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RESEARCH ARTICLE

Comparative study of fin shapes for thermal efficiency in heat sinks under free and forced convection

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Abstract

This paper compares different studies to show how various fin shapes affect the thermal performance of heatsinks in both free and forced convection heat transfer modes, which are vital for heat dissipation in electronic and industrial systems. Numerical analysis was conducted to assess the cooling efficiency of various aluminum fin designs, including cylindrical, flat, trapezoidal, pin, annulus, elliptical, and tapered types. Some studies also explore the use of advanced materials, such as hybrid and quaternary nanomaterials, to improve thermal conductivity and reduce weight. Results show that elliptical fins with a side ratio between 2 and 2.65 offer the best heat transfer performance (exceeding 90%) under forced convection. Conversely, flat and cylindrical fins are most effective in natural convection. Importantly, the best fin shape and nanomaterial integration not only significantly enhances heat sink performance by decreasing thermal resistance compared to conventional designs but also promotes energy savings. These findings offer new insights into designing thermally efficient, compact, high-performance heat sinks, surpassing existing research and emphasizing the benefits of innovative shapes and materials for advanced cooling solutions.

Keywords: Heatsink, fin shapes, thermal efficiency, nanomaterials, CFD

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1. Introduction

Heat transfer is a fundamental phenomenon in engineering and physical science, occurring in almost all common conditions such as natural, forced or mixed convection [1-5]. In these channels, fins are often inserted to enhance the efficiency of heat transfer [6-10]. They not only extend the effective heat-exchange surface but also ease more efficient cooling [11-14]. Fins also develop flow disruptions which cause, during this flow process, good fluid mixing and therefore improved system efficiency. The heat transfer/flow field interaction at the fin surfaces is a complicated problem of fluid flow with convective effects and conduction in fins. These strongly coupled transport phenomena, especially in heat transfer between liquids and gases influenced by buoyancy and fins (as previously mentioned), need to be studied when evaluating the enhancement of heat transfer performance in engineering systems [15-17]. Research on flow field analysis and shape optimization for maximum heat transfer rates has been conducted through experiments, theory, and numerical methods. For example, see the computations in [18].

The influence of the fin height on flow structure and heat transfer rate was studied, and it was found that the volume of fins played a significant role to retard the fluid stream and enhancing the pressure drop in this channel. Huang and Tung [19] also studied the performance of wavy fin-shaped heat sinks, using both experimental and numerical methods with different fin geometries. Additionally, Duan et al. heated a sink with plate-type fins, who had detailed studied pressure drop and fluid flow characteristics. They emphasized elliptically profiled bottom plates, which will maximize the thermal performance while minimizing energy losses [20]. Tarq et al. [21] reports that collage fin design can be improved to maximize heat transfer rate - a particularly relevant consideration for better cooling performance. Studies on the shapes of fins are summarized in Table 1.

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Table 1. Various studies have been conducted on the shapes of Fins

Author(s)	Year	Key to the research
Sajjad Ali et al. [22]	2025	Study on heatsink performance with various fin shapes. Folded fins show superior heat transfer efficiency.
Noor H. Dhaher et al. [23]	2022	Star fins outperform cylindrical fins in heat dissipation and convection heat transfer.
Xianchang Li [24]	2008	Analyzed heat sink performance with jet impingement. Rectangular fins outperform elliptical fins.
Kanwalpreet Kaur et al. [25]	2025	Developed a model for heat transfer in various fin geometries, highlighting temperature-dependent properties.
Abhinandan Jain et al. [26]	2016	Review of heat transfer by different shaped fins. Efficient fin design improves cooling and reduces costs.
Muhammad Ishaq et al. [27]	2021	Diamond-shaped fins enhance heat transfer in double-pipe heat exchangers.
Lei Luo et al. [28]	2019	Pin fins and dimple shapes improve heat transfer. Elliptical pin fins show significant improvement.
Jae-Hun Maeng et al. [29]	2011	Twist and wavy fins outperform circular spiral fins in heat exchanger performance.
Reijo Karvinen et al. [30]	2012	Discussed methods for perfecting plate fin geometries to maximize heat dissipation.
Wei Jin et al. [31]	2019	Oblong pin-fin shapes enhance heat transfer, with NACA pin-fins showing a low friction factor.
Ambarish Maji et al. [32]	2019	Analyzed staggered pin fins with perforations for enhanced heat transfer performance.
A. S. Ramana et al. [33]	2019	Investigated the effect of staggered arrangements and knurled surfaces on heat dissipation.

This is stimulated by an increasing request for thermal management of industrial systems/electronic devices and the need to exploit a more compact and effective heat exchange [34]. In recent literature, surveys on different fin types like cross-fin, wavy or Y-type plate fins, radial plate fins and plate-pin hybrids were published. Others Different configurations have been suggested to reduce the volume of heat exchangers without reducing heat transfer rates, such as fins with fillets or slots/dimples/rods. On the other hand, some are devoted to the advanced materials of fin designs, which can enhance heat transfer and performance in turn.

For example, composites or nanomaterials can be incorporated into fins to enhance heat dissipation while keeping lightweight characteristics, which is important for electronic cooling [26]. Moreover, issues related to performance limitations are addressed through advanced and novel fin geometries in passive cooling technologies. Approaches to reduce energy consumption in industrial processes passively are also presented [34]. Since these materials and configurations are currently being perfected by engineers, the long-term reliability and maintainability of such systems become increasingly important, especially for systems that tend to foul or wear over time. Overall, the impact of fin geometries on heat transfer in both free and forced convection within the thermal-efficiency range is a key factor in designing best heat sinks for various engineering applications, as shown in Table 2, [35-41].

Table 2. Literature explores the thermal performance of various fin configurations

Studies performed	Fin shape	Physical aspects discussed	Use of nanofluid		
			Nano	Hybrid	Ternary
Ganeshkumar et al. [42]	Radial	Analysis under thermal radiation and TD thermal conductivity using DTM in the absence of nanofluid	×	×	×
Rai et al. [43]	Circular	Curvature and nanoparticle concentration	√	×	×
Poursharif et al. [44]	Triangular	Porous surface and magnetic field	√	×	×
Haq et al. [45]	Parallel Fins	Natural convection and SWCNTs nanomaterial	√	×	×
Hamida et al. [46]	Different fins	Examined the effects of the electric field with various voltage stages	×	√	×
Manohar et al. [47]	Spherical porous fin	Natural convention, radiation.	×	√	×
Turkyilmazoglu [48]	Elastic longitudinal fins	Stretching/shrinking and Biot number	×	×	×
Jalili et al. [49]	Curved fin	Nanofluid is taken as a functional fluid with convective effects	√	×	×
Naphon et.al.[50]	Minin rectangular fin	Discussed the heat transmission with heat sinks	√	×	×
Kalhid et al. [51]	Annular Fin source setup	Natural convective heat transfer coefficient.	√	√	√

Table 2 Refers to various investigations on the thermal performance of different fin shapes under different conditions, including nanofluids, hybrid nanofluids, ternary nanofluids, and nanoparticles such as ZnO, SnO2, Al2O3, MgO, and hyperiid NPs [52-57]. The fin types analyzed include radial, circular, tri-axial, parallel, spherical porous, elastic longitudinal, bent, and annular fins. Other studies have also examined factors like subsaturated surface temperature, thermal radiation, nanoparticle concentration, porous media, magnetic effects, natural convection, and electric fields. For instance, Ganeshkumar et al. [58]. Rai et al. [1] have used nanofluids with different fin geometries like their work [1] with a focus on the applications of nanofluids in circular fins with curvature and nanoparticle concentration.

