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A Review of the Thermal Phase Change Materials (PCM) and Metal Foams for Electronic Chips Cooling

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Abstract

Heat sinks, a type of heat exchanger used due to the simplicity of fabrication, low cost, and reliable heat dissipation, are widely employed to cool electronic devices. In recent decades, heat dissipation has remained a critical challenge in optimizing the thermal performance of heat sinks. Therefore, to ensure optimal performance and reliability, effective heat removal from these devices is essential across various operational conditions. This comprehensive review examines various methods for enhancing the thermal design of heat sinks. It includes investigations into both passive and active techniques that modify the solid or fluid domain to improve heat removal. The study encompasses different approaches, focusing on perforated plate-fin heat sinks, phase change materials (PCM) enhanced by metal foam, active cooling techniques, and cost optimization. The literature revealed a strong preference for plate fins as the primary heat sink design, comprising 70% of the investigated studies. Pin fins were utilized in 15% of cases, while a hybrid configuration incorporating both plate and pin fins was observed in the remaining 15%. The integration of fins with the chosen PCM significantly accelerated the melting process, leading to an average improvement in thermal performance. The composite incorporating foam and PCM demonstrated a substantial improvement in thermal conductivity. This study aims to summarize existing research efforts, identify limitations, and explore potential solutions for advancing the thermal performance of heat sinks.

Keywords- Heat sink, Fins, PCM, Metal foam, Thermal performance.

I. INTRODUCTION

Electronic thermal management involves the efficient removal and subsequent transfer of heat generated by individual components to a dedicated heat sink within the system. Electronic device manufacturers set a maximum allowed operating temperature. Excessive overheating of an electrical device can compromise its performance, lifespan, and lead to potential damage.

In many electronic devices, such as central processing units (CPUs), input watts are converted to external heat during use. Overheating electronics can also cause overheating or irreversible damage. Thus, a cooling system is essential to ensure that hot electronic components remain cool and operate at a specific temperature. Cooling systems can be divided into two categories: passive cooling and active cooling. Passive cooling is a fanless system that uses a Phase change material (PCM) with a temperature controller to cool electronic chips. PCM heat sinks exhibit the exceptional ability to manage high temperatures during transient events, making them particularly suitable for space-based applications where conventional convection cooling is ineffective due to low thermal conductivity for thermal management, which prevents their widespread adoption. Researchers have investigated various heat transfer techniques to address these limitations and improve the thermal efficiency of PCMs. These techniques include embedding heat pipes [1], incorporating metal foam structures [2-4] and dispersing nanoparticles within the PCM matrix [5-7].

Plate-and-pin fin heat sinks are widely utilized in thermal management applications, ranging from electronic components in personal devices to advanced gas turbine blades [8-10]. Jehhef [11] demonstrated the superior thermal performance of nanofluids over conventional liquid coolants, evidenced by improvements in average efficiency and Nusselt number. Meanwhile, perforated fin designs have shown advantages in air-side heat transfer compared to other plate fin configurations. Nanofluids have been shown to significantly enhance heat transfer coefficients within heat sinks subjected to high heat fluxes [12, 13]. Gholinia et al. [14] further investigated the potential of titanium oxide nanoparticles in combination with perforated nozzles and paddle blades. Their study revealed a progressive increase in heat transfer with rising nanoparticle concentrations (0.01 to 0.05), leading to a corresponding reduction in peak temperatures within the study region. Holizadeh et al. [15] revealed that the type of nanofluid and the shape factor of nanoparticles were influential parameters in mitigating exhaust gas temperatures in diesel engines. Sheikholeslami and Khalili, [16] introduced the application of nanofluid filters to enhance the efficiency of concentrated photovoltaic thermal modules. The suggested

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solar system used nanofluid as a cooling fluid and spectral filter. The results showed that as the concentration ratio increased from 3 to 30, a drop of approximately 13.57% was observed in electrical performance, while thermal performance exhibited a corresponding enhancement of about 5.68%. Rajput et al. [17] studied numerically the convection heat transfer from fin with a different number of perforations and hole diameters. According to the study, as perforations expand, the heat transfer rate increases up to a specific size and then reduces. Heat transfer enhancement of the perforated fin increases as perforation diameter and number increase. Bianco et al. [18] investigated the performance of non-finned and finned metal foam heat sinks to optimize heat transfer rates while minimizing pumping power consumption. The result showed a 3.3–3.5 times enhancement in dissipated heat rates for the finned metal foam heat sink compared to the metal foam heat sink under identical pumping power conditions.

Thamir et al. [19] investigated experimentally and numerically the effect of shape and geometry on the perforation of perforated fins on heat transfer. Triangular, rectangular and circular solid fins were used. The circular perforation exhibited the maximum temperature difference between the tip and base of the fin was about (45.57 %), (51.29 %) for rectangular perforation, followed by the triangular shape of perforation at (42.28 %), then finally (35.82 %) for nonperforated fins. Abbas et al. [20] also showed that as perforations increased, heat transmission coefficient increased and temperature difference reduced. Furthermore, as the number of holes in the fin rose, the heat transfer coefficient and rate also increased. Wadhah and Abdul Razzaq [21] focused on improving heat transmission from rectangular fins with circular perforation through natural convection. They found that when the power was turned on, the temperature for perforated fins reduced from (30-23.7) °C while the temperature for nonperforated fins declined from (30-25) °C (6W). Additionally, the results exhibited that as the hole diameter increased, the gap between the tip and base increased. The temperature for the perforated fins dropped from (250-36°C) at (220 W). Mahdi et al. [22] employed two mathematical models, the Boussinesq approximation and the enthalpy-porosity method, to investigate the phase change behaviour of the PCM. The findings showed a significant influence of orientation on the performance of the latent heat storage units, with distinct behaviour observed in horizontal and vertical configurations.

