



Numerical Study on Hydro-Thermal Performance Optimization of Mini-Channel Heat Sinks Using Surface Modification

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Abstract: In this paper, we present the optimization and investigation of fluid flow and heat transfer in advanced heat sink geometries by the application of Computational Fluid Dynamics. Three new heat sink configurations (C1, C2, and C3) were optimized and compared with the traditional straight-fin heat sink to analyze the thermal and hydraulic performance at varying operating conditions. Simulations were carried out for varying Reynolds numbers (200 to 1000) with constant heat flux (266,000 W/m²) to simulate the conditions for electronic applications with high power. Results indicate that fin thickness and shape play a crucial role in heat transfer efficiency and pressure drop. For instance, the Nusselt number increased by 47% (from 7.48 to 22 for Re=1000) with increased fin thickness from 1 mm to 2 mm, but the friction factor increased by 120% (from 0.17 to 0.374 for Re=1000) accordingly. Among the configurations, the maximum thermal performance was exhibited by C3 with the maximum Nusselt number (38.4 for Re=1000) representing an improvement by 123% with respect to the traditional design. The Thermal Performance Factor (TPF) for C3 was maximum at 1.456 for Re=600, representing the optimal balance for heat transfer enhancement and pressure drop. Temperature contours and velocity profiles indicated efficient heat dissipation and flow dynamics with temperature gradients ranging from 30 to 55 and velocity variations marking the recirculation zones responsible for heat transfer efficiency. These observations provide valuable information for the design of advanced heat sinks with potential for enhanced thermal management in electronic systems with high power. This work fills the gap that exists between experimental optimization and real-world application, moving toward the development of more efficient cooling technologies for modern electronics.

Keywords: Heat Sink Optimization; Computational Fluid Dynamics; Thermal Management; Nusselt Number Enhancement; Pressure Drop.

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1. Introduction

Thermal management is a core topic in modern electronic systems design that deals with the methods and technologies utilized in the regulation and dissipation of electronic components' heat [1, 2]. As technology progresses, the power density in electronic products is also increasing, and thermal management is critical in ensuring reliability, performance, and longevity in such products [3, 4]. Heat generation is a fundamental property of electronic operation, and, if left uncontrolled, can result in overheating, decreased efficiency, and device failure [5]. Thermal management is especially critical in high-performance computing, telecommunications, and consumer electronics, in which component density and compact design complicate thermal issues [6].

Heat sinks, as passive thermal management components, play a critical role in this application. They are specially designed in such a way as to enhance heat dissipation from hot surfaces to colder environments, predominantly through conduction and convection means [7, 8]. The choice of material and design for heat sinks directly affects their ability in dissipating heat from critical components [9, 10]. As industries shift towards smaller, faster, and more efficient products, traditional cooling solutions are limited by their thermal dissipation capacities [11]. As such, there is a growing need for innovative heat sink geometries and materials that can sustain larger thermal loads in very restricted areas [12]. Developing advanced heat sink geometries and materials through experimental testing and computational simulations is, therefore, important in advancing thermal management in modern electronics



[13]. Computational Fluid Dynamics (CFD) is presently an efficient technique applied to this process of optimization, allowing for the comprehensive investigation and improvement of fluid flow and heat transfer in complex heat sink designs [14, 15]. CFD allows scientists to simulate complex thermal processes and geometries that are hard to test experimentally, providing insightful information about the thermal management of electronics [16, 17].

Literature for heat sink performance in electronic devices presents several new approaches to achieving maximum heat dissipation efficiency. Research is focusing on experimental configurations, numerical simulations, and comparative studies to analyze various heat sink configurations and thermal hydraulic performance. H. A. Hussein [18] conducted a numerical study to examine the effectiveness of multi-mini-channel heat sinks (MMCHS) with pin fins arranged in a square layout. Flow maldistribution was studied and the research suggested using square fins and square pin fins as new heat sink shapes for better flow distribution. Partial differential equations for laminar flow were simulated using the finite element method when water was the single-phase coolant. The study showed that the modified channels moved heat more effectively than the standard rectangular channels. Between the heat sinks tested, the one with square fins and square pin fins stood out by having Nusselt numbers nearly double those of the regular heat sink. This means the SSPMMCHS had an average thermal resistance of 0.1052 which was almost twice as good as the 0.2008 recorded for the traditional heat sink. The performance index for the SSPMMCHS was 2.21, an extremely great improvement in the thermal performance. H. Xiao et al. [19] studied the enhancement of the conjugate heat transfer in mini-channel heat sinks by optimizing the flow patterns. In the paper, inclined parallelepiped ribs were used to produce longitudinal swirls to improve the efficiency of heat transfer. It was observed that the Nusselt number ratio (Nu/Nu_0) was 1.35 to 5.92 and the friction factor ratio was 1.27 to 8.75. Maximum average heat flux with optimized design was 3.2×10^6 W/m² with the substrate-fluid temperature difference being 60 K. It was concluded that the proposed design significantly enhanced the thermal performance at reasonable pressure drop penalties. The study by M. W. Uddin and N. S. Sifat [20] involved heat sinks with rectangular, oblique and curvy channels. The study noted that using counter flow made a big difference to how effective the heat transfer was. When the curved secondary channel was used at $Re = 1050$, its best PEC value was 1.53. There was a rise in average Nusselt number and a decrease in thermal resistance in counter flow setups, showing that the approaches worked well. Y. Researchers from Wang et al. [21] ran experiments to discover how an electric field could increase the heat transfer rate in mini-channel heat sinks. It was noticed that the application of 200 V caused the heat transfer coefficient to ascend by 178% and the CHF to increase by 123%. Bubble sizes were decreased and temperature uniformity was increased by the electric field, illustrating the potential provided by the electrohydrodynamic (EHD) techniques for thermal management. Y. Wang et al. [22] suggested a bionic parallel mini-channel heat sink (BPM-channel) for linear Fresnel photovoltaic cooling. It was seen that the BPM-channel achieved the highest thermal enhancement factor of 50% when compared to rectangular channels. The rotation angle had no influence on the pressure drop, with the differences only varying 4%, and the suggested structure is therefore suitable for dynamic applications. S. Wu et al. [23] suggested a tree-like mini-channel liquid cooling heat sink for the cooling of electronic chips.