Poursharif et al. [18] investigated porous triangular fins in the presence of a magnetic field employing nanofluids for heat transfer. Several other investigations such as Haq et al. [59] studied the effect of natural convention and type of nanomaterial (SWCNTs) on heat transfer for various fin geometries. The research work performed by Kalhid et al. [25] studied an annular fin arrangement, considering natural convection heat transfer, thermal conductivity and magnetic fields with different varieties of nanofluids. The results show that the effectiveness of fins can be enhanced significantly, especially with hybrid and ternary nanofluids in different fin design configurations and heat transfer enhancement. For example, working fluids consisting of triangular and spherical porous fins and nanofluids can provide great heat removal performance as well as high efficiency. On the other hand, for more complex geometries and configurations resulting from combinations of other thermal enhancing mechanisms with magnetic fields and radiation factors (e.g., annular fins), there is an excellent heat transfer improvement.

A number of studies have also focused on optimizing the heat sink geometry and thus performance of extended surfaces (fins) in free/unforced and forced convection; heat transfer problems; all with the view to maximize heat rates as they consider different types of thermal performances i.e., resolution resistance, pressure drop, etc. Investigation into the heat transfer efficiency of fin arrays Some essential geometric parameters (fin height, fin diameter, and fin material) and temperature difference between base and environment affecting the overall heat transfer effectiveness of a fin array have been studied thoroughly. It has also been found in the literature that these geometric parameters as well as difference between base and ambient temperature lead to an appreciable effect on heat transfer. Researchers have also decided that convection heat transfer coefficient from fin arrays rises with increasing approach velocities, the dimension of fin, number of fins, and height of fin and thermal conductivity in the material.

Furthermore, the investigator saw that compared with staggered arrangement, heat sink resistance while using in-line configuration is larger and pressure drops smaller. In-line and staggered heat transfer models can be equally adopted in the design of pin-fin heat sinks. It has also been explored for its impact on channel dynamics. In addition to these remarks, a recent trend in research is the development of novel heat sink configurations that also run under forced convection. Many experimental works from the past decades have already investigated wings attached to different pin fin shapes, and it has been reported that, in the presence of wings, pin fin heat sinks show better heat removal capability compared to those without wings.

Moreover, new branching and segment configurations have been designed to achieve the best balance between effective cooling and heat sink volume, as shown in Figure 1. In the past, parameters such as fin spacing and the lengths of fin/cooling fins were simulated numerically to investigate their effects on the thermal performance of heat sinks. Also included in the review is an analysis of forced convective heat transfer augmentation for typical plate-fin and slim-plate finned heat sink under sine wave vibration. Given the current trend toward thin, small electronic products, compared with traditional plate fins, several studies prove that more fins can be fitted per unit substrate with thin plate fins. In general, the results are informative about how fin shape affects thermal efficiency optimization in both free and forced convection [60-63,38].

Figure 1. Variation of fin density for similar fin constructions [64]

This figure shows how different fin densities affect thermal performance by comparing various fin configurations and their heat dissipation abilities.

Best thermal management is key issue in most engineering applications and crucial task for electronic devices and industrial systems which may experience deteriorative influence by overheating including performance degradation, decrease, etc. Finned heat sinks are generally employed to improve the heat dissipation of a part through enlargement of cooling area and convection. However, the efficiency of heat sinks strongly rely on fin pattern and material characteristics along with convection form (natural or forced).Although numerous analyses have been carried out, there is still a lack of understanding of the effects of different fin designs and advanced material modifications, such as the introduction of nanomaterials, on overall heat transfer under a variety of operational parameters.

The heat dissipation fin is necessary in compact high power density cooling device which can save energy and cost. To carry out this, the present study offers a comprehensive exploration of the hydrodynamic thermal performance between natural and forced convections of several different fin shapes (cylindrical, flat, trapezoidal pin annular elliptical trapezoidal tapered). By clarifying such complex relationships of fin shape, material properties and the flow on the fins, this work is hoped to contribute to guidance on design for higher efficiency with low environmental impact in thermal management systems.

Literature Gap and Motivation: Although heat sinks and fins have been extensively studied for thermal applications, there are still important unresolved questions about the understanding and application of fin shapes and engineered materials in different convective environments.

- Relatively little comparative research has been conducted on various fin profiles: individual studies have examined fins with cylindrical ends, flat, trapezoidal, pin-fin annular, elliptical, and tapered shapes. A comprehensive comparison of these different geometric configurations, from forced to free convection, is still lacking. It stays an open area of research to analyze how each shape performs under various operating conditions.

- Nanomaterial Enhancement: nanofluids and composites enhanced thermal conduction and dissipation of heat has been shown. Unfortunately, the synergetic influence of hybrids and ternary nanomaterials for various fin shapes has not been well established. Moreover, the thermal behavior of multilayered fins with these modern materials and novel geometries (like those following annular or ellipsoidal paths) deserves much more attention.
- Optimization of Fin Design for Small High Performance Heat Sinks. Whether in electronics or the general industry, miniaturization requires heat sinks to provide a balance between performance and size. The surface hole/notch and periodic features with nanomaterial enhanced fin structures are also the considered solutions, but systematic studies on these concepts have not been published until now.
- Effect of Combined Physical Phenomena: The combined impact of convection, radiation, magnetic fields, and other thermal physical effects on fin performance—especially in modern fin types like annular fins filled with a ternary nanomaterial—has not been thoroughly studied in the current literature.

To present the novelty of this study, the following steps are summarized as: This work presents a full-scale review of the studies and comparative analysis between different fin shapes for both natural and forced convection, also discussing them in terms of advanced nanomaterials and composites. It highlights the significance of elliptical-shaped fens with a dynamically determined aspect ratios (about 2–2.65), and heat transfer enhancements are above than 90% which would make such designs more effective especially in cases for cooling system applications. The whole gamut of work, from traditional fins to novel fin geometries such as perforated/many notches/several branches' fins; considering energy efficiency and thermal response together, has been considered for the study. The summary of interface gap materials and its contribution to thermal management provides a valuable perspective required during the design and manufacturing stage. By addressing these multi-dimensional factors, the current study fills some important voids in thermal management work today obtaining useful engineering recommendations to design efficient and compact heat sink for industrial applications, and electronic cooling.

2. Methodology

2.1. Theoretical framework

In this section, we summarize the fundamental equations used to describe how the natural and forced convection heat transfer performance of various specific fin geometries is affected. These equations are essential for understanding the thermal efficiency of the heat sink and are used to model the heat transfer mechanisms in this work.

Thermal efficiency of fins ηfin:

$$\eta_{fin}=Q_{fin}\backslash Q_{max} \tag{1}$$

Q_{fin} actual heat transfer from the fin, and Q_{max} maximum possible heat transfer.

Heat Transfer Rate for Forced Convection:

$$Q_{forced}=h.A.\Delta T \tag{2}$$

where h heat transfer coefficient, A surface area of the fin, and ΔT temperature difference between the fin and the surrounding fluid.

