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Analyzing Temperature Distribution in Multiple Fin Geometries to Optimize Heat Transfer Efficiency

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ABSTRACT

This study is quantitative research using Computational Fluid Dynamics (CFD) simulations to optimize pin fin design. Samples include aluminum pin fins with three different geometries: circular, square, and cone, and side lengths of 5 mm, 10 mm, and 15 mm. CFD simulations are conducted to quantitatively analyze temperature distribution across the surface and height of the fins. Results show that the highest temperature is localized at the base plate and decreases along the fin height. Circular and square fins demonstrate more uniform temperature distributions, while cone fins show significant gradients between base and tip. Smaller fin side lengths result in greater temperature differences. This research provides a detailed understanding of how fin geometry impacts heat transfer efficiency and temperature distribution, offering valuable insights for the development of more efficient fin designs in thermal management applications.

Keywords: Fin Geometries, Fin Size, Simulation, Temperature Distribution

INTRODUCTION

Heat and mass transfer are fundamental processes in numerous engineering applications, particularly within the disciplines of thermal and fluid engineering. The ability to control and enhance these processes is crucial for improving the performance, reliability, and efficiency of many critical systems, including refrigeration units, heat exchangers, power plants, automotive cooling systems, and electronic devices. One effective strategy for enhancing heat transfer involves increasing the surface area available for heat exchange, often achieved through the use of specialized structures such as pin fins [1].

Pin fins are slender, pin-like projections attached perpendicularly to surfaces to promote heat transfer by increasing the effective surface area and improving contact between the solid surface and the surrounding fluid [2]. The inclusion of pin fins disrupts the thermal boundary layer, promotes fluid mixing, and increases convective heat transfer rates. The geometric properties of these fins—such as shape, size, spacing, and arrangement—significantly affect the efficiency of the heat transfer process [3]. Consequently, optimizing fin geometry has become a focal point for researchers seeking to design high-performance thermal management systems. Pin fins have been widely employed in various industrial applications, including electronic device cooling, heat exchangers for process industries, compact heat sinks for avionics, and cooling channels in gas turbines [4].

In practical settings, effective heat and mass transfer solutions are integral to the functioning of systems across the industrial, technological, and environmental sectors. Within mechanical engineering education, understanding these phenomena is essential, particularly for students who will be responsible for designing next-generation thermal systems. Laboratory practices focused on heat transfer provide students with opportunities to engage in experimental and simulation-based learning. Through activities such as analyzing finned surfaces, students develop a deeper understanding of the principles governing thermal management, system optimization, and energy efficiency. The use of pin fins in laboratory practice offers significant educational benefits [5], illustrating how surface area enhancement can improve thermal performance, and providing tangible examples of design trade-offs between heat transfer enhancement and increased fluid resistance [6].

Despite the extensive body of research on pin fins, many studies have traditionally focused on conventional fin geometries namely, circular and square cross-sections [7] with less attention given to non-standard shapes such as cones, ellipses, or irregular profiles. Computational Fluid Dynamics (CFD) simulations have become an indispensable tool for investigating pin fin performance [8]. CFD techniques allow researchers to perform detailed, non-invasive analyses of fluid flow and heat transfer phenomena under varying geometric and operating conditions, leading to deeper insights into system behavior and enabling the exploration of novel fin designs [9]. However, a review of the existing literature reveals that certain aspects of pin fin design remain underexplored.

Specifically, while there have been numerous studies analyzing aligned and staggered pin fin arrangements [10], variations in pin fin cross-sectional shape combined with changes in side length or diameter have not been sufficiently investigated. Many prior studies have focused either on a fixed fin geometry or on gross thermal performance metrics, without fully analyzing localized phenomena such as temperature gradients along the fin height [11]. Furthermore, the influence of varying surface area, resulting from fin shape and size modifications, on the temperature distribution between the base plate and the fin tip has not been comprehensively characterized.

Recent studies [12][13] suggest that fin geometry can have profound effects not only on overall heat transfer rates but also on localized thermal behavior, which can impact thermal stress distribution and long-term material reliability. Particularly for high-performance applications such as microelectronics or aerospace systems, where temperature uniformity and localized overheating are critical concerns, a better understanding of these effects is essential. However, detailed investigations into the temperature distribution behavior of less conventional geometries, such as cones, under systematic size variations are largely absent from the literature.

To address these research gaps, this study investigates the thermal performance of pin fins with three distinct cross-sectional geometries: square, circular, and conical. Furthermore, variations in side lengths of 5 mm, 10 mm, and 15 mm are considered to systematically assess the influence of fin size on temperature distribution. CFD simulations are employed to model and analyze heat transfer characteristics under identical boundary conditions, including a set base temperature and forced convection environment with a known heat transfer coefficient [14].