Experimental tests showed that the TSMLCHS maintained its average surface temperature at 23.8 °C to 66.6 °C during heat fluxes ranging from 5 W/cm² to 8 W/cm², demonstrating its efficiency for applications with high heat flux. Tikadar et al. [24] studied the thermal and hydraulic performance of counter flow and inter-connected parallel mini-channel heat sinks. It was revealed that counter flow designs boosted the Nusselt number by 36% and reduced the friction factor by 31.13% when compared to the conventional designs. The Performance Evaluation Criteria (PEC) was 1.33, which indicates overall performance improvement. H. A. Hussein [25] studied the thermal and hydraulic performance of circular mini-channel heat sinks with L-shaped multi-channel configurations. In comparison to the traditional designs, it was discovered that the hotspot temperature was lowered by 8 °C and the thermal resistance was decreased by 18.3% with the performance index increased by 1.194. V. Nagendra et al. [26] investigated the impact of ribs on the thermo-hydraulic performance of counter-flow mini-channel heat sinks. It was established by the study that the ribs with the direction along the flow direction (0-degree orientation) provided the maximum Performance Evaluation Factor (PEF) and thermal uniformity. Optimum sizes for the ribs were identified, and Nusselt number and pressure drop correlations were derived. Dixit et al. [27] conducted the advancements in electronic cooling with the utilization of minichannel heat sinks. Fin thickness and spacing were optimized to reduce the base temperature by 44.84%, and heat transfer coefficients were boosted by 72% with the utilization of nanofluids. Hybrid helical-straight minichannels boosted thermal performance by 94.5%, and ribbed serpentine configurations reduced the base temperature by 13.9%. Finally, F. N. Ghadhbani and H. M. Jaffal [28] investigated the effect of channel configurations on heat transfer and fluid flow in multi-minichannel heat sinks. The study found that wave-shaped channels achieved the highest Nusselt number enhancement (30.5%) and the best performance factor (1.3), while arc-shaped channels exhibited the lowest pressure drop (16% reduction compared to conventional designs).

Despite significant advancements in heat sink technology in accordance with recent literature, inconsistencies remain in the optimization and the real-world application of heat sink geometries, particularly under variable operating conditions. Most recent research does not account for the scalability of new designs or performance for a vast array of real-world applications, thus limiting the use in compact and power consuming electronic devices. This paper seeks to bridge the inconsistencies by undertaking an intensive CFD simulation on three new heat sink geometries. It seeks to investigate their thermal performance under varying environmental and operating conditions and compare the results with traditional heat sink models to identify efficiency, scalability, and cost. The expected outcome of this paper is to enhance the understanding of heat dissipation processes in new heat sink designs and to provide empirical findings to inform the creation of more efficient thermal management in the electronic industry. This paper seeks to bridge the gap between experimental optimization and real-world use, offering new information that can lead to significant breakthroughs in electronic device cooling technologies.

2. Numerical Modeling

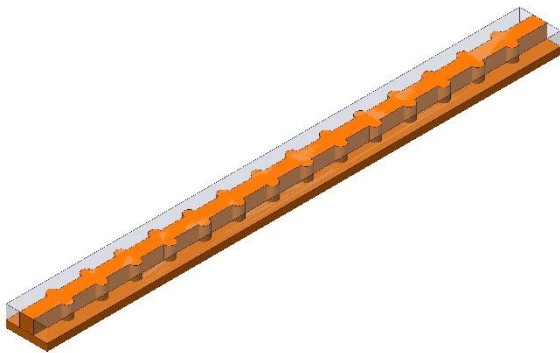
2.1 Description of the Physical Model

The physical model for this research was designed to compare the thermal performance of innovative heat sink configurations to evaluate the heat dissipation capacity enhancement against the standard. Heat sinks in this context include three innovative configurations with one standard straight-fin structure to be used for comparison, as presented in Figure 1. All the models were constructed with one fin, leveraging symmetry on both sides to facilitate the simulation process in the ANSYS environment.

