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Electronics Heat Sinks: Analyzing The Impact Of Fin Count On Forced Convection Cooling

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Abstract: This research presents a comprehensive analysis of heat sinks employed in electronic devices, focusing on their performance under forced convection. The study investigates two distinct heat sink configurations: a four-fin and an eight-fin design. Utilizing ANSYS simulation software, we examined heat transfer characteristics, temperature distribution, and thermal performance. The results demonstrate that the eight-fin heat sink exhibits significantly improved cooling efficiency compared to its four-fin counterpart as Eight-fin heat sink design lowers maximum and minimum temperatures by 2.55°C and 2.76°C, respectively, compared to the four-fin counterpart. It dissipates heat more effectively, resulting in lower device temperatures and enhanced thermal management. The comparison is supported by detailed graphs and data, revealing the thermal advantages of the eight-fin heat sink. This research provides valuable insights for optimizing heat sink design in electronics, ultimately contributing to more reliable and efficient electronic devices. Understanding the impact of fin arrangement on forced convection cooling will aid engineers and designers in making informed choices for future electronic thermal management solutions .

Keywords: Heat Transfer, Heat Sink, Electronic Chip, Chip Cooling ,Convection

1. INTRODUCTION

Electronic devices have become an integral part of our daily lives, and their performance relies heavily on effective thermal management. The rapid advancement of technology has led to increased power densities within these devices, resulting in elevated temperatures that can compromise their reliability and longevity. To mitigate these thermal challenges, heat sinks have emerged as a crucial component in electronics cooling systems. Heat sinks are designed to dissipate excess heat generated by electronic components through conduction, convection, or radiation. Among these modes of heat transfer, forced convection has gained prominence due to its efficiency in dissipating heat. In forced convection cooling, a fluid (typically air) is actively circulated over the heat sink's surface to enhance heat removal. The design of heat sinks plays a pivotal role in determining their cooling performance. One key parameter that significantly influences their effectiveness is the number of fins. Fins are thin protrusions on the heat sink's surface, which increase the surface area available for heat transfer. The arrangement and number of fins can vary, and this variation can have a profound impact on the heat sink's ability to dissipate heat efficiently. This research focuses on the comparative analysis of two commonly used heat sink configurations: the four-fin and eight-fin designs. By utilizing advanced simulation techniques and ANSYS software, we aim to examine the thermal performance of these two configurations under forced convection conditions. The primary objective is to assess how the number of fins affects temperature distribution, heat dissipation, and overall thermal efficiency. Understanding the thermal behaviour of different heat sink designs is critical for optimizing electronic device performance and reliability. This study seeks to provide valuable insights that can aid engineers and designers in making informed decisions regarding heat sink selection and design, ultimately contributing to the development of more efficient and reliable electronic systems.

Objectives

- Thermal Performance Assessment
- Temperature Distribution Analysis
- Heat Dissipation Comparison
- Influence of Fin Count
- Average Air Temperature Calculation
- Heat Sink Design Optimization
- Practical Cooling Application
- Simulation Validation
- Contribution to Electronics Cooling

2. LITERATURE REVIEW

[1] The authors emphasize in the first section of their research paper, "Improved design of heat sink including porous pin fins with different arrangements," the increasing need for high-performance electronic devices and the critical need for effective cooling systems to control the heat these devices are producing. The study presents both active and passive cooling techniques in this context, emphasizing the benefits of active techniques such as forced convection, which are commonly used because of their greater efficiency in cooling thermal components. Researchers have looked into a number of tactics to improve the thermal efficiency of coolant fluid flows, with a focus on using porous medium such metal foams. Metal foams are known to increase the rates at which heat transfers by promoting greater fluid-solid interaction and improving local mixing. This section's literature review showcases earlier studies that have used metal foams to great effect in a variety of heat transfer applications, such as heat exchangers, thermal energy storage, PEM fuel cells, and battery thermal management. The section also notes that although using porous heat sinks might improve heat transmission, there may be difficulties due to an increase in pressure drop; however, this is a trade-off that is deemed acceptable considering the overall improvements in thermal performance. In conclusion, the introduction summarizes the goals of the study, which include determining the ideal pin-fin arrangement and examining the effects of spaced and aligned designs on heat sink performance. This establishes the context for the in-depth exploration and quantitative analysis that are provided in the document.

[2] The study "Influence of fin height on heat transfer and fluid flow characteristics of rectangular microchannel heat sink" looks at how different fin heights in rectangular parallel microchannel heat sinks affect fluid flow characteristics and heat transfer. Fin heights are varied from 0.4 to 1.0 mm for seven distinct situations, including one where the heat sink is fully enclosed and has a fin height of 1.0 mm. Single-phase liquid water is used as the coolant in three-dimensional numerical simulations, which span a variety of operational parameters such as heat flux from 100 to 500 kW/m2 and Reynolds numbers from 100 to 400. The goal of the article is to maximize heat transfer rate and overall thermal performance by optimizing fin height. The findings show that heat transfer rises with fin height, however the potential for heat transfer is reduced at much smaller fin heights (0.4–0.6 mm). Because of the increased flow blockage caused by fin height, pressure loss also increases. It's interesting to note that a 0.8 mm fin height works better than 0.9 mm and 1.0 mm fin heights, even outperforming the fully closed heat sink. The research findings indicate that the net convective surface area and the flow characteristics of the open space are significant determinants of the heat sinks' overall thermal performance. The study expands on earlier studies on microchannel heat sinks and emphasizes the significance of fin height optimization for improving heat transfer efficiency, especially in applications involving small electronic devices that produce a lot of heat.

