ES-311: <u>HEAT AND MASS TRANSFER</u>

<u>Numerical computation of Heat Sink design</u>

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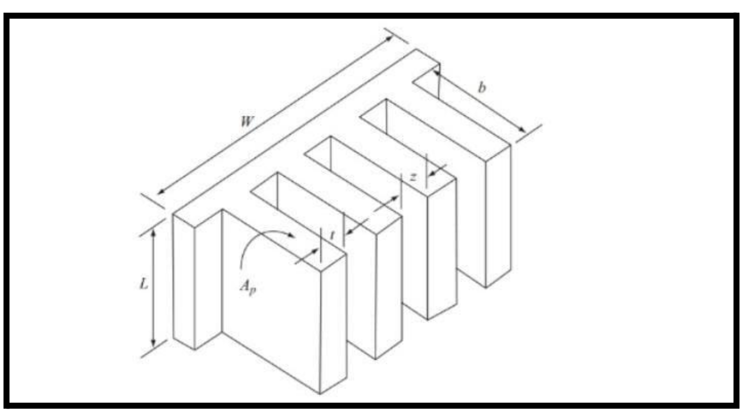
Introduction:

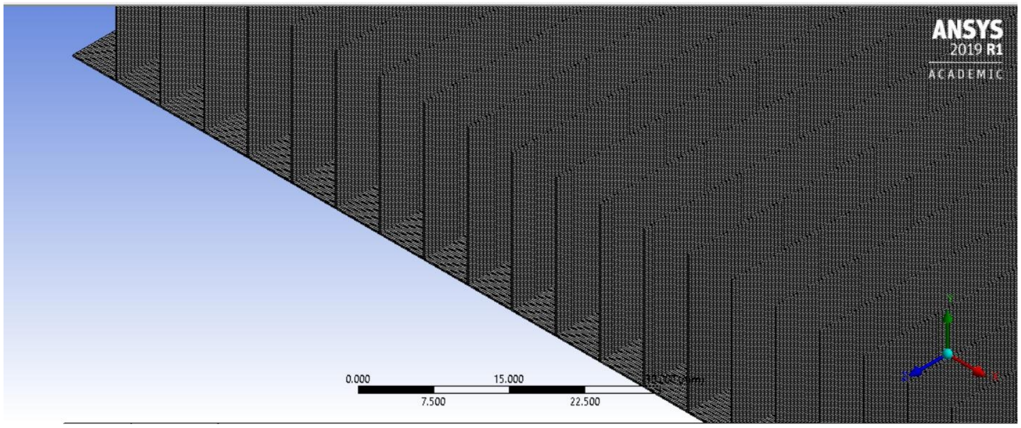
As electronic components become smaller and more powerful, heat dissipation challenges intensify. Heat sinks play a pivotal role in mitigating thermal issues, ensuring operational stability, and preventing premature component failure. In order to effectively manage the heat produced during operation, a heat sink is an essential cooling component in electronic equipment. It is made of highly thermally conductive materials, such as aluminium copper which promotes conduction and convection heat transmission. It keeps electronic parts from overheating by dispersing extra heat, guaranteeing continuous peak performance, and prolonging the life of gadgets. Heat sinks are essential for preserving the dependability and effectiveness of contemporary electronic systems. They are crucial for temperature control in a variety of applications, including industrial machinery and computers. The aim of this project is to design a fin array-based heat sink for cooling electronic components by natural convection. We aim to vary the length and shape of the fins and study how these parameters would affect the heat dissipation of the components.

Problem Statement:

The rear wall of a box containing electronic components is cooled by natural convection using a multiple fins array, as shown below. The box geometry gives that W= 15cm and L=12cm. The rear wall must passively dissipate 180 W to an environment at 25℃ at atmospheric pressure without exceeding a surface temperature of 85℃. The fin height (profile length) b is limited to 19 mm. First, show whether the heat dissipation can be achieved by natural convection without fins. If necessary, design the fin array to accommodate the requirements. Estimate the fin thickness, the profile length, the spacing, the number of fins, the overall efficiency, and the thermal resistance to maximize the heat transfer rate from the box. For the properties of copper, the density is 8850 kg/m^3, and the thermal conductivity is 398 W/m-K.