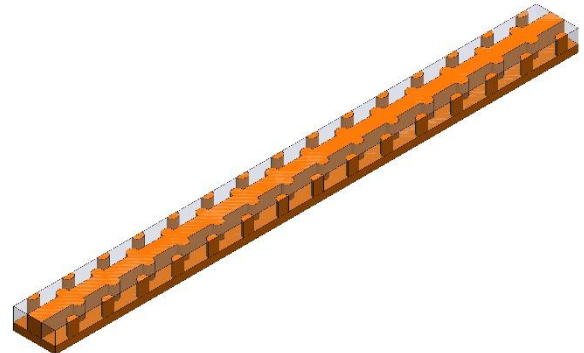
Heat sink materials are assumed to have homogeneous thermal properties with high thermal conductivity for efficient heat transfer. Simulations were conducted with boundary conditions to

analyze the performance at varying operating conditions. Of specific interest, the air velocity at the inlet was varied to be equal to the Reynolds numbers 200, 400, 600, 800, and 1000 to obtain an overall insight into the flow dynamics for different laminar and turbulent flow conditions. Additionally, the constant heat flux of 266,000 W/m² was applied to all the models to simulate the conditions of high heat generation typical in power electronic applications.

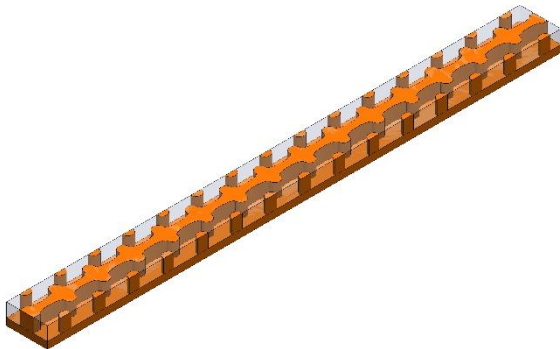
This technique enables the comprehensive comparison of the thermal performance for various heat sink geometries and also indicates the possibility for enhancement by geometric modification. Results derived by the numerical simulation are to be used to guide the heat sink designs for the purpose of optimizing the thermal management in electronic components.



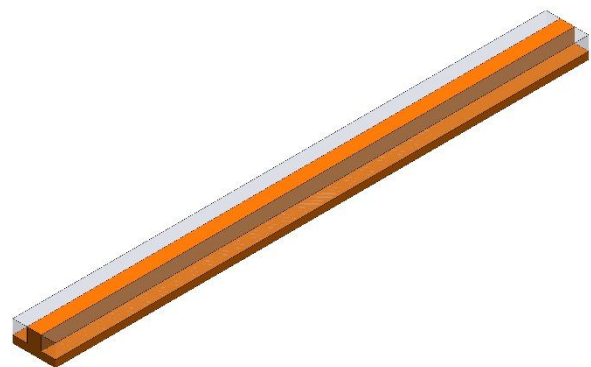
a) Configuration 1 (C1)



b) Configuration 2 (C2)



c) Configuration 3 (C3)



d) Traditional heat sink (T)

Fig. 1: Three Advanced Configurations and One traditional Configuration.

2.2 Description of the Numerical Model

The numerical model was specifically designed to mimic the thermal and fluid dynamics performance of the new heat sink designs presented above. Utilizing the ANSYS program, the finite volume method was employed to ensure precision in the solution for the complex interactions among the solid and fluid domains of the heat sinks.

Boundary Conditions and Model Configuration Simulation setup entailed the application of certain boundary conditions to represent operating conditions realistically. **Figure 2** indicates that the velocity inlet condition was prescribed at one side of the heat sink model with the velocities scaled to be the equivalent of the Reynolds numbers 200, 400, 600, 800, and 1000. Such a choice was to cover the laminar and transitional flow conditions to be able to acquire insight into the performance of heat sink configurations under various flow conditions. A constant pressure outlet was prescribed at the opposite side of the model.

Meshing each heat sink's computational domain was discretized with a structured mesh to enhance the stability and accuracy of the simulations. **Figure 3** shows that the mesh was also refined approximately the fins to resolve the fine thermal gradients and fluid flow details approximately the fins. Refinement near the fins was required to accurately model the heat transfer and fluid dynamics, particularly at the higher Reynolds numbers at which flow separation and reattachment can play a dominant role in performance. The mesh contained approximately 1,464,750 nodes to achieve a fine resolution to enable the thorough investigation of the thermal and flow phenomena in the various heat sink configurations.

