.5 mm and 1 mm respectively. The dimensions of all the heat sinks used are 100mm×100mm with a height of 25mm. For 2×2 crossed fins configuration, the distance between the wall of the heat sink and the wall of the internal fin is d=46.5mm in both horizontal and vertical directions. For 3×3 crossed fins configuration, the distance between the wall of the heat sink and the wall of the internal fin is d=31mm in both horizontal and vertical directions. For 4×4crossed fins configuration, the distance between the wall of the heat sink and the wall of the internal fin is d_1=23.25mm in both horizontal and vertical directions as shown in Fig 1. A heat sink with no fins is also considered for comparison. Except the bottom surface all other surfaces are insulated. A constant heat flux is given by a heater through the bottom surface. The three different heat fluxes considered in this study are: 1000 W/m^2, 1500 W/m^2 and 2000 W/m^2.

The PCM employed for this study is Paraffin wax. The thermo-physical properties of the PCM, with a melting temperature of 58 ℃ are described in Table 1, where the properties of aluminium are also presented together. The amount of PCM is kept same in all the cases. The PCM is filled in all the cavities in the heat sinks.

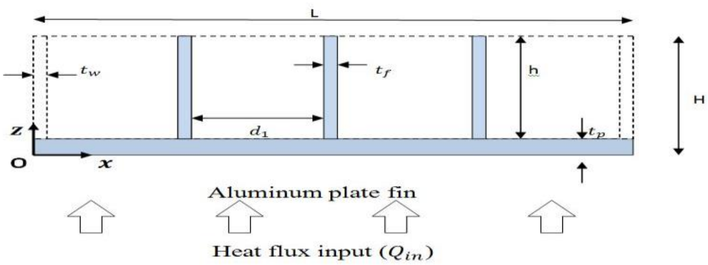


Fig 2: Numerical configuration of PCM enclosure with a constant heat flux input from the bottom surface

2.1.2 *Scheme of crossed fin heat sink configurations*

To enhance the melting rate of PCM crossed fins are used as Thermal Conductivity Enhancers. As the number of crossed fins increase, the melting rate tends to increase. The comparison of melting time is carried out to determine the optimum number of fins required. Heat transfer primarily occurs through natural convection. In cases 1 to 4, the number of crossed fins increases from 0 to 4. In each case the mass of heat sink is kept the same. The amount of PCM in each case is also the same. The fins and the heat sinks are made up of Aluminium. The fin thickness is varied in all the cases to negate the effect of any additional mass of the fins. All the four cases are tested for 3 different heat fluxes: 1000, 1500 and 2000 to observe their effects on the heat sinks.

2.1.3 *Governing Equations*

In this study, the enthalpy-porosity approach is employed to simulate the solid-liquid phase change during the PCM melting process. In this technique, the whole computational domain is considered as a porous zone, and the porosity of each cell is characterized by the liquid fraction γ varying from 0 to 1. The necessary assumptions are made for the numerical model development:

(1) Three-dimensional and unsteady (transient) state;

(2) Laminar, Newtonian and incompressible flow of liquid PCM motions;

(3) Constant thermal-physical properties such as specific heat, thermal conductivity.

(4) PCM volume expansion after melting is not accounted;

(5) Radiation heat transfer is neglected.

To evaluate the effect of natural convection on PCM melting, the Boussinesq approximation is introduced, which is valid for the density variation of buoyancy force:

$$\rho = \frac{\rho_l}{\beta(T - T_l) + 1} \quad (1)$$

Where, ρ_l *is the* density of the liquid PCM,

T_l is the melting temperature and

β is the thermal expansion coefficient.

With above methods and assumptions, the conservation equations for the PCM-based TES system are given as:

Continuity equation: $$\frac{\partial\rho}{\partial t} + \nabla.(\rho\vec{u}) = 0 \quad (2)$$

Momentum equation: $$\frac{\partial}{\partial t}(\rho\vec{u}) + \nabla.(\rho\overrightarrow{u}\,\vec{u}) = \mu\nabla^2\vec{u} - \nabla p + \rho\overrightarrow{g} + \overrightarrow{S} \quad (3)$$

Energy equation: $$\frac{\partial}{\partial t}(\rho H) + \nabla.(\rho\vec{u}H) = \nabla.(k\nabla T) \quad (4)$$

The source term $\overrightarrow{S}$ in the momentum equation takes the following form:

$$\overrightarrow{S}=A_{mush}\left(\frac{(1-\gamma)^2}{\gamma^3+\varepsilon}\right)\bar{u}$$

Where A_{mush}, a mushy zone constant, reflects the behaviour of PCM melting and is set at 10^5 at this study. ε=0:001 is a small constant and introduced to avoid division by zero. γ is the liquid fraction to characterize the phase change according to the temperature:

If $T<T_s$, $\gamma=0$

If $T_s<T<T_l$ $\gamma=\frac{T-T_l}{T_l-T_s}$

If $T_l<T$ $\gamma=1$

The enthalpy H in the energy equation is computed as the sum of the sensible and latent enthalpy:

$$H=h_{ref}+H_{sen}+H_{lat}$$

Where h_{ref} is the reference enthalpy at the reference temperature T_{ref};

$H_{sen}= \int_{T_{ref}}^{T} C_p\,\Delta T$ is the sensible enthalpy, and latent enthalpy $H_{lat}= \gamma L_h$ changes between zero (for a solid) and L_h (for a liquid) with the liquid fraction γ that varies from 0 to1.

Table 1: Properties

Material	Density kg/m^3	Thermal Conductivity W/m-K	Specific Heat J/kg-K	Heat of Fusion J/kg	Solidification/ Melting Temperature (K)	Dynamic Viscosity Pa-s	Thermal Expansion Coefficient (/K)
PCM	900	0.21	2800	193200	331/335	0.0235	0.0001
Aluminium	2719	202.4	871	-	-	-	-

2.1.4 *Initial and Boundary Conditions:*

The following initial and boundary conditions are used in this study:

1. Initial condition:

$$t = 0, \quad T(0) = T_i = 30°\text{C} \qquad \bar{u}(0) = \bar{u}_i = 0$$

2. Heat flux input at the bottom surface of the container

$$-k\frac{\partial T}{\partial z}\Big|_{\substack{x=0-100mm \\ y=0-100mm \\ z=0}} = q''_{in}$$

3. Insulation boundary conditions at the side walls of the container:

$$-k\frac{\partial T}{\partial x}\Big|_{\substack{x=0 \\ y=0-100mm \\ z=0-25mm}} = 0\,; \qquad -k\frac{\partial T}{\partial x}\Big|_{\substack{x=100mm \\ y=0-100mm \\ z=0-25mm}} = 0$$

$$-k\frac{\partial T}{\partial y}\Big|_{\substack{x=0-100mm \\ y=0 \\ z=0-25mm}} = 0\,; \qquad -k\frac{\partial T}{\partial y}\Big|_{\substack{x=0-100mm \\ y=100mm \\ z=0-25mm}} = 0$$

4. Insulation boundary conditions at the top surface of the container:

$$-k\frac{\partial T}{\partial z}\Big|_{\substack{x=0-100mm \\ y=0-100mm \\ z=25mm}} = 0$$