The Nusselt number (Nu) is used to calculate the convective heat transfer coefficient in forced convection:

$$Nu=C\cdot Re^{m}\cdot Pr^{n} \tag{3}$$

Heat Transfer Rate for Free Convection:

$$Q_{free}=hfree.A.\ \Delta T \tag{4}$$

where h_{free} is the convective heat transfer coefficient for natural convection, and A is the surface area of the fin.

The convective heat transfer coefficient for free convection (h_{free}) is expressed as:

$$hfree=C\cdot(Gr\cdot Pr)^{1/4} \tag{5}$$

Gr Grashof number and Pr Prandtl number.

Grashof number (Gr):

$$Gr=\frac{g\beta\Delta TL^{2}}{\nu^{2}} \tag{6}$$

g gravitational acceleration, β thermal expansion coefficient, ΔT temperature difference, L characteristic length, and ν kinematic viscosity.

2.2. Materials and methods

In this section, the method of investigating the influence of various fin shapes on the thermal performance of the heat sink is described. This document includes procedures for the experiment with different heat sink shapes such as cylindrical, flat, trapezoidal, pin, annular, elliptical, and tapered types.

Table 3 reviews the most important patents and journal articles for different cooling methods with fins, heat sinks, etc. The research looks at various approaches, including surface modification, addition of heat-conducting particles, enhancement of fin geometries and introduction of higher performance materials to enhance efficiency in transferring the heat from mechanical and electronic systems.

Table 3. Overview of heat transfer enhancement studies and patents

Study/Patent Title	Authors	Year	Key Findings
Enhancement of Heat Transfer through Fins	Chandra Kr Dubey, Varun Pathak, M. P. Srivastava [65]	2024	Focuses on parameters influencing heat transfer efficiency through fins, including geometry, material choice, and surface modifications.
Investigation of the Effect of Different Fins Configurations on the Thermal Performance of the Radiator	Amol Dhumal, Nitin Ambhore, Sandeep Kore, et al. [66]	2024	Investigates the thermal performance of radiators with different fin densities; higher density (10 FPI) leads to lower outlet temperatures.
Triangular Fin	Ranjan Singh [67]	2024	Examine the design of cooling fins, particularly the interaction between fins and fluid flow, focusing on optimization for heat transfer scenarios.
Heat Transfer Enhancement in a Rectangular Cooling Channel with Airfoil Shaped Fins	Lesley M. Wright, Andrew F. Chen, Hao-Wei Wu, et al. [68]	2021	Airfoil fins improve heat transfer by 6-8 times but incur a significant pressure drop (70-90 times), with optimization strategies discussed.
Enhancing Engine Cylinder Heat Dissipation Capacity Through Direct Optimization (DO) Techniques	Abhishek Agarwal, Megersa Olumana Dinka, Masengo Ilunga [69]	2024	Optimized engine fins improve thermal performance, reducing cylinder temperature and increasing heat flux by 25.87%.
Enhancement of Heat Transfer Analysis and Optimization of Engine Fins of Varying Geometry	K. Karthikeyan, C. Saravanan, Dr. T. Senthil Kumar [70]	2024	Perfects engine fin geometry using thermal analysis to improve heat dissipation and cooling efficiency.

Many studies have shown that fins increase the heat transfer surface area or reduce thermal boundary layers. This study compared three configurations of aluminum fins, flat fins, rectangular-edged fins, and circular perforated fins with rectangular edges —under three different voltage conditions. Ultimately, adding fins shortened the time to reach steady-state and resulted in lower temperatures than a finless heat sink.

Different geometries of fins used for efficient heat dissipation are shown in Figure 2: straight fins, pin fins, annular fins, and radial fins. Straight fins (a) are simple linear structures that aid in heat dissipation, but they have a less effective surface area to volume ratio compared to more complex designs. Pin fins (b), which are tubular and arranged in parallel, are commonly used in small heat exchangers with high heat fluxes in limited spaces, providing a high surface area for heat transfer. Circular annular fins (c) are commonly used in central heating systems (e.g. Turbine engines or radiators) using natural convection to enable the full surface area of whole perimeter to be used for heat dissipation. Radial fins (d), which are radially protruded from the center to outside, are used mainly for heat removal systems of motors and engines since they have a bigger unit area part capable of adjusting heat. Moving the annular fins into this temperature range can be an advanced method for heat transfer enhancement, as proved in Figure 4. The system employs ternary nanomaterials that even have better thermal conductivity κ and excellent heat dissipation properties than binary nanomaterials. The magneto-radiative effect produces a combined impact on the heat transfer performance of annular fins. It also depends on natural convection, a process that allows the dissipation of heat without the application of external forces. Caustic scattering is a very advanced technique to improve thermal transport efficiency in complex systems such as engines and electronic devices, by using these methodologies at micro and nano scale and controlling physical principles to improve thermal transport.

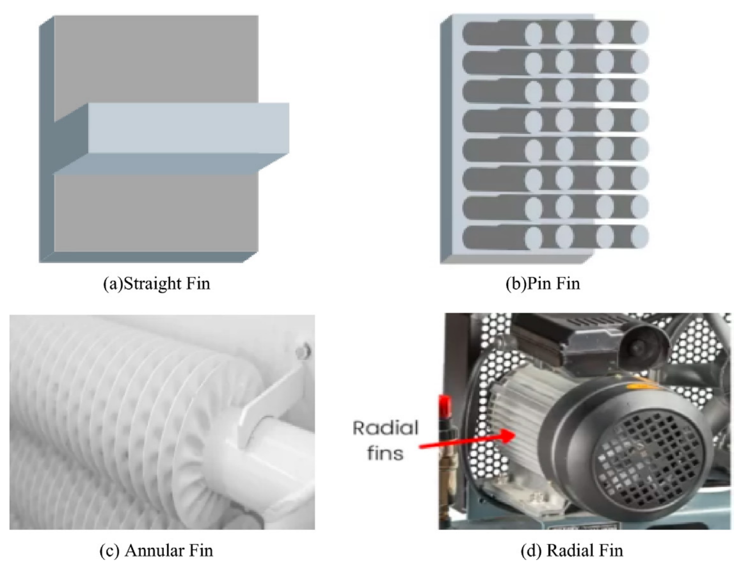


Figure 2. Thermal management in annular fin using ternary nanomaterials [51]

The flow lines and temperature field for two kinds of heat sink shapes; parallel-plate finned heat sinks Figure 3. The temperature isolines and streamlines of the parallel plate finned heat sinks are also presented. The temperature profiles of the heat sink are shown from 300 K (blue) to 326 K (red): The color bar is in Kelvin and is temperature. The arrows are the lines of flow of the fluid, presumably air or coolant, and depict the interaction of the fluid with the heat sink. They show the direction of flow and handle convection which helps heat transfer. The flow lines layout shows a linear flow through the fins, which allows for efficient release of the heat produced by the heat sink in the adjacent fluid. The temperature profile shows higher temperatures near the base of the fins, decreasing progressively toward the tips, showing heat removal by the fluid as it flows over the fins.