Furthermore, the study confirmed that the impact of fin geometry on natural convective heat transfer is demonstrably dependent on both the specific geometrical arrangement of the fins and the relative orientation of the flow. Kandasamy et al. [23] reported a direct correlation between increased input power (within the 2–6 W range) and enhanced transient cooling performance of PCM-based heat sinks. Additionally, PCMs with higher melting points exhibited minimal influence on heat transfer at lower power levels. Hasan and Hussain [24] revealed a positive correlation between decreasing metal foam porosity and the thermal performance of the heat sink. The incorporation of metal foam resulted in a significant improvement in the thermal performance of the Cascade Thermal Energy Storage system, as evidenced by the enhancement of both the total thermal power and the average Nusselt amount of heat transfer fluid within the system. Specifically, the total thermal power increased by a range of 16.82% to 35.23%, while the average Nusselt number exhibited an improvement between 24.25% and 42.03%. Hussain and Jasim [25] experimentally showed that adding 10 PPI metal foam to wax increased its thermal conductivity by 37 to 39 times. The impact of metal foam presence, mass flow rate, and pore density (10 and 40 PPI) on the solidification and melting processes were also investigated. Ding et al. 2022 [26] reported an initial decrease in melting time and heating wall temperature with an increasing copper foam fraction within the hybrid fin-metal foam structure, followed by a subsequent rise in both parameters. Hadi et al. [27] investigated the transient behaviour of a solar power plant equipped with a parabolic receiver across six geographically distinct locations in Iran. The investigation focused on the impact of integrating a latent heat storage system on the plant performance. They should say that north-south tracking demonstrably enhances collector energy absorption by reducing the angle of incidence.

Existing literature and previous studies have demonstrated a shortage of research investigating features, which are the integration of PCM with active cooling heat sinks, the substitution of foam fins for solid fins in passive heat sinks, and cost optimization strategies for heat sinks. This review aims to provide a comprehensive guide to the thermal management of electronic components utilizing plate fins heat sinks. Specifically, it investigates the application of PCMs, focusing on organic and composite PCMs due to their widespread use in electronic chip cooling. The role of metal foam in enhancing the thermal conductivity of PCMs is critically examined. Additionally, active cooling techniques and cost optimization strategies are discussed. Each section of this review presents a concise overview of the key parameters influencing the performance of heat sinks.

II. PLATE FIN HEAT SINKS

Rectangular plate-fin heat sinks are widely used in industrial applications due to their simple configuration and manufacturing efficiency. Researchers have employed experimental and computational techniques to address the inherent limitation of laminar flow in parallel heat sink channels, which constrained the maximum heat transfer capacity.

The effect of the thickness, number, height, and length of fins was investigated by [28]. They reported the achievement of the target core temperature of 65 °C through a combined strategy: increasing the number and height of fins while concurrently reducing the fin thickness. Because of the way these geometric factors interact, there is a possibility that the mass of the heat sink may grow by around 24% of the original mass, but the temperature will drop significantly. They suggested expanding the use of the approach that they had developed to investigate several different kinds of heat sinks. Li and Chao [29] experimentally indicated that the heat sink with the tallest fins outperformed the others in terms of thermal performance while keeping the width of the fins constant.

Conversely, the optimal fin width, corresponding to the highest thermal performance, exhibited a positive correlation with increasing Reynolds number (Re). In contrast, the fin height remained constant. Flow passageways are restricted in fins that have a greater width. Thinner fins resulted in a reduction of heat transfer capacity in the heat sink area. In both cases, the thermal efficiency of the heat sink was reduced. Optimizing the fin width for every range of Re numbers was generally recommended. Muhammad [30] and Yang et al. [31] showed that by filling the inline finned heat sink with 90% of various PCMs, the thermal conductivity of the heat sink was improved. As a result, the heat sink performs superiorly when removing heat. The inline design guarantees that the temperature of the PCM is evenly distributed upon integrating the PCM into the heat sink. This allows the PCM to transmit the maximum amount of heat possible.

Arshad et al. [32] investigated the flow field and heat transfer characteristics of PCM-based fin heat sinks with 2 mm and 3 mm thicknesses. Numerical simulations showed that increasing the pore thickness from 2 mm to 3 mm at a power of 4-6 W resulted in a longer melting time of PCM. The observed increments were 6.63%, 3.59%, and 1.90%, respectively. Furthermore, a consistent trend is observed where the temperature rise is demonstrably lower with a fin thickness of 3 mm compared to a thickness of 2 mm. Therefore, with a 3 mm fin thickness, it is recommended to utilize a more appropriate number of fins. Rostamian et al. [33] explored the thermal performance of heat sink configurations incorporating both pure and microencapsulated PCMs. They showed that the square heat sink with seven fins exhibited superior performance compared to configurations utilizing either a square geometry with three fins or a circular design with twelve fins. It has been determined that the geometric structure, as well as the number of fins, can have an effect on the rate of heat transmission.

