Thermal Conductivity Enhancement of Copper Foam-Paraffin Phase Change Materials

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Abstract- Phase change materials (PCMs) play a crucial role in thermal energy storage systems due to their heat transport and storage capabilities. However, their low thermal conductivity limits the rate of energy storage and release. Incorporating copper metal foam into PCMs can significantly improve their thermal conductivity. This study investigates the thermal conductivity enhancement of a metal foam-paraffin composite compared to pure paraffin. The copper metal foam, known for its high thermal conductivity, effectively increases the heat transfer rate within the composite. Theoretical and experimental thermal conductivity measurements of the copper foam/PCM composite were conducted and compared. Results demonstrated that the composite's thermal conductivity reached 5.5 W/mK at 13 W, substantially higher than the 0.2 W/mK of pure PCM. Additionally, the copper/PCM composite reduced the temperature of the heat sink by 25-30%. This enhancement is attributed to the improved thermal pathways provided by the copper foam's structure, despite the inverse relationship between infiltration ratio and pore density.

Index Terms- Aluminium Heat Sink, Copper Metal Foam, Paraffin, Phase Change Material

I. INTRODUCTION

Efficient thermal management is crucial for electronic devices (EDs) to ensure optimal performance, reliability, and energy efficiency. Researchers worldwide are investigating analytical and experimental approaches to address the challenge of excess heat generation. Traditional active cooling methods, such as macro fans, have limitations due to their bulkiness, noise, and power consumption [1]. In contrast, passive cooling strategies using phase change materials (PCMs) have gained attention. PCMs offer excellent thermal properties, including high heat capacity, non-toxicity, and flexibility in composition and melting temperatures. They allow efficient thermal control without compromising reliability or cost-effectiveness [2-4]

Phase Change Materials (PCMs) also plays a vital role in various engineering applications including thermal energy storage (TES). Paraffin wax is commonly used as a phase change material (PCM) in solar energy storage systems [5-7]. Paraffin wax, a PCM, boasts high latent heat capacity, but its heat transfer efficiency is limited. Researchers explore enhancing PCMs using metal and its oxide [8-11], which improves thermal conductivity. Copper foam, being chemically inert and lightweight, offers a high surface area-to-volume ratio. The TES bridges the gap between renewable energy availability and demand, while PCMs and copper foam enhance heat storage efficiency.

In our study, copper foam was used to increase the thermal conductivity of the paraffin wax. An aluminium heat sink with a heater was used to study the thermal conductivity of the copper foam/PCM composite. The outcome showed improved heat transmission due to the copper foam. Further experiments will measure the thermal conductivity of the PCM combined with copper metal foam at various power levels. A comparison of thermal performance between pure paraffin, copper metal foam, and copper-paraffin wax composites will also be carried out.

II. LITERATURE REVIEW

Energy storage as sensible heat requires large volumes, while latent heat storage involves phase changes and is proportional to the latent heat of fusion and substance mass [12]. Latent heat offers advantages like maintaining uniform temperature and high energy density [1], making Phase Changing Materials (PCMs) suitable for waste heat recovery, solar energy, and cooling electronic devices [13]. PCMs can store 5-14 times more heat energy than conventional sensible storage systems [14, 15]. The high storage density of PCMs allows for the development of more compact and efficient thermal storage systems compared to traditional sensible heat storage methods [14]. However, PCMs often suffer from low thermal conductivity, which can limit their effectiveness [16]. Researcher focuses on enhancing heat transfer within PCM-based thermal storage devices to maximize their performance and develop economical and compact thermal energy storage systems [13]. Ideal PCMs should have high thermal conductivity, be non-toxic, non-corrosive, low-cost, and chemically inert [17-19].