The governing equations comprise a set of partial differential equations related to continuity, momentum, and energy, as delineated below [29, 30]:

I. Continuity equation:

$$\frac{\partial(\rho u)}{\partial x} + \frac{\partial(\rho v)}{\partial y} + \frac{\partial(\rho w)}{\partial z} = 0 \quad (1)$$

II. Momentum equation:

u-momentum (x-direction):

$$\frac{\partial(\rho u^2)}{\partial x} + \frac{\partial(\rho uv)}{\partial y} + \frac{\partial(\rho uw)}{\partial z} = -\frac{\partial p}{\partial x} + \mu \left[\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2} \right] \quad (2)$$

v-momentum (y-direction):

$$\frac{\partial(\rho uv)}{\partial x} + \frac{\partial(\rho v^2)}{\partial y} + \frac{\partial(\rho vw)}{\partial z} = -\frac{\partial p}{\partial y} + \mu \left[\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} + \frac{\partial^2 v}{\partial z^2} \right] + \rho g \quad (3)$$

w-momentum (z-direction):

$$\frac{\partial(\rho uw)}{\partial x} + \frac{\partial(\rho vw)}{\partial y} + \frac{\partial(\rho w^2)}{\partial z} = -\frac{\partial p}{\partial z} + \mu \left[\frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2} + \frac{\partial^2 w}{\partial z^2} \right] \quad (4)$$

III. Energy equation:

$$\frac{\partial(\rho uT)}{\partial x} + \frac{\partial(\rho vT)}{\partial y} + \frac{\partial(\rho wT)}{\partial z} = \frac{\mu_{eff}}{Pr_{eff}} \left[\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right] \quad (5)$$

The effective thermal resistance (R_{th}) is the primary metric that indicates the system's efficacy and the cooling performance of the heat sinks. A decreased value is associated with an increase in system efficiency. The heat transfer coefficient and R_{th} calculations utilized in thermal analysis is illustrated in Equations (6) and (7). The friction factor is determined by Equation (9) and the Reynolds number is calculated by Equation (8).

$$R_{th} = \frac{T_{source} - T_{in}}{q} \quad (6)$$

$$h = \frac{q}{T_{source} - T_{bulk}} \quad (7)$$

$$Re = \frac{\rho u D_h}{\mu} \quad (8)$$

$$f = \frac{2 \Delta P D_h}{\rho L u^2} \quad (9)$$

The TPF measures how much the efficiency of heat transfer rises with the extra resistance caused by the new design of the heat sink [31]. If the TPF value is more than one, the advantages of improved heat transfer beats out the drawbacks caused by the raised pressure drop [32]. This measurement is vital when deciding whether changes in the design, including the fin configurations or the introduction of new materials, bring about a net gain in the efficiency of the thermal management. The TPF can be expressed as follows:

$$TPF = \frac{Nu_{av}}{Nu_{av,o}} \left/ \left(\frac{\Delta P}{\Delta P_o} \right)^{\frac{1}{3}} \right. \quad (10)$$

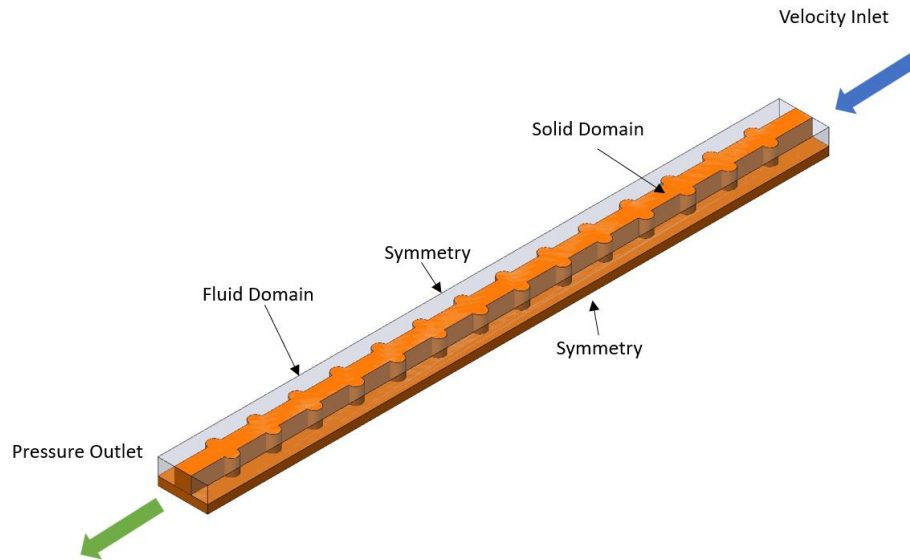


Fig. 2: Schematic of Boundary Conditions Applied in Heat Sink Simulations.