Sahoo et al. [34] observed that an excessive fin number within the domain impeded PCM convection, then limiting further heat transfer enhancement. Because it confirmed that Natural convection within the PCM was confirmed to contribute to a reduction in heat sink base temperature, it was determined that an increase in the fin number led to a delay in the commencement of melting. This occurred owing to instantaneous heat conduction through the fins. However, PCM began to melt in many locations on the fins, resulting in PCM melting in a shorter period. However, for a fixed heat sink domain, increasing the fins number at the expense of PCM volume can compromise the performance due to reduced PCM capacity.

Nevertheless, if the volume of PCM remains constant and the number of fins increases, the size of the domain will also increase. Therefore, the enhancement of heat sink performance is contingent upon the sacrifice of size, cost, and weight. Also, observed that plate fins were employed in 70% of the analyzed studies, as indicated in Figure 1, due to their ease of manufacture.

Therefore, it is evident that doing optimization research is necessary to figure out how many fins should be in a given area for the heat sink to work best. While an increase in fin count demonstrably reduces the base temperature, it limits how long electronic equipment can be used because there is less PCM, which means there is less time for latent heating. So, the fins number should be carefully selected based on how long the electronic equipment will be used and the highest temperature it can handle.

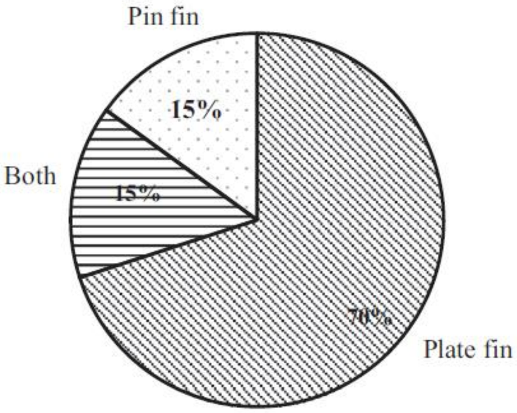

Figure 1. Types of fins used in the analysis for previous research in the case of finned Heat Sink [34]

III. PERFORATED FINS

Perforated fins significantly enhance the thermal and hydraulic performance of heat sinks. This enhancement can be attributed to their ability to disrupt vortices and boundary layers that typically form behind solid plate fins and pin fins. Moreover, the incorporation of perforated fins offers the advantages of reduced weight and minimized material consumption within the appliance design. [17] and [35] employed two forms of circular perforation with different diameters (12 and 10 mm) and different numbers of holes (8 and 10) while taking into account that the size of the cut metal in both types of perforation is fixed. The experiment results showed that the perforated fins performed better in heat transmission than solid fins. In order to obtain the same area and size of the cut, as well as the same weight for the perforation utilized, it was able to establish the entire area of the cut-off section and then divide it by the number of holes necessary to analyze it.

Al-Doori [36] focused on improving the heat transmission from rectangular fins with circular perforation through natural convection. They found that when the power was turned on, the temperature for perforated fins reduced from (30-23.7 °C) while the temperature for nonperforated fins declined from (30-25 °C) at (6W). Additionally, the results exhibited that as the hole diameter increased, the gap between the tip and base increased. The temperature for the perforated fins dropped from (250-36 °C) at (220 W). Al-Jessani and Al-Bugharbee [37] also showed that as perforations increased, the heat transmission coefficient increased and temperature difference reduced.

Furthermore, as the number of holes in the fin rose, the heat transfer coefficient and rate also increased. Rajput and Kulkarni [38] studied numerically the convection heat transfer from fin with a different number of perforations and hole diameters. According to the study, as perforations expand, the heat transfer rate increases up to a specific size and then reduces. Heat transfer enhancement of the perforated fin increases as perforation diameter and number increase.

Ibrahim et al. [39] investigated the influence of perforation shape and geometry on heat transfer in perforated fins experimentally and numerically. Triangular, rectangular and circular solid fins were used. The circular perforation exhibited the maximum temperature difference between the tip and base of the fin was about (45.57 %), (51.29 %) for rectangular perforation, followed by the triangular shape of perforation at (42.28 %), then finally (35.82 %) for nonperforated fins. Hiba and Ihsan [40] studied the effect of the perforation on the thermal performance of the heat sink, as shown in Figure 2. They showed that the perforations cause a temperature increase of around 5.3% when the fin is perpendicular to the horizontal plane and a temperature decrease of about 20.4% when the fin is parallel to the horizontal plane in the natural convection. When compared to the heat sink without perforation and 15 perforations under natural convection, the temperature increases by approximately 1.33% and 2.6%, respectively, when the computer case is vertical and horizontal. However, forced convection perforation results in a temperature reduction of roughly 3.53%. Meganathan et al. [41] showed that high heat transfer is achieved via the rectangular fin with perforations, which has better thermal performance and uses less material compared with the normal heat sink.