Paraffin wax is a popular phase change material (PCM) for thermal energy storage, but its low thermal conductivity limits its efficiency [20, 21]. To address this issue, researchers have explored the addition of various nanoparticles and metallic foam to enhance thermal conductivity. Aluminium oxide (Al_2O_3) nanoparticles at 3 wt% improved thermal conductivity by 18.6% and thermal effusivity by 28.2% [21]. Another study found that Al_2O_3 nanoparticles at 1, 2, and 3 wt% increased thermal conductivity by 37.1%, 42.3%, and 60.32%, respectively [22]. Titanium dioxide (TiO_2) nanoparticles were also investigated, with a 5 wt% concentration resulting in a 10% increase in thermal conductivity at 15°C [23]. Also, several studies have explored the use of graphite-based materials to address this issue. Expanded graphite (EG) has been shown to increase thermal conductivity up to 6.5 times that of pure paraffin, with higher EG content resulting in greater enhancement [24]. Similarly, graphite powder composites with paraffin demonstrated reduced melting periods and improved thermal response [25]. Numerical investigations using graphite foam in latent heat storage exchangers revealed effective heat transfer rate improvements [26]. While metal foams generally outperform expanded graphite due to their interconnected structures, both materials can suppress natural convection in liquid PCMs [27].

Different experiments aimed to enhance thermal conductivity using metal foam and graphite in conjunction with paraffin wax and calcium chloride as the heat medium. The results indicated that incorporating open-cell metal foam (expanded graphite) significantly improved heat transfer, effectively doubling the thermal conductivity of paraffin wax. The final measurements demonstrated that the addition of graphite substantially increased the overall heat transfer efficiency [28]. Other Studies have demonstrated that metal foams can double the overall heat transfer rate during melting compared to pure PCMs [29]. Paraffin and metal foams are the most frequently used PCM and porous support, respectively, in the research by [30]. Experimental findings highlight nickel foam's effectiveness in maintaining optimal battery temperatures, and proved cost-effectiveness compared to other foams makes it a favourable choice for battery thermal management [5].

Additive manufacturing has enabled the fabrication of porous metal structures with controlled geometry, leading to improved thermal performance, such as a 38% reduction in total melting time [31]. However, porous materials can suppress natural convection in the liquid phase, particularly for low-viscosity PCMs, resulting in varying heat transfer performance across different regimes [27]. Future research should focus on bridging the gap between phase change heat transfer and material preparation [30].

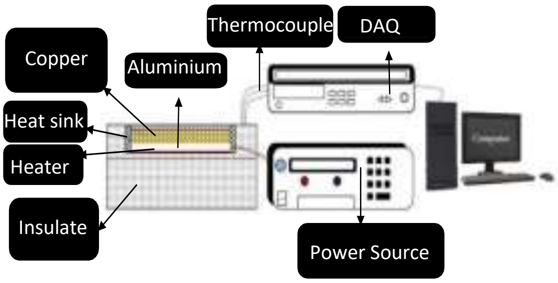
The effective thermal conductivity of open-cell metal foams impregnated with paraffin for latent heat storage has been extensively studied. Experimental and numerical investigations have shown that metal foams significantly enhance the thermal conductivity of paraffin-based composites [32, 33]. The effective thermal conductivity increases as porosity decreases, with the thermal conductivity of the metal foam having a major impact [32]. Pore size, however, has minimal effect on the effective thermal conductivity due to negligible interstitial heat transfer between the foam and paraffin under typical thermal boundary conditions [19]. Numerical models, including pore-scale investigations, have been developed to accurately predict the effective thermal conductivity of these composites, showing good agreement with experimental results [19, 34]. These studies provide valuable data and insights for engineering applications, particularly in thermal energy storage and management systems [33, 34].

This study examines the thermal performance of copper foam/PCM composites using an aluminium heat sink and heater setup, assessing how copper foam improves paraffin wax's heat transmission and overall thermal conductivity at various power levels. Copper foam, being highly conductive, chemically inert, and low in bulk density, is effective for improving PCM performance, with porosity directly proportional to thermal conductivity. A comparative analysis of pure paraffin, copper foam, and copper-paraffin composites will be conducted. The investigation addresses previously overlooked issues in thermal management of microelectronics, offering flexible research opportunities to improve heat dissipation in space-constrained environments and aiding researchers in identifying and employing new design parameters.

III. EXPERIMENTAL SETUP

The experimental method involved evaluating various heat sink configurations with different foam types, design parameters, and power inputs to optimize cooling of advanced electronic packages. The setup included a heat sink, power supply, data logger, plate heater, insulation polyethylene sheet, and thermocouples. Custom-designed heat sink geometries were tested under different load conditions, with temperatures recorded at multiple points using a data acquisition system to analyze thermal performance. The heat sink, fabricated locally, featured a cavity for the heater and was insulated with a high thermal resistance polyethylene sheet. Temperature data was collected at 60-second intervals using thermocouples connected to a data logger and refined as needed. The detailed experimental setup and the flow diagram is depicted in Figure 1.

