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Melting performance of a composite bio-based phase change material: An experimental evaluation of copper foam pore size

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ABSTRACT

This paper presents an experimental study on the thermal performance of a composite heat sink consisting of a bio-based phase change material and copper foam. The experiments are carried out at three different heat loads (10, 15, and 20 W) using five copper metal foam samples with the same dimensions (10 × 9 × 0.3 cm), porosity (98%), and pore densities of 20, 35, 60, 80, and 95 pores per inch (PPI). The thermal performances are evaluated using the temperature profiles, the time required to reach specific temperatures, and the enhancement ratios of the heat sinks. The results favor the PCM-Copper composite sample with 95 PPI because it took the longest time to achieve a constant temperature when compared to its other pore density counterparts. Also, for the same sample under 20 W power input, the enhancement ratios are 1.29, 1.45, and 1.23 at critical temperatures of 50, 55, and 60 °C, respectively.

1. Introduction

Thermal management is critical for electronic devices as the operating temperature has a significant impact on their reliability and components. Inadequate thermal management leads to decreased performance, vital component failure, and user discomfort. However, as technological advancement progresses, the physical dimensions of electronics are shrinking, as is the space available for thermal management. Consequently, cooling electronics has emerged as a major concern in our contemporary era [1].

According to an American Air Force survey, temperature-related failures are responsible for more than 50% of all electronics failures [2]. Overheating, or even minor temperature changes, can greatly reduce the lifespan of electronic devices [3]. As a result, thermal management is a crucial consideration in device design because keeping the temperature within a certain range prevents heat damage to the components. Temperature changes in electronics are caused by changes in ambient temperature or heat generated by high-power-density integrated circuits [4].

When assessing and evaluating thermal management systems, the components used in such systems play a critical role in cooling performance; hence, many researchers have concentrated their efforts on improving these systems. Some proposed methods for improving cooling systems for electronics include heat pipes, extended surfaces, air-circulating fans, and heat sinks. Air and liquid active cooling methods are no longer viable options due to numerous concerns, including size, noise, maintenance, and power consumption [5].

Since phase change materials (PCMs) can store a significant amount of heat at a nearly constant temperature via the phase change process, they are suitable material options when considering cooling systems. PCMs have two key properties: a high melting enthalpy and the desired temperature range for phase transition [6]. Bio-based PCMs derived from animal fats and plant oils are non-flammable, nontoxic, inexpensive, and easily available [7]. They also have a higher latent heat density and a wider temperature phase-change range than other types of PCMs [7]. Therefore, bio-based PCM heat sink cooling could be a viable option for electronics thermal management.

Because bio-PCMs have poor thermal conductivity and thus a lower ability to transmit heat from the heat sink's base, high conductivity particles, nanoparticles, and porous materials, have been integrated into PCM-based heat sinks [8]. In recent years, several scientists have attempted to make PCMs more thermally conductive by integrating them into metal foams with high thermal conductivity, which causes heat to dissipate more rapidly throughout the composites [9].

The impact of metal foam on the thermal conductivity of PCMs has been the subject of several investigations. Xiao et al. [10] found that the thermal conductivities of paraffin (PCM)/nickel foam composite and paraffin (PCM)/copper foam composite were 3 and 15 times higher,

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respectively than paraffin (pure PCM). Li et al. [11] prepared a series of composites composed of hydrated salt (PCM) and copper foams with porosities ranging from 92.4 to 97.3% and pore densities ranging from 5 to 25 PPIs. They discovered that as compared to pure PCM, the effective thermal conductivity of the composite increased by 11 times compared to pure PCM.

Numerous studies have looked at how metal foams with different pore densities affect the heat transfer and the thermal performance of PCMs. Diani and Rossetto [12] conducted an experiment on the melting of PCMs implanted in copper foams of varying relative densities. The PCMs used in their study were RT42, RT55, and RT64HC, with the numbers in the names representing the PCM's typical melting point. They found that the higher the pore density of the foam, the better the thermal performance of the PCM composite. Mancin et al. [13] performed an experiment on the thermal performance of three different PCMs with melting temperatures of 53, 57, and 59 °C embedded in three different samples of copper foams with 5, 10, and 40 PPIs and a constant porosity of 95%. The experiments were carried out at three heat fluxes of 6.25, 12.5, and 18.75 kW/m2. An enhanced heat transfer rate and reduced surface temperatures were observed when using copper foams. Lazzarin et al. [14] investigated the effects of three aluminum foams with pore densities of 5, 20, and 40 PPIs on the melting heat transfer of PCMs with melting points of 40 and 45 °C. They concluded that utilizing aluminum foams shortened the melting and solidification periods of PCMs by around eight and six times, respectively. Moussa and Karkri [15] carried out a numerical study of paraffin RT27 embedded in four different copper foams with pore densities of 5, 10, 20, and 40 PPIs. They found that the rates of PCM melting and solidification increase as pore density increases.