Meshing formed in ANSYS STEADY-STATE THERMAL:



Mesh

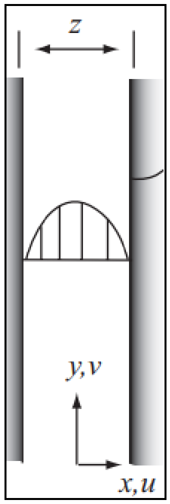
Governing equations:

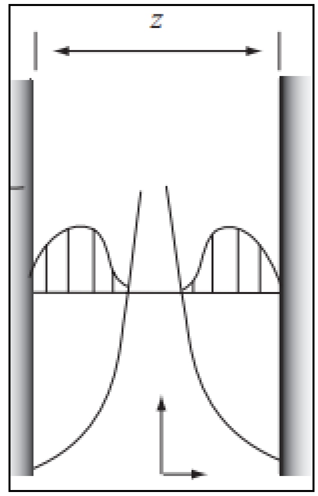
Assumptions:

The study often assumes that the system has attained a steady state, which means that temperatures and heat transfer rates do not change over time. Heat transfer is thought to occur largely in one direction along the length of the fin in one dimension.

- **Uniform Cross-Sectional Area**: It is believed that the cross-sectional area of the fin is consistent along its length. The uniform heat transfer coefficient (h) is considered to be constant across the whole surface of the fin.
- **Thermal Radiation:** We are not accounting for thermal radiation in the analysis.
- **Heat Loss at the Tip:** It is assumed that there is no heat loss from the tip of the fin to the surroundings.
- **Internal Heat Generation:** Within the fin material itself this is typically ignored in the analysis.

Momentum equation in small spacing channels and large spacing channels:





For deriving the average velocity ($\bar{v}$) in the small channel, momentum equation in y-direction:

$$\rho(u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y}) = -\frac{\partial P}{\partial y} + \mu\nabla^2 v - \rho g$$

In a fully developed flow, we have the slipping conditions:

$$u = 0 \ \ and \ \frac{\partial v}{\partial y} = 0$$

$$\frac{\partial^2 \upsilon}{\partial y^2} = -\frac{g\beta(T_o - T_\infty)}{\nu}$$

where v represents the kinematic viscosity ($v = \frac{\mu}{\rho}$). The obtained velocity profile is **parabolic**

$$\upsilon = \frac{g\beta(T_o - T_\infty)}{8\nu}\left[1 - \left(\frac{x}{z/2}\right)^2\right]$$

For finding the average velocity along the length z, we get:

$$\overline{\upsilon} = \frac{g\beta(T_o - T_\infty)z^2}{12\nu}$$

Mass flow rate for the small channel can be calculated as:

$$\dot{m} = \frac{\rho g\beta(T_o - T_\infty)z^2}{12\nu}Wb$$

Substituting the mass flow rate equation in heat transfer rate from the fins can be obtained as:

$$q_{f,small} = \rho c_p Wb\frac{g\beta(T_o - T_\infty)^2 z^2}{12\nu}$$

Consider **large spacing channel**, by assuming **laminar flow** the Nusselt number for the natural convection for a vertical plate:

$$\overline{Nu} = \frac{\overline{h}L}{k_{air}} = 0.517Ra_L^{\frac{1}{4}} \quad \text{.....(12)}$$

Here, Rayleigh's number is defined as :

$$Ra_L = \frac{g\beta\,(|T_o - T_\infty|)\,L^3}{\nu\alpha} \qquad \text{....(13)}$$

Through Newton's law of cooling, heat

$$q_{f,large} = 1.034\frac{W}{z}bk_{air}Ra_L^{\frac{1}{4}}(T_o - T_\infty)$$

We will be computing heat transfer rate **without fins** at the rear wall with the help of following equations:

$$q = h * (W * L)\theta_b$$

If the flow is laminar, we can get h as

$$h = \frac{k_{air}}{L}0.517\,Ra^{1/4}$$

From here we can get a heat transfer rate and compare it with our **optimal requirement of 180W.**

Optimization:

We will be using "Bar-Cohen and Rohsenow" suggested correlation

$$\frac{z_{opt}}{L} = 2.714Ra_L^{-1/4}$$

To identify h_z we will use Rayleigh number and Elenbaas number equations

$$El = Ra_z\frac{z_{opt}}{L}$$

From composite relation and curve fitting average Nusselt number is expressed as

$$Nu_z = \frac{h_z z}{k} = \left[\frac{576}{El^2} + \frac{2.873}{El^{1/2}}\right]^{-1/2}$$

$$h_z = \frac{k_{air}}{z_{opt}}\left[\frac{576}{El^2} + \frac{2.873}{El^{1/2}}\right]^{-1/2}$$

We will be using the heat transfer rate for the fin derived above..