(a)



(b)

Figure 1: (a) Experimental setup (b) Flow diagram of experiment

The setup includes a custom-designed aluminum heat sink, insulation polyethylene sheet (1 cm thick), a data logger, thermocouples, and a DC power supply. The heat sink is insulated to prevent heat transfer to or from the surroundings. A 100mm x 100mm silicone rubber plate heater is adhered to the sink base to simulate heat input, facilitating rapid temperature changes in confined areas due to its thin and lightweight nature.

The DC power supply, connected to the heater, provides the necessary power ranging from 5W to 15W, suitable for most portable electronic devices. K-type calibrated thermocouples are inserted at various locations on the heat sink to measure temperature. These thermocouples are connected to a data acquisition system, which records temperature data at 60-second intervals.

The heater is positioned at the base of the aluminum heat sink, which is covered by a polyethylene sheet to reduce heat losses. The thermocouples are connected to the data logger, with their soldered ends placed in the heat sink. The power supply is connected to the heater to set the heating process, maintaining a room temperature of 25°C.

Initially, the thermal conductivity of copper metal foam at different power levels (7W, 10W, and 13W) was measured. The copper metal foam was then infiltrated with PCM through a solidification process. Subsequently, the thermal conductivity of the PCM-infiltrated copper metal foam at the same power inputs (7W, 10W, and 13W) was measured.

A. *A brief description of the experimental setup:*

I. DC Power Supply: Provides the required power to the heater at the bottom of the heat sink. DC power supply module by XUNGTONG PS-1502DD, 0- 15V/0-2A) was used to delivers the desired power to the heater. The power supply provides analog control over output current and voltages with high reliability and accuracy. The output accuracy under (25°C ± 5°C) fluctuation of temperature in voltage: 0.04% +120mV, and in current: 0.1%+12m A.

II. Data Acquisition System: Records temperature data from the thermocouples. The data acquisition system (Datalogger) in this research is National instruments technologies with 4-Ch ±80 mv, 24-Bit thermocouple input ±1.5V, and Isolation-40 ℃≤ Ta≤70 ℃. There are 4 switches, outputs, and plug-in modules.

III. Phase Change Material (PCM): Paraffin wax is selected for experimentation. This PCM is having maximum thermal conductivity nearly 0.69 W/m-K, latent heat ranges from 175-240 KJ/Kg and melting temperatures 42- 44°C . Paraffin wax is well known by their different melting and latent heat ranges depending on the application. The thermophysical properties of PCM are shown in Table 1.

Table 1: Properties of Phase Change Material

Sr. No	Property	Typical value
1	Melting temperature range	42-44°C
2	Congealing temperature range	50-1300°C
3	Energy storage capacity	175-240 kJ/kg
4	Heat capacity	2000 J/kg.K
5	Density @15°C	880-900 kg/ m3
6	Flash point	186°C
7	Maximum thermal conductivity	0.69 W/m-K

IV. Copper Metal Foam: The thermal behavior of copper foam in heat sinks was experimentally studied, focusing on 100 mm x 100 mm foam with 97% porosity. This high porosity foam, featuring numerous pores, was analyzed for its impact on thermal conductivity. Copper foam was integrated with PCM to create composites for improved thermal dissipation. The structure of the copper foam is shown in Figure 2, and its properties are detailed in Table 2.

Figure 2: Optical view of copper foam

Table 1: Properties of Copper Metal Foam

Properties	Thermal conductivity (W/m-K)	Density Kg/ m^3	Pore Density (PPI)	Specific heat (KJ/Kg-K)	Purity (%)
Copper Foam	(380-387)	(447-267)	35-15	0.381	>99

V. K-type Thermocouples: Measure temperature at various locations on the heat sink. This research activity has utilized k-type (Chrome-Alum) thermocouples with the sensitivity of 41 µ v/° C. K type-thermocouples are commonly available having temperature range -200°C to 1350°C range. A total three k type Thermocouples have been used in this research.

VI. Silicone Pad Heater: Adhered to the sink base to simulate heat input. Mimicry of heat generation across heat sink is done using 100 x100 mm^2 OMEGA® silicon rubber heater (SRFG-202/10-P-220V) of square shape. The plate heater facilitates in heat transferring due to which temperature change speedily in confined areas.