[3] This study investigates the use of staggered and linearly organized perforated pin fins to improve heat transfer in a heat sink. The study looks at pin fins in three different shapes: elliptical, diamond-shaped, and circular, each with a different perforation geometry. The effects of fin number, form, perforation geometry, and dimensions are investigated using three-dimensional computational fluid dynamics (CFD) simulations for both linear and staggered configurations. The findings show that perforated fins consistently show greater heat dissipation rates than solid fins, up to a specific number and size of perforations. Furthermore, heat transfer rates can be further increased by changing the hole geometry and fin form. In terms of system performance, staggered configurations perform better than linear setups. On the other hand, although it varies with fin form and arrangement, pressure drop through the heat sink reduces as the number and size of perforations rise. In order to determine the optimal perforated fin design that maximizes heat transmission while minimizing pressure loss, the study uses optimization analyses utilizing the MOORA method and

entropy generation minimization. In order to determine the second law efficiency of heat sinks with different kinds of perforated fins for both linear and staggered layouts, exergy analysis is finally carried out. This thorough investigation adds to our knowledge of the ways in which various fin forms, perforation configurations, and arrangements impact heat transfer and heat sink system performance, providing important information for heat exchanger design and optimization.

[4] A numerical analysis of laminar forced convection in heat sinks including micro pin-fin structures is presented in this research. On a 1 cm by 1 cm substrate, the study examines pin-finned microchannel heat sinks (MCHSs) as well as pin fin heat sinks (PFHSs). Pin fin arrangements might be staggered or oblique. The hydraulic and heat transfer performance of the heat sinks is analyzed in the study using the Naiver-Stokes and energy equations. When pumping powers are comparable, the heat removal capacities of finned MCHSs and PFHSs with varying heights of micro pin fins are contrasted with those of an ideal, basic MCHS. The findings demonstrate that, at medium and high pumping powers, the finned heat sinks' heat removal is less than that of the ideal basic MCHSs for the same pumping powers. For lower pumping powers, the finned heat sinks do, however, perform marginally better than the ideal plain MCHS. The optimization of these heat sinks through entropy generation minimization is also covered in the study. High heat flux microprocessors and other high-performance integrated circuits may need to cool down as a result of this study. It offers information on the thermal and hydraulic characteristics of various heat sink designs, which can help choose the right cooling options for a range of uses.

3. PROBLEM STATEMENT

For a 1 Watt electronic chip with a maximum package temperature limit of 50°C, equipped with an off-the-shelf heat sink and subjected to 1 m/s airflow, the critical question is whether this cooling arrangement is capable of maintaining the chip's temperature within the prescribed range. The problem also involves a comparative evaluation of two heat sink configurations, one with four fins and the other with eight fins, to determine their influence on the chip's maximum temperature. Additionally, the analysis will yield the average temperature of the air exiting the heat sink, contributing to the selection of an effective cooling solution and optimized heat sink design for proficient electronic chip cooling.

4. MATERIALS AND METHODS

4.1. Geometry for 4 fins heat sink :

The thermal analysis of the electronic system was conducted with a detailed consideration of the geometry of its key components. The heat sink, a crucial element for heat dissipation, featured dimensions of 10 mm in width, 10 mm in length, and 11 mm in height as shown in the fig.1. It was designed with four fins, each possessing a thickness of 1 mm and spaced 2 mm apart. The heat sink's total surface area amounted to 1120 mm^2. Additionally, the electronic chip, responsible for the generation of heat, measured 10 mm in length, 10 mm in width, and 1 mm in height, resulting in a total chip area of 240 mm^2. The chip was securely mounted on the heat sink. Surrounding this thermal system was an enclosure with dimensions of 30 mm in length, 75 mm in width, and 22 mm in height, resulting in a total enclosure area of 10080 mm^2 . The enclosure was situated at a distance of 15 mm in the front, 10 mm on each side, and 50 mm at the rear from the heat sink. This comprehensive geometry description serves as the foundation for the subsequent thermal analysis and assessment of heat dissipation efficiency

