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Review on PCM Heat Sink for Electronic Thermal Management Application

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Abstract - **A significant challenge in thermal management has arisen as a result of the rising demand for high-performance electronic devices. The efficiency, size, and weight of conventional cooling methods like liquid and air cooling are constrained. Due to their high storage of latent heat capacity and isothermal phase transition behavior, phase change materials (PCMs) have become a promising thermal management solution. The purpose of this experimental study is to evaluate the performance of a PCM heat sink for electronic thermal regulation. The PCM heat sink is made up of a PCM module attached to a typical heat sink. To improve heat dissipation capabilities, the PCM module uses a PCM material with a suitable phase change temperature and encapsulation. The experimental setup involves simulating real-world operating conditions by applying controlled heat loads to electronic components. By observing temperature changes, thermal resistance, and transient response, the PCM heat sink's thermal performance is assessed. To evaluate the superiority of the PCM heat sink, a comparison is made with traditional air-cooled and liquid-cooled heat sink configurations. The experimental investigation's findings show that the PCM heat sink performs better in terms of thermal management than traditional cooling techniques. The phase change process used by the PCM efficiently absorbs and stores extra heat produced by electronic parts, improving temperature regulation and lowering temperature gradients. Lower component temperatures and higher operational reliability are the results of the PCM heat sink's improved thermal resistance and heat dissipation efficiency. A further benefit of the PCM heat sink's isothermal behavior during the phase transition is that it prevents temperature spikes and lessens the effects of heat stress on the electronic devices. The long cooling times provided by the PCM material's high latent heat storage capacity allow for prolonged operation without affecting device performance. This experimental study concludes by demonstrating the efficiency of a PCM heat sink for electronic thermal management. The design of heat sinks with PCM integration offers notable enhancements in temperature control, thermal resistance, and system overall reliability. The results of this research help to advance thermal management strategies, which makes it easier to create efficient electronic devices with better cooling capacities.**

Keywords: **Thermal Storage, PCM, Electronic Cooling, Performance**

I. INTRODUCTION

Researchers worldwide are actively engaged in the creative creation of new technologies to address the growing concerns about thermal management of electronic equipment and efficient cooling remedies. Electronic device failure can result from increased heat concentrations, which can potentially cause device malfunction. To prolong the lifespan of electronics and improve system performance, thermal management employing phase change material (PCM) based heat sinks is crucial. The PCM for a certain application is chosen so that its melting temperature is lower than the device's maximum working temperature. One significant benefit that aids in achieving high storage density is the high latent heat of fusion of the PCMs. The PCM's cycling stability makes it suitable for frequent use.

Despite the fact that the majority of PCMs are endowed with high latent heats of fusion, high specific heats, good chemical stability and good cycling stability, the low thermal conductivity is a cause for concern, and methods are frequently required to improve the heat transmission [1]. Various factors such as PCM layout, combination, thickness, melting temperature, and power rating were analyzed. The results demonstrated that specific PCM designs and combinations improved thermal regulation and reduced heat sink temperatures, with higher melting temperatures extending the regulation period and increasing heat sink temperature, thicker PCMs increasing regulation duration, and higher power ratings shortening the regulation time while raising heat sink temperature [2].

About PCM design then PCM inserts were also studied in which it was found that inserts play important role in on heat dissipation rate. The use of honeycomb inserts to replace machined fin structures has shown comparable thermal performance during heating and cooling with the advantage of light weight, ease of assembly and reduced cost [3]. The thermal conductivity of PCM heat sink can be increased by developing efficient Topology structure which can be used to study functionality of design where it is seen that the tree-like structure heat sink exhibited lower Tw values than the fin-structure heat sink by up to 4 ◦C under the same heat flux for the same PCM. The tree-like structure heat sink has demonstrated an increase in operational time by approximately 8 times as compared to the case where no fin structure was used and up to 13% as compared to the conventional fin-structure design [4].

II. TYPES OF PCM HEAT SINKS

A. Cavity Based Heat sinks (Using Single or Multiple PCM)

In this type of PCM cavity is created in which PCM is filled and thus by applying varying factors the performance is tested.

The experiment involves the manufacturing of four heat sinks to investigate the impact of phase change material (PCM), PCM thickness, and PCM arrangements on heat dissipation. The heat sinks include one without PCM (consisting of a heat source attached to a metal plate) and three with PCM denoted as A, B, and C.