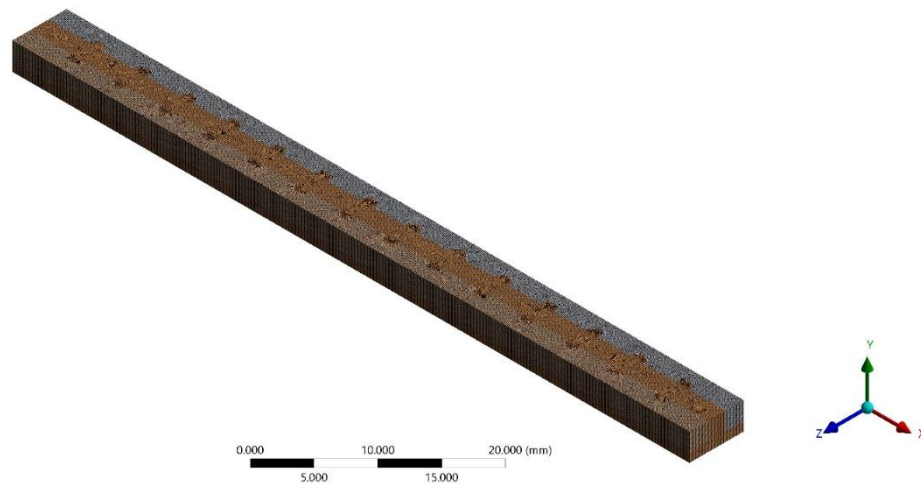


Fig. 3: Mesh Configuration for Heat Sink Computational Model.

3. Results and Discussion

The performance of various heat sink configurations at different operating conditions will be examined here by comparing the results obtained by the experiments and the simulations. Computational fluid dynamics simulation findings, shown in Figure 4, highlight the significance of fin thickness and the Reynolds number on heat transfer efficiency for heat sinks. For the fin thicknesses we have used 1 mm, 1.5 mm, and 2 mm, the Nusselt number is observed to increase with the thickness, demonstrating the thermal benefits provided by increased convective heat transfer surface areas. For example, at $Re=200$, the values for Nu increase from 7.48 for 1 mm fins to 10 for 2 mm fins. This trend is seen at higher values for the Reynolds numbers, with the value for 2 mm fins reaching 22 for $Re=1000$, against 17.2 for 1 mm fins. **Figure 5** illustrates how the Reynolds number (Re) rises; the friction factor (f) falls across different fin thicknesses (1 mm, 1.5 mm, and 2 mm). At a Reynolds number of 200, the friction factors for these thicknesses are 0.466, 0.639, and 0.977, respectively, indicating that thicker fins exhibit higher flow resistance. As the Reynolds number increases to 1000, these values decrease to 0.17, 0.23, and 0.374, showing a consistent reduction

across all fin sizes. This trend highlights that while thicker fins may improve heat transfer by increasing surface area, they also lead to higher frictional losses, impacting the system's overall energy efficiency. The decrease in friction factor with increasing Reynolds number suggests that at higher flow velocities, the adverse effect of increased fin thickness on hydraulic resistance is somewhat mitigated. **Figure 6** shows the Thermal Performance Factor (TPF) for heat sinks with different fin thickness (1 mm, 1.5 mm, and 2 mm) at different Reynolds numbers (Re). The values for the TPF, comparing heat transfer enhancement to the penalty in the form of pressure drop, typically increase with increasing fin thickness and Reynolds number. Of special interest are the 1.5 mm fins, which show the most linear enhancement in TPF across the entire spectrum of the Reynolds numbers, ranging from 1.021 at $Re=200$ to 1.269 at $Re=1000$. This reflects the optimal balance in performance with the optimum trade-off between heat transfer efficiency and fluid resistance. The 2 mm fins, with the early lead at $Re=200$ at 1.017, show less spectacular enhancement to 1.185 at $Re=1000$, with diminishing returns at higher flow rates. This observation reveals that thicker fins can improve heat transfer but the accompanying increase in the pressure drop can limit the

overall performance gain at higher flow conditions. The simulation reveals that the 1.5 mm fin thickness provides the best thermal performance, reflected by outstanding values for the TPF. Results to follow will be for this thickness when assessing other heat sink configurations so that efficient optimization can be established because of demonstrated efficiency in balancing heat transfer improvement and pressure drop.

The results shown in **Figures 7, 8, and 9** show significant differences in performance for three heat sink configurations (C1, C2, C3) and the standard (T) arrangement at varying Reynolds numbers (Re). **Figure 7** shows that configurations C2 and C3 consistently have higher values for Nu than for C1 and T, with C3 peaking at the value 38.4 for Re=1000, representing increased heat transfer. C1 and T, with less dramatic increments, show less efficient heat dissipation. **Figure 8** shows that the friction factors for C2 and C3 are substantially higher than for C1 and T, peaking at Re=200 with values 2.48 and 2.13, respectively. This shows increased flow resistance in the more complex configurations. **Figure 9** shows that with the increased friction factors, C2 and C3 have increased values for TPF, especially at mid-Reynolds numbers, representing increased balance between heat transfer enhancement and flow resistance. The peak for the TPF for C3 is at Re=600 with the value 1.456, representing optimal performance at the rate of flow.

