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ADVANCEMENTS IN HEAT SINK DESIGN: A COMPREHENSIVE REVIEW OF THERMAL MANAGEMENT AND OPTIMIZATION STRATEGIES

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Abstract
Heat sinks are essential elements that disperse thermal energy from systems operating at high temps, including aerospace vehicles, semiconductor chips, and turbine engines. Over the last several decades, significant research has been focused on heat sinks to improve heat dissipation, reduce hot spot area temps, and lower components' temp in the hot section. The enhancement of heat sinks thermal performance faces several obstacles and requires the adoption of novel designs, materials, and adaptable production techniques. This study aims to provide a comprehensive review of the current research on enhancing the thermal efficacy of heat sinks and identify potential directions and recommendations for future investigations.

Keywords: Heat sink, heat transfer, Fins efficiency, fins shapes.

Introduction

As electronic devices continue to advance in performance and compactness, effective heat dissipation remains a critical challenge [1], [2]. With increasing power densities, traditional air-cooling systems struggle to meet the high heat dissipation demands of modern electronics. Users prefer fast CPUs, but as central processing units (CPUs) grow more powerful, they generate more heat, making thermal management essential for preventing damage to components and maintaining device efficiency. The thermal design optimization of heat sinks aims to reduce their size and weight while maximizing heat removal, which is especially vital as electronic devices shrink [3].
In mechanical engineering, heat sinks (HS) transfer thermal energy from processors, dispersing it through natural, mixed, or forced convection [4], [5]. Suboptimal heat dissipation in a heat sink can lead to excessive temperatures, risking damage to electronic components [6]**.** As a result, manufacturers have introduced innovative technologies to enhance heat dissipation and boost device performance [7]. However, the miniaturization of computers increases system flow resistance, restricting fluid movement between heat sink fins, which can reduce fan efficiency and hinder effective heat removal. Therefore, precise heat sink design is essential to ensure efficient heat transfer and prevent electronic components from overheating.

Effective thermal management in heat sinks remains a high research priority. Air remains the most commonly used coolant in electronic systems due to its availability, as well as the simplicity, reliability, and affordability of the necessary equipment [8]. Although significant progress has been made, a large body of literature suggests that achieving a perfectly optimized heat sink remains challenging. Thus, it is valuable and essential to continue studying, designing, and developing diverse heat sink models to improve this vital technology.

Heat Sink

A heat sink is an exchange of heat that facilitates the passage of heat from a heat-producing equipment or source to a surrounding fluid. The fluid used is often air. However, it may also be any non-conductive fluid for heating transfer. The Heating sinks may be cooled passively via natural convection or actively through forced convection involving a fan. Heat sinks are often fabricated using aluminum or copper [9]–[15]. A heat sink is specifically designed to efficiently disperse excess heat generated by the functioning of mechanical or electrical apparatus. If the waste heating is not effectively dissipated from the component, it might accumulate and lead to device malfunctions or decreased performance. A heat sink utilizes the principles of radiation, convective, and conductive transfer of heating to transfer heat from a higher-temp source to a lower-temp fluid [16]. Thermal energy is transferred from this source to the sink by conduction. Heat sinks are fabricated using materials with high heat capacity, meaning they can retain more heat per unit mass. Radiation and convection transfer heat from the sink to the neighboring fluid. Increasing the surface area in contact with the heating exchange fluid enhances the heat transmission rate. Adding fins to the heat sink base material may significantly enhance the surface area. A heat sink might be either passive or active. An active heat sink utilizes forced convection generated by a fan or pump to efficiently move heat from the device, whereas a passive heat sink relies on natural convection [17].