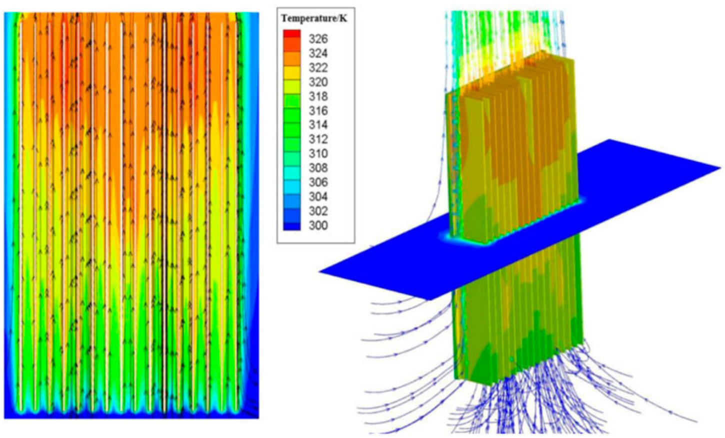


Figure 3. Temperature distribution of parallel-plate-finned heat sinks. The temperature profile across a parallel-plate fined heat sink, showing the gradient from 300 K (blue) to 326 K (red), which visualizes heat removal efficiency (Zhang et al) [71]

3. Result and discussion

This section discusses the most significant numerical simulation and experimental results, and the analysis of these results. Under natural and forced convective boundary conditions, the heat transfer rate, thermal resistance, and the effectiveness are investigated with the variations of fin shapes. It pays special attention to emerging materials such as hybrid and ternary nanostructured materials and proves how their properties stimulate thermal conduction and weight reduction. Quantitative information like temperature profile, heat transfer coefficient, pressure drop, also are reported.

The thermal performance of heat sinks mainly depends on forced convection, and many studies have emphasized the role of forced air flow in boosting the heat transfer rate from the heat sink fins to the surrounding air. Optimal heat sink geometries, surface finishes and cooling methodologies were analyzed for different heatsink shapes and structures. Although heat is dissipated between the fins of the heat sink and air, analysis of various fin shapes and cooling techniques suggests that forced airflow can significantly increase heat exchange from the fins to air surrounding the heat sink. There was also an investigation of thermal resistance, Nusselt number and fin pitch for different pin-fin configurations. Some fins configurations had higher convection heat transfer coefficients and lower thermal resistances, which highlighted that the design of fins is important to obtain better thermal performance.

Another study considered both convection and radiation heat transfer for a fined cylindrical heat sink with an installed motor fan and several vertical channels. Experiment results revealed that the active heat sink with a motor fan obviously excelled its finless counterpart in total heat transfer, showing that forced convection (like flow of air brought by a fan) was important to the enhancement of cooling efficiency. Moreover, the thermal performance of plate-fin heat sinks has gained attention and research related to enhancement in their thermal performance by use of unconventional geometry and advanced designs as well. Results showed that a plate-fin heat sink showing parallel flow outperforms conventional designs having vertically arranged symmetric half-round hollow pins (which is common in commercially available products); however, slight changes in the manufacture and application processes are needed. Forced convection is essential to help improve heat sink performance, and many works have been explored which show that forced air flow enhances cooling of fins to surrounding air, leading to better overall cooling efficiency. [37,63,72].

This research was started with an extensive heat transfer and fin design analytical study. Brigham and Vanfossen [75] studied short pin fin and long pin fin in stagger patten paddle with results of heat transfer analysis at different length of the fins, and array arrangements. The long pin fins had higher heat transfer levels compared to the short pins and 8-row array was more efficient than the 4-rows array. In contrast, the report emanating from Metzger et al. [76] studied the pin-fin shape and array orientation, on pressure loss and heat transfer. They considered only the cylindrical pin fins and concluded that: "Heat transfer is increased by each cylinder or pin. .. The presence of a staggered array reduces pressure loss. whilst oblong pin fins yielded better heat transfer but at the expense of pressure loss.

Another important parameter for data acquisition was Murat Çobanoğlu et al. [77] CFD analysis for comparison of various heat sink designs. They concluded that total surface area and fin spacing are the major factors dominating heat sink performance, while fin density results in thermal performance due to its influence on flow path of working fluid as depending on layout of fin.

Some works have been done in the cooling of pin-fin heat sink, Z Jian-Hui [78] showed that a best fin spacing value for pin-fin evaporator to be 8-12 mm was necessary. Additionally, Lindstedt et al. [64], working on single-fin and fin-array heatsink best shapes showed that trapezoidal fins gave the most practical trade-off between thermal resistance, fan power and mass. All in all, they provided workable data for comparing the effects of different fin geometries on thermal performance in both free and forced convection heat transfer experiments.

Idan et al. [79] studied the influence of externally forced vertical vibrations on the thermal heat coefficient for a flat plate. The present paper emphasized the impact due to vibration on free convection from an aluminum flat plate. Tests included adjusting the inclination of the plate to different angles (0° – 90°) and applying various vibratory frequencies (2 –16 Hz), and amplitudes (1.63 – 7.16 mm). It was found that at $\theta = 0°$, the heat transfer coefficient first increased by as much as 13.29% with the amplitude augmentation and then declined with further increase of the amplitude. The Nusselt number for all vibrations and no vibrations increased with the Rayleigh number. Vibration decreased the heat transfer effectiveness at higher frequencies even more for inclination plate condition.

Figure 4 depicts the physical model of an annular fin interacting with various thermal and magnetic effects. The main part in the figure describes the prime surface at the outer surface of the fin and Ta at the inner side to Tb. This annular fin is subjected to various physical effects, such as convection, radiation, and magnetic field. Heat transfer through the fin is considered as the model, in which the heat flux (q) is imposed in the radial direction of the fin and the magnetic effects exist throughout the surface. The radial varies from the outer radius (ro) to the inner radius (ri) of the tube for detailed analysis, as differential element dr. The ring is thermally perturbed by gradients and by ambient magnetic fields that change the behavior of conduction and convection of heat. The picture presents a study model for modeling complex thermal phenomena, including heat dissipation between the inner and outer surfaces of the fin under different physical conditions.

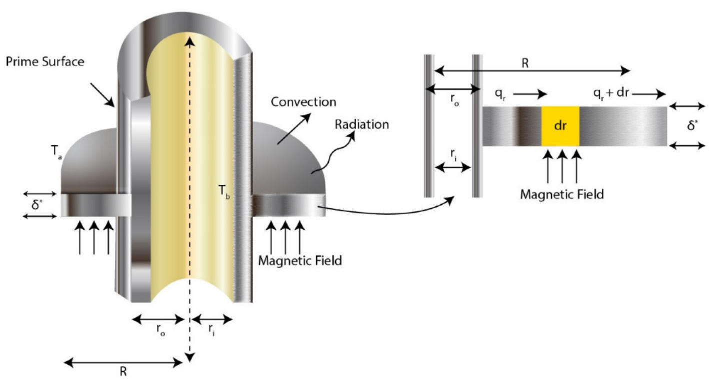


Figure 4. Annular fin subjected to thermal and magnetic influences [51]

Table 4 compares gaps and materials used for part components in thermal management. As the gap becomes larger, different thermal materials are used to achieve efficient heat transfer from the heat sink to the source. For smaller gaps (less than 0.5 mm or 18 mil), materials serve as a bridge to improve heat dissipation. Material choice becomes even more critical with respect to the interface gap because the heat sink dissipates so much heat away from major components.

Table 4. Choice based on interface gap.

