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Improving Thermal Conductivity in Heat Sink Using Copper Foam-Paraffin Phase Change Materials

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Phase change materials (PCMs) play a vital role in thermal energy storage systems because of their ability to absorb and release heat. However, their low thermal conductivity limits how quickly energy can be stored and retrieved. Adding copper metal foam to PCMs significantly improves their thermal conductivity. This study explores the increase in thermal conductivity of a metal foam-paraffin composite compared to pure paraffin. Copper metal foam, known for its excellent thermal conductivity, enhances the heat transfer rate within the composite. Both theoretical and experimental evaluations were conducted to measure and compare the thermal conductivity of the copper foam/PCM composite. The results showed that the composite achieved a thermal conductivity of 5.5 W/mK at 13 W much higher than the 0.2 W/mK observed in pure PCM. Additionally, the copper/PCM composite reduced the heat sink temperature by 25–30%. This improvement is attributed to the enhanced thermal pathways created by the structure of the copper foam, despite the inverse relationship between infiltration ratio and pore density.

Keywords: Aluminum Heat Sink, Copper Metal Foam, Paraffin, Phase Change Material

Introduction:

Efficient thermal management is crucial for electronic devices (EDs), ensuring not only optimal performance but also high reliability and energy efficiency. Researchers around the world are actively exploring both analytical and experimental methods to tackle the serious issue of excess heat generation.

Traditional active cooling techniques, like large fans, face several drawbacks, including bulky size, constant noise, and high-power consumption [1]. In contrast, passive cooling methods using phase change materials (PCMs) have gained global attention. PCMs offer excellent thermal properties, such as high heat capacity, non-toxicity, and customizable composition and melting points. These materials provide efficient thermal control while remaining reliable and cost-effective, making them true game-changers [2][3][4].

PCMs also play a key role in many engineering fields, especially in thermal energy storage (TES). Paraffin wax, a widely used PCM, is particularly important in solar energy storage systems [5][6][7].

Despite its high latent heat capacity, paraffin wax has limited thermal conductivity. To overcome this, researchers are exploring ways to enhance PCMs with metals and metal oxides [8][9][10][11], significantly improving their heat transfer performance. Copper foam, known for being chemically stable and lightweight, also offers a large surface area-to-volume ratio.

The TES framework helps bridge the gap between the supply and demand of renewable energy. Combining PCMs with copper foam further enhances heat storage efficiency. In our study, copper foam was used to improve the thermal conductivity of paraffin wax. An aluminum heat sink with a heater was used to precisely evaluate the thermal behavior of the copper foam/PCM composite. Our results showed a clear improvement in heat transfer, thanks to the copper foam.

Literature Review:

Storing energy as sensible heat requires large volumes, while latent heat storage based on phase changes is directly related to the material's latent heat of fusion and mass [1]. Latent heat storage offers several advantages, such as maintaining a constant temperature and achieving high energy density [2], making Phase Change Materials (PCMs) ideal for applications like waste heat recovery, solar energy systems, and electronic device cooling [3]. PCMs can store 5 to 14 times more heat than conventional sensible heat storage methods [4][5]. Their high storage density enables the creation of more compact and efficient thermal storage systems compared to traditional methods [4]. However, a common drawback of PCMs is their low thermal conductivity [6].

To address this, researchers are actively working on improving heat transfer within PCM-based systems to enhance performance and develop cost-effective, compact thermal energy storage solutions [3]. An ideal PCM should have high thermal conductivity, be non-toxic, non-corrosive, inexpensive, and chemically stable [7][8][9].

Paraffin wax is a commonly used PCM, but its low thermal conductivity limits its effectiveness [1][2]. To solve this issue, researchers have explored the addition of nanoparticles and metal foams. For example, adding 3 wt% aluminum oxide (Al_2O_3) nanoparticles improved thermal conductivity by 18.6% and thermal effusivity by 28.2% [2]. Another study showed that 1%, 2%, and 3% Al_2O_3 nanoparticles increased thermal conductivity by 37.1%, 42.3%, and 60.32%, respectively [3]. Titanium dioxide (TiO_2) nanoparticles at 5 wt% also increased thermal conductivity by 10% at 15°C [4].