Heat sinks A and B have a single cavity each, while heat sink C has two separate cavities, all made of clear acrylic. The purpose of the experiment is to observe the melting profile of the PCMs and analyze the effects of PCM type, PCM thickness, and arrangement on heat transfer within the heat sinks [2].

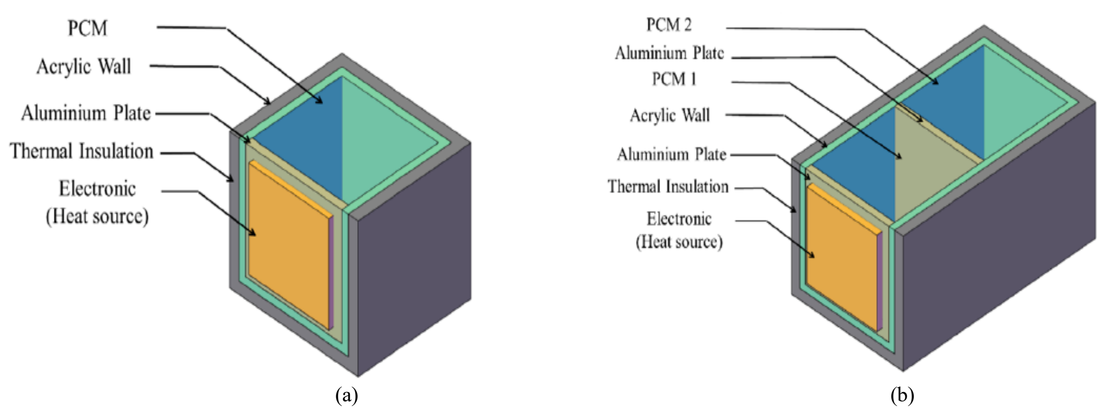

Fig. 1 Schematic of the (a) heat sink A&B, (b) heat sink C [2]

B. Metallic Foam Heat Sink

In these various metals are used. Copper foam matrix is used as PCM based Heat sink for investigating thermal performance. To enhance the thermal conductivity, a copper open cell metal foam is press-fitted into an aluminum casing. Two enhancement ratios were calculated to quantify the effectiveness of the heat sink. The first ratio, comparing the operation time of the heat sink with and without a metal matrix filled with PCM, showed a 7.5-fold increase in operation time for the PCM-filled heat sink. The second ratio, comparing the operation duration of the PCM-filled heat sink with a metal matrix to that without PCM, indicated a 3-fold increase in operation time. Similar results were obtained for an aluminum metal foam-filled PCM heat sink. The study also investigated the impact of heat sink orientation on its performance and found that the heat transfer performance remained comparable across different orientations. Furthermore, orientation did not significantly affect the heat transfer performance of the metal foam-filled PCM heat sinks [5]. The studies were also conducted in hybrid cooling and copper foam is found to be one of the best configuration in forced or natural convection at higher heat fluxes i.e., 2.5 and 3 kW/m2 [6].

C. PCM Heat Sink with Fins

It is most widely used type of heat sink as we know that fins provide more surface area to dissipate heat into atmosphere. The fin based heat sink matrix filled with PCM demonstrated an operating time enhancement of over 4 times compared to a heat sink matrix without PCM, at a set point temperature of 42 °C and a power level of 8 W [7]. The study discovered that depending on the heat flow value, different heat sink configurations had different running times and enhancement ratios.

The four-finned MF-PCM heat sink worked best for heat flux values of 1.3 and 2.0 kW/m2, whereas the three-finned MF-PCM heat sink performed better for a heat flux of 2.7 kW/m2, offering higher heat transfer rate and thermal conductivity [8]. In the preliminary investigation, phase change materials (PCMs) and various pin-fin topologies were used to examine various passive cooling issues for integrated circuits. The most efficient pin-fin shape without PCM was discovered to be triangular, followed by rectangular and circular pin-fins. Triangular pin-fins continued to be the most efficient after the development of PCMs, which can be due to their higher number and surface area ratio.

According to the examination of Stefan numbers, SP-31 was the best choice for a critical set point temperature (SPT) of 45 °C because it had the lowest Stefan number and paraffin wax had the highest. RT-54 was shown to be the most efficient PCM for a triangular pin-fin structure at an SPT of 60 °C, whereas RT-44 was the best option for all three heat sinks at this temperature [9].