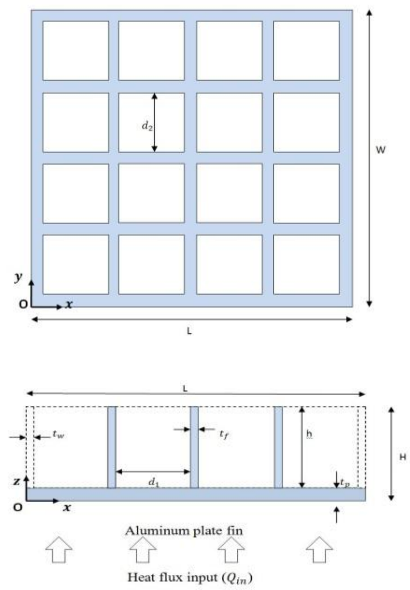
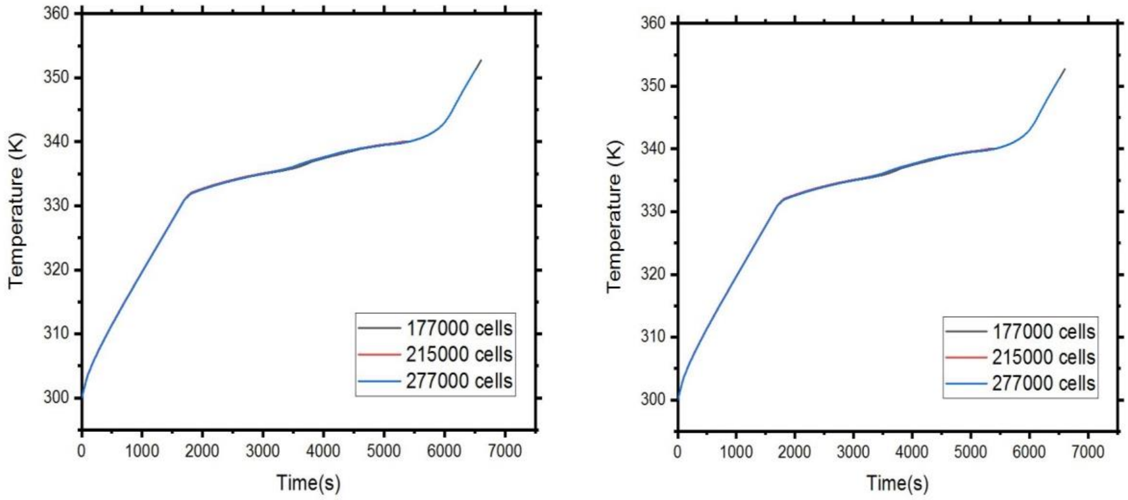


Fig 3: Schematic of heat sink

2.2 **Numerical Solution**

The finite volume method (FVM) is employed to solve the mass, momentum and energy conservation equations by ANSYS Fluent. The coupling between pressure and velocity is conducted by the well-known SIMPLE algorithm and the STANDARD scheme is selected for pressure correction equations. The momentum and energy equations are discreted by the second-order upwind scheme. The convergence is checked at each time step with the criterion that the scaled residuals are less than $10^{-5}$for the continuity equation, $10^{-5}$for the momentum equation and 10^{-7} for the energy equation.

The figures 4(a) and 4(b) show the time step and grid size independence studies conducted in the study to avoid their effects on numerical accuracy. Three different time steps were chosen for the study (0.5s, 0.7s, 1s). Three different mesh sizes were tested with 177000, 215000 and 277000 cells. All the meshes are generated in quadrilateral cells The mesh sizes did not have a large impact on temperature distribution. Hence a mesh size of 215000 was considered for this numerical study. Time step of size 0.5 s performed better than both 0.7s and 1s and hence it was used.



(a) (b)

Fig 4: (a) Independence analysis of time step size at 0.5, 0.7 and 1s with cell number about 215000

(b) Mesh size independence study with the cell numbers increasing from 177000, 215000 and 277000 when the time step is set at 0.5s

Chapter 3

Numerical Results and Discussion

3.1 Progression of melt front and its variation with time

Figure 5 shows the liquid fraction contours for 3×3 crossed fin heat sink at various time steps obtained using simulation. It depicts the nature of propagation of the solid-liquid interface. The melting starts at t=1200s.

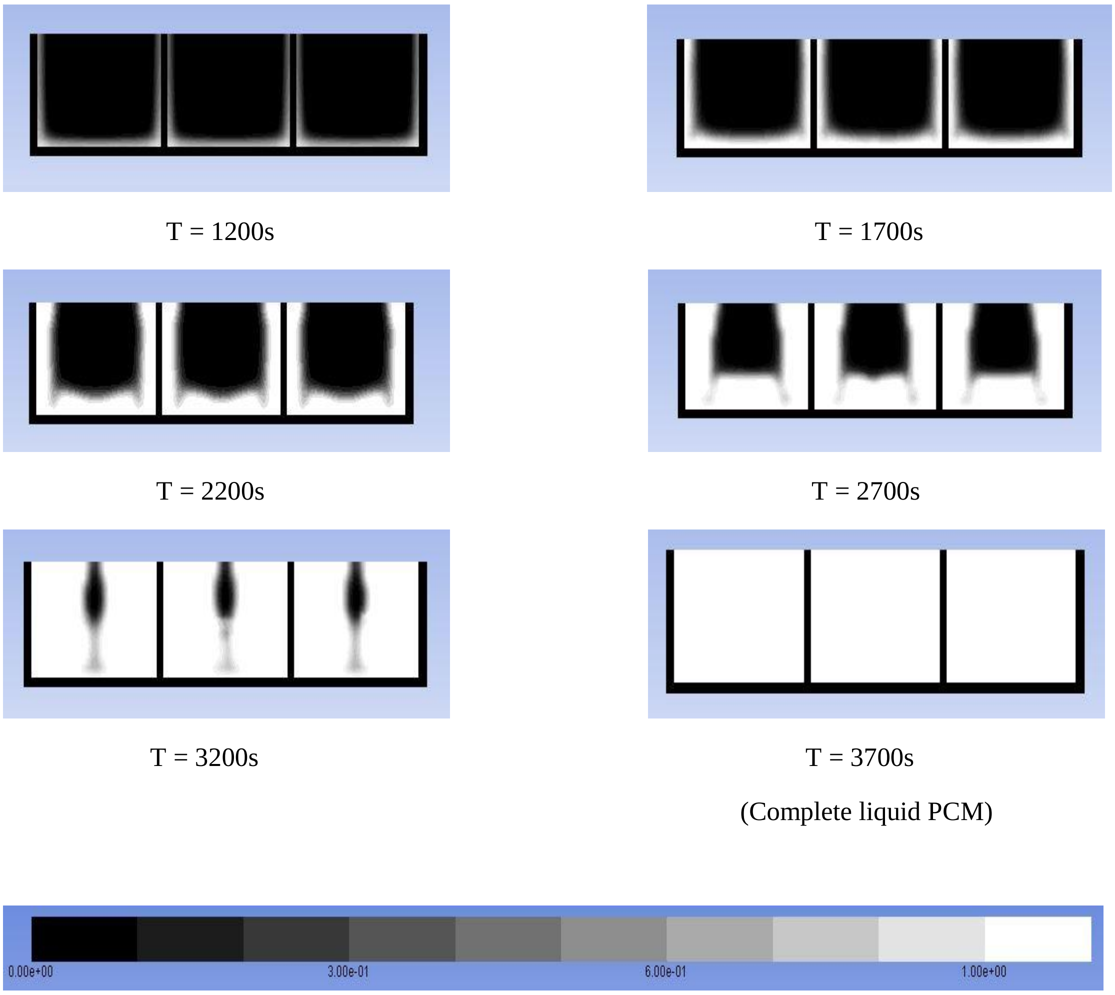
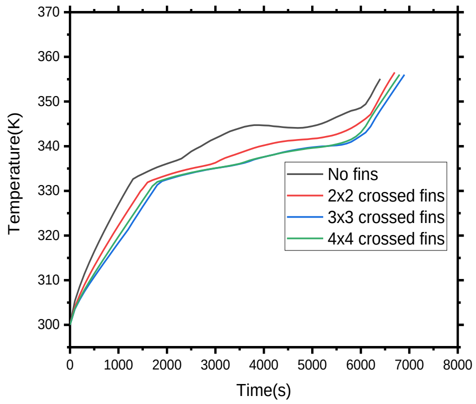