Considering adiabatic tip, we can write

$$\beta = mb_0 = \left(\frac{2h}{k}\right)^{1/2}t_0^{-3/2}b_0t_0$$

Removing β from the above equations we get

$$b_0 = \frac{1.4192\left(\frac{k\,t_0}{2h_z}\right)^{1/2}}{\left[1-1.125\left(\frac{kt_0}{2h_z}\right)^{1/2}\frac{h_z}{k}\right]}$$

Number of fins (n) = $\frac{W_b}{z_{opt}+t_o}$

Fin Efficiency:

$$\eta_f = \frac{\tanh mb}{mb}$$

Thus, we can write heat transfer from a single fin in terms t_0 as

$$q_f = \eta_f h_z\, 2(L + t_0)\, b_0\, \theta_b$$

Note that η_f, b_0 are in terms of t_0

Deriving Final Equation:

Surface area of a single fin

$$A_f = 2(L + t_0)\, b_0$$

Total surface area available for heat transfer

$$A_t = n_f[2(L + t_0)b_0 + L_b z_{opt}]$$

Overall Efficiency

$$\eta_0 = 1 - n_f \frac{A_f}{A_t}(1 - \eta_f)$$

Total Heat Transfer Rate

$$q_{total} = \eta_0 h_z A_t \theta_b$$

Methodology:

The primary goal of this project is to design an efficient fin array-based heat sink for electronic component cooling through natural convection. The project involves a comprehensive analysis and development of fin parameters, including length, spacing, and thickness, to optimise heat dissipation. The focus is on developing a heat sink that can passively dissipate 180W of heat from the rear wall of a box containing electronic components to an environment at 25°C without exceeding a surface temperature of 85°C. Two materials, aluminium and copper, are considered for the fin array. The methodology integrates theoretically finding the optimum fin design and validating it with numerical simulations using ANSYS.

Problem Statement Understanding:

Given Parameters
Length of base = $12\ cm$
Width of base = $15\ cm$
Maximum Temperature at base = $85^{o}C$
Ambient Temperature = $25^{o}C$
Total Heat Dissipation = $180\ W$
Profile Length = $19\ mm$ (max)
Air is at atmospheric pressure, and the materials to be used are aluminium and Copper.

This involves a dual approach, leveraging theoretical calculations to formulate an initial fin design and subsequently refining and understanding the temperature distribution across the optimised design using ANSYS Steady State Thermal software.

Fin Array Design

In the formulation of our fin array design, we derived that the total heat dissipation, denoted by the equation,

$$q_{total} = \eta_{O} h_{z} A_{t} \theta_{b}$$

is inherently dependent on the fin thickness (t). However, considering the practical constraint that the profile length must not exceed 19mm, this equation now involves two variables, the fin thickness (t) and the profile length (b). Due to the equation's complexity, determining thickness through algebraic means is impractical.

Given the intricate nature of the function, computational calculations become essential for determining heat dissipation across varying values of both thickness (t) and profile length (b). To facilitate this, we implemented a Python code. Within this code, we defined a function that takes thickness (t) and profile length (b) as parameters, providing the corresponding heat dissipation for that particular design. This computational approach allows us to explore a range of fin configurations and systematically analyse their heat dissipation.