The originality of this study lies in the detailed evaluation of the cone fin geometry, which has not been extensively analyzed in previous works. The conical shape, characterized by a continuously decreasing cross-sectional area along its height, introduces unique thermal behavior compared to uniform cross-section fins. The cone fin's tapering design may influence the conduction path, heat dissipation, and surface temperature distribution differently than traditional geometries [15]. By systematically studying cone fins alongside square and circular fins under controlled conditions, this research aims to provide new insights that could inform the design of more efficient thermal management solutions for advanced engineering applications.

The inclusion of square and circular geometries, although already widely investigated in prior studies, serves an important purpose in this work. These geometries are utilized for the validation of the CFD modeling approach by comparing simulation results against expected thermal behavior observed in existing literature. Furthermore, comparing all three geometries under identical simulation parameters allows for a consistent and fair assessment of how geometric differences impact temperature distribution and heat transfer efficiency [16].

Beyond its contribution to filling existing research gaps, this study also aims to support educational objectives. By integrating computational modeling with fundamental thermal analysis, this research offers students and practitioners a deeper understanding of how fin design influences heat transfer performance. The use of CFD simulations provides an opportunity for students to engage with advanced analytical tools that are increasingly essential in modern engineering practice [17]. Furthermore, understanding the relationship between fin geometry and thermal behavior can assist in the design of more sustainable, energy-efficient systems in fields ranging from renewable energy to high-performance computing [18].

The structure of this study is organized as follows. The next section details the methodology employed, including the geometric modeling, boundary condition settings, and CFD simulation procedures [19]. Subsequently, the results section presents and discusses the findings, focusing on temperature distribution trends for each fin geometry and size variation. Finally, the conclusions summarize the key insights obtained and propose directions for future research, particularly regarding the optimization of cone fin configurations for practical applications.

In this study, several important factors are considered to ensure the reliability and relevance of the results. The side length/diameter of the pin fins, the material properties (aluminum for both base plate and fins) [20], the fin arrangement pattern, and the forced convection conditions are carefully controlled to isolate the effects of geometry and size on heat transfer performance [21][22]. By maintaining consistent experimental and simulation conditions, the study provides clear and interpretable results that can be compared across different geometries and dimensional scales.

Moreover, this research emphasizes the practical significance of understanding detailed temperature distribution patterns rather than merely evaluating average thermal performance. Localized overheating or excessive thermal gradients can lead to material degradation, increased maintenance requirements, or failure in real-world applications. As thermal management continues to play a pivotal role in the design of smaller, faster, and more efficient systems, insights from detailed studies such as this one become increasingly valuable.

In conclusion, this study contributes both to the academic understanding of fin-based heat transfer mechanisms and to the practical advancement of thermal management strategies. Through a comprehensive analysis of three pin fin geometries under systematic variations in size, using CFD as a powerful investigative tool, this research advances knowledge in the field while also reinforcing the educational value of simulation-based analysis in engineering curricula.

RESEARCH METHOD

This research is classified as quantitative research using computational simulation techniques through Computational Fluid Dynamics (CFD) software. The simulation involves three types of fin geometries arranged in an aligned pattern: circular, square, and cone. For the square fin geometry, the side lengths are varied at 5 mm, 10 mm, and 15 mm to study the influence of size on thermal performance. To clarify the research workflow, a flowchart of the research methodology is presented in Figure 1. This research is also based on the use of laboratory equipment shown in Figure 2, with the primary analysis focusing on heat transfer along the surface of pin fin cross-sections.

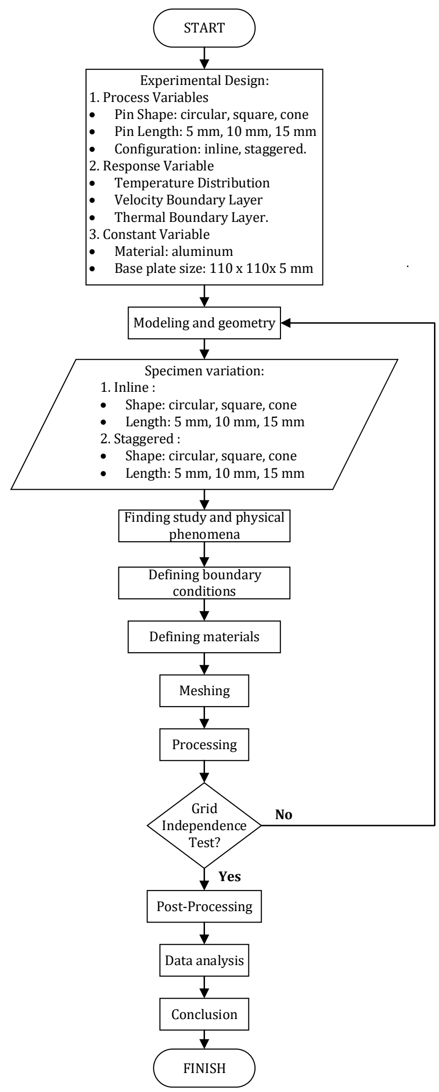

Figure 1. Research methodology flowchart

The study focuses on pin fins with varying cross-sectional shapes, namely square, circular, and cone. Additionally, variations in the fin side length for the square shape are examined, with values of 5 mm, 10 mm, and 15 mm. The data used for this research is derived from experimental data on various relevant parameters, such as the dimensions of the base plate, including length, width, and thickness, as well as the side length and diameter of the fins, and the arrangement of the fins. This data will serve as the foundation for designing the CFD simulations to be conducted in this research.