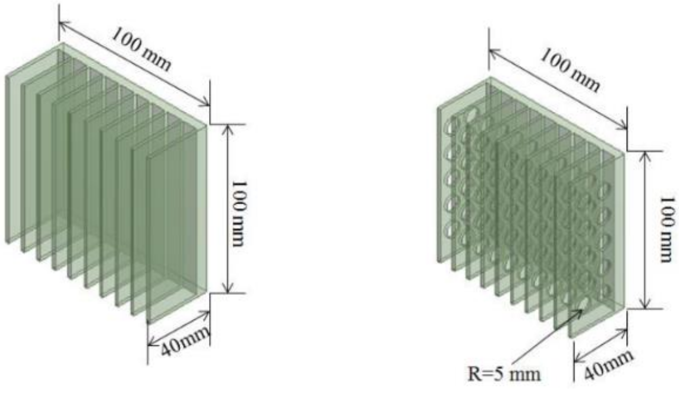

Figure 2. Schematic diagram for perforated heat sinks [39]

IV. PCM-BASED HEAT SINK

The PCM has been widely employed in various sectors, and it offers benefits in electronic thermal management. To optimize PCM utilization and enhance thermal management performance, the PCM is usually paired with other heat sink kinds, like plate-fin, rather than being used directly for the integrated circuit or package, as shown in Figure 3 [42]. PCMs are broadly classified into three categories: solid-liquid, solid-solid, and liquid-gas. Among these, solid-liquid PCMs are often favoured for thermal energy storage due to their favourable properties. Within the solid-liquid category, organic, inorganic, and eutectic PCMs are distinguished, as shown in Figure 4 [43].

The ability of the PCM to efficiently absorb, store, and release heat plays an important role in enhancing the cooling capacity. As a result, many studies have focused on improving PCM thermal performance [44] and [45]. Yang et al. [46] developed a new PCM, a stainless steel, which exhibits excellent thermal conductivity and latent heat. Krishna et al. [47] deposited trichocene and Al 2 O 3 nanoparticles. According to the findings, nanoparticles encapsulated in PCM have the potential to increase thermal conductivity up to 32%. Ghanbarpour et al. [48] prepared a new composite PCM by adding polyethene glycol to mesoporous carbon FDU-15 using the melt impregnation method. This new composite exhibited a significant increase of 60% in thermal conductivity.

Farzanehnia et al. [49] investigated the direct incorporation of multi-walled carbon nanotubes into paraffin wax for the fabrication of nano-PCM composites and showed that PCM and MWCNTs reduced the cooling time by 6% and the peak temperature of the integrated circuit fatigued. Arshad et al. [50] suggested incorporating various nanoparticles and composite materials into the PCM. This approach aimed to synergistically improve thermal conductivity, melting time, heat storage capacity, and heat transfer rate density. As previously discussed, PCM is often integrated with various heat sink designs, with pin-fin configurations demonstrating superior adaptability. Sunku Prasad et al. [10] conducted a comparative study of conventional and PCM hybrid heat sinks to evaluate their thermal performance at constant and variable temperatures, as shown in Figure 5. The PCM heat sink demonstrated a comparable base temperature to the conventional heat sink while exhibiting a heat transfer coefficient within the range of 30 to 40 W/m^2K during steady-state operation. Throughout the cooling phase, hybrid heat sinks exhibited a ten-fold lower reduction in the heat transfer coefficient compared to PCM heat sinks. The conventional heat sink has failed to control the base temperature below the SPT even at h = 50 W/m2-K. Practically unacceptable peak temperatures (higher than 125 °C) are reached for conventional heat sink under variable heat flux condition, as shown in Figure 6.

Mozafari et al. [51] evaluated different PCM couples by having them fill up different enclosures individually. They reported that the different PCMs couples of RT44/n-Eicosane are practicable for high critical temperature devices due to the lowest average transient temperature and longer operating time. Mahdi et al. [52] investigate the thermal behaviour of paraffin wax Melting temperature range (48.3–62 °C) during the melting process within a shell-and-tube latent heat storage unit by analyzing various configurations and orientations. The incorporation of fins in conjunction with the selected PCM demonstrably accelerated the melting process, with an average observed enhancement of 50%.

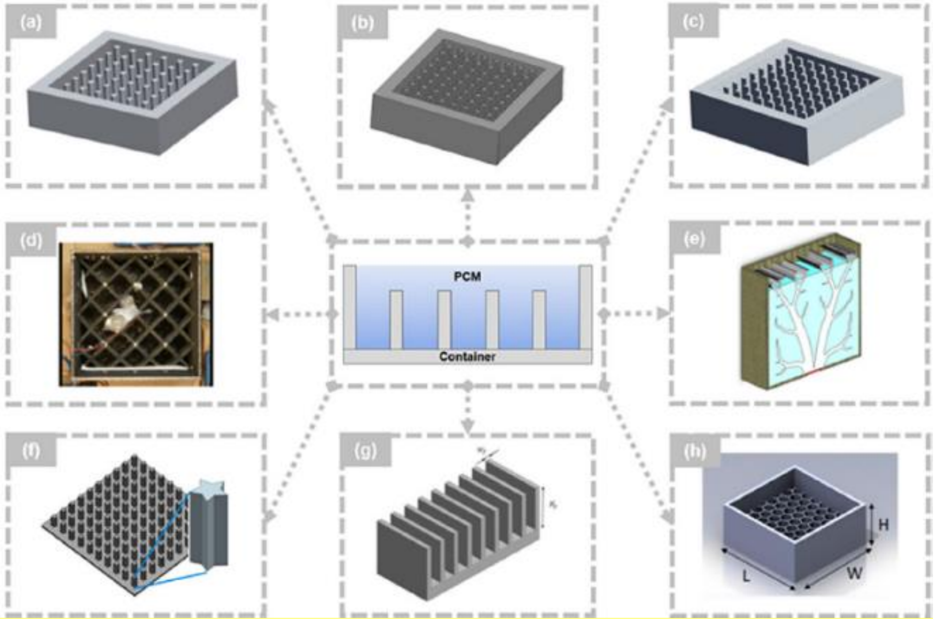

Figure 3. Types of Heat Sink Combined with PCM [42]