Interface gap values	Product types available	
< 0.05 mm	< 2 mil	Thermal grease, epoxy, phase change materials
0.05–0.1 mm	2–5 mil	Phase change materials, polyimide, graphite or aluminum tapes
0.1–0,5 mm	5–18 mil	Silicone-coated fabrics
> 0.5 mm	> 18 mil	Gap fillers

3.1. Cylindrical fins

Cylindrical fins for heat sink design have become highly popular among researchers. Under natural convection conditions, the thermal behavior of cylindrical fins has been examined in experimental studies. Li et al. [80] Studied the thermal resistance of a cylindrical heat sink with rectangular fins under natural convection, focusing on the effect of number of fins and angle of fin inclination. The effect of two fin designs, radial fins and inclined fins, on the thermal resistance was studied. It was found that thermal resistance was increased by 30% for radial fins when compared to inclined fins. Shehab [81] also, in experimental work, extracted the convective heat transfer coefficient of the same notched fins in natural convection. Results revealed a 45% increase in the heat transfer coefficient of the notched fins compared to the unnotched fins, underscoring the importance of geometric modifications on thermal performance.

In addition, the effect of fin spacing on the heat sink cooling effectiveness under natural convection has been numerically simulated by Bhaumik and Behera [82]. Their results showed that the optimal spacing is decided by the degree of natural convection and the heat transfer area per unit length of the heat sink wall. As a conclusion, whether via experimental studies or numerical studies, the factors that have undergone investigation, like fin orientation, notched fin geometry, and fin spacing , all have a considerable effect on the thermal efficiency of the circular shape heat sinks working under natural convection conditions [83].

Table 5 gives a review of some of the studies of cylindrical fins, about their performance, research contributions, potential applications, and aims. The application suite is diverse, encompassing solar distillation systems and micro heat exchangers, and explores how various fin shapes, materials, and geometries impact heat transfer.

Table 5. Cylindrical fins in heat transfer systems: A comprehensive review of recent studies

Study	Authors	Findings	Contributions	Practical Implications	Objectives
1. A comparative assessment of innovative hemispherical solar distillers with cylindrical and conical fins (2023)	Attia, Kabeel, Abdelgaied et al. [84]	Conical fins provide 70.24% higher productivity than conventional distillers.	Optimized fin design (conical) improves solar distillation efficiency.	Enhancing solar distiller productivity.	Compare cylindrical and conical fins in solar distillation.
2. Thermal performance maximization in a complex heat exchanger with solid and hollow cylindrical fins (2024)	Godi et al. [85]	Half-hollow fins outperform solid and hollow fins in thermal conductance.	Hybridization of fin geometry maximizes thermal efficiency.	Enhances micro heat exchanger performance in thermal systems.	Maximize thermal conductance in micro heat exchangers.
3. Optimization of Thermal and Geometric Parameters of Cylindrical Fins during Natural Convection (2023)	Bunjaku, Filkoski [86]	Optimal fin diameter increases heat transfer rate.	Model for selecting best fin dimensions in heat exchangers.	Improving heat exchangers is important in engineering.	Perfect cylindrical fin dimensions for thermal efficiency.
4. Invariance, Conservation Laws, and Exact Solutions of the Nonlinear Cylindrical Fin Equation (2014)	Ali, Bokhari, Zaman et al. [87]	Derivation of exact solutions for heat transfer in cylindrical fins with temperature-dependent thermal diffusivity.	Developed theoretical framework for cylindrical fin heat transfer.	Affects the design and efficiency of cylindrical fins under varying thermal conditions.	Solve heat transfer equations for cylindrical fins with nonlinear thermal conductivity.
6. Performance assessment of hemispherical solar distillers with the extended cylindrical iron fins (2022)	El Hadi Attia et al. [88]	Extended cylindrical iron fins improve distiller productivity by up to 31.25%.	Optimized fin distance increases water evaporation.	Improve solar distillation efficiency with minimal material usage.	Evaluate impact of extended cylindrical iron fins on distiller performance.
7. Minimized Thermal Resistance in Microchannel Heat Exchanger with Cylindrical Fins (2024)	Nahum et al. [89]	Rectangular channel configuration reduces thermal resistance more than a cylindrical configuration.	Found configuration for perfecting heat exchangers.	Improves microchannel heat exchangers' thermal efficiency.	Minimize thermal resistance in microchannel heat exchangers.
9. Enumerating Heat Transfer Rate of Cylinder Fin Body by Varying Geometry and Material (2018)	Krishna [90]	Varying geometry and materials (e.g., Aluminum) impacts heat dissipation efficiency.	Parametric models predict heat dissipation for engine cooling.	Useful in automotive engine cooling systems.	Investigate effects of fin geometry, material, and thickness on heat dissipation.

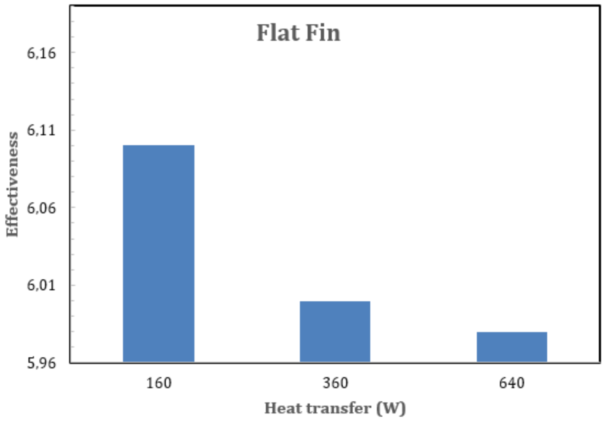
3.2. Flat fins

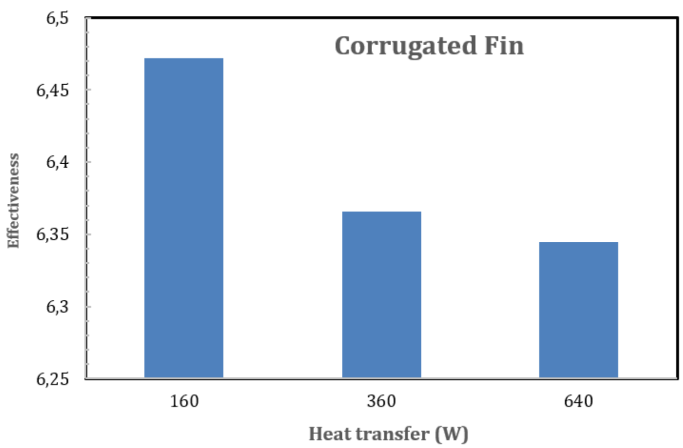
Flat fins are one of the most common heat sink configurations used to improve the thermal performance of the device by natural and forced convection heat transfer. The fins are carefully designed to maximize the surface area to improve thermal conduction. Flat fins have large surface area in free convection which helps in effective heat dissipation and helps in removal of heat from the source. Similarly, in forced convection scenarios, flat fins also perform exceptionally well. However, if a fan or blower is attached to it, turbulence occurs and the cooling efficiency of the heat sink with flat fins can be improved. This increases the convective HTC, leading to a considerable increase in the thermal dissipation for aluminum heat sinks. During the heat transfer analysis and thermal efficiency discussions, it is clear that the combined effect of the flat fins maximize area available for rejection (A) which enhances good heat dissipation between source and sink. They dissipate heat efficiently through natural convection or forced airflow.