Graphite-based materials have also been investigated. Expanded graphite (EG) increased thermal conductivity up to 6.5 times compared to pure paraffin, with improvements rising with EG content [5]. Similarly, graphite powder mixed with paraffin reduced melting time and improved heat response [6]. Numerical studies using graphite foam in latent heat storage systems showed enhanced heat transfer [7]. While metal foams generally outperform expanded graphite due to their 3D interconnected structure, both materials help suppress natural convection in liquid PCMs [8].

Experiments combining metal foam or graphite with paraffin wax and calcium chloride showed significant improvements in thermal conductivity. Open-cell metal foam (such as expanded graphite) greatly improved heat transfer, effectively doubling conductivity. The addition of graphite also boosted thermal performance [1]. Other research found that metal foams could double the heat transfer rate during PCM melting compared to pure PCMs [2]. Paraffin wax and metal foams are the most frequently used PCM and support materials [3]. Nickel foam, in particular, proved efficient for maintaining battery temperatures, while other cost-effective foams are also promising for battery thermal management [4].

Additive manufacturing allows precise fabrication of porous metal structures, improving thermal performance, with one study reporting a 38% reduction in total melting time [1]. However, porous materials can suppress natural convection in liquid PCMs, especially those with low viscosity, which affects overall heat transfer behavior [2]. Future research should aim to bridge the gap between heat transfer mechanisms and material design for phase change applications [3].

Many studies have focused on how metal foams infused with paraffin improve latent heat storage. Experimental and numerical analyses confirm that metal foams greatly enhance thermal conductivity in paraffin-based composites [1][2]. Thermal conductivity increases as foam porosity decreases, while the foam's own conductivity is a critical factor [1]. Pore size has little effect on the composite's thermal performance due to minimal heat exchange between the paraffin and foam under normal conditions [3]. Advanced numerical models, including pore-scale simulations, have shown strong alignment with experimental data, offering valuable insights for thermal storage applications [3][4].

Novelty Statement:

Prior research has extensively studied how metal foams enhance latent heat storage and confirmed their effectiveness in improving the thermal conductivity of paraffin-based composites through experimental and numerical analyses, this study presents novelty by specifically addressing overlooked issues in microelectronics thermal management. It offers flexible solutions for improving heat dissipation in tight spaces, providing guidance for developing innovative thermal designs. A key differentiating aspect is the execution of a detailed comparative analysis of pure paraffin, copper foam, and copper-paraffin composites utilizing a specific aluminum heat sink and heater experimental setup.

Objectives:

- The primary objectives of this study are to investigate the thermal storage properties of copper metal foam mixed with phase change material (PCM), specifically paraffin wax.
- The research aims to explore the increase in thermal conductivity of a metal foam-paraffin composite compared to pure paraffin and assess how adding copper foam improves heat transfer and thermal conductivity of paraffin wax under different power inputs.
- This involves evaluating the thermal behavior of copper foam/PCM composites using an aluminum heat sink and heater setup and conducting a detailed comparative analysis of the thermal performance of pure paraffin, copper foam alone, and the combined copper-paraffin composite.

Methodology:

The experimental method involved evaluating heat sink configurations using different foam types, design parameters, and power levels to optimize thermal management in electronic devices. A custom-fabricated aluminum heat sink, embedded with a silicone heater and insulated using a polyethylene sheet, was tested under various thermal loads. Temperature measurements were taken using K-type thermocouples connected to a data logger, and readings were recorded at 60-second intervals. Full details of the experimental components and setup are provided below:

The detailed experimental setup and the flow diagram of the experiment and the methodology adopted is depicted in Figure 1.