Fig 5: Progression of melt front of PCM for 3×3 crossed fin heat sink

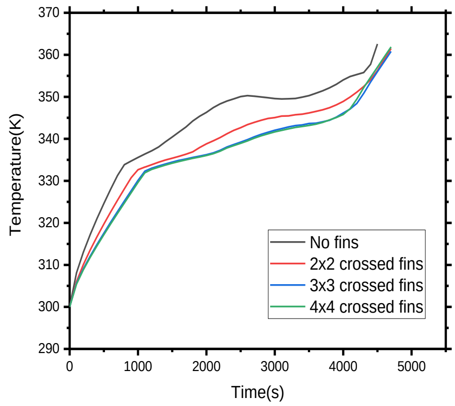
It is clear from above figure that PCM starts melting from the proximity of the fins and heat sink boundary. The figure shows the variation of solid-liquid interface with time. Initially melting is aided by conduction but gradually convection takes over.

3.2 Effect of heat sink configuration on its temperature

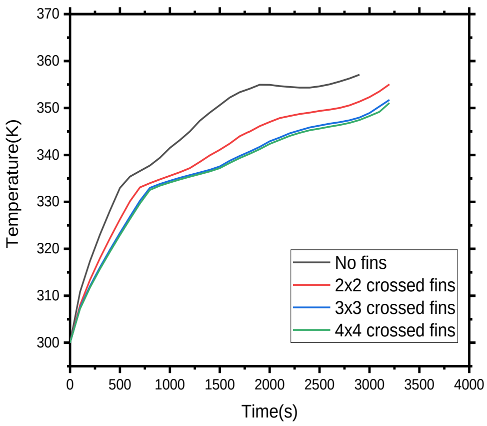
The figure shows the temperature variation during the heating phase for all the heat sink designs used at various input levels (1000 W/m^2, 1500 W/m^2 and 2000 W/m^2) using paraffin wax PCM. It shows that the presence of fins contributes to the fact that the overall temperature variations of the heat sinks with fins are far less than without fins.



(a)



(b)



(c)

Fig 6: Temperature profiles of crossed fin heat sinks at various heat fluxes

(a) 1000 W/m^2 (b) 1500 W/m^2 (c) 2000 W/m^2

Since mass of the heat sink is kept constant, the specific heat of all the heat sinks is same. Also the PCM amount is constant in all the heat sinks, hence total latent heat storage capacity is same. As the number of fins increases, rate of rise in temperature decreases. The 3×3 crossed fins and 4×4 crossed fins show comparable thermal performance and are superior to other heat sinks in terms of lower heat sink temperatures.

3.3 Set point temperature

Many electronic components tend to fail above 60°C. The figures 7(a) and (b) compare the heat sinks based on time taken by them to reach a set point temperature of 65°C and 75°C.

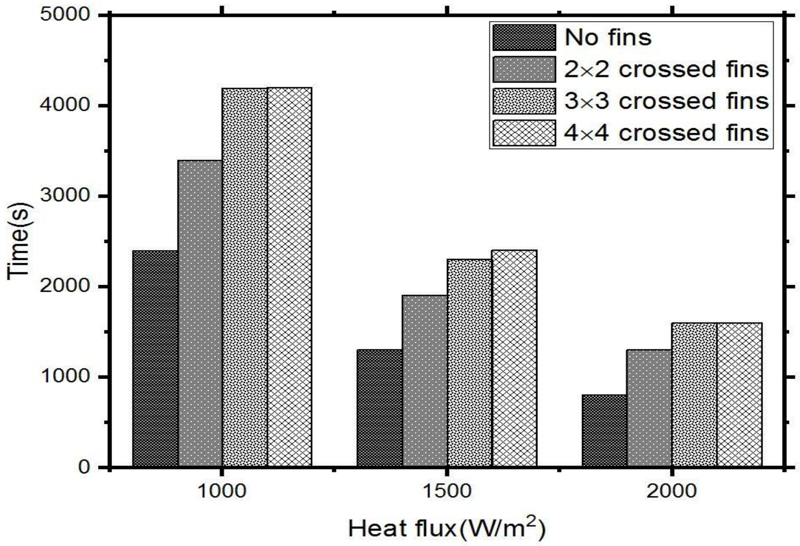


Fig 7(a): Time to reach 65°C (338K)

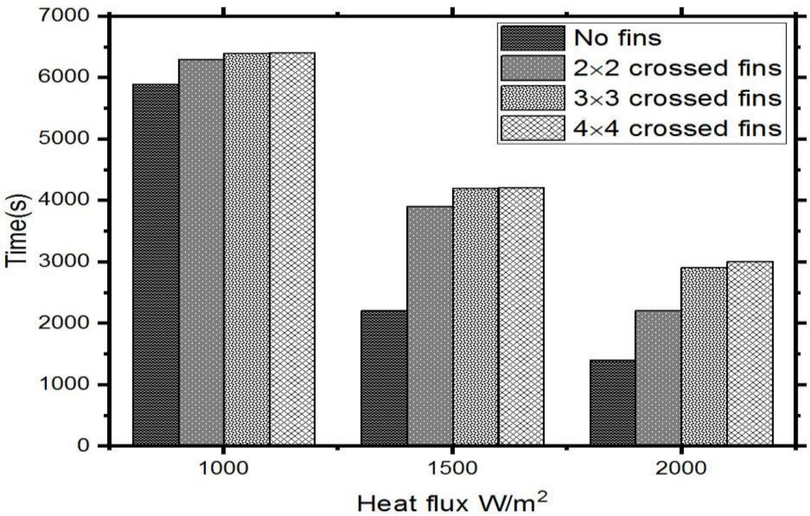


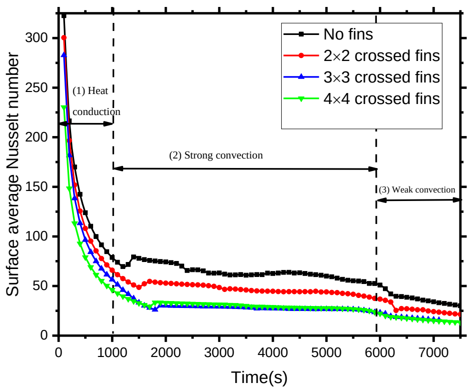
Fig 7(b): Time to reach 75°C (348K)

To reach a set-point temperature of 65°C, heat sink without fins takes the least time i.e. 2400s at 1000 W/m^2. While 2×2 crossed fins takes 29.41% more time than heat sink without fin, 3×3 crossed fins takes 19.04% more time than 2×2 crossed fins. 3×3 crossed fins and 4×4 crossed fins take comparable time, and they both perform superior than the other two heat sinks.

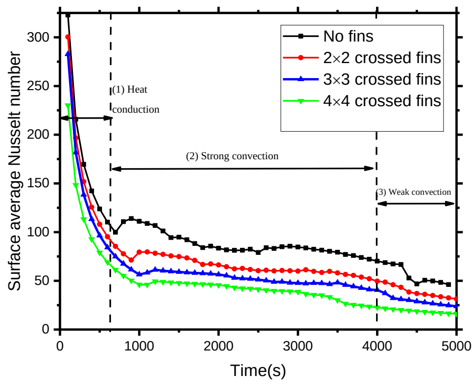
Similar is the progression when time to reach 75°C is considered. Again heat sink without fins takes the least time i.e. 5900s at 1000 W/m^2. While 2×2 crossed fins takes 6.35% more time than heat sink without fin, 3×3 crossed fins takes 1.56% more time than 2×2 crossed fins. Here too, 3×3 crossed fins and 4×4 crossed fins take comparable time to reach 75°C.