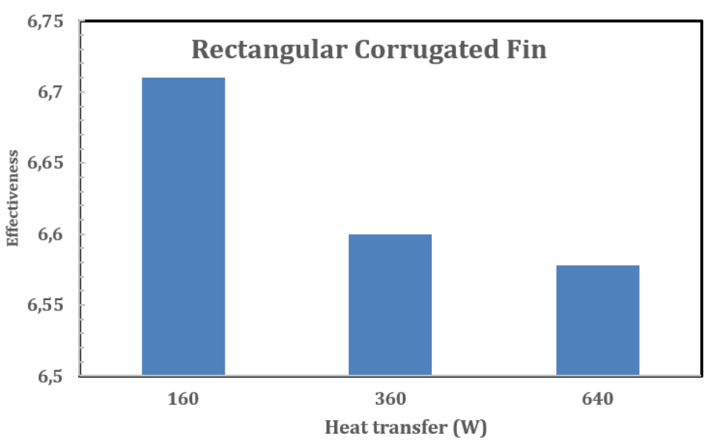
Several fin geometries were tested to decide the best look to improve thermal performance by both free and confined-concentration convective modes, and flat fins outperformed all others as flow inducers. The features to form increased effective surface area and heat spreading distance are very suitable for thermal management such as enhancing the efficiency of heat-sink [91,92].

Figure 5 shows the data for a variety of fin types, i.e., flat fin, corrugated fin, rectangular perforated corrugated fin and triangular perforated corrugated fin for various heat transfer rates (160W, 360W and 640W). For all fin types, the cooling effectiveness dropped after a fixed amount of heat input, so their capability of removing heat worsens with an increase for heat. The information for the flat fin shows that the smallest effective head starts behind 0.60 at 160 W, dropping somewhat with increasing heat transfer rates. All the test results show that for both the rectangular perforated corrugated fins, the effectiveness of corrugation channel is at least better when compared to that at 160W and becomes worse with increasing heat flux at values of 360 W and 640W.

In contrast, the effectiveness of the rectangular perforated corrugated fins decreases gradually but peaks at 160 W. The triangular perforated corrugated fin behaves in a similar fashion, but its performance is not as efficient, although it experiences a more abrupt drop in effectiveness when adding channels up to 160W Together, these trends suggest that regardless of whether it be rectangular or triangular fin design efficiency decreases with increasing heat load due to heat saturation and constrained surface area for heat elimination leading to diminishing returns on resiliency at higher heat fluxes.







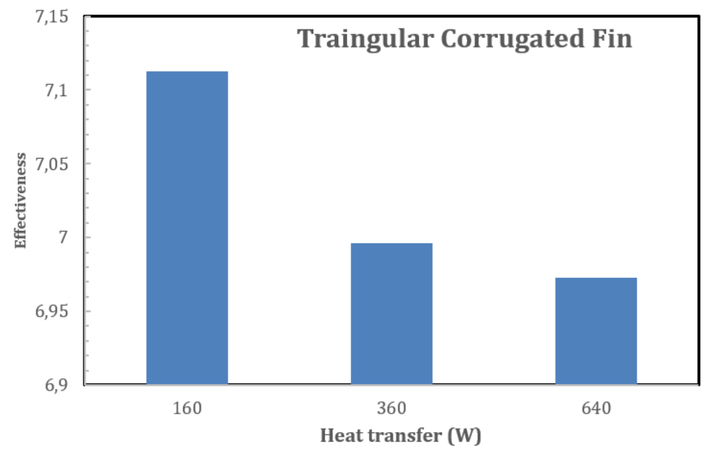


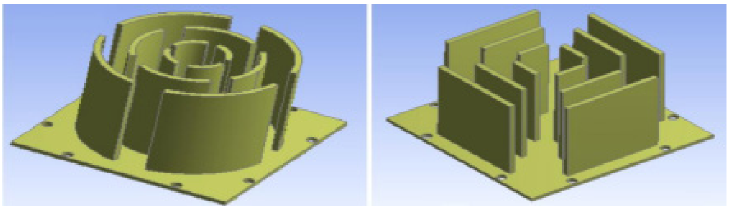
Figure 5. The average effectiveness of the fins at different powers for mixed convection [93]

3.3. Annular fins

A parametric study investigated the effects of fin shape, profile, and arrangement on circular fins under steady-state natural convection and forced convection heat dissipation. The primary aim was to compare two dissimilar fin shapes fabricated from the same material, with identical extended surface area, width and thickness.

The investigation aimed to evaluate the total heat transfer coefficient, fin efficiency, effectiveness, and temperature distribution under different base-plate temperatures and free-stream air velocities. The study concluded that heat transfer in the forced convection case was strongly influenced by fin geometry. Further, in tests under natural convection, there was no appreciable difference between the two fin shapes. In contrast, under forced convection, the concentric staggered circular shape was superior to the other shapes. This shows that the concentric, state-combined elliptical micro fins and nanomaterials further reduce the rectangular fins in forced-convection flows.

not only to fully perfect the geometry for fluid flow but also to capitalize shape on the best heat transfer efficiencies from Figure 6. It is concluded that the geometry configuration of the fins, and natural as well as forced convection play significant role in heat transfer by their effect on thermal performances. Investigation of the influence of different fin shapes on the thermos performance is important for optimization of heat sink designs with at most possible increase of heat elimination to a minimal waste material, size and costs (and pressure drop weight). This study offers important insights into the performance of different fin geometries and could help develop a new heat sink design [74].



(a) **(b)**

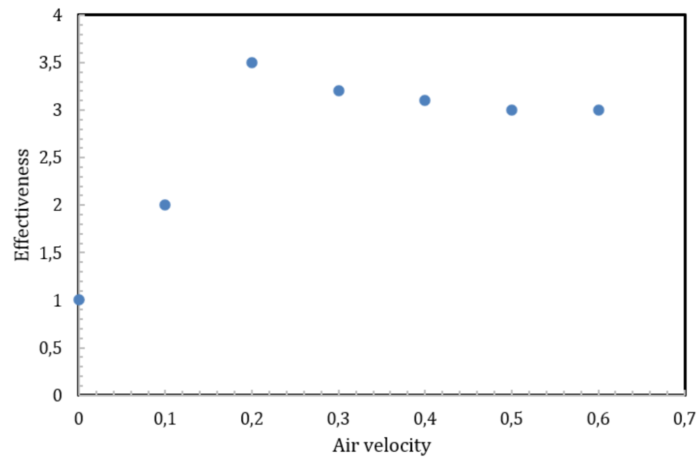
Figure 6. Comparison of concentric staggered annular fins and rectangular fins **(a)** Concentric Staggered Annular Fin, **(b)** Staggered Rectangular Fin [74]

3.4. Elliptical fins

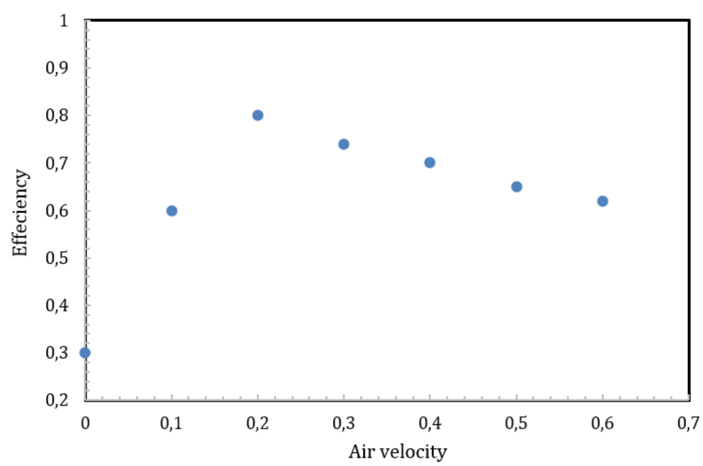
Many studies and articles have examined how elliptical fin shapes with different major-to-minor axis ratios (a/b) affect heat transfer performance at various cooling air velocities. Results indicate that the fin efficiency for all designs exceeds 1, implying improved heat transfer rates. Specifically, there was a 177% increase in effectiveness, and overall efficiency improved by 80% under forced convection compared to free convection at zero air velocity.