Figure 3: Silicon Pad Heater

VII. Heat Sink: Custom-designed from aluminium for high heat transfer. Heat sink having dimensions of 105mm x105mm x32mm is manufactured from Aluminium. Aluminium is light weight metal, low density (30% of copper), excellent corrosion resistance, and having high thermal conductivity. The polythene sheet insulation (1cm) of very strong heat resistive material prevents any thermal loss of heat and was employed throughout the entire assembly. The heat sink's top side was tightly covered with 1 mm aluminium plate one- dimensional. The heat sink is fabricated through welding and filing from the local market.

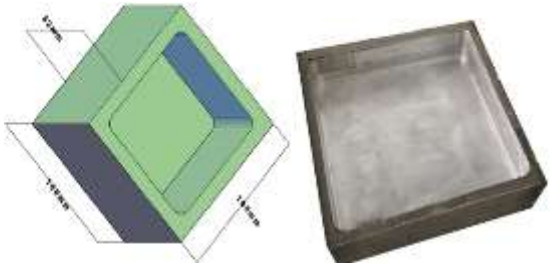


Figure 4: Heat Sink with its dimensions

B. *Infiltration of Copper Metal Foam and its Solidification:*

I. Paraffin wax is heated in a container for the solidification of copper metal foam. Paraffin wax having volume 300 milliliters and having mass 400 grams is melted in a container which converts from solid into liquid. The melted PCM is infiltrated into the copper metal foam having mass 80 grams. After some time, the liquid PCM change into solid which infiltrated into the copper metal foam. Infiltrated copper foam is a place for testing in a heated cavity.

IV. EXPERIMENTATION PROCEDURE

The heat sink, fabricated locally, features a cavity at the bottom where a heater is inserted beneath an aluminum plate. It is insulated with a high thermal resistance polyethylene sheet to prevent heat loss and is enclosed with a 1 mm aluminum plate to ensure one-dimensional heat flow and avoid leakage. The experimental setup, depicted in Figure 1, includes a data logger and DC power supply connected to the heat sink. Two K-type thermocouples are inserted at specific locations within the heat sink, connected to a computer running LabVIEW software. The DC power supply was set to various power levels using Ohm's law, and transient temperature variations were recorded every 60 seconds by the thermocouples. The data logger captured time-temperature profiles, which were refined as needed. The procedure was repeated under different conditions to ensure accuracy.

V. RESULTS AND DISCUSSIONS

The Thermal storage properties of metal foam composite with phase change material is investigated at power levels of 7W,10W,and 13W.The flexible silicon heating pad fixed at the bottom of copper foam which produce heat in three direction but fiber block insulation is provided at the rear and side walls of the heat sink to ensure 1-D heat flow from sink. K Type three thermocouples are connected into the data logger and another soldering side is placed in a heat sink. The power supply is connected into the heater for heating processes . The room temperature is kept 25°C. The tests were performed for the thermal conductivty of copper metal foam mixed with PCM at different power having power level at different position is 7W, 10W and 13W. It is also made the comparison between copper metal foam, metal foam/paraffin wax composite and pure paraffin wax.

A. *Temperature Profiles at Power Input of 7 Watt*

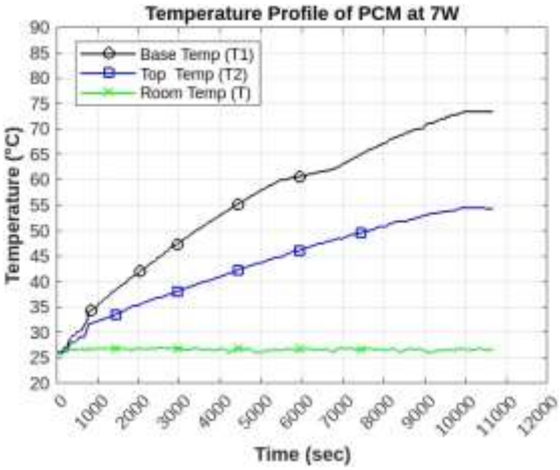
At input of 7 watt, the maximum temperature difference in paraffin wax during phase transition range is 10°C (3000sec) and in case of copper foam/paraffin wax the maximum temperature

difference during phase range is 5°C (1000 sec), Hence the maximum temperature difference drops from 10°C to 5°C by addition of copper foam in pure paraffin PCM.While In case of copper foam, the maximum temperature difference is 2.5°C. During all the three cases like in PCM, Foam/paraffin wax composite and copper foam, Temperature gets stability at 10000 sec,5000 sec, and 4000 sec respectively.