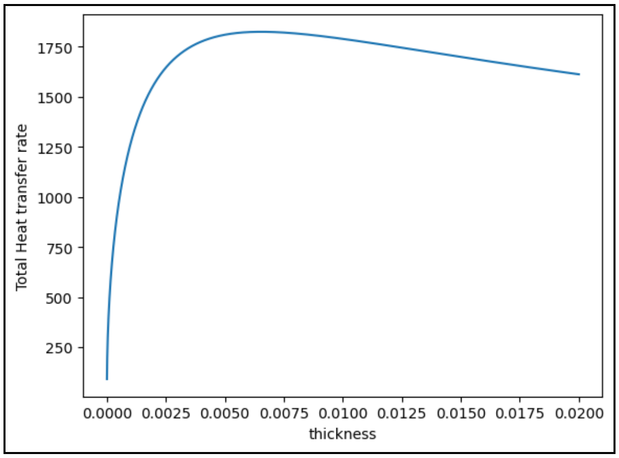
Mesh Interdependence analysis:
To enable the fluid flow around, the fins were divided into manageable sections, so that the entire cooling system was fragmented. For the trial simulations, an orthogonal quality mesh type was employed, utilising the ANSYS meshing program. The strategy includes refining the mesh in regions with sudden geometric changes or notable flow variations, while employing a coarser mesh in less critical areas to minimise computational time. A uniform mesh was maintained as the simulation involved complex solving.
The element size was **0.5 mm**, with the span angle centre kept coarse to prevent errors due to the complexity of the solution. The transition of the mesh is kept fast (its ratio=0.272) while a medium amount of smoothing was maintained to compensate for the fast transition and keep an optimum level of mesh quality. The growth rate was **0.5.** We've employed the Orthogonal Quality mesh metric. This results in a total of **4,094,068 nodes** and **582,960 elements** in the mesh.

Simulations:
We carried out the simulations using the above conditions for both Aluminium and Copper alloys. Steady-state thermal analysis has been used to obtain the results. First, the material for engineering data was set for the 2 cases under observation. A constant k value was assumed for the simulations, which was 236W/mK for Aluminium and 400 W/ mK for Copper. Using this data, the mesh was generated and executed. We obtained graphs for the temperature and total heat flux distribution in the fins.

Results:

Copper

Theoretical Results



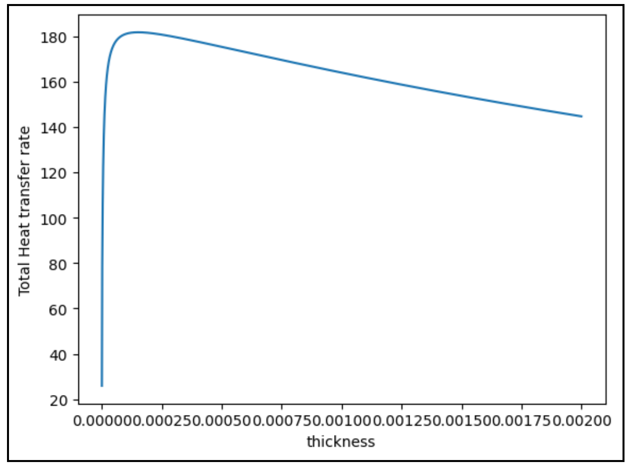
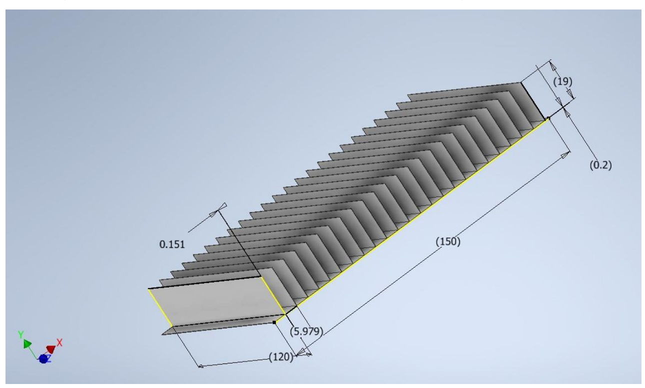


Figure 1: Heat dissipation vs thickness of fin without considering profile length restriction

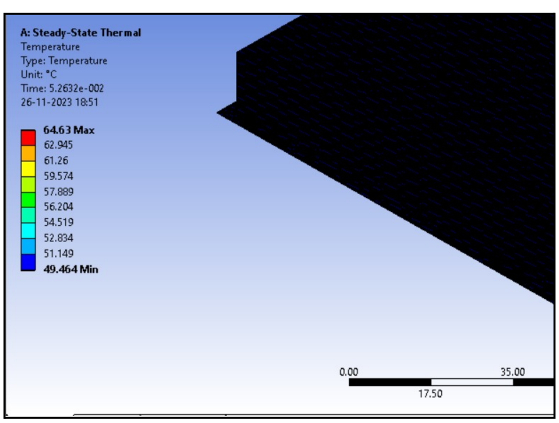
Figure 2: Heat dissipation vs thickness of fin with profile length = 19mm