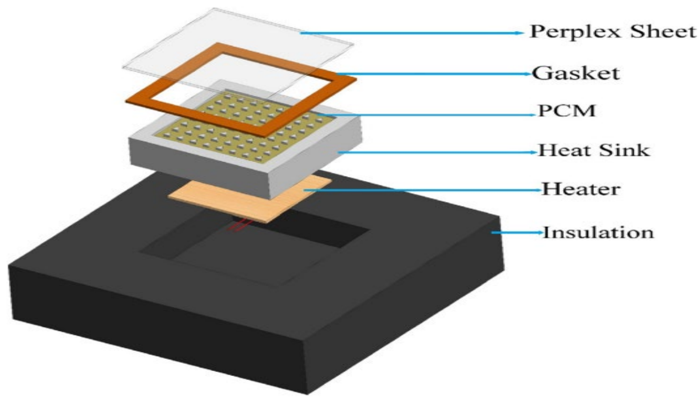

Fig. 2 Exploded view of the heat sink assembly [9]

D. Heat Sink Design and PCM Selection

A heat sink consisting of the 98% pure aluminum alloy 6063 is used in the experiment. It is affordable, lightweight, and has good thermal conductivity. On an aluminum block, the heat sink is produced via electrical discharge machining (EDM). There are 12 thermocouple holes in the heat sink's base, which is 5 mm deep. Three rectangular slots filled with phase change material (PCM) are also present. For each example, the PCM volume remains constant. The PCMs used are 1-hexadecanol and paraffin wax since they don't corrode aluminum and have enough latent heat. Table I provides a list of specific features [10].

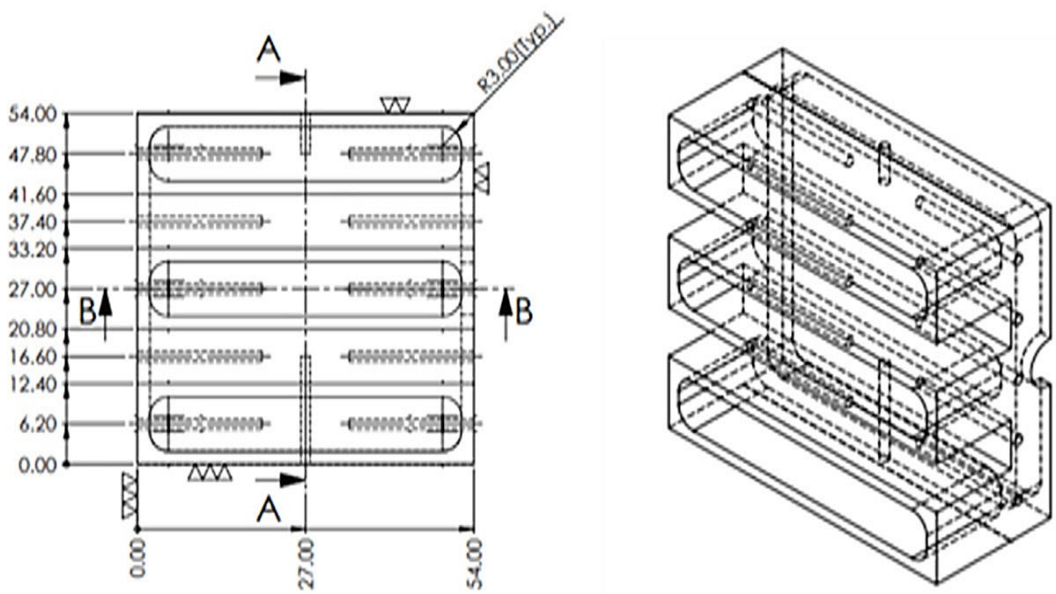

Fig. 3 Heat sink dimensions: (a) front view and (b) side view [4]

TABLE I THERMO PHYSICAL PROPERTIES OF PCM [10]

Materials	Melting point (°C)	Specific heat (J/kg K)	Density (kg/m^3)	Latent heat (kJ/kg)	Thermal conductivity (W/m K)
Paraffin	58–60	2,540	920	189	0.21
1-heaxadecanol	48–50	2,120	811	226.1	0.3

III. LITERATURE SURVEY

J. Y. Ho *et al.,* [4] This research study mainly emphasis on improving the thermal performance of phase change material (PCM)-based heat sinks using a topology optimization (TO) strategy. The goal is to develop enhanced structures that effectively dissipate heat through the high latent heat of fusion of the PCM. The study involves comprehensive numerical simulations considering steady-state heat conduction and transient heat conduction with phase change. The TO process results in a tree-like structure for the heat sink design, which is fabricated using selective laser melting (SLM), a metal additive manufacturing technique. Experimental characterization is conducted using three types of PCMs (RT35, RT35HC, and RT44HC) and different heat fluxes. The results demonstrate that the TO tree-like structure heat sink outperforms conventional fin-structure heat sinks, with up to 4°C lower wall temperatures. The choice of PCM depends on the heat flux, with RT35HC performing better at low heat fluxes and RT44HC achieving lower wall temperatures at high heat fluxes. Additionally, the tree-like structure increases operational time by up to 13% compared to the fin-structure design.