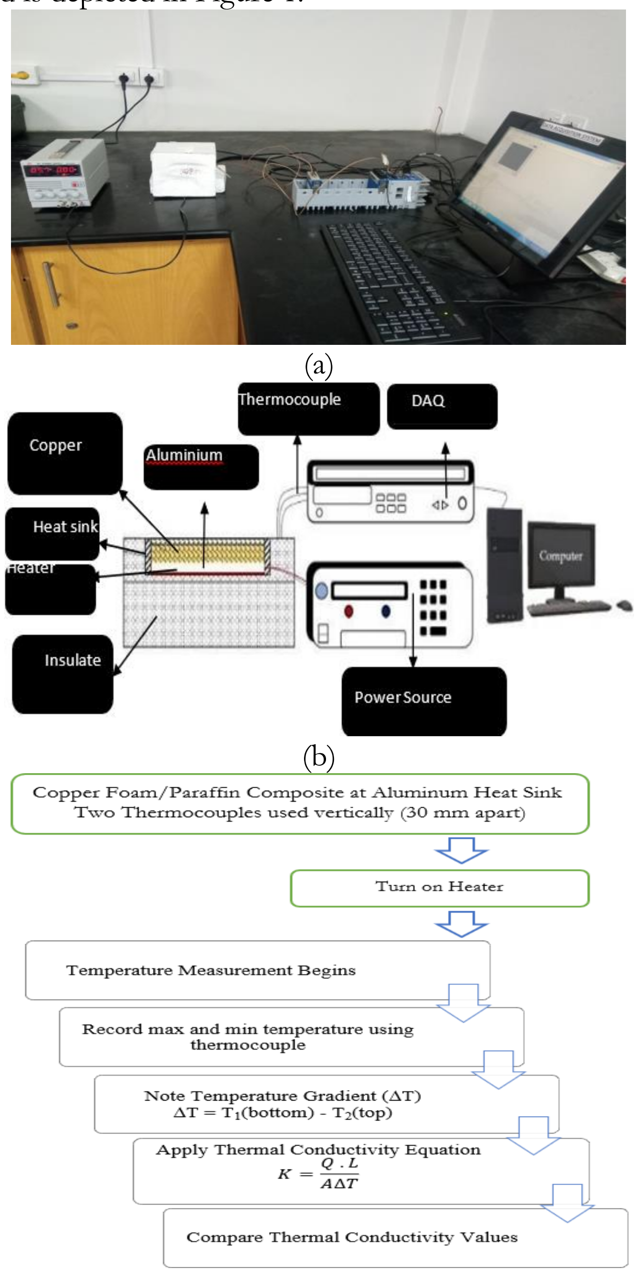


Figure 1. (a) Experimental setup (b) Flow diagram of experiment (c) Flow diagram of methodology

A Brief Description of the Experimental Setup:

1. 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.

2. Data Acquisition System: Records temperature data from the thermocouples at 60-second intervals. 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.

~~3.~~ 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	44°C–50°C
3	Energy storage capacity	175-240 kJ/kg
4	Heat capacity	2000 J/kg.K
5	Density @15°C	880-900 kg/ m^3
6	Flash point	186°C
7	**Maximum thermal conductivity**	0.69 W/m-K

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.

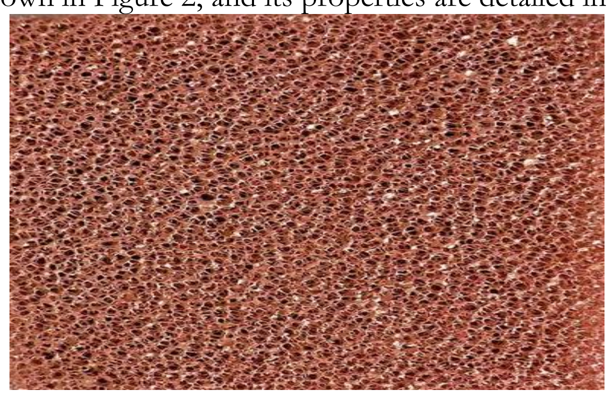


Figure 2. Optical view of copper foam

Table 2. 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

1. 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.

2. Silicone Pad Heater: Adhered to the sink base to simulate heat input. Mimicry of heat generation across heat sink is done using 100 x100 mm² 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

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.