The highest temperature of all the three temperature profiles at 7W power is 75°C, 80°C and 82°C respectively.

Due to high thermal conductivity of Copper Foam, it takes less time to stable as that of pure Paraffin wax and Copper Foam/Paraffin Wax Composite.

During the melting processes, the PCM near the heating plate (heater) melts easily due to high temperature and slowely decreases at the top.



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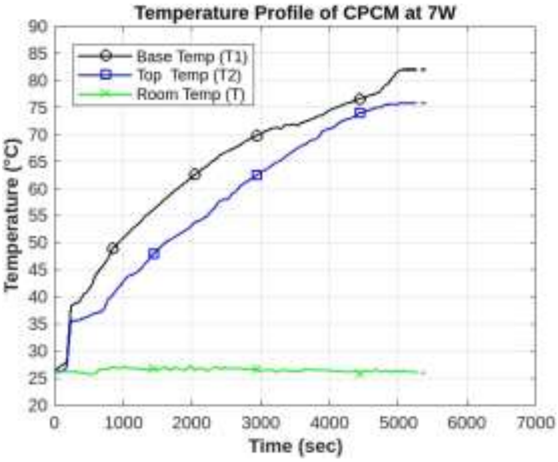
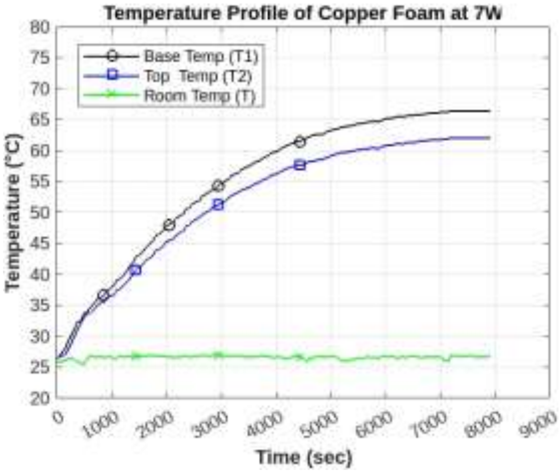


Table 2: Properties of different Heat sinks at 7 Watts

Heat Sinks	Temperature difference during Phase Transition 'dt''	Melting starting time of PCM 't''	Temperature Stability Time
Paraffin Wax	10°C	3000 seconds	10000 seconds
CPCM	5°C	1000 seconds	5000 seconds
Copper Foam	------	-------	4000 seconds

(b)



(c)

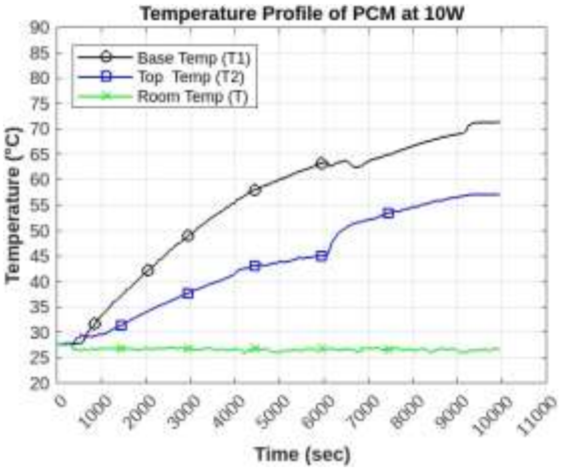
Figure 5: Temperature Profile at 7W of (a) PCM (b) CPCM (c) Copper Foam

B. *Temperature profiles at Power Input of 10 Watt*

For the power input of 10 watt, the paraffin wax maximum temperature difference during phase transition range is12°C (3000sec) and In case of copper oam/paraffin wax the maximum temperature difference during phase range is 6°C (1500 sec), Hence the maximum temperature difference drops from 12°C to 6°C by addition of copper foam in pure paraffin PCM. While In case of copper foam, the maximum temperature difference is 3°C. During all the three cases like in PCM, Foam/paraffin wax composite and copper foam, Temperature gets stability at 9000 sec, 6500 sec, and 4600 sec respectively.