The temperature contours in **Figure 10** illustrate the thermal performance of the different heat sink designs during simulation.

Temperature across the heat sinks ranges from approximately 30 °C to 55 °C. Blue to red color gradient indicates the progression from cold areas at the inlet to hot areas at the outlet, illustrating effective heat dissipation. This visualization validates the heat sink's capability to maintain lower temperatures even with the rise in operational conditions to ensure maximum performance of electronic components. Such observations validate the effectiveness of the design in heat extraction, which is crucial in power-consuming applications. The velocity profiles in **Figures 11 and 12** present the overall visualization of fluid dynamics in the heat sink channels. **Figure 11** indicates the heterogeneous distribution of velocities throughout the channels, ranging from 0.000 m/s to greater than 0.500 m/s, representing the existence of significant flow variation and hotspots for the fluid to speed up or slow down. **Figure 12** representation by streamlines gives an in-depth insight into the nature of the flow, illustrating the way the fluid moves around the obstructions in the channels. Of specific importance is the existence of vortex patterns around the fins, representing the recirculation areas, which can influence heat transfer efficiency and fluid mixing. Overall understanding of the flow patterns in the heat sinks aids in the identification of areas for improvement to improve thermal efficiency and lower flow resistance. The findings explain the dominant influences of fin configurations, flow conditions on the thermal and hydraulic performance of the heat sinks, and provide beneficial information for the optimal heat sink designs for real-world applications.

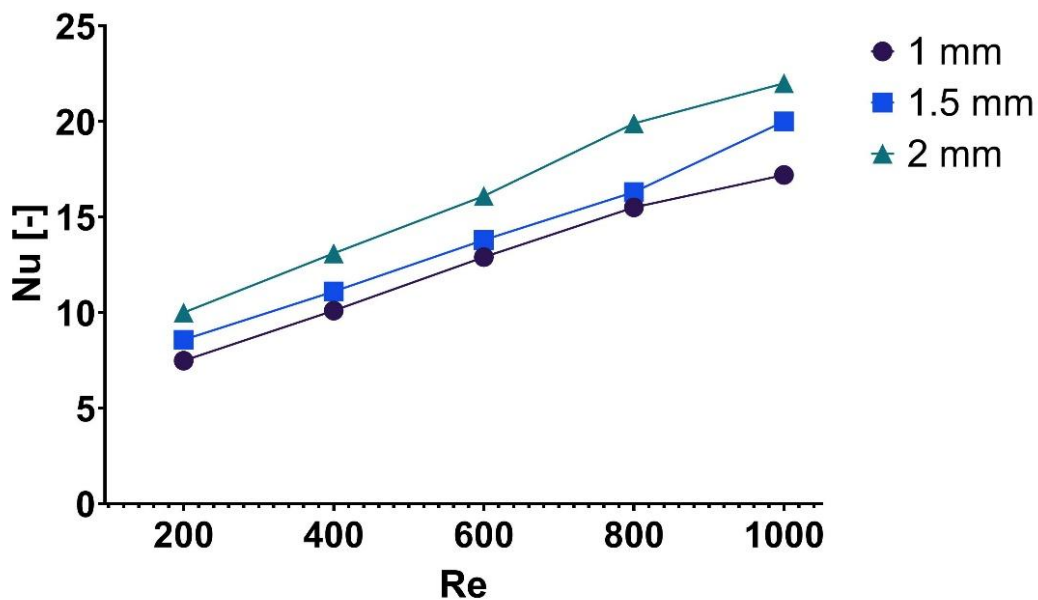


Fig. 4: Reynolds Number and Nusselt Number Variation for Various Fin Thicknesses.