Qu et al. [16] designed an electronic thermal management system using copper foam/PCM composite. They experimentally investigated the effect of porosity and pore density on the surface temperature of the composite using three samples of metal foams with 5, 15 and 20 pores per inch (PPIs) They concluded that a lower surface temperature can be obtained at a lower porosity and pore density. Hussain et al. [18] designed a thermal management system for high-powered batteries using PCM/nickel foam composite. They prepared three samples of the composites with the same porosity (97%) and different pore densities of 10, 20 and 30 PPIs. Their results showed that, compared to pure paraffin and natural convection, the surface temperature of the battery dropped to 24% and 31%, respectively. Ren et al. [17] investigated the effect of pore density of metal foam on the melting performance of an energy storage unit at various hot wall temperatures. They have discovered that increasing the pore density of the metal foam enhances the melting rate of the PCM/ nickel foam composite.

Many researchers have conducted both experimental and numerical investigations into the effect of porosity and pore density on the thermal performance of a PCM /metal foam composite. Marri and Balaji [19] have studied various configurations of PCM /metal foam composite formed from aluminum foams with porosities of 0.9, 0.94, and 0.97 and pore densities of 8, 14, and 20 PPIs filled with n-eicosane as the PCM during the charging and the discharging processes. Iasiello et al. [23] reported experimental and computational data on PCMs implanted in aluminum foams with varying heat fluxes, porosities and pore densities of 10, 20 and 40 PPIs. Twelve experiments were carried out using paraffin with a melting temperature of 57 °C as the PCM.

There have also been a number of numerical analyses of the performance of a PCM/metal foam composite. Zhuang et al. [21] conducted a numerical investigation of the phase change in copper foams with varying pore densities of 5, 25, and 40 PPIs. The numerical findings revealed that when pore density increases, the melting time of the composite decreases. Zhu et al. [22] numerically analyzed the energy storage efficiency of a PCM embedded in three different copper foams with pore densities of 5, 10, and 20 PPIs. They found that an increase in pore density (pore per inch) could restrict convective heat transfer, lowering the composite's storage performance. Srivatsa et al. [24] developed numerical models for three aluminum foams with pore densities of 10, 20, and 30 PPIs embedded in a PCM-based heat sink to study the effect of pore density on the thermal performance of the composite. They found a thermal performance enhancement ratio of 7–8 for the PCM composite. Tian and Zhao [20] investigated the effects of metal foams with pore densities of 10 and 30 PPIs on enhancing PCM heat transfer. According to the simulation results, metal foams with smaller pore sizes (greater pore density) perform better in heat transfer compared to those with larger pore sizes (lower pore density). Furthermore, when metal foams models embedded in PCM were compared to pure PCM models, it was discovered that the inclusion of metal foams could significantly improve the PCM's heat transfer performance by 3 to 10 times. Zhao et al. [25] conducted a numerical investigation of the solid-liquid phase change in four copper foams with different pore densities of 5, 10, 20, and 40 PPIs. They discovered that the pore density of the foam is critical to the melting and solidification of PCM and that the melt fraction of the composite rises as porosity decreases and pore density increases.

Table 1 [27,26,28–36] presents a summary of previous studies' findings regarding the effects of inserting various PCMs into different metal foams on the thermal performance of the composites. The preceding literature review and Table 1 reveal that there has been little to no research into the influence of copper foam with a pore density of more than 50 pores per inch (PPI) on the thermal performance of a bio-based PCM composite at a given porosity. Therefore, to fill this gap and help ongoing efforts to improve PCM cooling applications, the objectives of this study are to perform an experiment to test the thermal performance of a composite heat sink, consisting of a bio-based PCM and copper foams with pore densities ranging from 20 to 95 PPI; to carry out a parametric study of many parameters and achieve optimization; and to evaluate and compare the thermal performance of various samples using their temperature profiles, the time required to reach specific temperatures, and their enhancement ratios.

The next section will introduce, describe, and specify the various materials and methods employed in the current experimental study. This will be followed by a description and discussion of the collected experimental data and finally, the paper will end with a conclusion highlighting the key findings of the study.