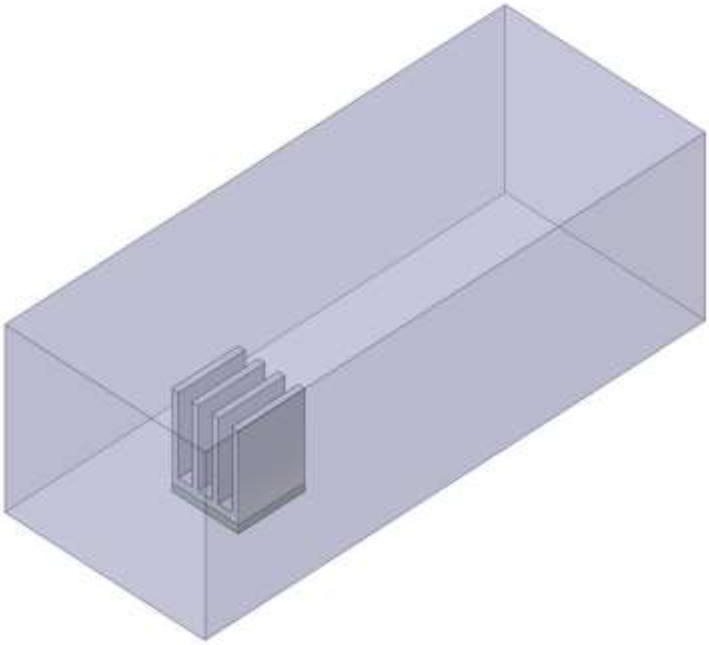

Figure 1. Geometry Of 4 Fins Heat Sink

4.2. Mesh for 4 fins heat sink :

In the computational mesh setup for our analysis, we employed distinct element sizes tailored to different components within the system as shown in the fig.2 . For the chip body, which represents the electronic chip, an element size of 0.00025 meters was selected. This fine-grained meshing approach, comprising 8,405 nodes and 6,400 elements, was chosen to capture the intricate details of the chip's geometry and facilitate precise thermal simulations. Similarly, for the heat sink body, an element size of 0.00025 meters was utilized, resulting in a mesh comprising 41,205 nodes and 32,000 elements. This fine mesh granularity allows for an accurate representation of the heat sink's geometry and its impact on heat dissipation. In contrast, for the enclosure that encompasses the entire system, we employed a coarser element size of 0.003 meters. This choice reduced computational complexity while still maintaining an acceptable level of accuracy for the enclosure's boundaries. The enclosure mesh consisted of 84,512 nodes and 431,877 elements, serving as the computational domain for the overall analysis. The combined mesh statistics for all domains in the simulation amounted to 134,122 nodes and 470,277 elements. This mesh configuration strikes a balance between computational efficiency and accuracy, enabling us to conduct a comprehensive thermal analysis of the entire electronic cooling system while efficiently capturing the intricacies of individual components.

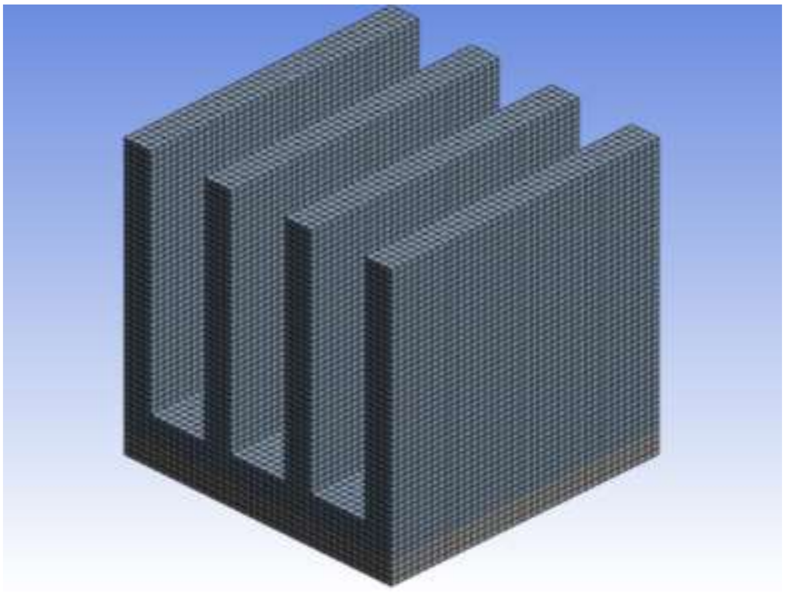

Figure 2 . Mesh Of Heat Sink

4.3. Boundary conditions for 4 fins heat sink :

In our computational simulation, boundary conditions play a pivotal role in replicating the real-world behaviour of the electronic cooling system. For the forced air convection analysis, we established essential conditions at various boundaries. At the inlet boundary of the computational domain, where air is introduced to simulate forced convection cooling, we specified an air velocity of 1 meter per second (1 m/s) and an initial temperature of 20 degrees Celsius (20°C). These values emulate typical environmental conditions that electronic devices encounter during operation. To accurately mimic the physical properties of the materials involved, we assigned copper as the material for the electronic chip and aluminum for the heat sink. The choice of materials and their respective thermal properties ensures that the simulation closely resembles the actual thermal behavior of the components. Furthermore, to capture the interplay between the chip and heat sink effectively, we employed thermal conditions that were coupled. This coupling accounts for the heat transfer between the chip and the heat sink, allowing us to study their thermal interaction in a more realistic and dynamic manner. These boundary conditions collectively provide the foundation for our computational analysis, enabling us to simulate the heat dissipation process and evaluate the performance of the electronic cooling system under forced convection.

4.4. Geometry for 8 fins heat sink :

In the geometry of our electronic cooling system, we have a chip with dimensions measuring 10 mm in length, 10 mm in width, and 1 mm in height, resulting in a total chip area of 240 mm² as shown in the fig.3. This compact chip is at the heart of our thermal analysis, generating heat that necessitates efficient cooling. Surrounding the chip are eight fins, each with a thickness of 0.5 mm and a separation gap of 0.86 mm. These fins are integral to our heat sink design, enhancing the surface area for heat dissipation. To encapsulate the entire system, we have an enclosure with dimensions of 30 mm in length, 75 mm in width, and 22 mm in height. This enclosure serves as the computational domain for our analysis, encompassing the chip, heat sink, and associated components, enabling a comprehensive study of thermal behaviour within the electronic cooling system.