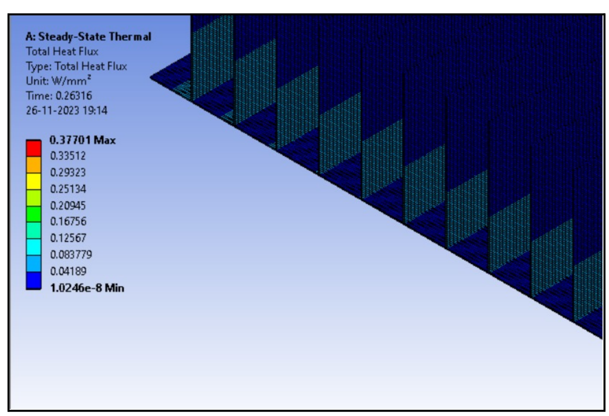
Graphs describe the importance of correct geometry, as for any low value of thickness reduces heat dissipation.

CAD of the desired geometry obtained from the above analysis



All the dimensions are in mm

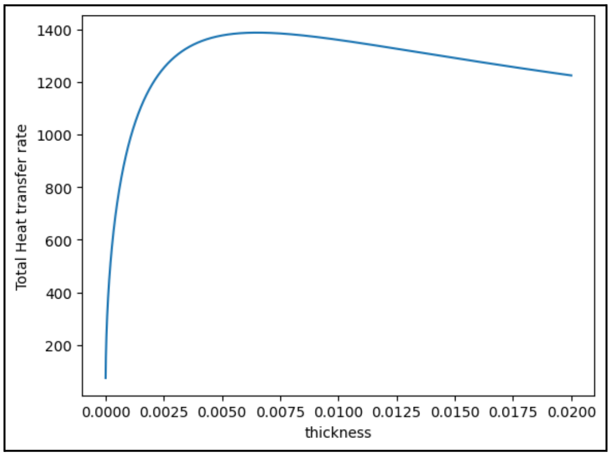




Temperature Distribution in Cu Alloy

Heat Flux Distribution in Copper Alloy

Aluminium



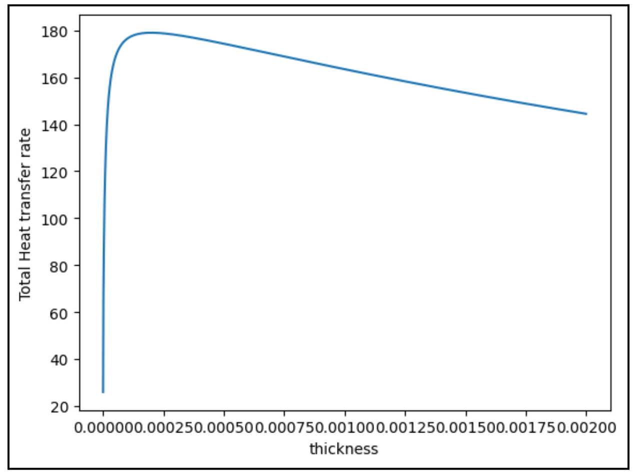


Figure 1: Heat dissipation vs thickness of fin without considering profile length restriction

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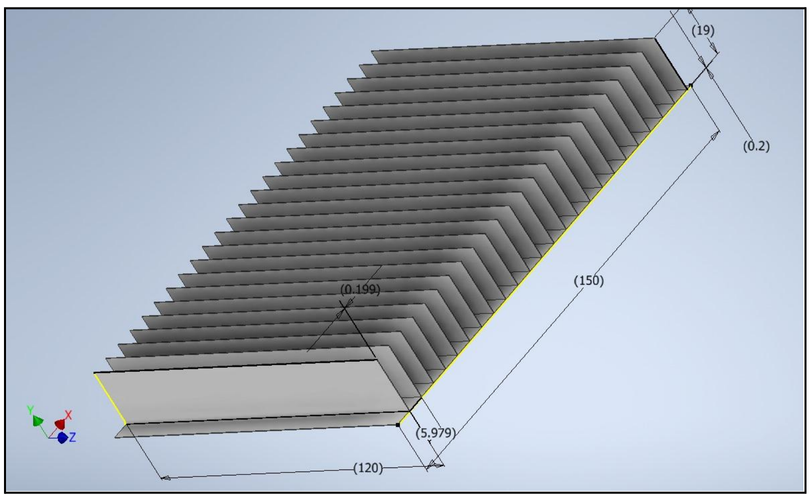