A heat sink is a passive heat exchanger that transmits the thermal energy produced by an electrical or mechanical device to a fluid medium, often air or a liquid coolant [18]. This process allows the heat to be dispersed away from the device, enabling control of the device's temp. Heat sinks are used in computers to dissipate heat from central processing units (CPUs), graphics processing units (GPUs), as well as certain chipsets and random-access memory (RAM) modules [19]. Heat sinks are used with high-power semiconductor devices like power transistors and optoelectronics like lasers and light-emitting diodes (LEDs), necessary when the component's inherent heat dissipation capacity is inadequate to regulate its temp. Every heat sink is essential in applications exhibiting fluctuating conditions [20]. Heat sinks are widely used for thermal management in several domains, including technology, industry, and natural systems. These components are so widespread that they may be easily disregarded, even by those knowledgeable about the technology [21]. A heat sink is precisely engineered to optimize the extent of its surface area that touches the cooling medium surrounding it, such as the air. The performance of a heat sink is influenced by variables such as air velocity, material selection, protrusion design, and surface treatment. The integrated circuit's die temp is influenced by the techniques used to connect the heat sink and the thermal interface materials. Thermal glue or thermal paste enhances the efficacy of the heat sink by filling up any empty spaces between the heat sink and the heat spreader on the device. A heat sink is typically constructed using aluminum or copper materials [18].

Temp and Reliability

The dependability of temp may greatly influence components such as steady-state temp during continuous operation and temp cycling. Within the temp range relevant to electronic equipment, it is well recognized that the dependability of electronics is significantly influenced by the temp of their components, with a strong negative relationship that approaches exponential dependence. For every 2 degrees Celsius increase in temp, the dependability of a silicon chip decreases by around (10 percent) [22]. The standard temp threshold for a silicon chip is 125 degrees Celsius. Nevertheless, there is sometimes a strong preference for a far lower design threshold to maintain an acceptable level of dependability, particularly in military goods. The failure rate of the component is also influenced by temp cycling. Research funded by the U.S. Navy [23] found that equipment exposed to intentional temp cycling of over 20 degrees Celsius had a failure rate that was eight times higher than usual.

Reliability may be assessed by examining the likelihood that a device can successfully carry out its designated tasks under specified circumstances for a particular duration. Product dependability is often regarded as the paramount component in establishing the quality and excellence of a gadget within the industry. To guarantee the reliability of electrical equipment, it is essential to have sufficient thermal management in place [24]. Using a heat sink is the primary method of regulating thermal management in a tiny device. A heat sink is a specialized device that improves the process of transferring heat from a hot surface, which is generated by a component in an electronic device, to a cooler environment. This cooler environment, also known as a fluid medium, maybe the surrounding air, water, refrigerants, or oil. Heat sinks using water as their fluid medium are known as cold plates [9]. The primary purpose of heat sinks is to enhance the surface area of an electronic component that comes into direct contact with a coolant. This design facilitates efficient heat dissipation, resulting in a decrease in the operating temp of the device.

Heating Transfer Technology

The thermal designs of electronic equipment have incorporated all three transfers of heating modes (radiation, convection, and conduction), as well as phase changes like boiling [25], condensation, melting, and solidification. Nevertheless, it is essential to note that electronic systems have no one-size-fits-all design approach. Several papers [26]–[29] have provided a comprehensive overview of the advancements in the transfer of heating technology for the thermal control of electronic equipment since 1977.

Transfer of heating Principle of Heat Sink

A heat sink facilitates the passage of thermal energy from a device with a higher temp to a fluid medium with a lower temp [30], [31]. The often-used fluid medium is air; however, it may also be oil, refrigerants, or water. The heat sink is often called a cold plate when water is used as the fluid medium. In the context of thermodynamics, a heat sink refers to a heat reservoir that can absorb a limitless quantity of heat without undergoing a substantial change in temp [32]. To effectively transfer heat by conduction, radiation, and convection, heat sinks for electronic equipment need to maintain a temp greater than the surrounding environment. Electronic power supplies exhibit low efficacy, generating excess heat that may impair the device's functionality.

Consequently, the design incorporates a heat sink to dissipate heat. Utilizing the average air temp represents an acceptable expectation for heat sinks of relatively limited duration. The logarithmic average air temp calculates compact heat exchangers [33]. According to Fourier's law of heat conduction, heat will flow from a location with higher temp to a region with lower temp when there is a temp difference in a body. The rate of heat conduction is directly related to the temp difference and the cross-sectional area in which heat is transmitted [34].