Figure 2. Schematic of the laboratory equipment

This research focuses on three variations of pin fin geometry—circular, square, and conical—arranged in a regular aligned pattern on a base plate. Both the pin fins and the base plate are made of aluminum, selected for its high thermal conductivity (237 W/m·K), density (2700 kg/m^3), and specific heat capacity (900 J/kg·K). The geometric dimensions used are as follows: circular fins with a diameter of 10 mm and a height of 73 mm; square fins with a side length of 10 mm and a height of 73 mm; and cone fins with a base diameter of 10 mm, a height of 73 mm, and a spacing (SL and SD) of 20 mm, see Figure 3. Additional variations are introduced by altering the square fin side lengths to 5 mm, 10 mm, and 15 mm, maintaining a constant height. All fins are mounted on a base plate measuring 110 mm × 110 mm with a thickness of 5 mm.

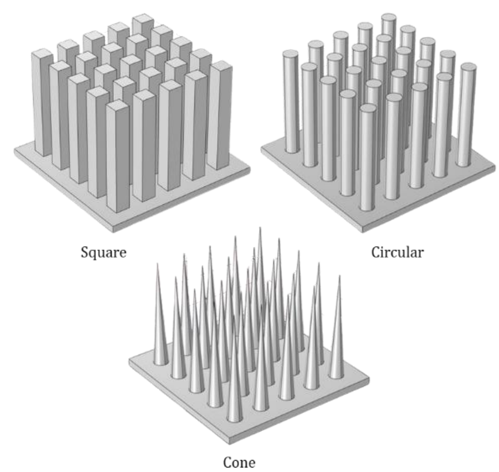

Figure 3. Design shape variation

CFD simulations are conducted with boundary conditions including a fixed base temperature of 323 K, ambient air temperature of 293,15 K, and a forced convection heat transfer coefficient of 1000 W/m^2·K. Perfect thermal contact between fins and base plate is assumed. A normal mesh grid is applied, with local refinement around the fin surfaces and junctions to capture temperature gradients. These parameters are chosen to realistically model the heat transfer behavior and evaluate the influence of fin geometry and size on thermal performance.

RESULT AND DISCUSSION

Figure 4 presents the temperature distribution contours along the surface of the fins for three pin fin geometries: circular fin, square fin, and cone fin. The contour visualization results illustrate the temperature changes along the height of each pin fin geometry. In the temperature distribution contour analysis, it can be observed that the highest temperature, indicated by the red color, is located on the base plate surface, close to 323 K.

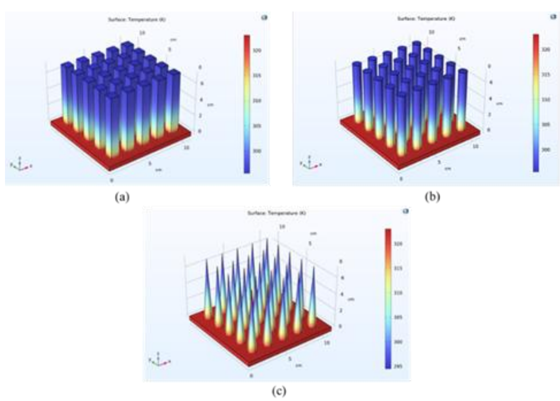

Figure 4. Temperature distribution contours: a) square fin, b) circular fin, and c) cone fin

Conversely, the area with the lowest temperature, at 295 K, is shown in dark blue and is located at the ends of the fins, where heat is more rapidly dissipated to the surrounding environment. This phenomenon demonstrates the heat transfer mechanism via conduction from the base plate to the fin tips, as indicated by the heat propagation along the fin surface [23], as well as convection in the surrounding area.

Figure 5 shows the changes in temperature along the surface of the fins. The surface area of the fins plays a crucial role in the heat transfer process, where a larger area provides more efficient heat transfer from the material. The temperature distribution near the base plate shows the highest temperature due to the direct contact with the heat source or the base temperature set at 323 K. However, as the height of the fin increases, the surface area exposed to the surrounding air also increases, resulting in more efficient heat transfer. Consequently, the overall temperature of the fin tends to decrease as the fin height increases.