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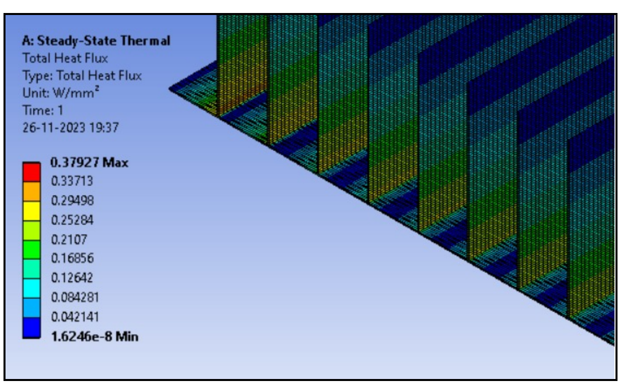
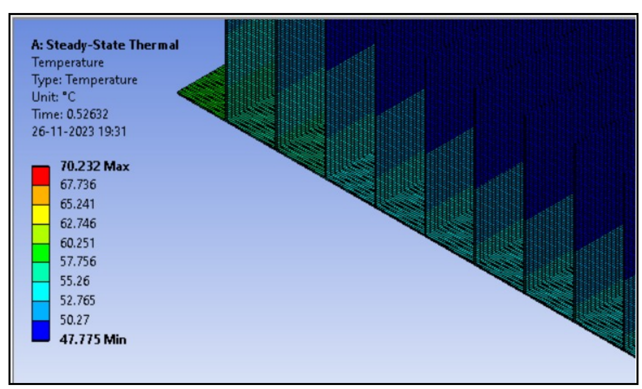


Heat Flux Distribution in Aluminum Alloy



Temperature Distribution in Aluminum Alloy

Heat dissipation without fins = 27.84 W.

Discussion and Inference

Heat sinks are primarily used for thermal management in technology, machinery, and natural systems. It increases the heat flow away from a hot device. This heat dissipation can be achieved by maximising the surface area and the flow rate of the fluid at a lower temperature that moves across its enlarged surface area. These heat sinks are designed based on the needs and functions of the device where the component is to be used. In our project, we have limited ourselves only to the surface area changes which affect the heat dissipation rate. After studying more on the functions of the heat sink we used optimisation techniques to obtain the various dimensions that would help us in our research.

The results of the theoretical calculations present us with an optimal fin geometry that promises maximum heat dissipation efficiency. However, a noteworthy observation arises when comparing the temperature distribution from the theoretical calculations with the results obtained through ANSYS. There exists a discrepancy between the two sets of results, indicating a variation in the thermal performance predictions.

The changes in fin thickness remain significantly low for both materials. This finding aligns with the acknowledgement in the methodology that the dominant mode of heat transfer in the fin is convective. The optimisation process focused on maximising the surface area exposed to convective heat transfer, which minimises the reliance on the material's thermal conductivity. Consequently, the changes in dimensions are subtle, emphasising the requirement of the optimal fin geometry in achieving efficient heat dissipation.

We conducted simulations based on the optimised dimensions. However, the required results could not be obtained. After many simulations, we considered changing the thickness of the base to 0.2mm. This variation in the dimension gave the required results. Since the convection from the base should be negligible. The above temperature distributions for both Aluminium and Copper are well within the limits as per the problem statement, which was 85 C. The maximum temperature reached for Copper is 64 C, and for Aluminium, it is 70 C. Since Cu alloy has reached a lower maximum temperature during the convection process this clearly proves that the Cu heat sink would be a better choice for being used as a heat dissipator as compared to the Al alloy.

This divergence in temperature distribution could be attributed to several factors. The theoretical calculations inherently assume certain simplifications and assumptions, including uniform heat transfer coefficients and neglecting the impact of complexities like fluid flow variations. On the other hand, ANSYS, being a computational tool, accounts for a more detailed and realistic simulation of the heat dissipation process, considering factors such as fluid dynamics and heat convection more comprehensively.

Conclusion:

In conclusion, this project has comprehensively explored heat dissipation challenges in electronic components, specifically delving into the design and optimisation of a fin array-based heat sink for natural convection cooling. The overall analysis involved a blend of theoretical considerations, simulations using ANSYS, and optimisation techniques to address the intricate thermal dynamics inherent in electronic systems.