Natural and Forced Convections

Natural convection systems provide significant benefits in several disciplines and engineering scenarios because of their low energy consumption, simplicity, dependability, quietness, economy, and ease of maintenance [35]. The items mentioned include heating systems, cooling systems, heat exchangers, radiators, heaters, photovoltaic panels, solar cells, condensers, evaporators, power stations, food businesses, and nuclear reactors [36].

A significant drawback of an essential natural convection system is its relatively poor transfer of heating rate compared to forced convection [37], [38]. A widely used technique to enhance natural convection is to increase the transfer of the heating surface since this helps maintain relatively constant ambient temp and thermal convection coefficients in most scenarios. Extended surfaces may be created by connecting or appending additional surfaces using components called "fins." Using fins in systems has become a prevalent technological and industrial convention. A multitude of research has been conducted on the transfer of heating using fins, demonstrating their significant efficacy in enhancing heat transmission [39].

Nevertheless, including a substantial quantity of comparatively large fins is likely not the favored approach owing to constraints on space efficacy and financial concerns. Furthermore, the geometric characteristics of the fins will impact both the fins' transmission effectiveness, either favorably or unfavorably. Hence, the fins' morphology, quantity, arrangement, altitude, and alignment are crucial factors in the study and must be duly considered to enhance thermal efficacy. Over time, the designs of fins have developed to enhance the heat transmission rate within the limited area enclosed by the fins. Various considerations, including weight, construction material, and ease of manufacturing, have been considered design constraints. The fins may have a basic form, such as rectangular, triangular, elliptical, or pin-shaped, or a complicated design, such as corrugated or spiral, according to the requirements. Nevertheless, the tilt orientation has significance and warrants consideration for at least two reasons. Firstly, the surface requiring cooling may not be in a vertical or horizontal position [40], [41]. Secondly, a heat sink that is initially vertical or horizontal may tilt during operation.

Forced convection is a heat transmission process where the movement of external factors, including pumps, fans, suction devices, and others, influences the movement of the fluid, which is valuable for creating fluid motion. This approach is critical due to its excellent transfer of heating capabilities from a heated item. Notable instances of this technique involve turbines, steam air conditioning, and so on [41]. Once analyzed, the forced convection process exhibits a more intricate mechanism than natural convection because, in this approach, we need to control two variables: fluid velocity and heat conduction. These two aspects are closely linked since fluid motion can improve heat transmission.