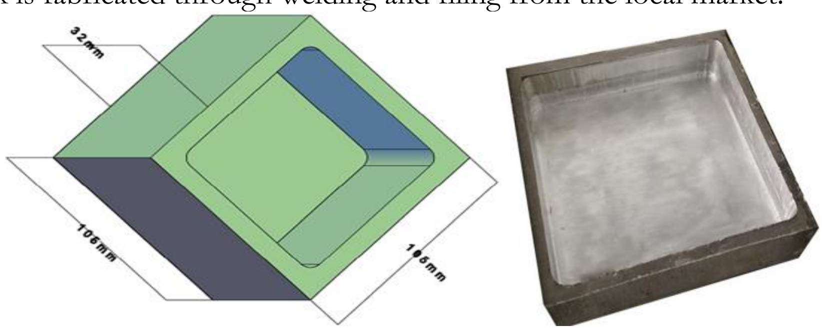


Figure 4. Heat Sink with its dimensions

Infiltration of Copper Metal Foam and its Solidification:

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.

Experimentation Procedure:

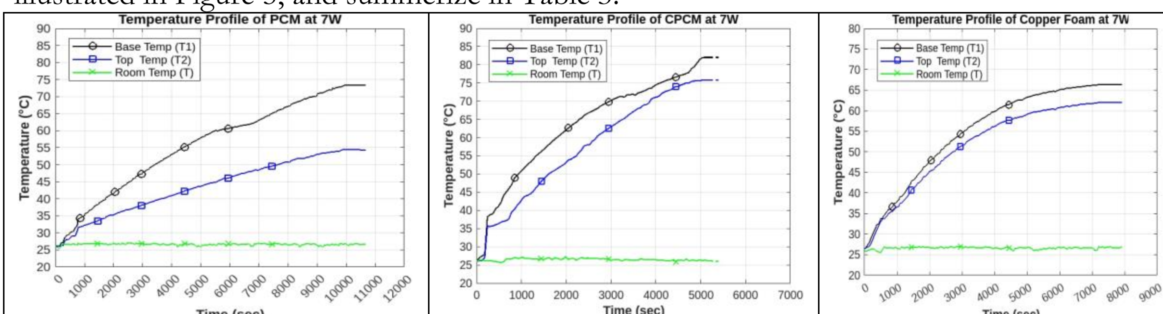
The heat sink, fabricated locally, features a cavity at the bottom where a heater is inserted beneath an aluminum plate. It is insulated with a high thermal resistance polyethylene sheet to prevent heat loss and is enclosed with a 1 mm aluminum plate to ensure one-dimensional heat flow and avoid leakage. 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.

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, however to ensure 1-D heat flow from sink fiber block insulation is provided at the backside walls of the heat 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.

Temperature Profiles at Power Input of 7 Watt:

At an input power of 7 watts, the thermal performance of three configurations;pure paraffin wax (PCM), copper foam/paraffin composite (CPCM), and pure copper foam was assessed. The maximum temperature difference during the phase transition was highest for PCM at 10°C, which reduced to 5°C in CPCM, and further to 2.5°C in copper foam. The onset of melting occurred at approximately 3000 seconds for PCM and 1000 seconds for CPCM, while no melting was applicable for copper foam due to its metallic nature. The temperature stabilization time followed a similar trend: 10,000 seconds for PCM, 5000 seconds for CPCM, and 4000 seconds for copper foam. Notably, despite PCM having the lowest peak temperature (75°C), copper foam recorded the highest (82°C), followed by CPCM (80°C). These results demonstrate that the addition of copper foam significantly enhances heat transfer, reducing both temperature lag and stabilization time. The temperature profiles are illustrated in Figure 5, and summerize in Table 3.



(a) (b) (c)

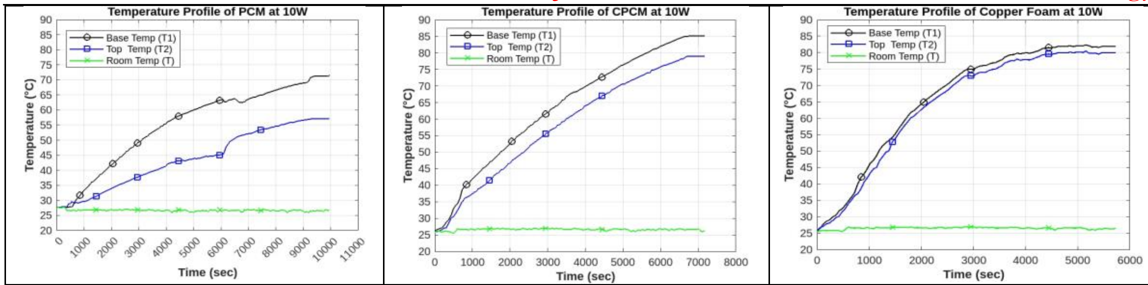
Figure 5. Temperature Profile at 7W of (a) PCM (b) CPCM (c) Copper Foam