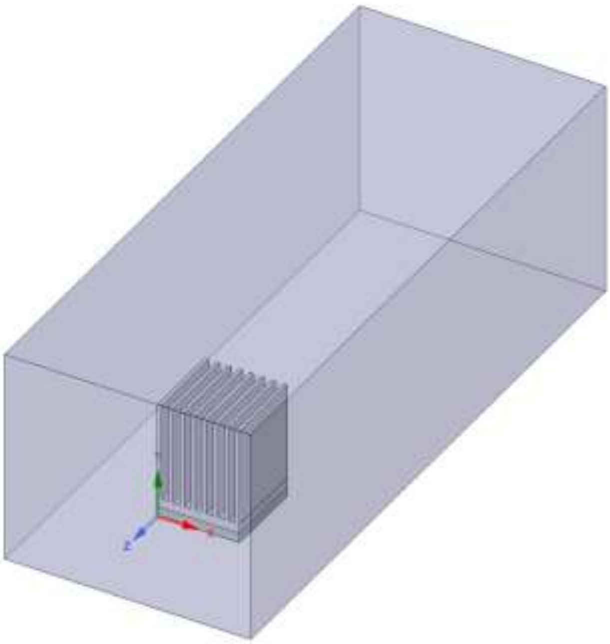

Fig.3 Heat sink with 8 Fins Geometry

4.5. Mesh for 8 fins heat sink :

In our computational meshing process, we meticulously structured distinct domains within the electronic cooling system, each with specific meshing characteristics. For the chip domain, we employed a mesh consisting of 12,740 nodes and 9,792 elements to ensure a fine-grained representation that captures the intricacies of the chip's geometry. Simultaneously, the enclosure domain was meshed with 289,394 nodes and 1,507,115 elements, providing comprehensive coverage of the entire computational space. This enclosure serves as the overarching domain encompassing the chip, heat sink, and surrounding components. The heat sink domain was meshed with 108,108 nodes and 79,458 elements, effectively capturing the geometry and thermal characteristics of this critical component. In total, our combined mesh for all domains comprised 410,242 nodes and 1,596,365 elements, striking a balance between computational efficiency and the precision needed to analyze the electronic cooling system's thermal behaviour accurately.

4.6. Boundary conditions for 8 fins heat sink :

The same boundary conditions that were meticulously applied to the 4-fin heat sink configuration were equally and rigorously applied to the 8-fin heat sink configuration.

5. RESULTS AND DISCUSSION

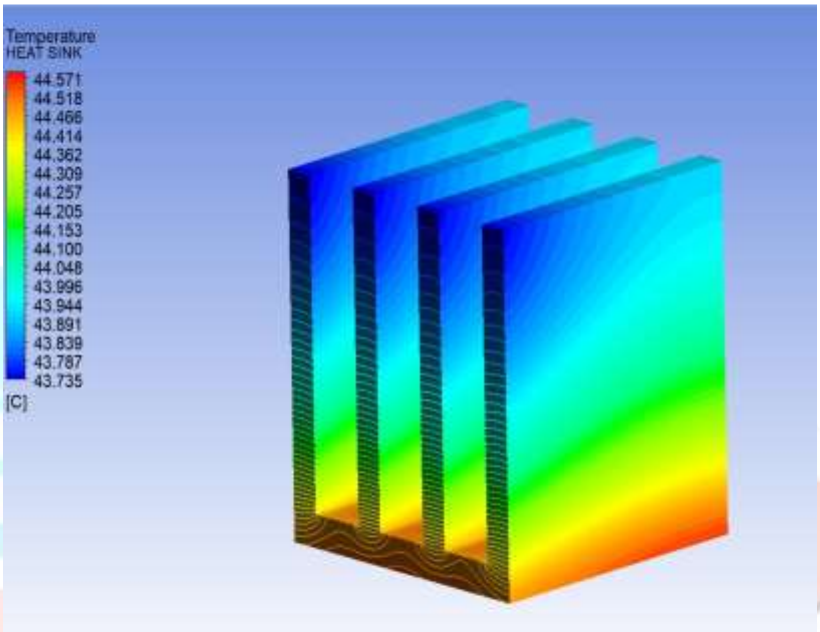

Fig.4 Heat Sink Temp Contour

In the thermal analysis of the 4-fins heat sink configuration, we observed that the heat sink reached a maximum temperature of 44.57°C and a minimum temperature of 43.74°C during operation as shown in the fig.4. Importantly, the chip's temperature remained well within safe limits, with a volume-average temperature of 317.71 K and a maximum temperature of 317.75 K. These results confirm that the design successfully maintains the chip's temperature below the critical threshold of 50°C, ensuring the safety and reliability of the electronic device. Additionally, the area-average temperature on the outlet side was recorded at 294.83 K, indicating efficient heat dissipation from the system. Overall, these findings validate the effectiveness of the 4-fins heat sink in maintaining proper thermal management for the electronic components.