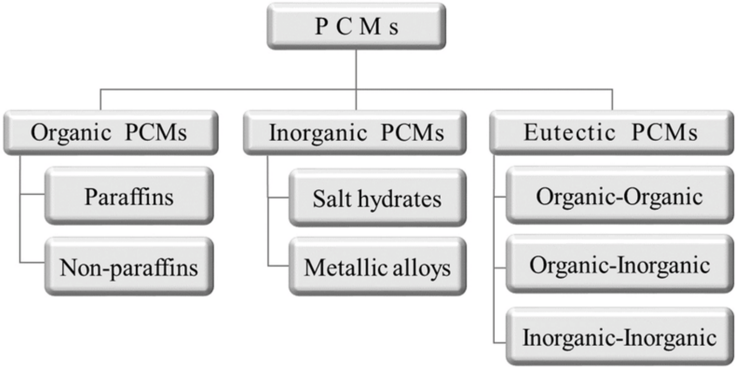

Figure 4. Types of PCM used in the Thermal Management of Electronic Chips [43]

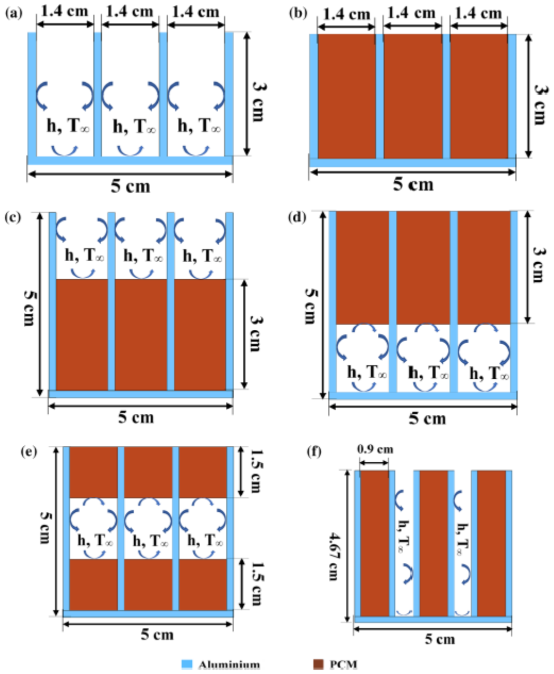

Figure 5. a. Conventional heat sink, b. PCM heat sink, c. hybrid heat sink-1 (HHS-1), d. hybrid heat sink-2 (HHS-2), e. hybrid heat sink-3 (HHS-3), and f. hybrid heat sink-4 (HHS-4) [10]

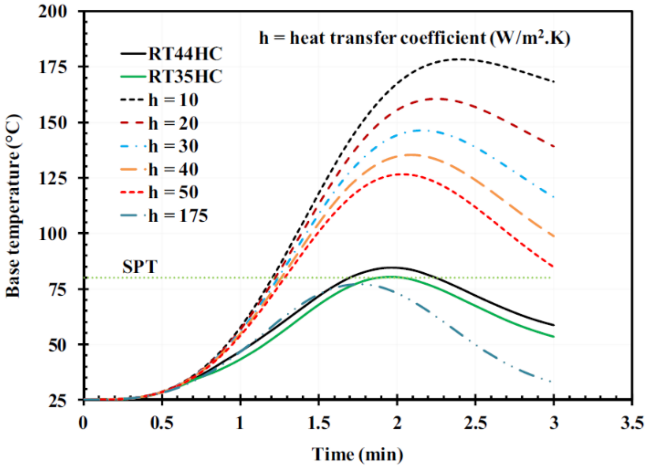

Figure 6. Comparative analysis of base temperature variations in conventional and PCM heat sinks under varying heat flux [10]

V. METAL FOAM-BASED HEAT SINK

The combination of metal foams and PCMs has emerged as a promising approach for thermal management in cooling systems. The low density of metal foams and their superior thermal conductivity contribute to improved system performance. The ability of PCM to store and release latent heat effectively mitigates the thermal energy generated by electronic components, while the metal foam structure facilitates efficient heat transfer within the PCM and to the surrounding environment. Researchers have employed metallic fins for heat transfer between the heat source (chip) and the PCM. However, these investigations highlight the challenge of achieving uniform heat distribution through the fins. Also, Metallic fins have the inherent drawback of adding weight to the electrical system. In response to the aforementioned limitations, researchers have turned to the utilization of metal foam as a promising strategy, which improved the cooling system's performance and reduced its weight [53]. The porous media approach was used to analyze metal foam embedded with PCM, and a non-equilibrium heat transfer model was employed to account for the disparate thermal conductivities of the foam matrix and PCM. Given the established effect of pore density, porosity and pore size on the thermal properties of metal foams, an essential characteristic of this investigation includes analyzing the effect of these parameters on electronic thermal management. Alfellag et al. [54] numerically compared the performance of Metal Foam Pin-Fin Heat Sinks to traditional solid pin-fin (SPF) Heat Sinks, as shown in Figure 7. They reported that when compared to solid pin-fin, the metal foam pin-fin shows greater improvements in heat dissipation and a decrease in frictional losses (SPF). Also, Feng et al. [55] reported that finned metal foam demonstrated superior thermal performance compared with convectional plate-fin, exhibiting its enormous potential in latent heat storage applications. As illustrated in Figure 8, the finned metal foam exhibited a 24% increase in average heat transfer coefficient compared to the plate-fin, and approximately seven times the coefficient of the plain metal foam. Additionally, Figure 9 demonstrates that the finned metal foam achieved the highest melting rate among the three structures, as evidenced by the steeper slope of its melt fraction versus the melting time curve.