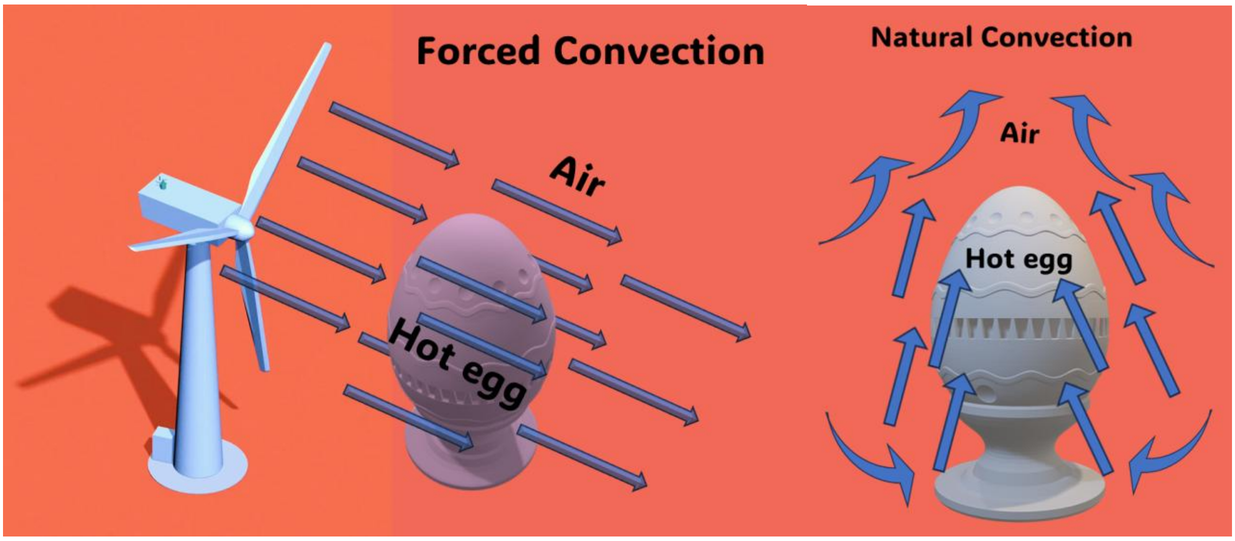


Figure 1. Forced and Natural convection.

Heat Sinks Materials

Manufacturers generally use aluminum as their preferred metal due to its high heat conductivity, around 235 W/(m/K). Another determinant of its appeal is its cost-effectiveness in production and exceptionally lightweight nature, which minimizes the strain exerted on a computer's motherboard. Copper is often regarded as the optimal metal for creating highly efficient heat sinks due to its high thermal conductivity of around 400 W/(m/K), surpassing all other naturally occurring metals. Despite its superior heat transmission capabilities, copper is less favored by manufacturers because of its higher cost and weight than aluminum [42].

Some contemporary and practical heat sink designs are now exploring combining aluminum and copper in constructing a heat plate. This approach aims to combine aluminum's lightweight characteristics with copper's superior thermal conductivity. The designs will combine the components mainly composed of aluminum, chosen for its reduced cost, and encased by a copper plate, selected for its excellent heat conductivity. Conceptually, these designs present a dynamic resolution to the potential issues each of the metals presents. Nevertheless, if the copper fails to form a sufficiently strong bond with the aluminum (a common occurrence with low-cost heat sinks), the inclusion of a. In that case, copper plate can have a detrimental effect on the heat sink rather than a beneficial one [43].

Graphite composite materials were suggested as an alternative to copper and aluminum. However, their thermal conductivity is lower than copper's, measuring 370W/(m/K). Graphite materials provide a significant advantage in their exceptionally lightweight nature, 70% lighter than aluminum [44]. An established principle followed by electronic designers in the industry is that the lower the cost of a heat sink, the higher the long-term expenses would be due to the need to replace components and conduct repairs. Cost-effective heat sinks often use elements like sleeve bearings in their construction, prone to rapid deterioration and may lead to lubrication issues. Heat sinks with ball bearings may have a higher initial cost, but they will undeniably have a longer lifespan, resulting in lower long-term expenses for the user.

Significance of thermal conductivity

Heat sinks are often constructed from metal because of their high thermal conductivity, enabling them to efficiently dissipate heat from the CPU, preventing overheating. Various metals may be used to construct a heat sink, each possessing distinct thermal conductivity properties [45]. The thermal conductivity of a substance may be precisely described as its capacity to transmit heat through it. Materials with greater thermal conductivity facilitate expedited and more effective heat transmission, whereas materials with lower thermal conductivity function as insulators by impeding the heat flow. Aluminum and copper are often used metals for constructing heat sinks due to their exceptional thermal conductivity properties.

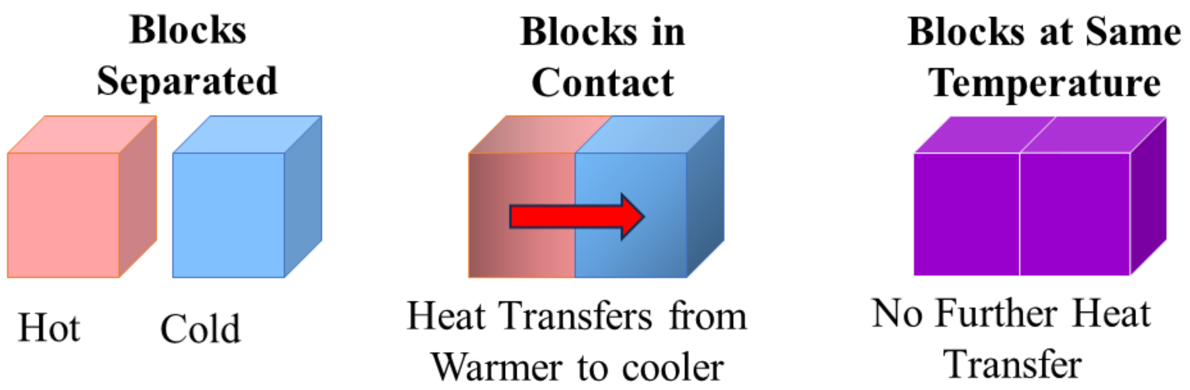


Figure 2. Transfer of heating energy mechanism.