Table 1
Summary of previous studies on the effect of inserting various PCMs in different metal foams on the thermal performance of the composites.

Reference	PCM	Metal Foam	Porosity	Pore density
Duan and Li [27]	Coconut oil	Copper foam	95%	10, 20, 40 PPIs
Bai et al. [26]	Distilled water	Copper foam	90%	8, 30 PPIs
Martinelli et al. [28]	Paraffin	Copper foam	91%	5–10 PPIs
Rehman and Ali [29]	Paraffin wax	Copper foam	95, 97%	15, 35 PPIs
Yao et al. [30]	Paraffin	Copper foam	97.4%	10 PPI
Qing Jin et al. [31]	Paraffin wax	Copper foam	96.1, 95.3, 94.9%	15, 30, 50 PPIs
Jackson and Fisher [32]	PureTemp 25	Copper foam	92.5, 94.7%	5, 20 PPIs
Jackson and Fisher [32]	PureTemp 25	Aluminum foam	92.1, 93.3%	5, 20 PPIs
Huang et al. [33]	Lauric acid	Copper foam	80, 90, 95%	10, 20, 40 PPIs
Chen et al. [34]	Paraffin wax	Aluminum foam	91.37%	9 PPI
Li et al. [35]	Stearic acid	Copper foam	98%	5, 20, 40 PPIs
Li et al. [36]	paraffin wax	Copper foam	85%	5, 20, 40, 80 PPIs

2. Materials and methods

The bio-based PCM for this study was purchased from Entropy Solutions LLC, which has a melting temperature of 29 °C and a fusion enthalpy of 202 kJ/kg. Table 2 summarizes the thermal properties of the PCM. Five samples of copper foams with different pore densities of 20, 35, 60, 80, and 95 PPIs were purchased from Shengshijing New Materials Company. The samples have the same dimensions of 10 × 9 × 0.3 cm and a porosity of 98%. The average pore sizes of the samples are estimated to be about 1.0, 0.5, 0.3, 0.25, and 0.2 mm for 20, 35, 60, 80, and 95 PPIs, respectively.

After the bio-based PCMs are melted at temperatures above 30 °C, the liquid PCMs are injected into 11 × 10 × 1 cm aluminum containers. The composites are allowed to solidify at room temperature after each copper foam is placed in the container. The flat plate transfers heat to the aluminum container that holds 40 ml of the bio-based PCM with a copper foam.

Fig. 1 illustrates the experimental setup, while the schematic diagram is provided in Fig. 2. As shown in Fig. 1, a TecQuipment Ltd. apparatus is utilized in this experimental study of the thermal response of the bio-PCM/copper foam composite with various pore sizes. A flat plate, an electrical heater, a dc power supply, a K-type thermocouple, and a data collection system comprise the equipment as shown in Fig. 2. The temperature of the heated plate is measured and recorded using the thermocouple and the data-collecting device, respectively.

To validate the accuracy of the experimental setup a measurement error analysis is carried out. Table 3 confirms the reliability of the thermocouple with a good resolution and a small error. According to the Table, the least accurate component, the heater, yields a temperature uncertainty of no more than 0.2 °C, which is adequate precision for the current study. As a result, it is concluded that the TecQuipment device provides adequate accuracy for reliable temperature readings.

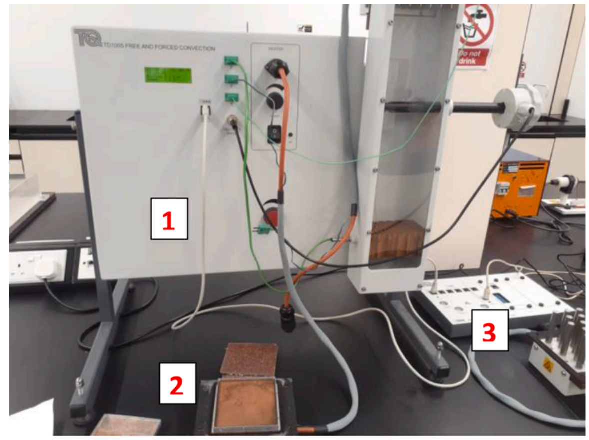

Fig. 1. The experimental setup: 1-TecQuipment Ltd. Apparatus, 2- Bio-PCM/ copper foam composite based heat sink is at the top of the flat plate and the heater, 3- data collection system.