3.4 Surface average Nusselt number

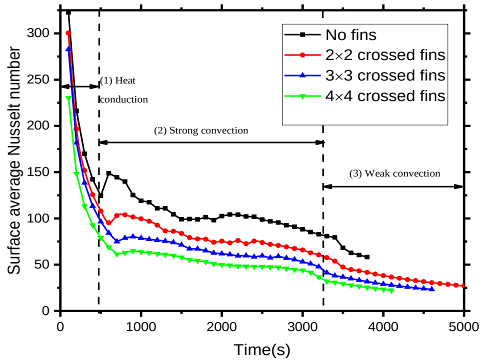
The heat transfer mechanisms that govern the melting process can be characterized using Nusselt number. The following figures show the variation of Nusselt number with time for all the fin configurations at three different heat fluxes. Based on the slope of the Nusselt number curve, it can be three divided into three different region of heat transfer mechanisms.



(a)



(b)



(c)

Fig 8: Effect of different fin configurations on Surface-averaged Nusselt number at various heat fluxes (a) 1000 W/m^2 (b) 1500 W/m^2 (c) 2000 W/m^2

Stage 1 heat conduction regime: The PCM starts melting initially due to the heat conduction from the bottom surface. It can be seen that Nusselt numbers starts with seemingly very large value and then drops very quickly. The reason for this large Nusselt number is the small thermal resistance of the very thin liquid layer at the startup time. As the melting proceeds, the thickness of liquid layer increases forcing the heat conduction resistance to increase. Hence the Nusselt number sharply decreases in this region. Furthermore, it is interesting to note that heat sink with 4×4 crossed fin configuration shows most steep decrease due to availability of more surface area compared to others.

Stage 2 strong convection regime: Nusselt number is prone to decrease at a slower rate in this region. Due to increase in melting and liquid fraction, heat transfer mechanism transforms and strong convection dominates. Though there is an increase in convection due to increase in fluid motions, conduction resistance still tends to increase. Hence the trend still decreases though the rate is much slower. It can be observed that heat sink with 4×4 crossed fin configuration shows slowest decline than others and closely followed by 3×3 crossed fin configuration, making them the most effective of all.

Stage 3 weak convection regime: In this region the Nusselt number decreases at a faster rate than the previous region but slower than the heat conduction region. Heat transfer is through weak convection. Due to the decreasing length of solid-liquid interface and weakening of the convection currents, convection rate slows down and hence the weak convection.

Chapter 4

Experimental Facility

4.1 Design of heat sinks

Four heat sink configurations were designed keeping the mass of the heat sink to be constant. Hence thickness of the fins was reduced to accommodate any further increase in number of fins. Heat sinks were made of Aluminum. The four heat sinks are as follows (a) 2×2 crossed fin configuration (b) 3×3 crossed fin configuration (c) 4×4 crossed fin configuration (d) heat sink without fin.

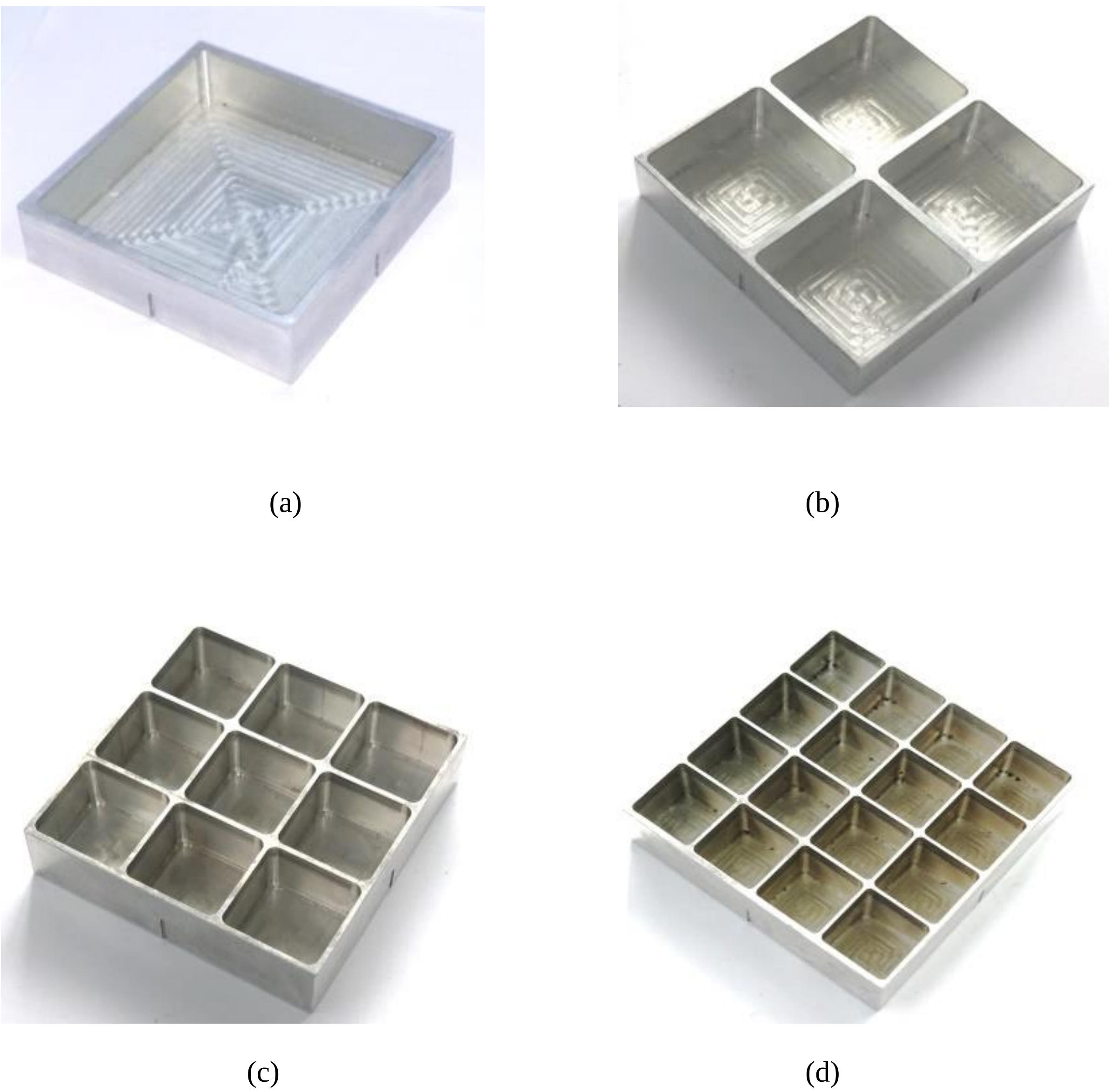


Fig 9: Heat sink models. (a) Without fin. (b) 2×2 crossed fin configuration (c) 3×3 crossed fin configuration (d) 4×4 crossed fin configuration

Table 2: Heat sink Dimensions

Heat sinks	**Dimensions of heat sink (L×W×H) (mm)**	**Number of cavities N**	**Fin Thickness (t_f)(mm)**	**Dimension of each cavity $(d_1 \times d_2$×h) (mm)**
Single cavity (No fins)	100 × 100 × 25	1	---	93 × 93 × 23
2×2 fins	100 × 100 × 25	4	3	46.5× 46.5 × 23
3×3 fins	100 × 100 × 25	9	1.5	31 × 31 × 23
4×4 fins	100 × 100 × 25	16	1	23.25 × 23.25 × 23

Figure 10 shows the detailed view of the heat sinks. All the different views and dimensions are clear from these diagrams.