The highest temperature of all the three temperature profiles at 10W power is 70°C, 85°C and 90°C respectively.

Due to high thermal conductivity of Copper Foam, it takes less time to stable as that of pure Paraffin wax and Copper Foam/Paraffin Wax Composite.



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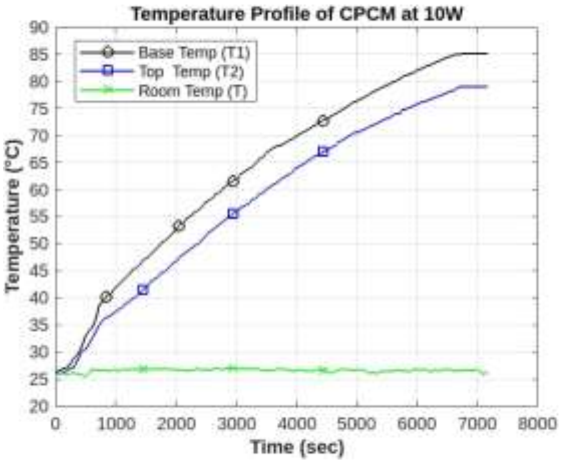
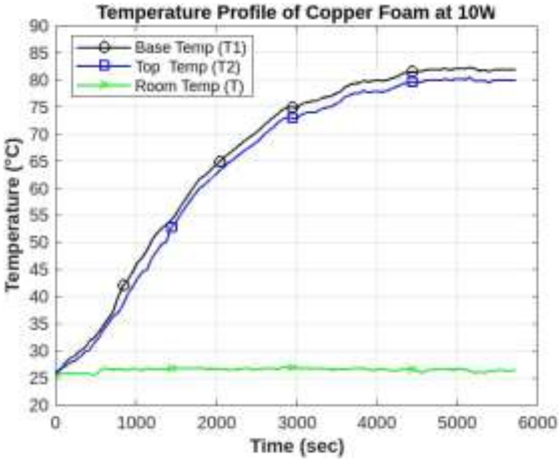


(b)

Table 3: Properties of different Heat sinks at 10 Watts

Heat Sinks	Temperature difference during Phase Transition 'dt''	Melting starting time of PCM 't''	Temperature Stability Time
Paraffin Wax	12°C	3000 seconds	9000 seconds
CPCM	6°C	1500 seconds	6500 seconds
Copper Foam	-----	---------	4600 seconds



(c)

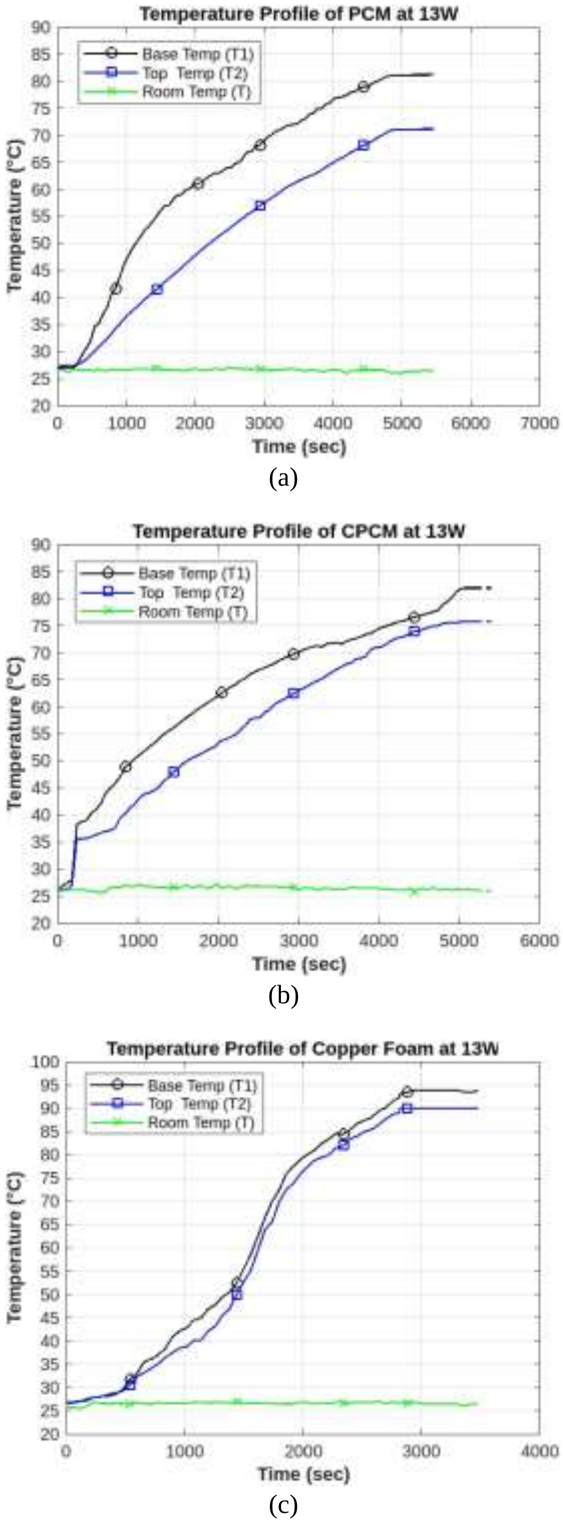
Figure 6:Temperature Profile at 10W of (a) PCM (b) CPCM (c) Copper Foam