3. Results and discussion

The main goal of this study is to determine the optimal pore density of the copper foam that best improves the thermal performance of bio-based PCM/copper foam composites. Therefore, five different copper foams (CF) with pore densities of 20, 35, 60, 80, and 95 PPIs are investigated. The thermal performance is evaluated using the enhancement ratio of the heat sink, temperature profiles, and the time required to reach a fixed temperature. In addition, measurements are taken for three different heat loads of 10, 15, and 20 W, which resemble varying heat loads from an electronic device to which the PCM/CF-based heat sink would be attached. The current section outlines the experimental results, followed by a comparison of all tested samples, allowing for the identification of the best copper foam bio-based composite pore density for optimal thermal performance.

Figs. 3,4 & 5 portray the transient temperature profiles of the heated plate for the five studied pore sizes in response to varying heat loads of 10, 15 and 20 W, respectively. The thermal performance of the heat sink samples is evaluated by identifying the final temperature of each sample after a specified time. A lower final temperature is indicative of enhanced thermal performance as it correlates to a larger amount of heat being absorbed by the heat sink.

Table 2
Thermal properties of PureTemp 29.

Property	Typical value
Melting temperature	29 °C
Latent heat, melting	202 kJ/kg
Specific heat capacity (solid)	1.77 kJ/(kg • °C)
Specific heat capacity (liquid)	1.94 kJ/(kg • °C)
Thermal conductivity (solid)	0.25 W/(m • °C)
Thermal conductivity (liquid)	0.15 W/(m • °C)
Density at 6 °C (solid)	0.94 g/cm^3
Density at 30 °C (liquid)	0.85 g/cm^3

It is possible to recognize from the figures that the incorporation of copper foam composite serves as a suitable method of improving the thermal performance of bio-based PCM. This is determined by observing that, regardless of the varying copper foam pore sizes, the PCM-CF composite had a lower final temperature when compared to the pure PCM under all three-heat loads of 10, 15, and 20 W. For example, the final temperatures in the PCM-CF 95PPI case are approximately 2, 3, and 4 °C lower than in the Pure PCM case for the 10, 15, and 20 W heat loads, respectively.

For a heat load of 10 W, PCM-CF 35PPI appears to indicate the most superior thermal performance, as it records a final temperature of 49.6 °C after a time interval of the 2000s. On the other hand, PCM-CF 60PPI reports the worst thermal performance, resulting in a final temperature of 51.6 °C after a period of the 2000s. The 15 W case follows a similar trend, with the PCM-CF 95PPI reporting a temperature up to 2.2 °C lower than the worst-performing PCM-CF 60PPI. The 20 W case also shows similar results with the PCM-CF 95 PPI reporting a temperature of up to 3.4 °C lower than the 20PPI, 35PPI, 60PPI, and 80PPI pore density variations. Furthermore, in the case of both 15 and 20 W heat loads, PCM-CF 35PPI appears to perform slightly inferior to the 95PPI case, reporting a final temperature of up to 1.1and 1.9 °C higher than the best-performing PCM-CF for 15 and 20 W heat load cases, respectively. In addition, PCM-CF 80PPI follows a near-identical temperature profile to PCM-CF 35PPI, with no significant difference in final temperatures.

From the variation of the heat load, it is possible to observe that the thermal efficacy of PCM-CF 95PPI increases at higher heat loads since the reported temperature difference between the 95PPI pore density and its other counterparts increased from 0.9 °C in 10 W case to 2.2 °C in 15 W case and finally 3.4 °C in 20 W case. This effect is desirable since an increased heat load would be neutralized more efficiently by the heat sink, thereby keeping the temperature of the system near-constant.

Overall, the results indicate the effectiveness of 95PPI pore densities as a means of augmenting the thermal performance of the bio-based PCM/copper foam composite to the greatest extent when compared to 20PPI, 60PPI, 35PPI, and 80PPI cases.

The time required for the heat sink PCM-Copper foam composite samples of varying pore sizes to reach a certain critical temperature is the desired measure of thermal performance. A longer duration for a sample to reach the desired critical temperature is indicative of superior thermal performance as it represents a higher rate of heat dissipation of the heat sink.