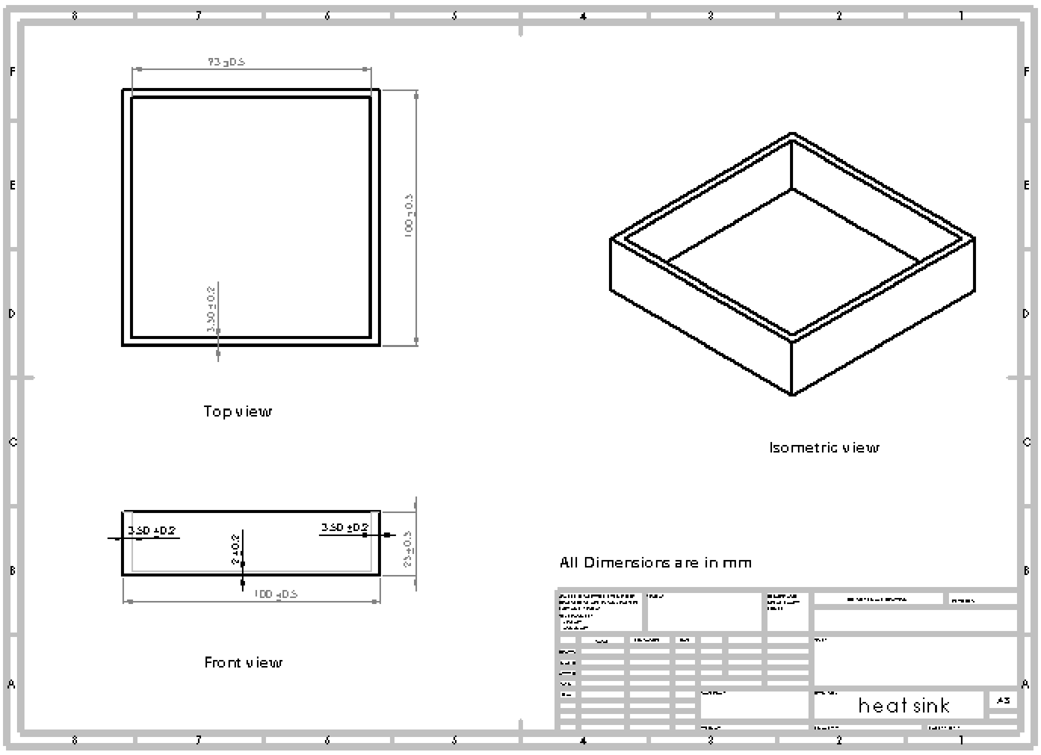


Fig 10(a): Detailed view of heat sink without fins

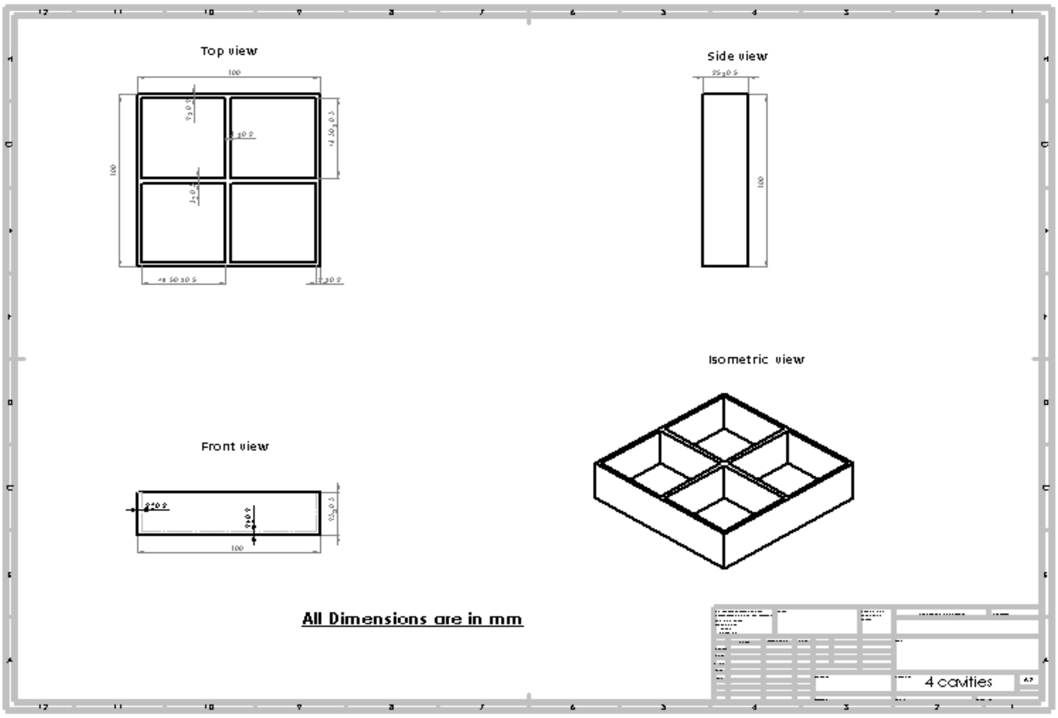


Fig 10(b): Detailed view of 2×2 crossed fin configuration

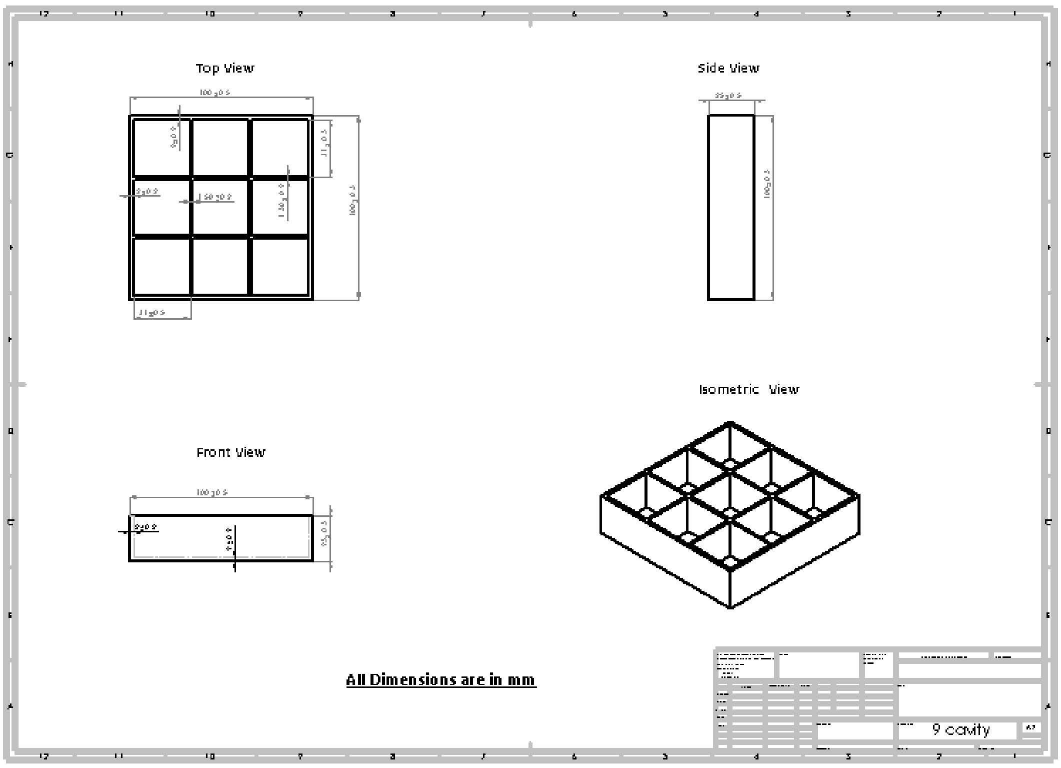


Fig 10(c): Detailed view of 3×3 crossed fin configuration

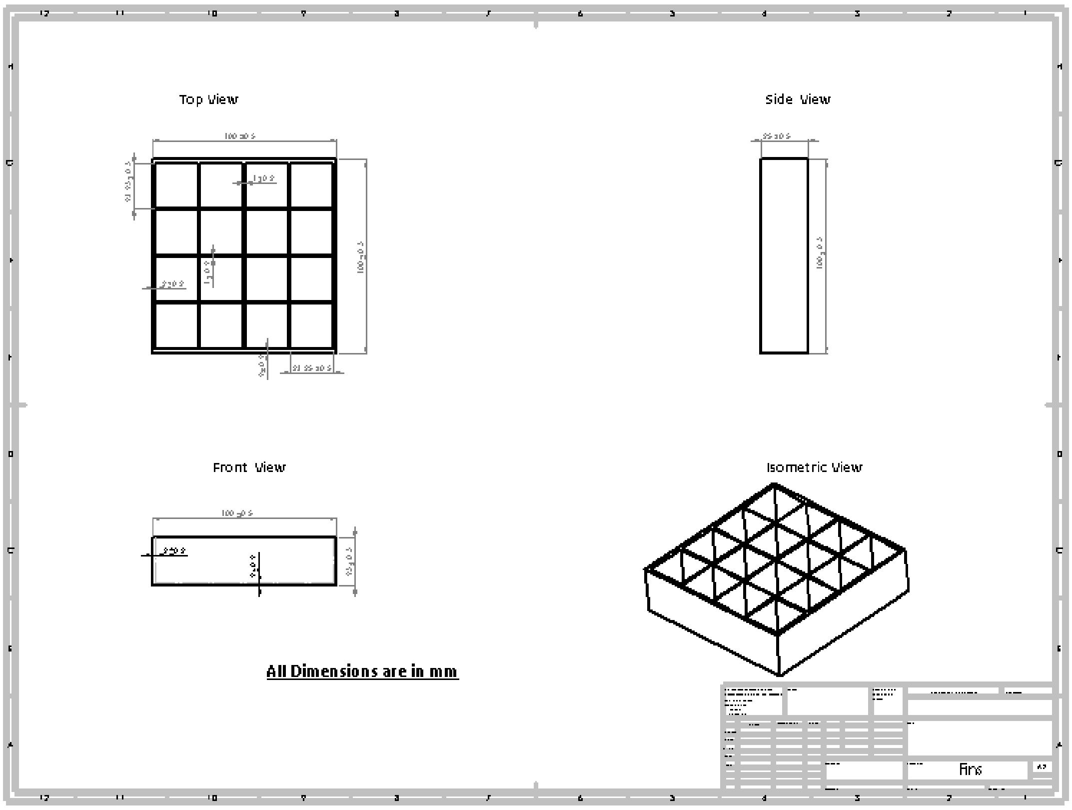


Fig 10(d): Detailed view of 4×4 crossed fin configuration

4.2 Location of thermocouples

Temperature measurements are made using K-type thermocouples. These thermocouples are fitted at various locations to record temperature. Three of these thermocouples are present in the center of the base of the heat sink named B1, B2 and B3. Three thermocouples on centers on three side walls are fitted named W1, W2 andW3 respectively. Twelve thermocouples, four on each side walls are fitted at heights of 5,10,15,20 mm respectively.