Ali [56] showed a significant enhancement in thermal conductivity for the copper foam-PCM composite with 95% porosity. Compared to pure PCM, the composite exhibited a 34-times increase in this key thermal property upon PCM impregnation within the metallic foam structure. Also, Ali et al. [57] found that the highest enhancement ratio in operating time is attended about 8 times for PCM/Copper foam as compared to copper foam alone. Iasiello et al. [58] utilized aluminium metal foam in conjunction with a PCM to construct a heat sink with enhanced heat transfer capabilities. The study was carried out under different heat fluxes, porosities, and number of Pores Per Inch (PPIs), and they showed a significant influence of porosity and PPI on both the base temperature of the heat sink and the melting time of the PCM and the. They showed that lower free convection currents are observed for higher PPI and constant porosity of aluminium metal foam, and high maximum velocity values are recorded for constant PPI and higher porosity. Also, Dogan and Ozbalci [59] investigated the effect of aluminium metal foam material on CPU cooling that is utilized as opposed to the standard plate-type aluminium heat sink. They found that 40 PPI aluminium metal foam is more effective than 10 PPI aluminium metal foam for high surface temperatures. Meng et al. [60] studied the effect of seven copper foam fin shapes within the PCM on the thermal performance of the heat sink, as shown in Figure 10. The results showed that the copper foam fins functioned as thermal conduits, facilitating heat transfer within the system. In addition, the most favourable CFF configuration was characterized by a longer left-side length, situated in proximity to both the hot and cold sources. Masip et al. [61] state that since low-porosity foams display strong thermal conductivity, decreasing foam porosity enhances heat sink effectiveness. However, convection was diminished as a result of reduced permeability. The implementation of metal foam with a wider pore structure demonstrably improved the performance of the heat sink. Thus, the effectiveness of a heat sink is determined by the relative dominance of porosity and permeability. The degree of internal natural convection affects how well foam-based PCM performs. Similarly, gravity is a factor in natural convection. Therefore, orientation influence has to be researched. The investigation identified orientation as a critical parameter influencing heat sink performance under conditions of steady heat generation.

Huang et al. [62] used an analytical approach to investigate the effect of porosity and pore density on the thermal performance of finned metal foam heat sinks. It was shown that decreasing porosity leads to lower operating temperatures but shorter reliability lifetimes for feathered-metal foam. Finned metal foam heat sinks with a porosity of 0.9 emerged as a desirable configuration to obtain the best melting performance.

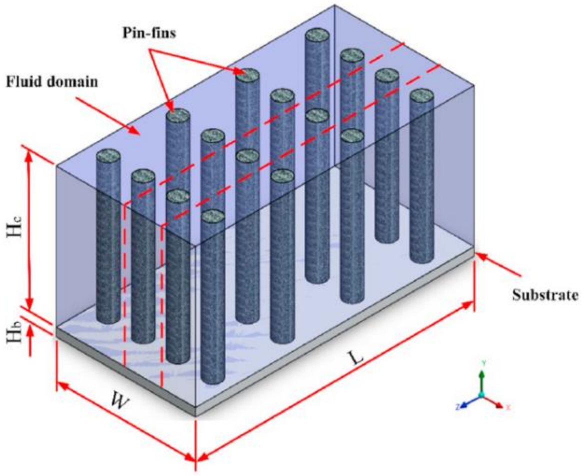

Figure 7. Schematic diagram of heat sink [54]

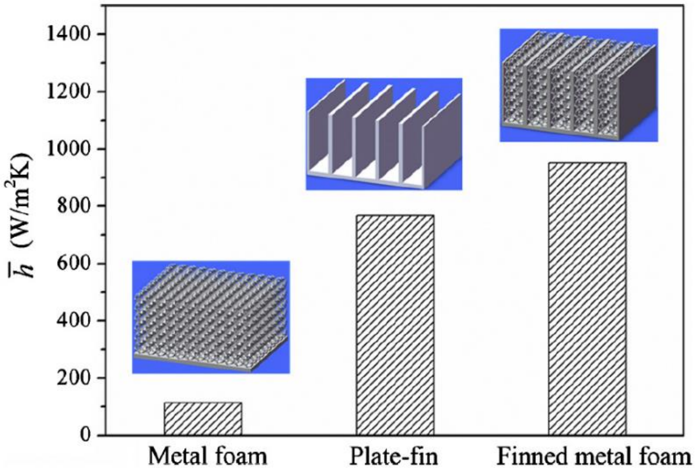

Figure 8. Comparative analysis of average heat transfer coefficients among three latent heat storage configurations [55]