Various heat sink kinds

The generated heat source

The source in question may include any system that generates heat and necessitates the extraction of this heat for proper operation. Examples include friction, nuclear, solar, chemical, electrical, and mechanical systems.

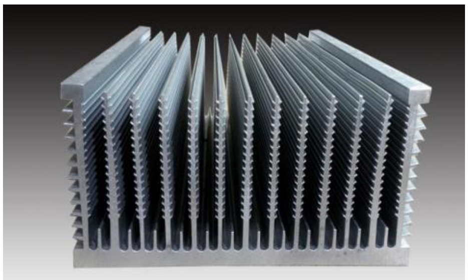
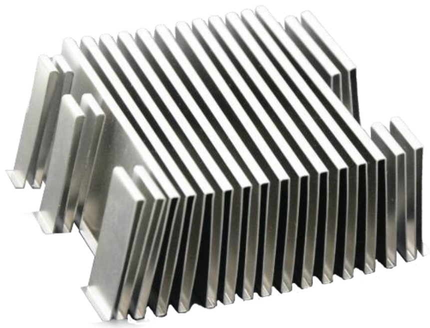
Transfer of heating away from the source

Heat pipes may also facilitate this process. In instances where there is direct contact between the heat sink and the heat source, heat is transferred from the source to the heat sink by natural conduction. The thermal conductivity of the heat sink material has a direct influence on this process. The prevalence of copper and aluminum in the fabrication of heat sinks is due to their high thermal conductivity.

Heat distribution throughout the heat sink.

The heat will naturally transfer through the heat sink using conduction, traveling from a region of high temp to a region of lower temp along the thermal gradient. Consequently, the thermal profile of the heat sink will need more consistency. Consequently, heat sinks often exhibit higher temps closer to the heat source and lower temps towards the outside edges of the sink.

Table 1: Summary of different heat sink information.

Name of Sink	Advantages	Disadvantages
Extruded [46] 	1) The raw materials are easily affordable 2) This type is easy to manufacture	1) Dimensions of extrusion are limited. 2) This limitation can reduce thermal conductivity.
Bonded [47] 	1) Fin and Base material can be manufactured using different materials. 2) This results in improved thermal performance.	1) Costly to manufacture. 2) Complex manufacturing processes.
Skived [48] 	1) These heat sinks have a high degree of design flexibility. 2) Manufacturers can achieve a high fin density.	1) They have a high weight and directional sensitivity. 2) Thicker base material
Stamped [49] 	Since their production can be easily automated, stamped heat sinks are very cheap.	On the other hand, poor functionality is by far the biggest drawback.
Forged [50] 	1) Cheap to manufacture 2) Ease of production automation	1) Heat flow management is poor 2) It usually comes with low performance.

Conclusions

This review highlights the critical importance of optimizing heat sink designs to meet the growing demands of thermal management in advanced electronic and mechanical systems. Achieving optimal heat sink performance requires precise balancing of key factors, including the number, thickness, and arrangement of fins, as well as material selection and airflow optimization. Findings suggest that increasing the fin density enhances heat dissipation while reducing weight, thereby improving overall thermal efficiency. Moreover, combining compact designs with efficient airflow management results in a cooling system capable of maintaining high power densities while minimizing size and weight. Such advancements in heat sink technology are essential for addressing the challenges posed by modern high-performance electronics and power systems. Future research should focus on integrating novel materials and innovative manufacturing techniques to further enhance the thermal and structural properties of heat sinks, ensuring their reliability and efficiency in increasingly demanding applications.

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