In this experimental study, three critical temperatures are identified based on phase-change temperatures for the three different input powers of 10, 15, and 20 W. These critical temperatures correspond to 40, 45,

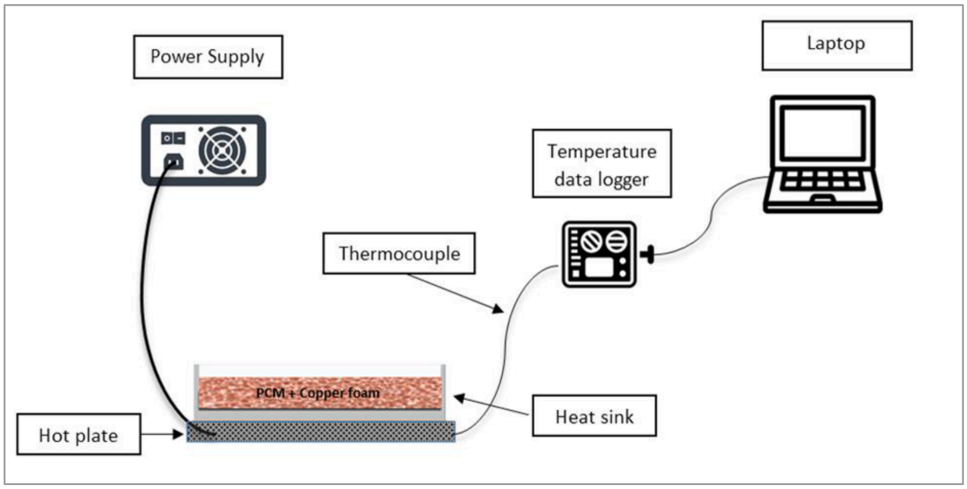

Fig. 2. A schematic diagram of the experimental setup.

Table 3
Instrument uncertainty.

Instrument	Uncertainty	Deviation
TecQuipment experiment (Heater) [Model: TD1005]	±0.1 W	0.1 W
TecQuipment experiment (K-Type Thermocouple) [Model: TD1005]	±0.2 °C	0.1 °C

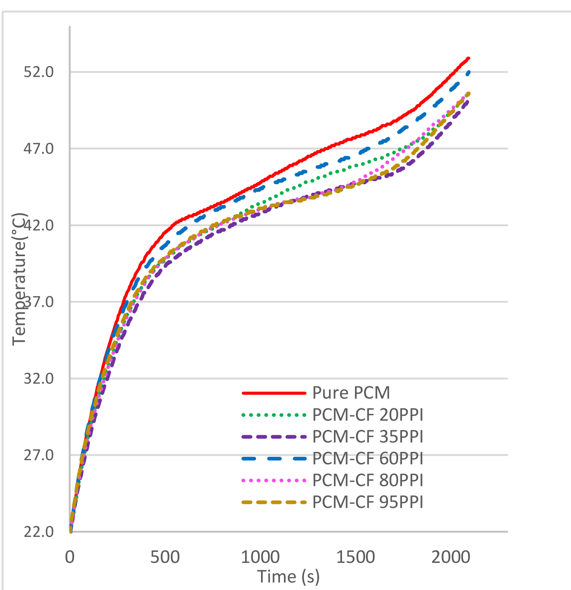

Fig. 3. Temperature profile of the heated plate at 10 W heat load.

and 50 °C for 10 and 15 W heat loads, while in the 20 W case, they are 50, 55, and 60 °C. In this regard, Figs. 6, 7 and 8 outline the results of the study for 10, 15 and 20 W heat load cases, respectively. In addition, in these figures, the time taken for a Pure PCM sample to reach the desired critical temperature is also outlined to serve as a control. It is clear that, regardless of the applied heat load or the pore density of the copper foam, the time taken for the PCM-CF composite to reach the desired critical temperature is always higher than that of the Pure PCM. For instance, comparing the duration of PCM-CF 95PPI to reach 50 °C at a heat load of 15 W with that of Pure PCM at the same heat load, the PCM-CF 95PPI composite takes 44% longer.

An additional observation, particularly important to the practical application of bio-based PCM/copper foam composite heat sinks, is that,

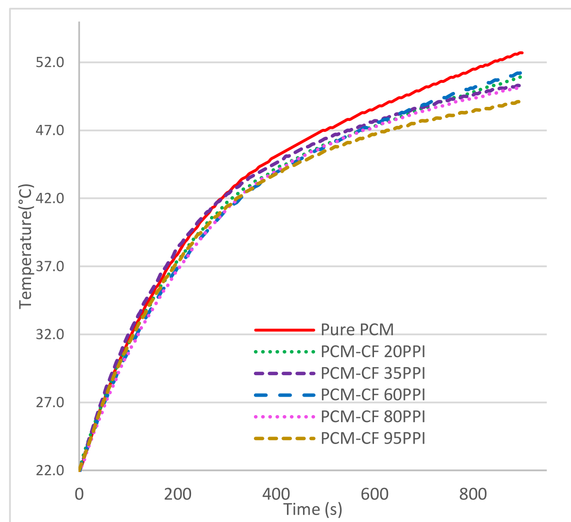

Fig. 4. Temperature profile of the heated plate at 15 W heat load.