Temperature profiles at Power Input of 10 Watt:

Under a 10-watt power input, similar trends were observed with more pronounced effects due to increased thermal load. The maximum temperature difference during phase change was 12°C for PCM, 6°C for CPCM, and 3°C for copper foam. Melting began at 3000 seconds for PCM and 1500 seconds for CPCM. Again, copper foam, not undergoing phase change, exhibited no melting interval. The time to reach temperature stability was 9000 seconds for PCM, 6500 seconds for CPCM, and 4600 seconds for copper foam. The peak temperatures recorded were 70°C for PCM, 85°C for CPCM, and 90°C for copper foam. These outcomes reaffirm the improved thermal response of copper foam and its composites, indicating more efficient heat dissipation at elevated power inputs. The corresponding temperature profiles are shown in Figure 6, and summerzie in Table 4.

Table 3. 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



(a) (b) (c)

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

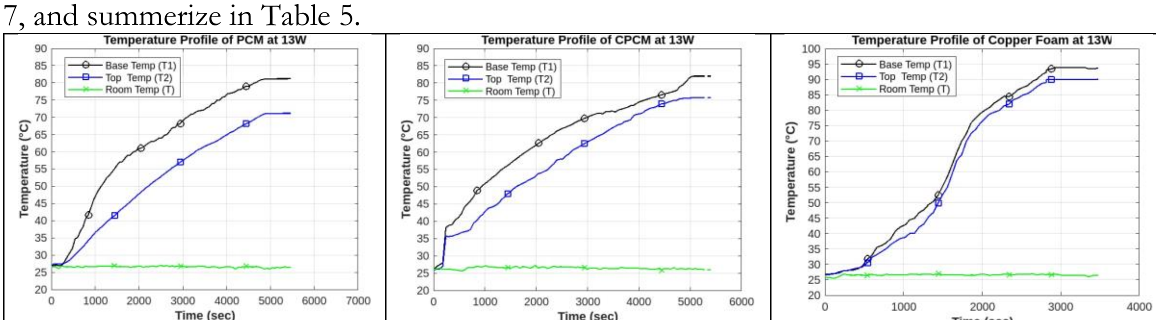
Table 4. Properties of different Heat sinks at 10 Watts

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

Temperature profiles at power input of 13 watt:

At a 13-watt input power, the thermal behavior of paraffin wax (PCM), copper foam/paraffin composite (CPCM), and pure copper foam was evaluated. The maximum temperature difference during the phase transition was observed to be 14°C for PCM, which decreased to 8°C in the CPCM configuration and further to 3.5°C in pure copper foam. The melting initiation time for PCM was around 1500 seconds, while it occurred earlier in CPCM at 1000 seconds; copper foam again did not exhibit a phase change. In terms of temperature stabilization, PCM reached steady-state at 5000 seconds, CPCM at 4800 seconds, and copper foam achieved stability fastest at 3000 seconds.

The peak temperatures recorded were 80°C for PCM, 85°C for CPCM, and 93°C for copper foam. The higher peak and faster stabilization time in copper foam are attributed to its superior thermal conductivity. During the melting process, it was noted that the PCM near the heat source melted first, with temperature gradients decreasing progressively toward the upper regions of the heat sink. The corresponding temperature profiles are shown in Figure 7, and summerize in Table 5.