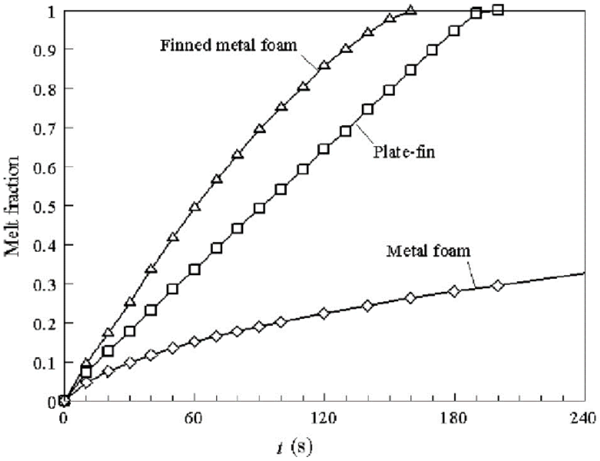

Figure 9. Comparative analysis of finned metal foam, plate-fin, and metal foam: melt fraction as a function of time [55]

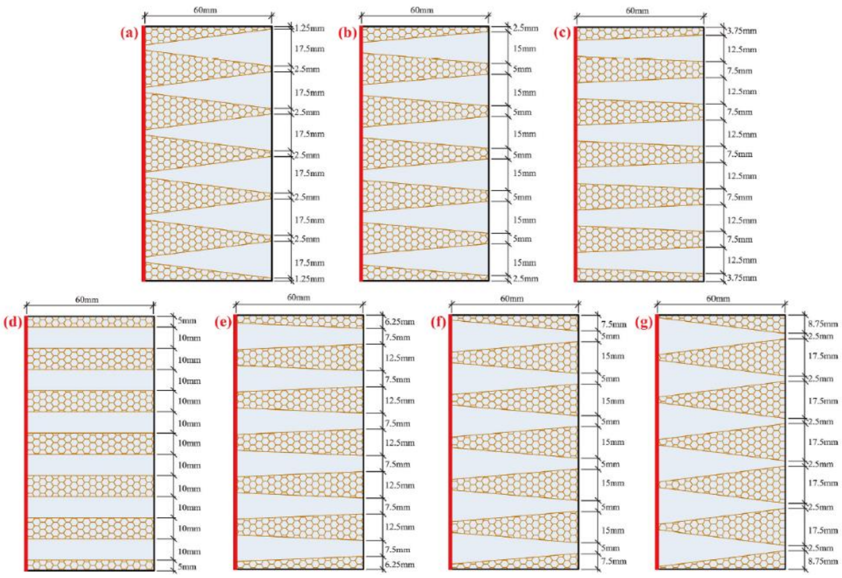

Figure 10. Physical models of LTES units with the different CFF shapes (a) Model-1: 17.5 mm (L)+2.5 mm (R); (b) Model-2: 15.0 mm (L)+5.0 mm (R); (c) Model-3: 12.5 mm (L)+7.5 mm (R); (d) Model-4: 10.0 mm (L)+10.0 mm (R); (e) Model-5: 7.5 mm (L)+12.5 mm (R); (f) Model-6: 5.0 mm (L)+15.0 mm (R); (g) Model-7: 2.5 mm (L)+17.5 mm (R) [60].

VI. ACTIVE COOLING SYSTEM

Some researchers have encompassed both passive and active cooling strategies together to achieve superior thermal management performance for electronic equipment [63] and [64]. Active cooling strategies employ an external power source to facilitate forced convection heat transfer via a fan, enabling air-based cooling [65]. Bianco et al. [66] compared the thermal performance and pumping power consumption of non-finned and finned metal foam heat sinks. The result showed a 3.3–3.5 times enhancement in dissipated heat rates for the finned metal foam heat sink compared to the metal foam heat sink under identical pumping power conditions. Andreozzi et al. [67] numerically studied the thermal performance of an impinging finned foam heat sink across various PPI, as shown in Figure 11. Notably, under equivalent pumping power conditions, these finned foam heat sinks exhibit a 26% reduction in thermal resistance when compared to optimal plate-fin heat sinks and a 2.5% reduction when compared to fully optimized microchannel plate-fin heat sinks.

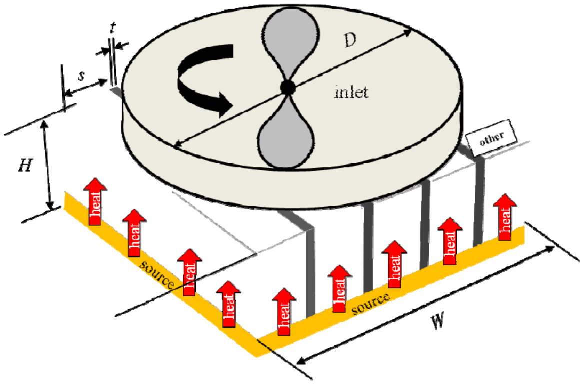

Figure 11. Finned metal foam heat sink with active cooling [67]

Saha and Dutta [68] conducted a comparative study to investigate the thermal behaviour of a conventional PCM heat sink in contrast to a hybrid design incorporating both active and passive cooling elements. Both heat sinks were subjected to a constant heat input followed by a cooling phase. Furthermore, the implemented design modifications resulted in a significant reduction in the heat transfer coefficient. Compared to top-surface cooling, the heat transfer coefficient decreased by over 90%, from 1200 W/m²·K to less than 100 W/m²·K. However, the melting and solidification times remained comparable. Kozak et al. [69] investigated the influence of a fan integrated with a PCM-embedded heat sink. The findings demonstrated that forced convection plays a significant role in diminishing chip temperature.