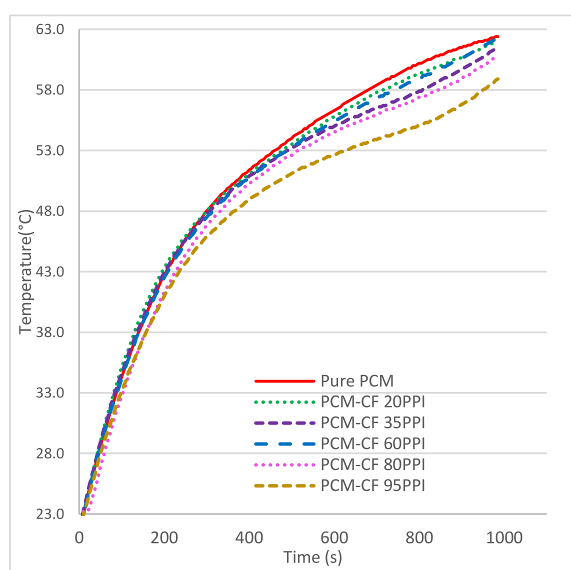

Fig. 5. Temperature profile of the heated plate at 20 W heat load.

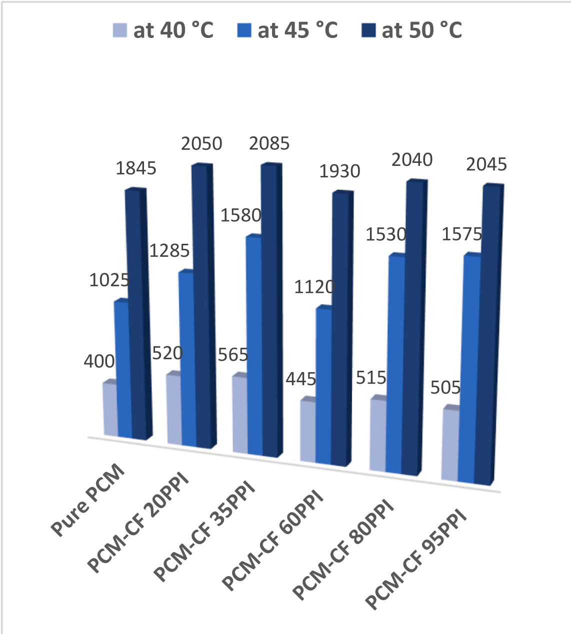

Fig. 6. Time (in seconds) taken to reach various temperatures at 10 W heat load.

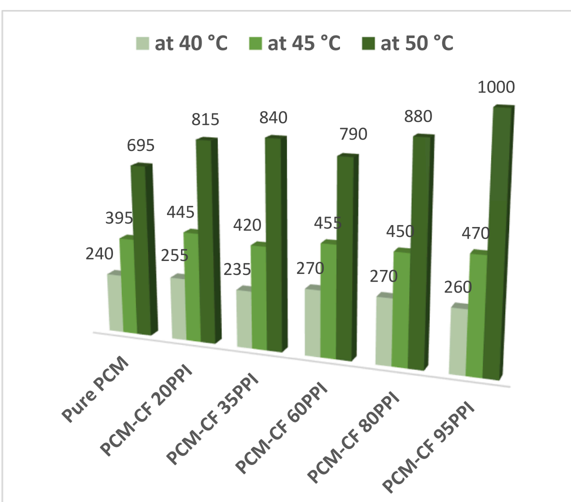

Fig. 7. Time taken (in seconds) to reach various temperatures at 15 W heat load.

as displayed in Figs. 6-8, the duration to reach a critical temperature appears to decrease significantly as the input power increases. For example, it takes 2085, 840 and 370 s for the PCM-CF 35 PPI case to reach a critical temperature of 50 °C, under 10, 15 and 20 W heat loads, respectively. This trend is also seen in all other pore density PCM-CF variations.