(a) (b) (c)

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

Table 5. 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

Thermal Conductivity of CPCM at Power Input of 7 Watt:

The experiment was conducted by placing a heater at the bottom of the aluminum heat sink. Two thermocouples, spaced 30 mm apart, were embedded vertically within the CPCM (Copper Foam/Paraffin Composite) to record temperature variation. The system initially exhibited transient heating behavior before reaching thermal equilibrium. The thermocouple closest to the heater recorded a maximum temperature of 82°C, while the top thermocouple recorded 76.5°C, indicating a vertical thermal gradient within the composite (Figure 5b).

Using the formula:

$$Q/_{t} = \frac{KAdt}{L} \qquad (1)$$

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

$$K = \frac{QL}{tAdt} \qquad (2)$$

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

Thermal Conductivity of CPCM at 10 Watt:

Using the same setup and measurement method, the power input was increased to 10 watts. The temperature stabilized after the initial transient period. The lower thermocouple recorded a maximum of 85°C, while the upper one measured 78.5°C, confirming the temperature gradient along the vertical axis (Figure 6b).

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

Thermal Conductivity of CPCM at Power Input of 13 Watt:

For the 13-watt case, the procedure remained identical. The maximum and minimum temperatures recorded were 82°C and 75°C, respectively. Although the peak temperature matched that of the 7W case, the overall gradient was steeper, indicating higher heat flow.

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

Validation of Experimental Result:

Empty heat sink having dimensions 105mm x105mm x32mm was validated with preceding study conducted by authors[12] at 7 Watts. Present experimentation is done with the same conditions as the preceding study. Figure 8 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.

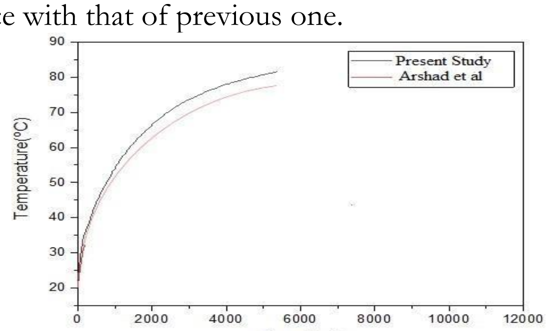


Figure 8. Comparison with previous study (for 7 watt only)

Conclusion:

The research focuses on investigating the thermal storage properties of copper metal foam mixed with phase change material (PCM), specifically paraffin wax, with a focus on how adding copper foam to PCM enhances heat dissipation. The study compares three specimens: PCM (Paraffin wax), copper metal foam, and the copper metal foam/paraffin wax composite (CPCM).

Key findings:

- Copper Metal Foam with PCM: Adding copper foam to PCM significantly lowers the base temperature of the heat sink. This is especially true with a volume fraction of 0.8 for PCM, which shows the best thermal performance.
- Thermal Behavior: The addition of copper foam decreases the temperature gradient between the base and the top of the heat sink, resulting in better temperature uniformity.
- Melting and Solidification: The copper foam accelerates the melting and solidification times of the PCM, improving thermal management.
  - At 7W: The maximum temperature difference in PCM was 10°C at 3000 seconds, but with copper foam, this dropped to 5°C at 1000 seconds.
  - At 10W: The maximum temperature difference in PCM was 12°C at 3000 seconds, which decreased to 6°C with copper foam at 1500 seconds.
  - At 13W: The maximum temperature difference in PCM was 14°C at 1500 seconds, reducing to 8°C with copper foam at 1000 seconds.
- Thermal Conductivity: The thermal conductivity of the Copper Metal Foam/Paraffin Wax composite increased with power input:
  - At 7W: 3.8 W/m·K
  - At 10W: 4.6 W/m·K
  - At 13W: 5.5 W/m·K

The results highlight that copper foam's high thermal conductivity significantly enhances the performance of PCM in heat sinks, making it an effective solution for thermal management in various applications.

Future Recommendations:

Future experiments will focus on measuring the composite's thermal conductivity at various power levels. Additionally, we plan to compare the thermal performance of pure paraffin, copper foam alone, and the combined copper-paraffin composite in detail.

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Author's Contribution. The work presented in this paper is of Author Fawad Ali, while Dr. Muhammad Alam Zaib Khan is his research advisor.

Conflict of interest. The is no conflict of interest for publishing this manuscript in IJIST.

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