C. *Temperature profiles at power input of 13 watt*

At input of 13W, in case of paraffin wax the maximum temperature difference during phase transition range is14°C (1500sec) and In case of copper foam/paraffin wax the maximum temperature difference during phase range is 8°C (1000 sec), Hence the maximum temperature difference drops from 14°C to 8°C by addition of copper foam in pure paraffin PCM.While In case of copper foam, the maximum temperature difference is 3.5°C. During all the three cases like in PCM, Foam/paraffin wax composite and copper foam, Temperature gets stability at 5000 sec, 4800 sec, and 3000 sec respectively.

The highest temperature of all the three temperature profiles at 13W power is 80°C, 85°C and 93°C respectively.

Due to high thermal conductivity of Copper Foam, it takes less time to stable as that of pure Paraffin wax and Copper Foam/Paraffin Wax Composite. During the melting processes, the PCM near the heating plate (heater) melts easily due to high temperature and slowly decreases at the top.



(a)

(b)

(c)

Figure 7: Temperature Profile at 13 W of (a) PCM, (b) CPCM, (c) Copper Foam

Table 4: Properties of different Heat sinks at 13 Watts

Heat Sinks	Temperature difference during Phase Transition 'dt''	Melting starting time of PCM 't''	Temperature Stability Time
Paraffin Wax	14	1500 seconds	5000 seconds
CPCM	8	1000 seconds	4800 seconds
Copper Foam	-----	------------	3000 seconds

D. Thermal Conductivity of CPCM at Power Input of 7 Watt

The heater was placed at the bottom of the aluminum heat sink. Two thermocouples were used to measure the temperature variations along with copper metal and PCM composite material. The thermocouples were equally spaced with a distance of 30mm between them. The process was transient for some time. The temperature rises gradually for both the thermocouples until it becomes steady and no further variation of temperature was seen. The experiment was continued for further 500 seconds until no further temperature rise was seen. The thermocouple close to the heat sink showed the maximum temperature. The maximum temperature reached at 7W was 82°C, as shown in Figure 5 (b) The temperature of the composite sample dropped along the vertical direction.

The minimum temperature recorded by Thermocouple was 76.5°C. Using the formula

$$Q/_t = \frac{KAdt}{L} \tag{1}$$

Where Q/t represents the power which is 7 W A is the area of Copper Foam which is 0.01 m^2 L is the length which is 0.03m, dt is the temperature difference which is 82-76.5 = 5.5

$$K = \frac{QL}{tAdt} \tag{2}$$

The thermal conductivity is found to be 3.8 W/m.k

E. Thermal Conductivity of CPCM at 10 Watt

Same procedure was employed, but the power input was incresed to 10 watt. Thermocouple was constantly reading the temperature. The experiment was continued for further 500 seconds until no further temperature rise was seen. The thermocouple close to the heat sink showed the maximum temperature at 10W was 85°C, as shown in Figure 6 (b). The temperature of the composite sample dropped along the vertical direction. The minimum temperature recorded by the Thermocouple was 78.5°C. Using same equation (2) with Q/t of 10 W, A area of Copper Foam which is 0.01 m2, L length which is 0.03m, and dt the temperature difference which is 85-78.5=6.5

The thermal conductivity is found to be 4.6 W/m.k

F. Thermal Conductivity of CPCM at Power Input of 13 Watt

Similarly the procedure was repeated for 13 watt. Thermocouple was constantly reading the temperature. Where, the thermocouple close to the heat sink showed the maximum temperature. The maximum temperature reached at 13W was 82°C. The temperature of the composite sample dropped along the vertical direction. The minimum temperature recorded by theThermocouple was 75°C.