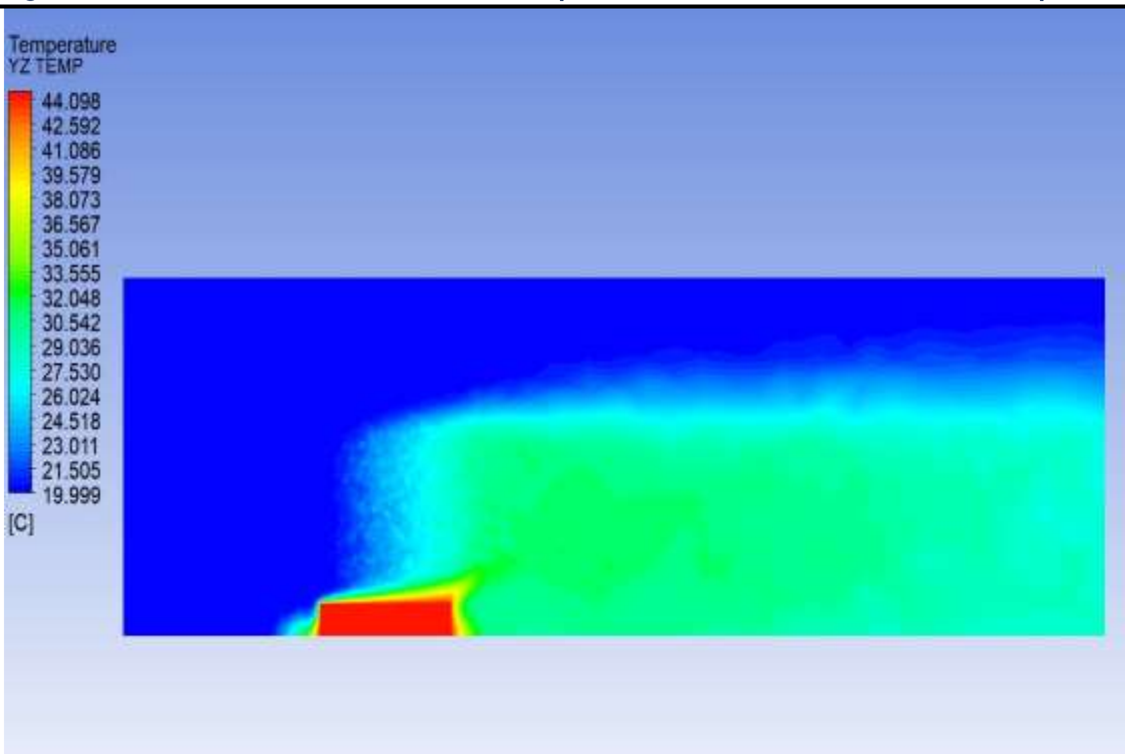

Fig.5 Heat Sink YZ plane temp Contour

A cross-sectional plane was meticulously examined along the YZ axis as shown in the fig.5, precisely at the X-coordinate of 0.005 meters. This investigation unveiled a temperature profile within this plane, with the minimum temperature recorded at 293.149 Kelvin and the maximum temperature peaking at 317.75 Kelvin. These findings provide valuable insights into the thermal distribution within the electronic cooling system, underscoring the effectiveness of the heat sink and airflow configuration in maintaining the desired temperature range for the electronic chip.

Two temperature profile lines series were plotted within the cross-sectional plane as shown in the fig.6, each representing distinct elevations above the base of the heat sink. The first series, positioned at 5 mm above the heat sink base and passing centrally through the plane, provided crucial temperature data. Simultaneously, the second series, located at a higher elevation of 8 mm above the base, offered additional temperature readings. These two line series collectively enabled a comprehensive visualization of the temperature distribution and variation within the heat sink, aiding in the assessment of its thermal performance under forced convection conditions.

In both Series 1 (5 mm Above Heat Sink Base) and Series 2 (8 mm Above Heat Sink Base) for the 4-fins heat sink, the temperature profiles reveal the thermal behavior at different elevations above the heat sink. In Series 1, temperatures range from approximately 19.99°C near the heat sink base to around 31.53°C at the highest point. This series shows that as you move away from the heat sink, the temperature gradually increases due to the heat dissipation process. It's noteworthy that the rate of temperature increase is relatively uniform until it reaches a peak. In Series 2, positioned at a higher elevation, temperatures range from about 19.99°C near the base to approximately 31.28°C at the highest point. Similar to Series 1, the temperatures increases as you move away from the heat sink upto a peak point , but the rate of increase is slightly different due to the elevated position. It demonstrates that temperatures are generally higher at this elevation compared to Series 1. These profiles are essential for understanding how temperature varies with height above the heat sink and are valuable for assessing the heat sink's effectiveness in cooling the surrounding air at different positions.

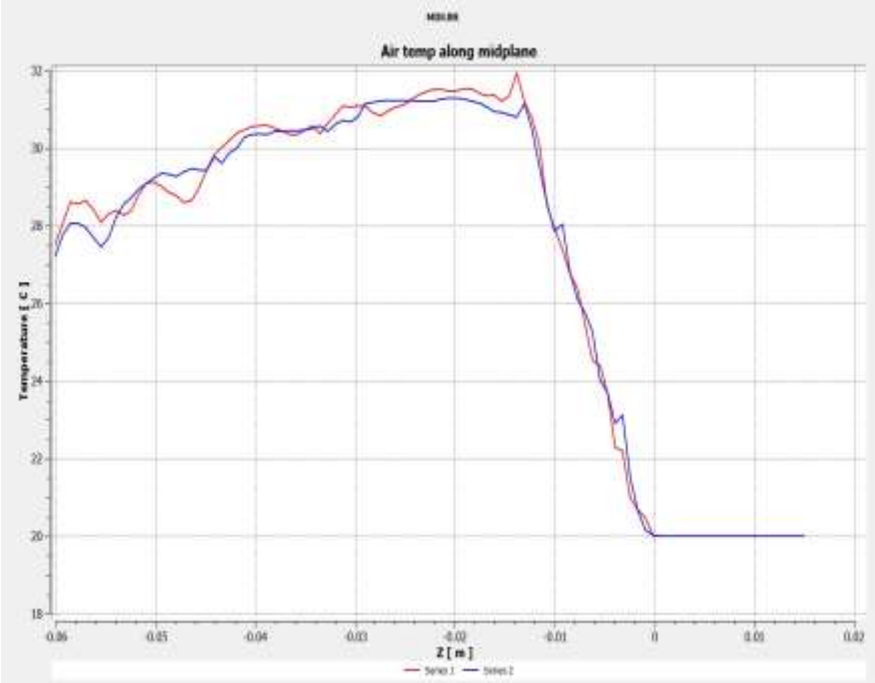

Fig.6 Air Temp along midplane of 4 Fins Heat sink

An additional plane located at the XY plate, specifically at a Z-coordinate of -40 mm (or 55 mm from the inlet), was examined to assess the temperature profile within this region as shown in the fig.7 . The study aimed to gauge the thermal conditions that would be experienced by another heat sink placed at a position 55 mm from the inlet. Within this plane, the analysis revealed a maximum temperature of 30.263 degrees Celsius and a minimum temperature of 20 degrees Celsius. These temperature measurements provide critical insights into the thermal environment at this specific location, assisting in the evaluation of potential cooling solutions for the placement of an additional heat sink.