Stupar et al. [70] studied the combined effect of forced cooling and an effective convective heat transfer field on the cooling phase of the PCM-integrated heat sink. The results showed that pressure convection exhibited limitations in heat dissipation capacity. Consequently, high-temperature diffusion is required to reduce the cooling time. In a similar work, [71] investigated heat sink designs in which the PCM occupies only half of the available domain, and the rest is exposed for ventilation. It was shown that forcing ventilation and Integration of the PCM is essential for continuous operation. This setting effectively maintains the chip at a safe temperature for long periods.

VII. COST OPTIMIZATION

A review of the existing literature underscores the potential of heat sinks integrated with PCMs and metal foams as a promising strategy for enhanced heat transfer and management. This approach capitalized on the increased heat dissipation of finned heat sinks, the thermal energy storage potential of PCMs, and the efficient heat conduction of metal foams. This area of research presented a significant challenge due to the multitude of variables that affected the outcomes. Therefore, a thorough understanding of the relationship between these design elements is essential for optimizing heat transfer performance. This optimization can be achieved by achieving a balance between cost reduction and extended operational time. Bianco et al. [58] find out the related design variables and optimal solution referred to in the thermal management system comprised of a finned heat sink, PCM, and metal foam. The cost function incorporates the quantities of both PCM and metal foam. Operating time is determined through a mathematical model that influenced volume-averaged porous media equations to predict temperature fields within the system. This model is implemented using the commercial finite element software COMSOL Multiphysics®. They reported the results using Pareto optimization, which visualized the trade-off between temperature and the evolution of the melting front. The Pareto front is the essential trade-off between operational time and device cost. Operating time ranges from approximately 2000 to 6000 seconds, while the associated device cost varies between 200 and 275 euros (€).

Debich et al. [72] suggest a methodology for obtaining an ideal design of PCM-based HS with the requisite degree of reliability. This methodology is based on combining several reliability-based design optimization RBDO methods with a PCM-based HS model. RBDO techniques seek the optimal balance of safety and cost while accounting for uncertainties in the researched model. They proposed the Robust Hybrid Method (RHM), which is a numerical application utilized to investigate the various deterministic design optimization (DDO) and RBDO methodologies. They conclude that the RHM technique evaluates both reliability and thermal limitations for thermal systems.

Furthermore, when compared to other approaches, including the DDO method, it clearly reduces computation time. Meganathan et al. [41] numerically reported the cost and the heat transfer of the heat sink cooling of electronic equipment by using the ANSYS Workbench. The weight and heat transfer values for the alternative design heat sink models are compared with the standard model. Besides the best heat transfer rate, the model requiring less weight is chosen to decrease the cost of the heat sink.

VIII. CONCLUSION

This paper presents a comprehensive review of techniques employed to enhance the thermal performance of heat sinks. Specific areas of focus include plate-fin heat sinks with perforations, PCMs integrated with thermal conductivity enhancers like metal foam, active cooling strategies, and cost optimization. The influence of various parameters on heat sink performance is analyzed through a critical examination of existing analytical, experimental, and numerical studies. A comprehensive literature review indicated a significant preference for plate fins as the predominant heat sink design, accounting for 70% of the studies. Pin fins were employed in 15% of cases, while a hybrid configuration combining plate and pin fins was observed in the remaining 15%.

The integration of the PCM significantly enhances heat dissipation from the heat sink, particularly in passive cooling scenarios. The thermal performance of a heat sink incorporating metallic thermal conductivity enhancers (metallic foams and nanoparticles) is influenced by various geometrical parameters, including the number of fins, fin thickness, fin height, the volume fraction of PCM and fins, substrate thickness, fin shape, and type of PCM. Although increasing the number of fins within the PCM is generally effective in reducing the base temperature, there is a point of diminishing returns beyond which additional fins may not significantly improve performance. This optimal number is contingent upon the dimensions of the heat sink, the type and quantity of PCM, and the shape and size of the fins. The enthalpy-porosity approach is a more suitable model for simulating phase change phenomena.

The thermal performance of heat sinks incorporating nanoparticles as thermal conductivity enhancers was found to depend upon the shape of the nanoparticles. Results indicated nanoparticles were effective additives, facilitating diffusion enhancements across all aspect ratios. Metal foams, characterized by their high thermal conductivity, extensive surface area, and interconnected structures, were observed to significantly enhance heat sink performance through increased heat diffusion. The efficiency of metal foams in this regard was strongly influenced by their porosity, pore density, and characteristic thermal conductivity. It was determined that heat transfer performance was optimized with lower porosity and higher pore density than configurations with higher porosity and lower pore density.

The forced convection is an essential factor in reducing chip temperatures, making it a preferred cooling method for extended electronic equipment operation. However, there is a notable shortage of research on integrating PCM with active cooling heat sinks. The optimized thermal management system design is crucial for enhancing reliability, thermal performance, and material efficiency.

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