When variation of the thermal performance with respect to the copper foam pore density is considered, it is observed that, in most cases, PCM-CF 95PPI appears to be the most effective. Furthermore, it appears as though a general trend is followed by all three-heat load cases. This trend sees the time for the samples to reach a critical temperature rises from PCM-CF 20ppi to PCM-CF 35PPI, then drops to PCM-CF 60PPI, and then rises again to PCM-CF 80PPI, after which maximizes at PCM-CF 95PPI. For example, in 10 W heat load cases, the time to reach 45 °C increases from 1285s to 1580s for 20PPI to 35PPI cases, drops from 1580s to 1120s for 60PPI cases, and then increases sharply from 1120s

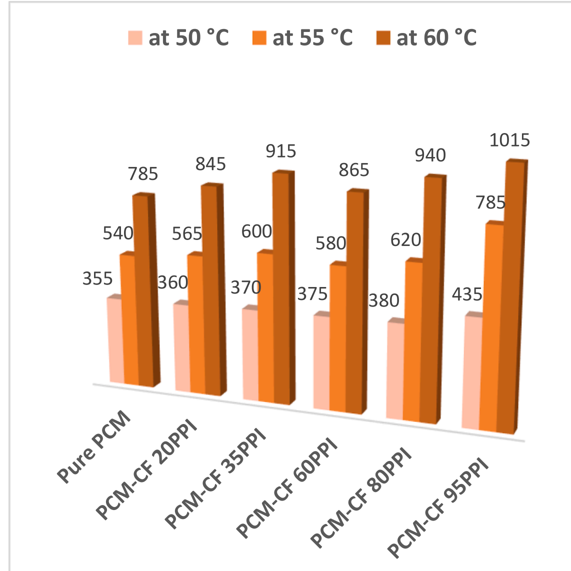

Fig. 8. Time taken (in seconds) to reach various temperatures at 20 W heat load.

to 1530s and 1575s for 80PPI and 95PPI cases, respectively. Also, 15 and 20 W heat load cases, shown in Figs. 7 and 8, follow a near-identical trend for all three critical temperatures.

Nevertheless, in most cases, it is clear that PCM-CF 95PPI appears to have the longest critical temperature achieving time when compared to its other varying pore density counterparts. PCM-CF 95PPI is followed closely by PCM-CF 80PPI and PCM-CF 35PPI with PCM-CF 60PPI reporting the shortest time. For example, if we consider the duration to reach 50 °C under 15 W heat load, PCM-CF 95PPI takes 120, 210, 160 and 185 s longer than 80PPI, 60PPI, 35PPI, and 20 PPI cases, respectively.

The results clearly indicate that PCM-CF 95PPI has the best thermal performance compared to 20PPI, 35PPI, 60PPI, and 80PPI pore density variants because it achieves a desired critical temperature more slowly based on the phase change temperature at different heat loads. In relation to the physical application of the heat sink, this suggests that a heat sink manufactured out of PCM-CF 95PPI would be able to sustain operation for an extended period of time compared to heat sinks based on pore densities of 20PPI, 35PPI, 60PPI, and 80PPI, respectively.

The enhancement ratio is a commonly used measure of the thermal performance. In this study, the enhancement ratio is defined as the ratio of the time taken for the PCM-CF composite to reach critical temperatures versus that of pure PCM. Therefore, an enhancement ratio value can be obtained for all five-pore density cases considering all three varied heat loads. Figs. 9, 10, and 11 display the enhancement ratio for all five studied pore sizes with respect to the heat loads of 10, 15, and 20 W, respectively. Additionally, it is important to clarify that an enhancement ratio above 1.00 indicates an improvement in thermal performance with respect to the Pure PCM. In addition, the value of the enhancement ratio indicates the extent to which the thermal performance of the Pure PCM has been augmented. From the figures, it is clear that in almost all cases, the enhancement ratio of the PCM-CF 95PPI is the highest in comparison to the other pore densities. For example, in the case of 20 W heat load, the enhancement ratios of the 95PPI case are reported as 1.29, 1.45, and 1.23, which are of higher order compared to the enhancement ratios of other pore density variants at the same critical temperatures and heat loads.

In addition, Figs. 9,10 and 11 also reveal that the enhancement ratio of bio-based PCM/Copper foam composite heat sinks varies with the heat load. For example, in the case of PCM-CF 35PPI at a critical temperature of 50 °C the enhancement ratio for 10 W heat load is 1.13,

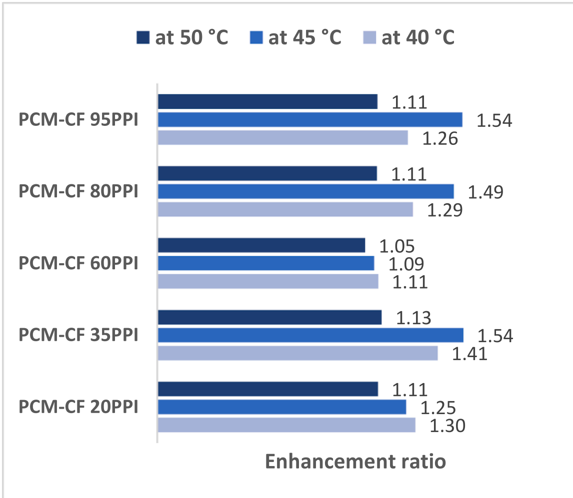

Fig. 9. Enhancement ratio of heat sinks at 10 W heat load.