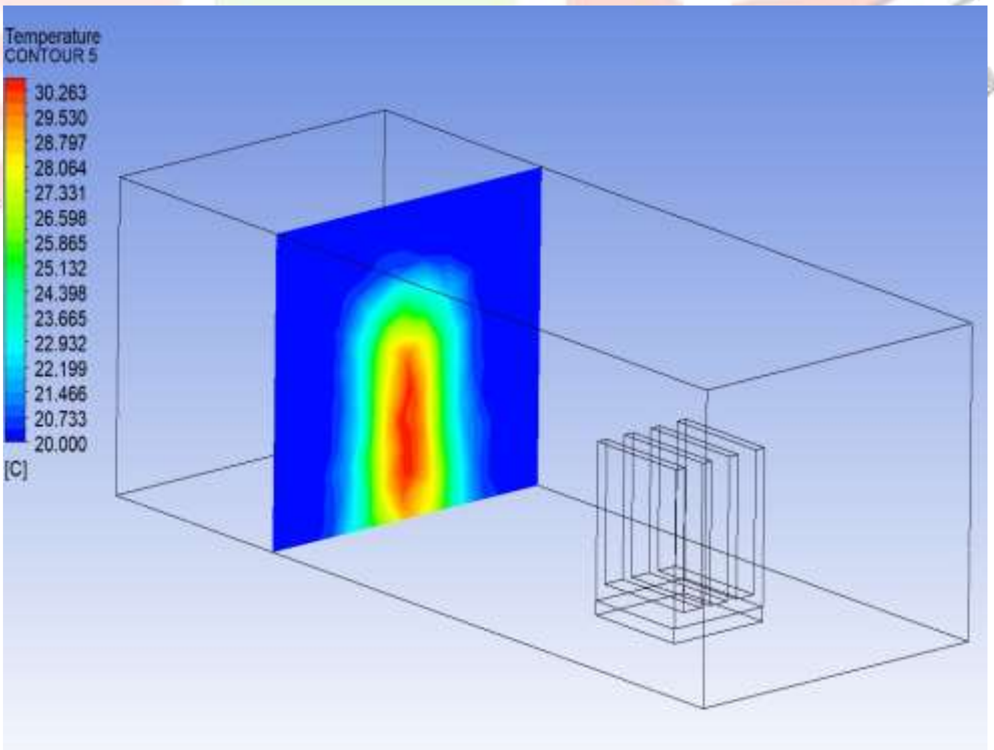

Fig.7 Temp Contour of XY plane

5.2. Result for 8 fins heat sink

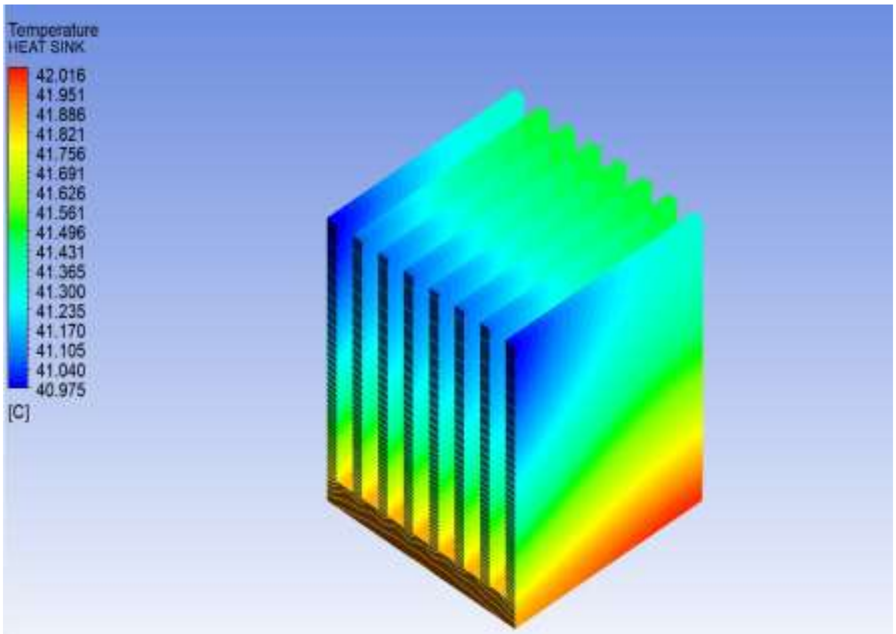

Fig.8 Heat Sink with 8 Fins temp Contour

The results of our contour analysis for the 8-fin heat sink configuration revealed several key findings as shown in the Fig 8. The maximum temperature observed on the heat sink surface reached 42.016 degrees Celsius, while the minimum temperature recorded was 40.975 degrees Celsius. These temperature extremes help us understand the thermal behaviour and distribution across the heat sink's surface, highlighting areas of significant heat dissipation. Within the chip itself, the volume-average temperature was calculated to be 315.145 Kelvin, with the maximum temperature value recorded at 315.2 Kelvin. These temperature metrics provide essential insights into the chip's thermal performance and confirm its ability to operate within acceptable temperature limits. At the outlet of the heat sink, the area average temperature was determined to be 294.931 Kelvin. This information is crucial for assessing the overall thermal effectiveness of the cooling system, specifically in terms of the temperature of the air exiting the heat sink. These results collectively indicate that the 8-fin heat sink configuration successfully maintained thermal conditions within the desired range, ensuring efficient cooling of the electronic chip.