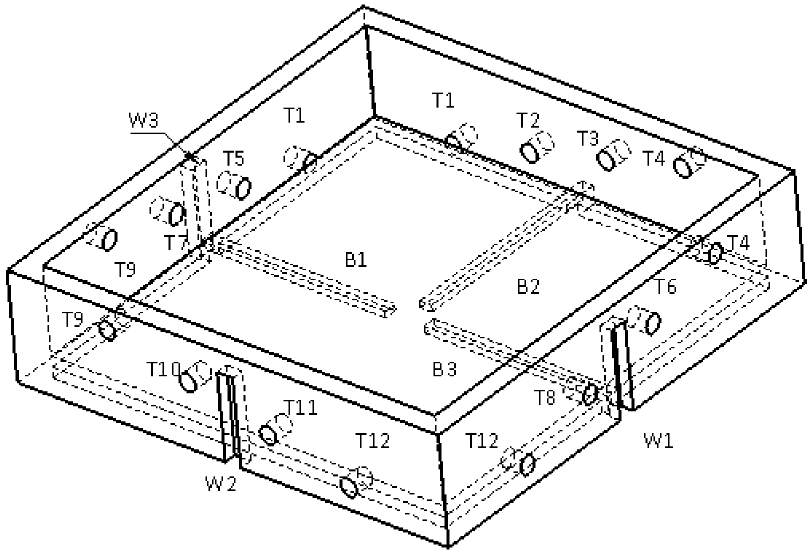


Fig 11: Location of thermocouples in the heat sink

Table 3: Position of thermocouples

Serial No.	Thermocouple	Position from base of heat sink (mm)	Position from respective side wall (mm)	Location
1	T_1	5	25	Wall 3
2	T_2	10	50	Wall 4
3	T_3	15	75	Wall 4
4	T_4	20	25	Wall 2
5	T_5	15	50	Wall 1
6	T_6	10	75	Wall 3
7	T_7	5	25	Wall 1
8	T_8	10	50	Wall 3
9	T_9	15	75	Wall 1
10	T_{10}	20	25	Wall 2
11	T_{11}	15	50	Wall 2
12	T_{12}	10	75	Wall 2
13	B_1 to B_3	-	45	Heat sink base
14	W_1 to W_3	-	50	Center of the three wall

4.3 Development of test facility

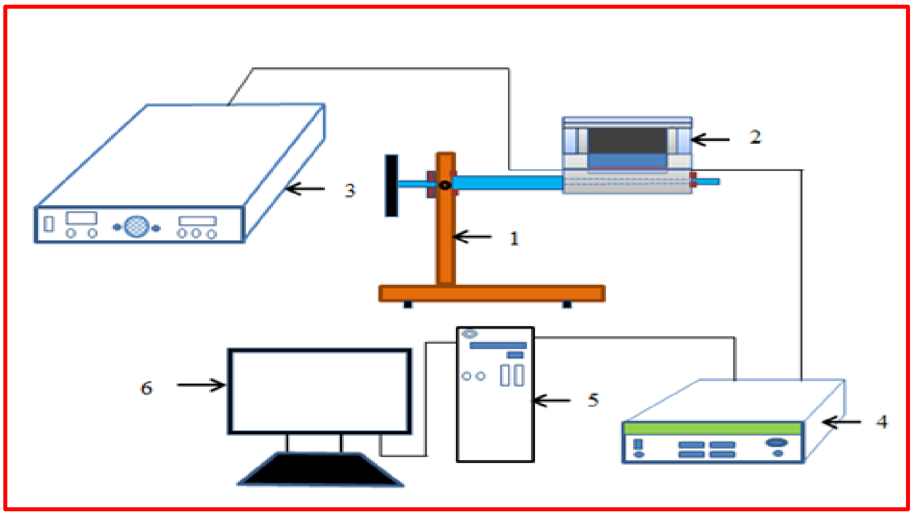


Fig 12: Schematic Diagram of test facility

The numerical representations are as follows:

1→ Support

2→ PCM filled heat sink assembly

3→ DC power source

4→ Data Acquisition System (DAS)