As the height of a fin increases, the surface area exposed to the surrounding air also grows, which significantly enhances the fin's ability to transfer heat to its environment. This increase in surface area allows for a greater rate of heat dissipation, leading to improved thermal performance of the fin. Studies have shown that the convection heat transfer coefficient and the overall heat transfer rate both increase with fin height, as the larger surface area provides more opportunity for heat exchange between the fin and the ambient air. This phenomenon has been consistently observed in experimental and numerical investigations, where fins with greater heights demonstrated higher Nusselt numbers and improved heat transfer efficiency compared to shorter fins [24].

Consequently, as the fin height increases, the overall temperature of the fin tends to decrease due to the enhanced heat transfer. This inverse relationship between fin height and fin temperature has been documented in various open access studies, which report that the temperature difference between the fin base and the environment diminishes as the fin height increases, resulting in lower average fin temperatures [25] [26]. The reduction in temperature is attributed to the decreased thermal resistance and the increased effectiveness of the fin in dissipating heat.

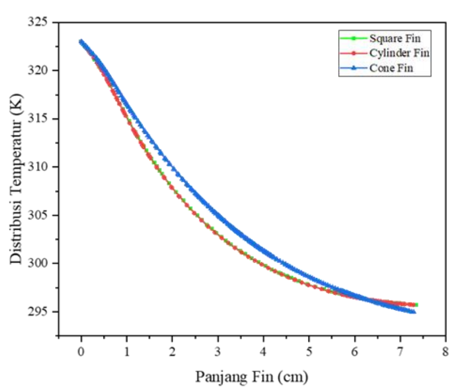

Figure 5. Comparison of temperature distribution with fin geometry variations

Regarding geometric variations, square and circular fins, with their larger surface areas, allow for more uniform heat transfer along the fin. In contrast, cone fins, with their sharper tips and smaller surface area, can exhibit significant temperature differences between the base plate and the fin tips.

Figure 6 illustrates the temperature distribution along the square fins with side lengths of 5 mm, 10 mm, and 15 mm. The contour results show that the lowest temperature is located at the tip of the fin, indicating that heat can be more efficiently transferred from the fin to the surrounding air at this point. Increasing the fin length tends to result in a larger temperature difference between the base and the tip of the fin.

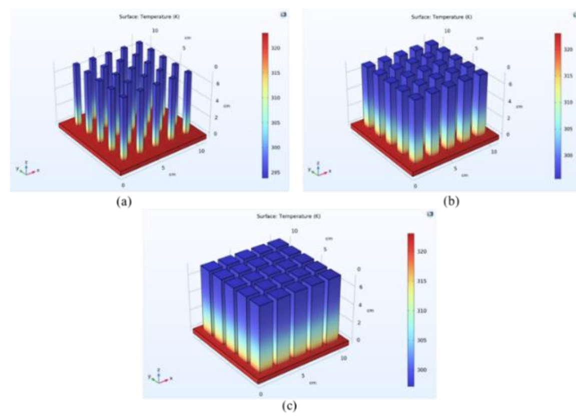

Figure 6. Temperature distribution contours for square fin: a) 5 mm, b) 10 mm, and c) 15 mm

In heat transfer, it is observed that as the surface area increases, the temperature difference between two specific points tends to be smaller for the same amount of heat transfer [27]. This relationship stems from the fundamental principles of conduction, where the rate of heat transfer is directly proportional to both the surface area and the temperature difference across the material

[28] . According to Fourier's law, increasing the surface area allows more heat to be transferred for a given temperature gradient, effectively reducing the required temperature difference to achieve the same heat flow [29] [30].

In this study, the comparison of fin side lengths directly impacts the surface area of the fin. For pin fins with a side length of 5 mm, the surface area is smaller compared to fins with side lengths of 10 mm or 15 mm. Consequently, the temperature difference between the base of the fin and the fin tip tends to be greater for the 5 mm side length fin compared to the 10 mm and 15 mm fins.

CONCLUSION

This study analyzes the heat transfer characteristics through three pin fin geometries: circular, square, and cone. CFD simulations help illustrate the temperature distribution along the surface and height of the fins. The results indicate that the highest temperature is concentrated at the base plate, consistent with the boundary condition set at 323 K. As the fin height increases, the temperature tends to decrease, reflecting the effective heat transfer from the base plate to the fin surface according to the ongoing heat transfer mechanisms. The temperature distribution analysis shows that the surface area of the fin has a significant impact on the temperature difference. A larger surface area results in a smaller temperature difference between the base and the tip of the fin. The circular and square geometries exhibit more uniform temperature distribution, while the cone fin shows a significant temperature difference between the base and the tip. This is also evident in the square fin with the shortest side length of 5 mm, which shows a significant temperature difference between the base and the tip compared to the 10 mm and 15 mm side lengths.

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