The improved thermal performance of the tree-like structure heat sink is attributed to optimized heat conduction paths that efficiently dissipate heat to the PCM. The study suggests the potential of TO PCM-based heat sinks for enhancing electronics cooling and provides guidelines for the design and implementation of TO structures for other cooling applications. The research highlights the ease of transitioning design concepts to physical prototypes through the combination of TO and SLM. Future work may consider the effects of natural convection during PCM melting in optimizing heat sink designs.

Idris Al Siyabi *et al.,* [2] The study examined the thermal performance of a small-scale heat sink based on phase change materials (PCMs) for electronic thermal control. A number of variables were taken into account, including PCM layout, combination, thickness, melting temperature, and power rating. The outcomes demonstrated that some PCM designs and combinations enhanced thermal regulation and decreased heat sink temperatures. Higher melting temperatures increased both the thermal regulation period and heat sink temperature, whereas increasing PCM thickness increased the thermal regulation duration. Furthermore, greater power ratings shortened the regulating time while raising the heat sink temperature.

Rajesh Baby *et al.,* [7] Experimental investigations were conducted to quantify the heat transfer performance of a PCM based plate fin matrix for both constant and intermittent heating conditions. The study establishes the need to characterize, quantitatively by way of experiments, the behavior of such heat sinks under intermittent operation as a design based on continuous heat duty will be oversized, more expensive and sub-optimal. The plate fin heat sink matrix is made from an aluminum slab of overall dimensions 80x62 mm^2 base with height of 25 mm using the conventional milling process. The thickness of the fins used is 1.4 mm with a height of 20 mm. Generally, PCM should meet the following requirements. The melting temperature of the PCM should be lower than the maximum temperature of the device. The ratio of the total volume of fins to the empty heat sink volume is taken as 15% for the present study, based on earlier studies wherein this volume fraction of the heat sink gave the best heat transfer performance for plate fin heat sinks.

Nandan, R. *et al.,* [10] Due to the heat generated by the miniaturization of electronic devices, reliability problems have arisen. Finned heat sinks (FHS) made of paraffin-based PCMs have limited thermal conductivity, yet they provide passive cooling. By integrating fins with PCM and taking into account variables like input power and PCM layout, research is primarily focused on optimizing PCM-based FHS. In a study, multiple PCMs are compared, and thermal behavior under varied power input and the influence of a fan are analyzed in order to evaluate a PCM-based FHS for cooling a CPU chip.

Rohit kothari *et al.,* [8] The thermal performance of heat sinks based on phase change materials (PCMs) for cooling mobile electronic devices is the main topic of the experimental study. Tests are conducted using various heat sink configurations and input heat flux values. The addition of PCM enhances thermal control while lengthening the operating period needed to reach the specified temperature. Performance-wise, metal foam (MF)-PCM composite heat sinks outperform standalone PCM heat sinks. Heat flux and heat sink configuration affect operating time and enhancement ratio. Higher heat flux values benefit more from MF-PCM heat sinks. Four-finned MF-PCM heat sinks have the highest enhancement ratio. The conclusions highlight the advantages of heat sinks based on PCM technology as well as the effects of various variables on their thermal performance.