The project underscored the pivotal role of heat sinks in ensuring operational stability and preventing premature component failure, emphasising the use of highly conductive materials like aluminium and copper. The governing equations and assumptions provided a theoretical foundation for subsequent computational analyses conducted in ANSYS. Simulations for both copper and aluminium alloys offered material-specific insights into heat dissipation dynamics.

The discrepancy between theoretical assumptions and practical outcomes highlights the inherent limitations of simplified models. While ANSYS simulations offered a real-world perspective with practical parameters, the absence of a theoretical model with practical considerations limited us from getting a fair idea about the discrepancy. We confidently conclude that, from our analysis, optimisation is among the most potent areas for future research. We experimented with simple optimisation techniques, but we strongly believe that optimisation techniques specifically oriented for designing heat management devices would also be very beneficial.

The project underscores the need to reconcile theoretical frameworks with practical complexities for more effective electronic system cooling strategies.

Novelty:

Optimising Fin Geometry Beyond Initial Scope: The project initially aimed to vary fin length and shape to optimise heat dissipation efficiency. However, the team extended this by adjusting additional fin geometry parameters such as thickness and Nusselt's number, enhancing the fin array's performance significantly.

Advanced Simulation Techniques: Utilising ANSYS ICEM CFD for mesh generation and flow analysis allowed for more precise simulations. The team employed Orthogonal Quality mesh metric for a comprehensive understanding of fluid flow and heat transfer around the fins.

Integration of Optimization Algorithms: The project incorporated optimization algorithms like Gradient Ascent, Newton's Method, or Derivative Free Optimization to refine the fin thickness and achieve maximal heat dissipation. This approach was beyond the original plan of using basic analytical and numerical methods.

Comparative Analysis with Theoretical Models: A detailed comparison of the simulation results with theoretical models provided additional validation of the research findings. The close resemblance of results from both methods added credibility to the project's outcomes.

CAD Modeling and Efficiency Analysis: Creating a CAD model and conducting efficiency analyses for the fin design were significant additions. These steps provided a visual representation of the heat sink and a quantitative measure of its performance, respectively.

The team's exploration into advanced simulation techniques, material science, environmental considerations, system-level integration, data analysis, and user experience demonstrates a multifaceted and innovative approach to heat sink design in electronic components.

Critical analysis:

Upon a critical analysis of the results observed and the existing theory, we realise that the simulations generally aligned with the expected trends. The temperature distributions and heat flux patterns across the fins, although not precisely mirrored, demonstrated a coherent reflection of the theoretical expectations. The project's successful translation of theoretical insights into a tangible simulation environment affirms the robustness of the initial conceptualization. However, discrepancies emerged, emphasising the need for a nuanced understanding of real-world complexities. The assumed constant heat transfer coefficients and uniform fluid flow rates in the theoretical model diverged from the dynamic conditions encountered in the simulations. Variations in fluid flow, heat transfer coefficients, and other practical considerations contributed to deviations in temperature profiles and heat dissipation rates.

Challenges:

In the project, we encountered notable challenges during the design and validation of a heat sink utilising optimization techniques within the ANSYS software framework. Initial attempts with ANSYS Fluent, constrained by the complexity of the 3D geometry, prompted a transition to ANSYS steady-state thermal analysis. In the subsequent stages, the following challenges were encountered:

- Meshing Complexity:

Achieving an optimal mesh configuration for the intricate 3D geometry posed a significant challenge. Parameters governing meshing, such as element size and number of layers, required meticulous optimization to ensure a high-quality mesh.

- Parameter Optimization for Meshing:

The determination of suitable parameters for meshing optimization became crucial. Identifying the appropriate combination of mesh parameters, including element size and layering, demanded iterative adjustments to enhance mesh quality and computational efficiency.

- Simulation Errors:

Despite efforts to optimize meshing parameters, simulation errors persisted. These errors necessitated a systematic approach to troubleshooting, involving adjustments to mesh characteristics, temperature settings, and element size to rectify simulation discrepancies.

- Iterative Adjustments for Mesh Quality:

The resolution of simulation errors involved an iterative process. Systematic adjustments to mesh parameters, temperature settings, and element sizes were made to enhance the overall quality and reliability of the simulation results.

- Sensitivity to Mesh Changes:

Sensitivity analysis revealed that changes in mesh parameters had a discernible impact on simulation outcomes. Fine-tuning these parameters, in conjunction with other simulation variables, became essential for achieving accurate and consistent results.