5→ CPU

6→ Desktop monitor

The following gives a photographic look of the test facility where the experiments were performed-:

Fig 13: Photographic view of test facility

The numerical representations in the above photograph are as follows:

1→ Heat sink made of aluminium

2→ Tracking mechanism

3→ Thermocouples (K-type)

4→ DC power source (Aplab L3260, 32V/60A, India)

5→ Data acquisition system (Agilent 34972A, USA)

6→ Digital Camera (Sony RX10M2)

7→ Camera stand

8→ Computer Desktop

9→ CPU

Table 4: List of components

Sr. no.	**Components**	**Description/ Utility**	**Specifications**	**Images**
1	Tempos TPA	To measure thermal conductivity of PCM	Meter Group USA, single needle sensor Accuracy: ±10 % W/m °C, Range 0.02-2 W/m°C	
2	Data Acquisition System	To record temperature data at a regular interval at various points inside the heat sink	Agilent-34972A 32 channels	
3	Variable DC source	Power supply to the heater to mimic the heat generation of electronic components	APlab L3260,32v/60A Voltage range 0-30 V, Current range 0-4 A	

4	Heater	To mimic the heat generation by electronic components	Sunrise product India, Power: 2-50W, Size: 100mm × 100mm × 4mm	
5	Phase Change Material (PCM)	Thermal management purpose	Sigma-Aldrich USA, Organic PCM: Paraffin wax, Melting point: 58°C-62°C	
6	K-type thermocouple	Temperature measurement	Temp range: -270°C to 1260°C	
7	Digital Camera	To study the position of solid-liquid interface during melting/solidification	Model: Sony RX10M2 Resolution: 640x480 Pixel size: 17 micron Sampling rate: 50fps	

The properties of the materials i.e. PCM (Paraffin wax) and Aluminum used in this experimental work are considered same as mentioned in Numerical study.

Chapter 5

Experimental Results and Discussion

5.1 Comparison between Numerical and Experimental Data

Comparison of Experimental results and Numerical results is done to verify the accuracy of numerical results. Figure 14 shows the 4×4 crossed fin heat sink and its schematic that is used for the comparison.

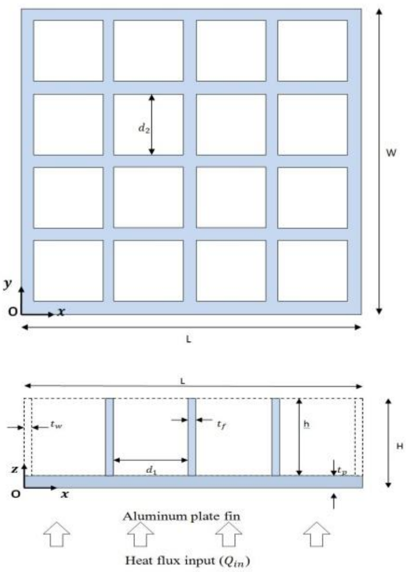


Fig 14: 4×4 crossed fin configuration and its schematic

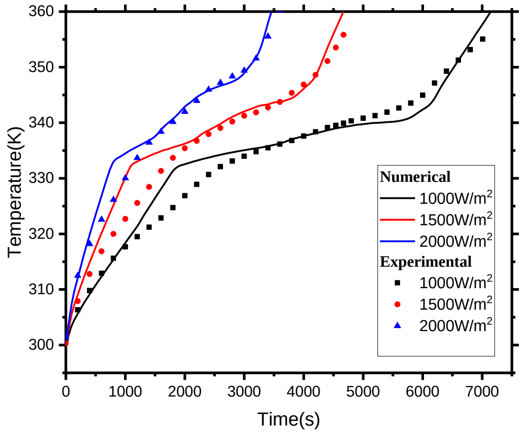


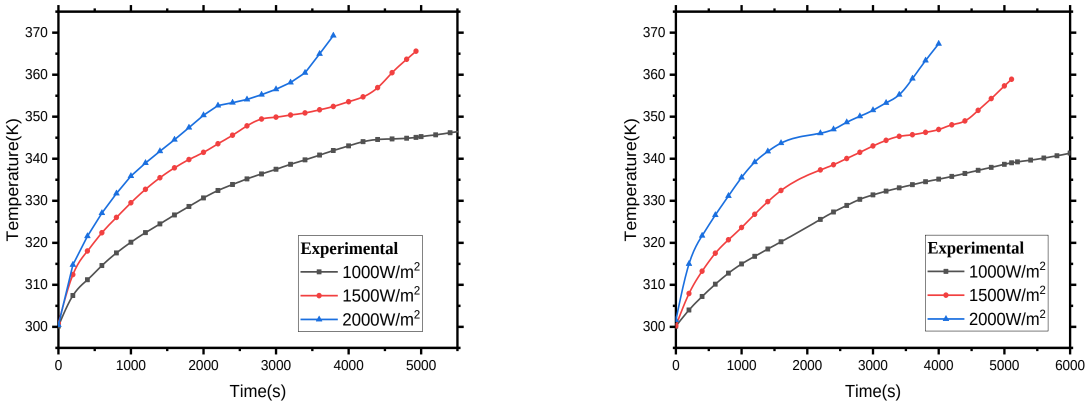
Fig 15: Comparison of Numerical and Experimental results

Figure 15 shows the comparison between the Numerical and Experimental results obtained for variation in temperature in 4×4 crossed fin configuration at three different heat fluxes. The error obtained in the Experimental approach was only ±2.11%. Thus it can be stated that the two approaches fairly agree with each other. The minor differences in the results can be due to the fact that thermo-physical properties for numerical study such as thermal conductivity, specific heat are kept constant. Also the volume change after melting was also neglected. Another reason could also be due to some human error during experiments. Nevertheless, owing to it's very less error, we can now establish that our results are fairly accurate.

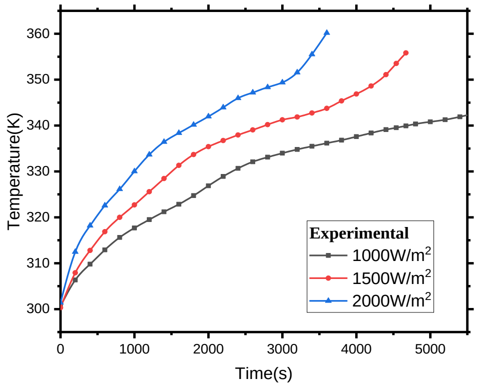
5.2 Experimental Results

5.2.1 Effect of heat flux

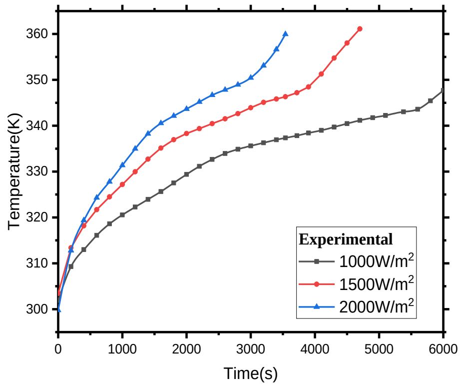
Figure 16 shows the effect of heat flux on the variation of temperature for four different heat sinks experimentally. The temperature considered is of the base of the heat sink.