TABLE II THERMO PHYSICAL PROPERTIES OF PARAFFIN WAX, TCE, AND INSULATOR [8]

Properties	Paraffin Wax (PCM)	Aluminium (TCE)	Plexiglass	Ceramic Glass Wool
Melting Temperature (°C)	58-62 (Datasheet)	660.37	-	-
	61.5 (DSC curve)			
Latent Heat (kJ/kg)	194.2	-	-	-
Specific Heat (kJ/kg-K)	2.89	0.896	1.470	
Density (kg/m	750 (liquid)	2719	-	128
	900 (solid)			
Thermal Conductivity (W/m-K)	0.12 (liquid)	218	0.19	0.12
	0.21 (solid)			

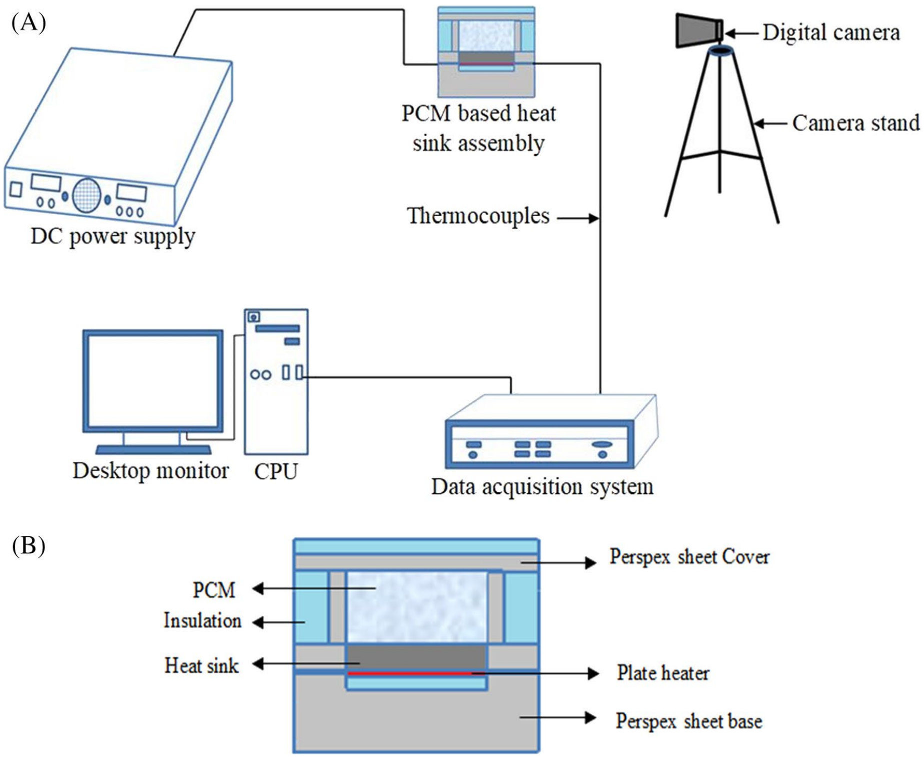

Fig. 4 Schematic experimental setup (A) and PCM heat sink assembly [8]

M. Mozafari *et al.,* [11] The study focuses on the use of heat sinks embedded with phase-change materials (PCMs) for passive thermal management of electronic devices. Investigations into various PCMs and heat fluxes are done to evaluate the thermal performance of each. In comparison to single PCM cases, the results demonstrate that a mixture of n-Eicosane and RT44 PCMs obtains the best overall thermal performance, in longer operational times and lower peak temperatures. The study favors the use of PCMs heat sink designs for equipment with high critical temperatures.

IV. CONCLUSION

To avoid device failure brought on by excessive heat, effective cooling systems and thermal management of electronic devices are essential. Heat sinks made of phase change material (PCM) have emerged as a possible solution to these problems. High latent heat of fusion, cycle stability, chemical stability are only a few advantages of PCM heat sinks. However, due to their poor thermal conductivity, researchers have looked into a number of ways to increase heat transmission. Studies have been done on a variety of PCM heat sink designs, including finned heat sinks, metallic foam heat sinks, and cavity-based heat sinks. These heat sinks' thermal efficiency, capacity for heat dissipation, and duration of operation have all been assessed. To improve their design and performance, experimental studies, numerical simulations, and optimization approaches have been used. According to research, PCM-based heat sinks are capable of controlling temperature, lowering heat sink temperatures, and extending the life of electronic devices. Performance of the heat sink is greatly influenced by the PCM selection, as well as by its arrangement, combination, thickness, melting temperature, and power rating. In comparison to traditional fin-structure heat sinks, optimized designs, such as tree-like structures and topology optimization, have shown greater thermal management and lower wall temperatures. PCM heat sinks with integrated fins have demonstrated improved thermal control and longer running times. Compared to freestanding PCM heat sinks, metallic foam-filled PCM heat sinks have performed better. It has been discovered that the usage of particular PCMs and optimized heat sink topologies can improve cooling effectiveness and optimize heat transmission.

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