All fin effectiveness values were greater than 1 for all elliptical fin aspect ratios investigated, verifying that the fins are heat transfer promoters at these aspect ratios. This performance shows the heat transfer system was practical as well as efficient, with an effectiveness of between 3.2 and 3.85 being the range, and fin efficiency varying from 90% to 96%. The results also revealed that the elliptical fin, with an aspect ratio of 2.65 was the best for free convection conditions and yielded higher heat transfer. Furthermore, elliptical fins offered better performance than circular fins for heat transfer rate and efficiency under different environmental conditions—the surface temperature of the elliptical fins decreased with increasing length along the central axis. The present manuscript is mainly focused on the experimental part, showing that the use of elliptic fins improves the heat transfer in forced convection heatsinks. To this end, the manuscript responds to this inquiry by confirming the significant impact of aspect ratio on the convection heat transfer, thereby providing insight into the improved thermal efficiency of heat sinks in various convection modes. [94-96].

Figure 7 presents a heat transfer performance analysis of elliptical fins for different air velocities and axis ratios. The effectiveness of the elliptical fins is shown in Figure 7(a). It gets worse with air velocity but only up to a point. Then it levels off and then gets worse. Thus, low to moderate air speeds ease heat transfer while high speeds hinder thermal distribution. The power-input efficiency of the elliptical fin is also shown in Figure 7(b). Like the effectiveness plot, the fin efficiency increases with increasing air flow velocity but saturates or slightly decreases at higher velocity. Initially a high flow rate may be desired but eventually the heat transfer efficiency may decrease if the velocity is too high.



(a) Effectiveness



(b) Fin efficiency

Figure 7. Effectiveness and efficiency of elliptical fins with varying air velocities [51]

The variation of the efficacy of elliptical fins with the (a/b) ratio for different free-air velocities is shown in the diagram. It depicts the relation between air velocity and fin efficiency, showing that there is best fin efficiency in a specific operational window. Efficiency decreases outside this range at high air velocities due to turbulence and thermal boundary layer effects.

Novelty and effectiveness of elliptical fins with nanomaterial integration: Nano structuring of elliptical fins forms an innovative heat sink, where the synergy between structure and material enhances thermal efficiency. It is claimed that elliptical streamlined fins enhance heat transfer efficiency by generating turbulent flow and postponing the flow separation. Elliptical fins (with a radius ratio of 0.50) showed considerable improvements in heat transfer compared to conventional fin geometries, in agreement with the results of Danışmaz [97].

Nanomaterials, especially nanoparticles, including silver (Ag), copper oxide (CuO), aluminum oxide (Al_2O_3) and carbon nanotubes (CNT), have been widely used due to their better thermal properties than traditional fluids and solids. Nanofluids are particles of nanoscale suspended in base fluids in colloidal form and have better thermal conductivity than traditional heat transfer fluids. This improvement is due to the increase in the effective surface area by nanoparticles and thus more efficient dissipation of heat in liquids.

Nanomaterials improve this phenomenon. Nanofluids are suspensions of nanoparticles in a base fluid, which have enhanced thermal conductivity compared with common commercial fluids. Bahiraei et al. [101] investigated the heat transfer efficiency of an elliptical pin-fin heat sink with circular or elliptical pin fins and silver–water nanofluid, reporting significant improvement in heat dissipation. Similarly, Arshad et al. [102] investigated the effectiveness of microfine heat sinks cooled by nanofluid and mono-nanofluid with both enhanced heat transfer.

It is also possible to combine elliptical microfine and nanomaterials to further reduce thermal resistance. This cross-fertilization serves not only to fully perfect the geometry for fluid flow but also to capitalize on enhancements in heat transfer performance. Some of these hybrid architectures may therefore provide a possible avenue for addressing the performance-cooling requirements in electronics and other industries that require improved thermal management systems.

3.5. Industrial applicability of hybrid and ternary nanomaterials in heat sink design

The introduction of hybrid/ternary nanomaterials for heat sink design shows promising improvements in heat transfer performance, opening potential applications in industrial sectors. Al_2O_3 thermal insulation and other properties gave very good results with hybrid nanomaterials such as CuO-Al alloys. It has been seen that CuO-Al_2O_3 hybrid nanofluids show a 32.82% increase in thermal conductivity at 80°C, which is superior to single part nanofluids.

The potential of ternary nanomaterials consisting of three different nanoparticles has been studied for the enhancement of thermal properties. The thermal efficiency can be enhanced by ternary nanocomposites due to synergistic effects of different nanoparticles, which improves the heat dissipation for heat exchangers and electronic cooling systems.

These developments underline the industrial importance of nanomaterial-based heat sinks, particularly in industries where advanced thermal management is critically important. These nanomaterials show improved thermal conductivity and stability, providing a solution for manufacturing compact, thermally efficient cooling systems that are critical in modern electronics and industry. [103-106].

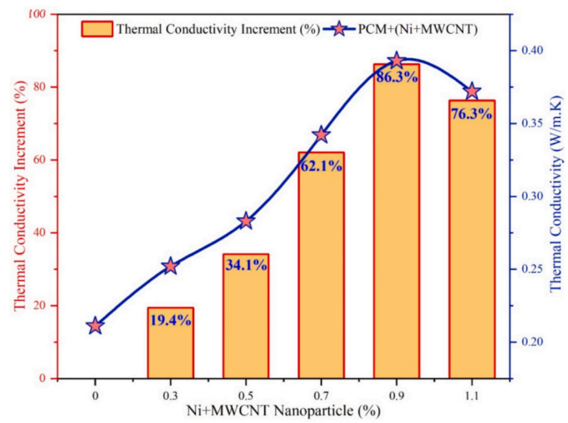


Figure 8. Thermal conductivity increment of PCM with hybrid nanomaterial [107]

3.6. Discussion

The results clearly prove the heat-removal capabilities of different fin shapes in both free and forced convection in the heat sink and show a quantifiable improvement from new nanomaterials, further enhancing sink performance. Both experimental and numerical results show that the thermal performance of elliptical fins leads to improved lifetime reliability of the LEG nanomaterial-enhanced fins, increasing support for 90% efficiency in forced convection. This significant benefit is attributed to the elliptical channel configuration's enhancement of maximum mixing and surface area. This configuration maximizes surface area while perfecting flow resistance, thereby increasing the heat transfer rate and overall efficiency. This is consistent with recent studies, which have shown that elliptical fins can significantly improve the cooling efficiency of high-density electronic systems through aspect ratio optimization.