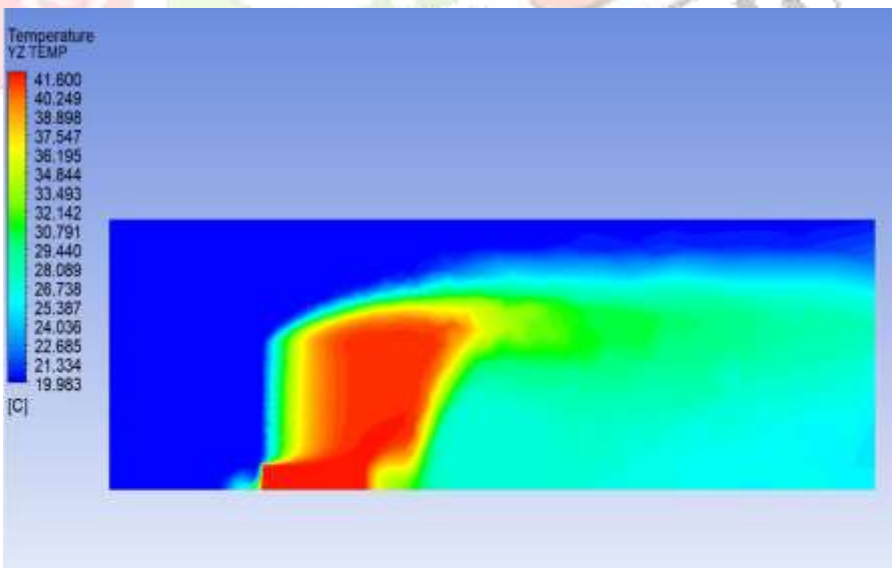

Fig.9 Heat Sink with 8 fins YZ plane temp Contour

A cross-sectional plane located precisely at X-coordinate 0.005 meters along the YZ plane was analyzed as shown in the fig.9, and the temperature distribution within this plane was meticulously studied. The temperature profiling revealed notable findings, with the maximum temperature observed reaching 41.6 degrees Celsius and the minimum temperature recorded at 19.98 degrees Celsius. These temperature values provide critical insights into the thermal distribution within the electronic cooling system at this specific location, which is vital for assessing the system's overall performance and thermal management efficiency.

In our analysis, a graph was meticulously constructed to represent the air temperature along the midplane of the electronic cooling system as shown in the fig.10. Within this graph, two distinct temperature profiles were depicted for comparative purposes. The first temperature profile, referred to as "Series 1," was drawn at a height of 5 mm above the base of the heat sink. This profile provides insights into the temperature distribution at a specific elevation within the cooling system, aiding in the assessment of the thermal performance. Similarly, the second temperature profile, known as "Series 2," was drawn at a higher elevation, precisely 8 mm above the base of the heat sink. This profile offers additional temperature data, allowing for a comprehensive evaluation of how temperature varies within the cooling system at different heights above the heat sink. These two temperature profiles contribute significantly to our understanding of the thermal behavior within the electronic cooling system and assist in assessing the effectiveness of the heat sink and forced convection cooling strategy.

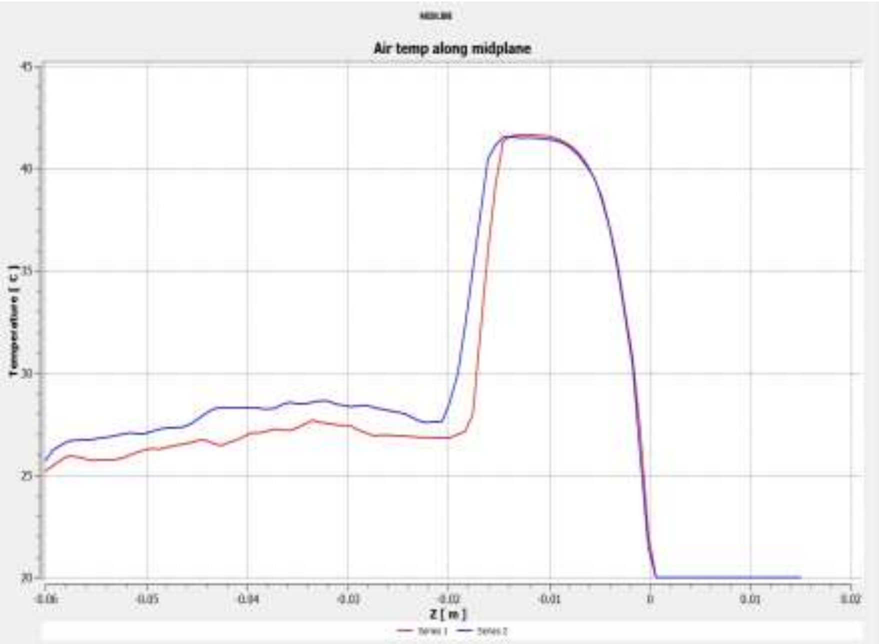

Fig.10 Air Temp along midplane of 8 Fins Heat sink

In our analysis, a graph was meticulously constructed to represent the air temperature along the midplane of the electronic cooling system. Within this graph, two distinct temperature profiles were depicted for comparative purposes. The first temperature profile, referred to as "Series 1," was drawn at a height of 5 mm above the base of the heat sink. This profile provides insights into the temperature distribution at a specific elevation within the cooling system, aiding in the assessment of the thermal performance. Similarly, the second temperature profile, known as "Series 2," was drawn at a higher elevation, precisely 8 mm above the base of the heat sink. This profile offers additional temperature data, allowing for a comprehensive evaluation of how temperature varies within the cooling system at different heights above the heat sink. These two temperature profiles contribute significantly to our understanding of the thermal behavior within the electronic cooling system and assist in assessing the effectiveness of the heat sink and forced convection cooling strategy.