(a) (b)



(c)



(d)

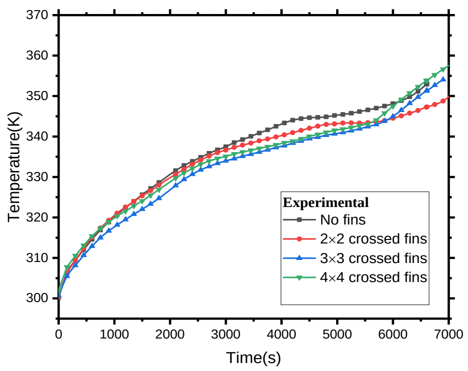
Fig 16: Effect of heat flux on temperature at different fin configurations

(a)No fins (b) 2×2 crossed fin (c) 3×3 crossed fin (d) 4×4 crossed fin

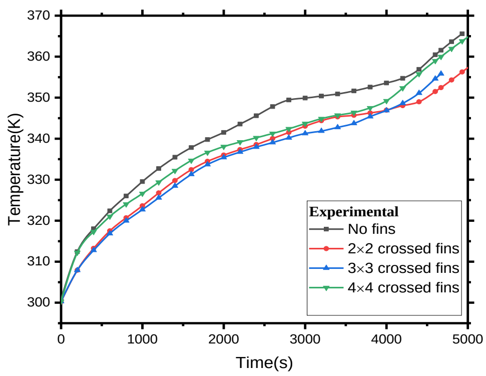
For all the heat sinks, the temperature increases as the heat flux increases as expected. As the heat flux increases, the time spent in the latent heat region reduces in all the cases.

5.2.1 Effect of fin configuration

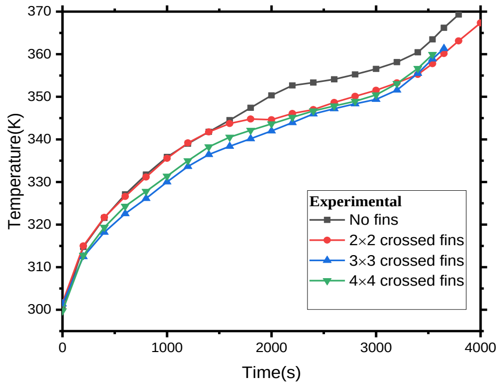
Figure 17 shows the variation of temperature obtained experimentally in three different cross finned heat sinks and an unfinned heat sink at various input heat fluxes (1000 W/m^2, 1500 W/m^2 and 2000 W/m^2). The results obtained were identical to the numerical results obtained for the variation of temperature in different configurations of heat sinks.



(a)



(b)



(c)

Fig 17: Effect of fin configurations on temperature at different heat flux

(a) 1000 W/m^2 (b) 1500 W/m^2 (c) 2000 W/m^2

For the experiments, the mass of the heat sink was kept similar in all the cases by compensating for the thickness of fins. The amount of PCM used was also kept the same in all cases. Due to this, the specific heat and the latent heat storage capacity was the same in all the cases.

The heat sink with no fins showed the largest rise in temperature followed by 2×2 fin configuration. The heat sink with 3×3 fin configuration showed almost the same rise in temperature as 4×4 fin configuration heat sink in all the cases.

5.2.3 Set Point Temperature (SPT)

The figures 7(a) and (b) compare the heat sinks based on time taken by them to reach a set point temperature of 65°C and 75°C. The temperatures are chosen the same like the numerical study for better comparison

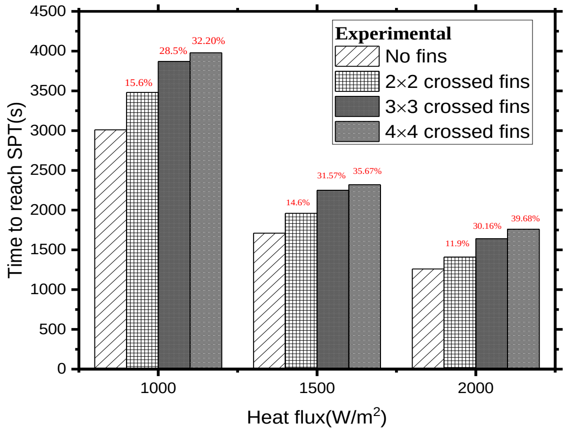


Fig 18(a): Time to reach 65°C (338K)

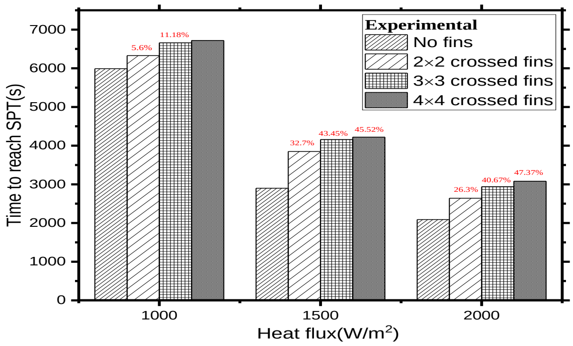


Fig 18(b): Time to reach 75°C (348K)

The above figure shows the time required to attain set point temperatures of 65°C and 75°C experimentally in all the four configurations at the three different heat fluxes. The temperatures chosen were the same as used in the numerical study to get a better understanding.

In both the cases, a similar pattern was observed. The heat sink with no fins took the least time to attain the SPT. The heat sink with 3×3 crossed fin configuration took almost the same time as the 4×4 fin configuration in all the cases.

To reach a SPT of 65°C, the time required by 4×4 crossed fin configuration is 35.67% higher than the unfinned heat sink while it is 31.57% higher in 3×3 crossed fin configuration than the unfinned heat sink for a power input of 1500 W/m^2

To reach a SPT of 75°C, the time required by 4×4 crossed fin configuration is the same as 3×3 crossed fin configuration and is 11.18% higher than the unfinned heat sink for a power input of 1000 W/m^2

Chapter 6

Conclusions

Passive cooling techniques have been used in this study. It is noted that fins provide better thermal performance than heat sink without fins. Both Numerical and Experimental investigations have been carried out. Performances of three different heat sinks were analyzed and then compared with the performance of heat sink without fins at three different heat fluxes i.e. 1000 W/m^2, 1500 W/m^2, 2000 W/m^2.The four heat sinks considered were 2×2 crossed fin configuration, 3×3 crossed fin configuration, 4×4 crossed fin configuration and heat sink without fin.

The key findings obtained from the present investigation are as follows:

1. The effect of three different crossed fin configurations was analyzed for different heat fluxes and then compared to heat sink with no fins.
2. As the heat flux increases PCM melts at a faster rate.
3. 4×4 crossed fin configuration takes almost same time as 3×3 crossed fin configuration.5.88% less time than 2×2 crossed fin and 8.57% less time than without fin heat sink.
4. The melting phase for 2×2 crossed fin begins earlier than both 3×3 crossed fin and 4×4 crossed fins for all three heat fluxes.
5. Latent heat time in without fin heat sink configuration was observed to be the largest followed by 2×2, 3×3, 4×4 fin configurations respectively in all three heat fluxes.
6. Time required to melt is the least for 4×4 crossed fins followed by 3×3 crossed fin , 2×2 crossed fin and without fin heat sink respectively.
7. Time taken to reach 65°C and 75°C is least for without fin heat sink configuration followed 2×2 crossed fins and is approximately same for 3×3, 4×4 crossed fin configuration.
8. Surface average Nusselt numbers of all the four heat sink configurations are compared and is concluded that heat conduction is dominant initially. After some time convection takes over.

9. The experimental results agree well with its Numerical counterpart. The maximum error is found to be ±2.11%.

10. 4×4 crossed fin configuration performs slightly better than 3×3 crossed fin configuration and much better than 2×2 crossed fin configuration and without fin heat sink.

Hence, it is recommended to use 3×3 crossed fin configuration due to its manufacturing ease and thermal performance at par with 4×4 crossed fin configuration.

6.2 Scope of future study

1. To study the effect of other Thermal Conductivity Enhancers (TCEs) on these heat sink configurations.
2. To increase the number of crossed fins and determine a much more optimum configuration.
3. To study the effect of different PCMs on these heat sink configurations.

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