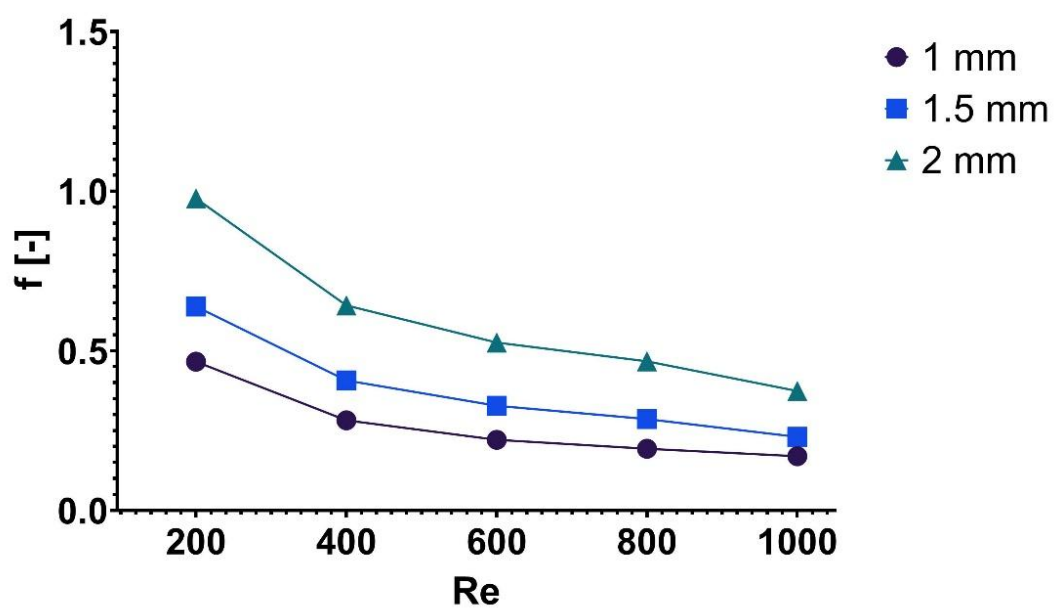


Fig.5: Friction Factor for Different Fin Thicknesses as a Function of Reynolds Number.

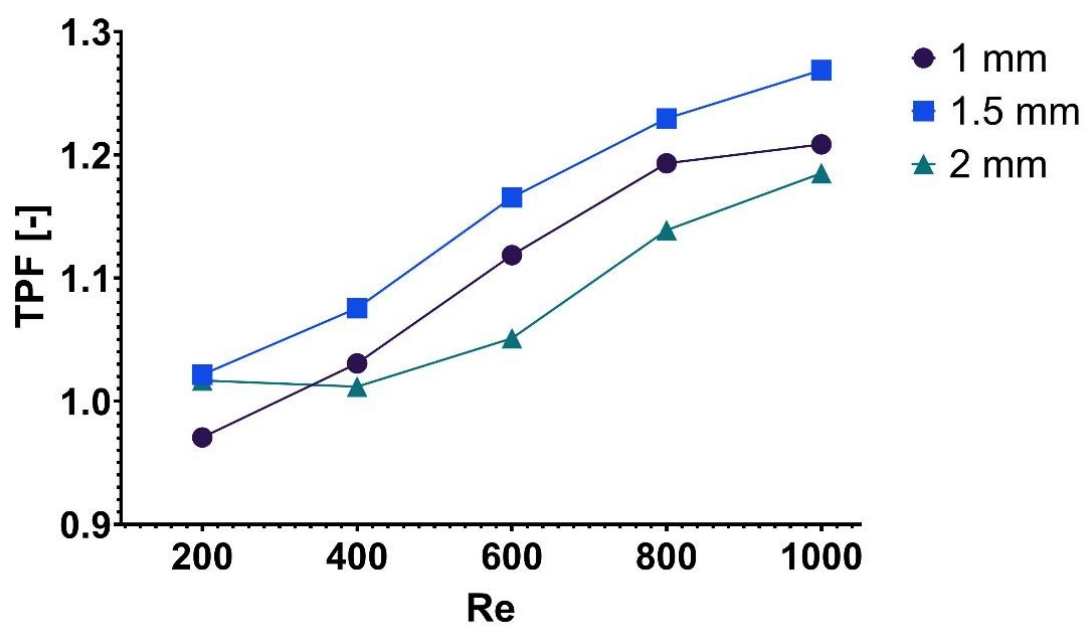


Fig. 6: Thermal Performance Factor (TPF) Across Different Reynolds Numbers for Varied Fin Thicknesses.