Future Work:

Material Analysis for Fin Construction: Investigate different materials for fin construction to optimise heat transfer efficiency and durability under various operating conditions.

Three-Dimensional Modelling and Analysis: Extend the research to three-dimensional simulations to capture more complex interactions and provide a more comprehensive understanding of heat transfer dynamics in heat sinks.

Integration with Renewable Energy Sources: Explore the possibility of integrating the heat sink design with renewable energy sources for sustainable and efficient cooling solutions in electronic devices.

Scalability and Real-World Applications: Conduct scalability studies to assess the feasibility of the designed heat sinks in different sizes and types of electronic devices, ranging from small consumer electronics to large industrial equipment.

Experimental Validation and Prototyping: Move from simulations to real-world prototyping and experimental validation to test the practical viability of the designed heat sinks under actual operating conditions.

Advanced Optimization Techniques and Machine Learning: Employ more sophisticated optimization techniques, possibly incorporating machine learning algorithms, to find optimal fin designs in a more automated and efficient manner.

Heat Sink Integration with Electronic Component Design: Study the integration of heat sinks into the early stages of electronic component design, aiming for a holistic approach to heat management in electronics manufacturing.

Long-Term Durability and Maintenance Studies: Investigate the long-term durability and maintenance requirements of the optimized heat sinks, focusing on their lifespan and performance consistency over time.

The potential future directions for this research project span material science, advanced simulation techniques, sustainability considerations, real-world application, and the integration of emerging technologies like machine learning. These areas offer exciting opportunities for advancing the efficiency and effectiveness of heat management solutions in electronic devices.

Contributions:

Name	Roll No.	Contribution
Ananya	21110021	Worked meticulously in spearheading the ideation phase for design parameters of fins. Conclusion part of the interim was that it was insightful work. Worked on refining the report meticulously.
Vaishnavi	21110232	Took the lead in executing the simulation phase, overseeing crucial aspects like mesh formation, temperature profile analysis, and the generation of detailed heat flux graphs. Validated the optimally designed fin parameters, particularly with the utilisation of two distinct materials, Aluminium and copper, resulting in an intricately designed and optimised system. For the final report and video submission she contributed for the simulation results, methodology, and critical analysis part.
Lokesh	21110113	Worked meticulously on optimization phase for the design parameters of fin through the Numerical analysis, collaboratively worked on Python code for numerical analysis and optimization. For the report and video submission he contributed for the Novelty part and governing equations.
Dhruv	21110055	Diligently engaged in refining

		the design parameters of the fin through rigorous numerical analysis during the optimization phase. Collaboratively contributed to crafting Python code tailored for both numerical analysis and optimization purposes. For the report and video submission he contributed for the Optimization, critical analysis, Graphs and Discussions through inference.
Harsh	21110073	Contributed for the simulation phase of the project, overseeing crucial aspects like mesh formation, temperature profile analysis, and the generation of detailed heat flux graphs. Crafted the CAD model design for the fins based on optimised design parameters. For the final report and video submission he worked on Challenges faced and edited the whole video.
Sankarshan	20110184	Coordinated the components of this project involving simulation and Numerical analysis and optimization with proper feedback meetings with TA. Engaged majorly on numerical analysis and optimization phase of the project by collaboratively working on Python code. For the report work, he contributed for designing Governing equations and Numerical analysis of those equations to obtain optimised solutions.

Shreyansh	21110201	For report and video submission, he contributed for the conclusion and critical analysis part of the whole project.
Roshan	21110224	For report and video submission, he contributed for the Introduction part of the whole project and involved in the ideation phase of project.

References:

1) Code for obtaining optimal geometry: https://colab.research.google.com/drive/1Ic2SZNx5XmUCE8Sl0g-I4z8H0tqwCW_S#scrollTo=I0J8W7m-_RWc
2) Book Referred: Thermal Design Heat Sinks, Thermoelectrics, Heat Pipes, Compact Heat Exchangers, and Solar Cells by HoSung Lee
3) https://www.sciencedirect.com/science/article/pii/S2451904917303190
4) https://www.sciencedirect.com/science/article/pii/S0017931005006733
5) http://www.elsevier.com/locate/apthermeng
6) https://www.arrow.com/en/research-and-events/articles/understanding-heat-sinks-functions-types-and-more
7) Discussion with TA during project meet.