Series 1, located 5 mm above the heat sink base, exhibits a temperature profile ranging from 19.99°C to 22.09°C near the base, gradually decreasing as we move away from the heat sink. On the other hand, Series 2, positioned 8 mm above the heat sink base, displays temperatures varying from 19.99°C to 30.41°C near the base, with a similar gradual decrease further away. These profiles illustrate the thermal behavior at different heights above the heat sink, highlighting how temperature changes vertically. The data reveals that Series 2, being at a higher elevation, experiences slightly elevated temperatures compared to Series 1, underscoring the significance of height in temperature distribution within the electronic cooling system.

An XY plane situated at a Z-coordinate of -40 mm, equivalent to 55 mm from the inlet, was meticulously examined to understand the temperature profile within this specific region as shown in the fig.11. This analysis was conducted to evaluate the thermal conditions that would be encountered by an additional heat sink placed at a distance of 55 mm from the inlet. Within this XY plane, our study unveiled a maximum temperature of

29.741 degrees Celsius and a minimum temperature of 20 degrees Celsius. These temperature values provide critical insights into the thermal environment at this particular location, offering valuable information for assessing the feasibility and effectiveness of installing an additional heat sink at this position within the electronic cooling system.

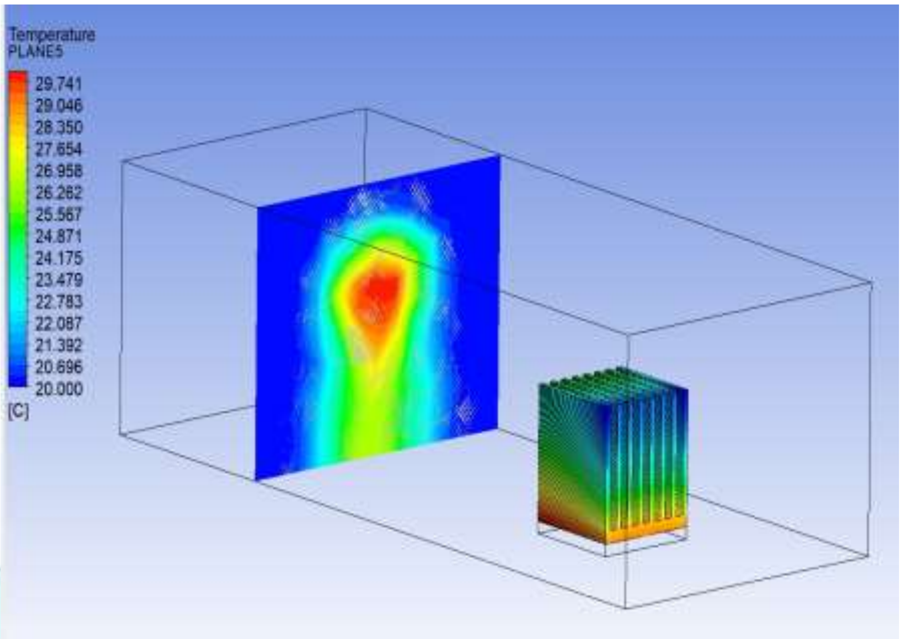

Fig.11 Temp Contour of XY plane

5.3. Validation

The results obtained from our thermal analysis offer robust validation of the design's effectiveness. These findings definitively establish that the selected configuration successfully maintains the chip's temperature below the crucial 50°C threshold. This achievement not only ensures the safety of the electronic device but also underscores its overall reliability in operation. The thermal management system, comprised of the heat sink and airflow, has proven to be a highly efficient and dependable solution for maintaining the chip within its safe temperature range.

6. CONCLUSIONS

Table 1. Comparison of both 4 and 8 fins heat sink

Parameter	4-Fins Heat Sink	8-Fins Heat Sink
Maximum Heat Sink Temperature (°C)	44.57	42.02
Minimum Heat Sink Temperature (°C)	43.74	40.98
Volume Average Chip Temperature (K)	317.71	315.15
Maximum Chip Temperature (K)	317.75	315.20
Area Average Outlet Temperature (K)	294.83	294.93
Temperature on YZ Plane at X = 0.005 m (°C)	Max: 41.60, Min: 19.98	Max: 41.60, Min: 19.98
Temperature on XY Plane at Z = -40 mm (°C)	Max: 30.26, Min: 20.00	Max: 29.74, Min: 20.00

In conclusion, this project focused on the thermal analysis of two different heat sink configurations, namely the 4-fins and 8-fins heat sinks, to assess their effectiveness in dissipating heat from a copper chip. The results obtained from the simulations and temperature profiles provide valuable insights into the thermal performance of these two designs. For the 4-fins heat sink, the maximum temperature observed on the heat sink was 44.57℃, with a minimum temperature of 43.74℃. The chip's volume-average temperature remained within acceptable limits at 317.71 K, ensuring the chip's safety. Temperature profiles on various planes, such as YZ and XY, revealed the distribution of heat within the system. On the other hand, the 8-fins heat sink exhibited slightly better thermal performance, with a maximum heat sink temperature of 42.02℃ and a minimum of 40.98℃. The volume-average chip temperature was 315.15 K, demonstrating effective heat dissipation. Similar temperature profiles on YZ and XY planes showed how the additional fins improved cooling. Furthermore, the inclusion of Series 1 and Series 2 temperature data provided a more detailed view of the temperature distribution around the heat sink. These findings enable engineers and designers to make informed decisions when selecting a heat sink configuration for electronic devices. In summary, the 8-fins heat sink exhibited slightly superior thermal performance compared to the 4-fins heat sink, making it a promising choice for applications where efficient heat dissipation is crucial. However, the specific choice should consider factors such as space constraints, cost, and design requirements to optimize overall performance and reliability.

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