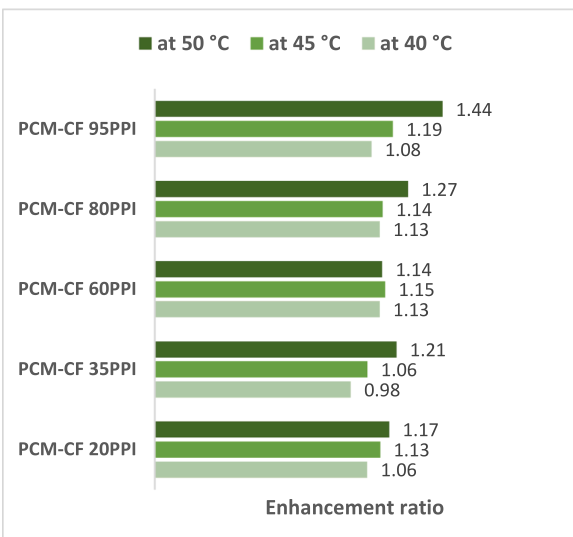

Fig. 10. Enhancement ratio of heat sinks at 15 W heat load.

whilst the enhancement ratio of 15 and 20 W loads at the same critical temperature are 1.21 and 1.04, respectively. The critical temperature of consideration also appears to influence the enhancement ratio. For instance, in the case of PCM-CF 35PPI at a power input of 10 W, the enhancement ratio for the 50 °C critical temperature is 1.13, while the enhancement ratio of 45 and 40 °C are 1.54 and 1.41, respectively. Similar variations are also observed by the PCM-CF 60PPI and the PCM-CF 20PPI.

Overall, from a holistic point of view, the results indicate that higher pore densities, or in other words, smaller pore sizes, will establish a larger contact surface between the two materials, which will in turn improve heat dissipation between the PCM and copper foam, leading to an enhanced thermal performance of the PCM composite-based heat sink.

Conclusion

The thermal performance of a bio-based PCM/copper foam composite heat sink was investigated experimentally at various copper pore sizes and heat loads. The transient temperature profiles, the time required for the heat sink to reach a selected temperature, and the heat

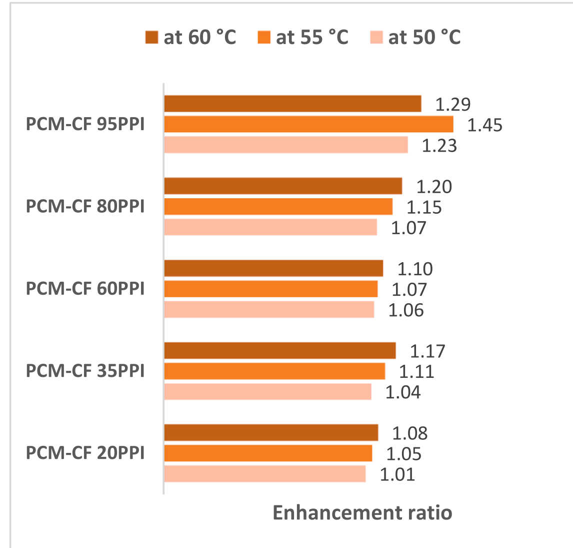

Fig. 11. Enhancement ratio of heat sinks at 20 W heat load.

sink enhancement ratios were employed as separate measures of thermal performance. The empirical research reveals two key findings. First, it confirms the effectiveness of copper foam as a technique for improving the thermal performance of bio-based PCM. Second, it illustrates that the 95 PPI copper foam pore density samples yield the best thermal performance. 80 and 35 PPI pore sizes follow as second and third, respectively, whereas 60 PPI samples show the worst thermal performance. As a result, it is feasible to infer that the PCM-CF 95 PPI is the most appropriate choice for heat sink applications. Furthermore, the impacts of the power input level on the time taken to reach a critical temperature were investigated, and the final results show that increasing heat loads (input power) results in a shorter time to reach the stated critical temperature. Finally, the impacts of heat load and critical temperature variations on the enhancement ratio were presented.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors are unable or have chosen not to specify which data has been used.

Acknowledgments

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