One important finding of this study is the use of advanced nanomaterials in many studies as hybrid and ternary composites when incorporated into fins. Researchers have discovered that fins made from these materials have improved thermal conductivities and lower densities, both of which are crucial properties for cooling in modern electronics. For instance, the base temperature in annular and elliptical fins of ternary nanomaterials was lower than that of copper, resulting in a higher overall heat transfer coefficient. Thus, the idea that material enhancements can improve heat sink functionality was confirmed. This result is also consistent with earlier studies, and the present work adds new quantitative data comparing different geometries and material combinations performed from the same experimental setup.

Moreover, according to the report's case study analysis of various fin shapes, the studied configuration is not necessarily the best for a particular operation: elliptical fins are found to be best for forced convection. On the other hand, simpler structures (e.g., flat or columnar fins) are preferable for passive cooling purposes. Notched, perforated, and branched fins were seen to perform much better in this model at low heat input levels, suggesting that further development of the fin surfaces could enhance performance at a specific unit scale.

So, the results could be helpful for designing and perfecting heat sinks in engineering applications. By proving how incorporating advanced materials and geometry optimization can enhance thermal management, this report offers engineers meaningful guidance in designing high-performance, compact, lightweight, and energy-efficient cooling solutions. Future work should study the design of more geometrically complex features, account for time-dependent operational conditions, including heat transfer in fins during dynamic operation, and the lifetime reliability of LEG nanomaterial-enhanced fins to improve support for future heat sink design.

3.7. Comparison of fin types

By comparing it with Table 7, the best fin shape can be chosen based on specific cooling conditions, needed thermal performance, and fabrication constraints. Performance can be further enhanced across various fin types by incorporating materials such as nanomaterials.

- Flat and circular fins are very effective to enhance natural convection, owing to the large surface areas being of a large Base area.
- Elliptical fins offer superior thermal performance under forced convection, particularly at best aspect ratios.
- Pin fins and trapezoidal fins configurations are among the best thermal designs for the trade-off between heat transfer & pressure losses in high-flux, forced-convection collectors.
- Annular fins with ternary nanomaterials take advantage of the overall physical effects for optimal heat dissipation under both natural and forced convection.
- Novel geometries, including branched and tapered fins, offer a potential thermal solution but with added design complexity.

Table 7. Comparison of fin shapes on heat transfer and pressure drop

Fin Shape	Heat Transfer Efficiency	Pressure Drop	Best Use Scenario	Remarks
Elliptical	Highest (up to 90%+, forced)	Low	Forced convection, compact systems	Optimal at aspect ratio 2–2.65; minimizes airflow resistance
Flat	High (especially natural)	Moderate (increases with air velocity)	Natural convection, general cooling	Large effective area; simple structure
Cylindrical (Pin)	High (both modes)	High (especially dense arrays)	Both, especially where turbulence is needed	Suitable for enhancing turbulence, but it increases the pressure drop
Annular	Moderate to High (with nanomaterials)	Moderate	Systems with advanced materials	Enhanced with ternary/ hybrid nanomaterials
Trapezoidal	Moderate	Moderate	Space-constrained or hybrid applications	Good surface area, moderate flow resistance
Tapered/Branched/ Notched	Moderate to High (at moderate loads)	Moderate to High	Special designs, targeted cooling	Increases turbulence, higher ΔP possible

4. Conclusion

This paper was a comprehensive review of studies on various fin shapes used in heat sinks, highlighting their significant contribution to fin performance in both natural and forced convection. Based on the review paper,

Studies have shown that the geometry, arrangement and material composition of fins have a significant influence on heat transfer performance, pressure drop and thermal resistance. The efficiency of natural convection in flat and cylindrical fins is more than the efficiency in the case of the fins with a larger effective surface area depending on the flow conditions. Compared to the helicoidally fined tubes, where the eccentricity effects could be significant, the ideal theoretical aspect ratios of the order of 2.0-2.65 for the heat transfer coefficient in the case of forced convection are not affected by all the studied Reynolds numbers. The employment of novel materials such as hybrid and ternary nanomaterials greatly enhances the thermal conductivity (TC) and hence more efficient electronic cooling through improved heat dissipation while keeping light weight and cost-effective designs. Significant improvements in thermal regulation have been seen to occur with changes in shape like notches, holes and branched fins.

5. Future research

This research proves that only a synergistic design, combining optimized geometry and cutting-edge materials, can effectively accelerate progress toward efficient and high-performance heat sinks for various industrial and electronic applications 5. Scope for Future Research.

While this study offers significant insights into the impact of various fin shapes on heat sink performance under both natural and forced convection, several areas stay open for future exploration. Future research could focus on:

1. Advanced Fin Geometries: To evaluate the feasibility of new generation (branched, perforated, wavy) fin designs that are more effective for heat removal, especially in small form factor applications such as electronic devices.
2. Hybrid Nanomaterials: The synergistic effect of hybrid and ternary nanostructures in various fin shapes is studied, as their combined impact could markedly improve thermal conductance and overall heat sink performance.
3. Thermal Management in Microsystems: Fin shapes for microelectronics focus on perfecting fin design where space, weight, and cooling efficiency are essential.
4. Real-world system applications: Examining how these fin designs perform under actual conditions, such as random vibration, dynamic airflow, and long-term operational reliability.

Focusing on these directions, future work will yield more useful conclusions on the development of novel heat sinks for advanced cooling applications.

Nomenclature

A	Area, m^2
C_p	Specific heat, J/kg.K
k	Thermal conductivity, W/m.K
μ	Dynamic viscosity
COP	Coefficient of performance
Dw	Distilled water
N	Number of turn
P	Pitch (m)
d (m)	Tube diameter, m
D_c (m)	Diameter of coil, m
$\dot{m}$	Flow rate, kg/s
h	Heat transfer coefficient, $W/m^2.K$
LPM	Litre per minutes
Nu	Nusselt number
Pr	Prandtl number
Re	Reynolds number
LMTD	Logarithmic mean temperature difference
L	Shell and coil length, m
U	Overall heat transfer coefficient, $W/m^2.°C$
vol%	volume percent
wt%	Weight percent

Greek letters

ρ	Density, kg/m^3
φ	Volume fraction of nanoparticles
μ	Dynamic viscosity, Pa.s
ε	Effectiveness
λ	Coil torsion, Pc/ π Dc
α	Alpha
η	efficiency

Subscripts

c	Coil or cold fluid
h	Hot fluid
i	Inner or internal
o	Outlet
t	Tube
ex	exergy

Author contributions statement

Intisar Khalaf: Conceptualization, Writing – original draft, Writing – review & editing. Zhala Azeez Mohammed: Conceptualization, Writing – original draft, Writing – review & editing. Adnan M. Hussein: Methodology, Investigation, Formal analysis, Validation. Mohammed Waleed Muayad: Methodology, Investigation, Formal analysis, Validation. All authors reviewed and approved the final version of the manuscript.

Declaration of interests

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 manuscript.

Data availability

No new datasets were generated for this study. The data and information discussed in this manuscript are derived from the published studies cited in the article.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this manuscript, the authors used generative AI-assisted technology solely to improve language, grammar, and readability only. The authors after reviewed and edited the generated content as necessary.

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