Using again equation (2) with Q/t of 13 W, A area of Copper Foam which is 0.01 m2, L length which is 0.03m, and dt the temperature difference which is 82-75=7

The thermal conductivity is found to be 5.5 W/m.k

VI. Validation of Experimental Result

Empty heat sink having dimensions 105mm x105mm x32mm was validated with that of the preceding study conducted by Arshad et al [27] at 7 Watts. Present experimentation is done with the same conditions as the preceding study. Figure 5.10 shows the base temperature of both heat sinks which is almost same for both present study and previous study. So, the present study showed good accordance with that of previous one.

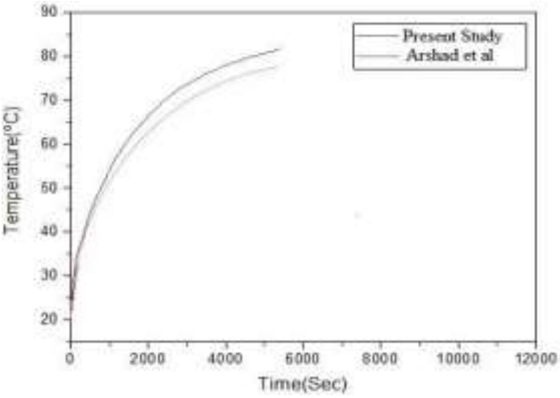


Figure 8: Comparison with previous study (for 7 watt only)

VII. CONCLUSION AND FUTURE RECOMMENDATIONS

The present thesis consists of copper metal foam having 97% porosity. PCM (Paraffin Wax) with melting point 42-44°C have been infiltrated in copper foam. In this research work, thermal storage properties of Copper Metal Foam mixed with Phase Change Material were investigated. Three specimens PCM (Paraffin wax) Copper Metal Foam, and Copper Metal Foam/Paraffin wax Composite were compared. Copper Foam based Paraffin Wax Heat Sink is analyzed at different Power level of 7W, 10W and 13 W and having fixed (0.8) Volume fraction of PCM, relatively more volume fraction of Paraffin Wax(0.8) is suited because it can low base temperature of heat sink prominently. Results revealed that adding of Paraffin Wax within Copper Metal Foam lowers the base temperature of the heat sink. Temperature gradient ''dt'' between base and top surface of heat sink is lower for Copper Foam based heat sink as compared to CPCM and Paraffin Wax based heat sinks for all power levels as shown in figures 5 to 7.

Adding Copper Metal Foam to PCM (Paraffin wax) can fast the melting and solidification time of PCM. At input power of 7W, the maximum temperature difference is 10°C (3000 sec) in case of PCM and 5°C (1000sec) in case of CPCM, so by adding Copper Foam in PCM dropped maximum temperature difference from 10°C to 5°C at 7W. At input power of 10W, the maximum temperature difference is 12°C (3000 sec) in case of PCM and 6°C (1500sec) in case of CPCM, so by adding Copper Foam in PCM dropped maximum temperature difference from 12°C to 6°C at 10W. At input power of 13W, the maximum temperature difference is 14°C (1500sec) in case of PCM and 8°C (1000sec) in case of CPCM, so by adding Copper Foam in PCM dropped maximum temperature difference from 14°C to 8°C at 13W.The maximum thermal conductivity of Copper Metal Foam/Paraffin wax Composite at 7 W, 10W and 13W is 3.8 W/m. k, 4.6 W/m. k and 5.5 W/m. k respectively.

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NOMENCLATURE

K	Thermal conductivity[W/mK]
Q/t	Power [Watt]
A	Area [m2]
L	Lenght [m]
t	Time [Seconds]
TES	Thermal Energy Storage
PCM	Phase Change Material
CPCM	Copper Form/Phase Change Material