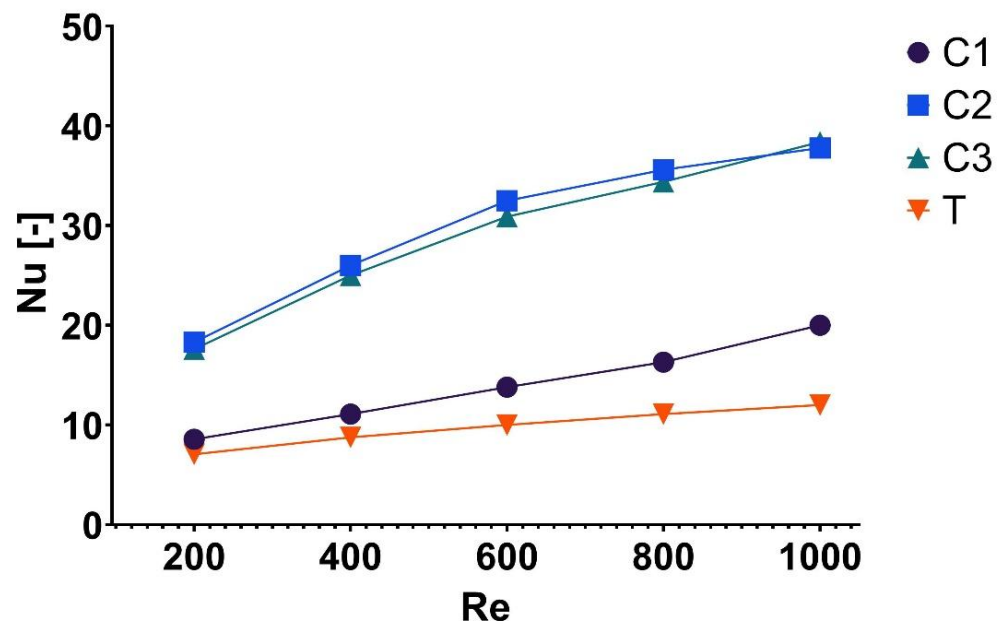


Fig. 7: Relationship between Nusselt Number and Reynolds Number for Different Designs of Heat Sinks.

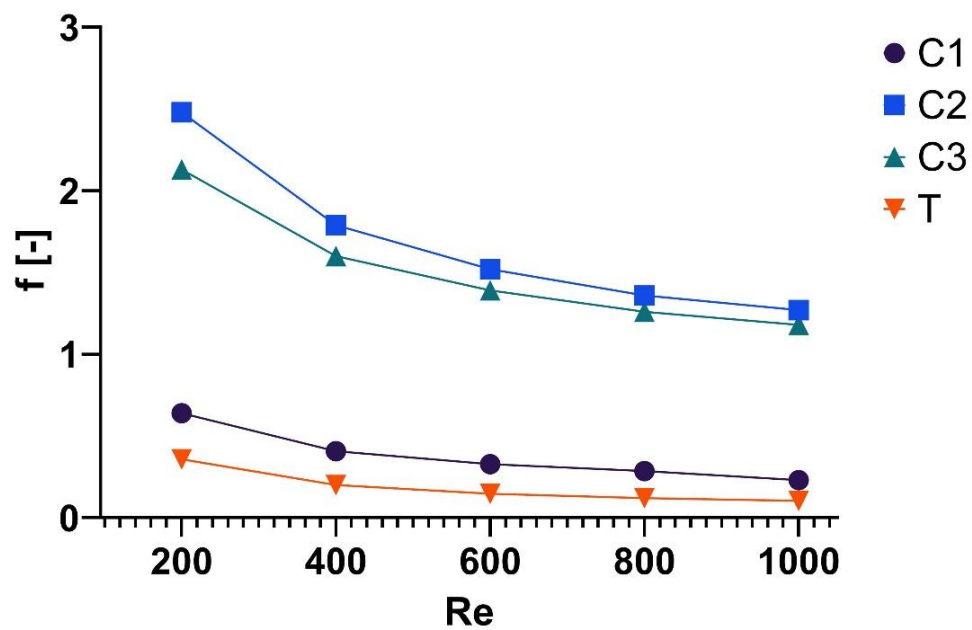


Fig. 8: Friction Factor Across Different Reynolds Numbers for Various Heat Sink Configurations.

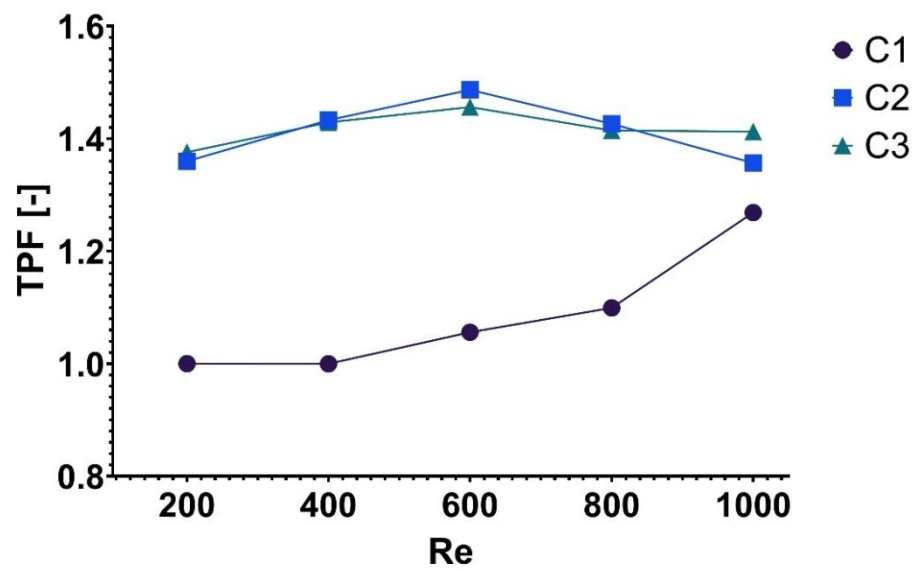
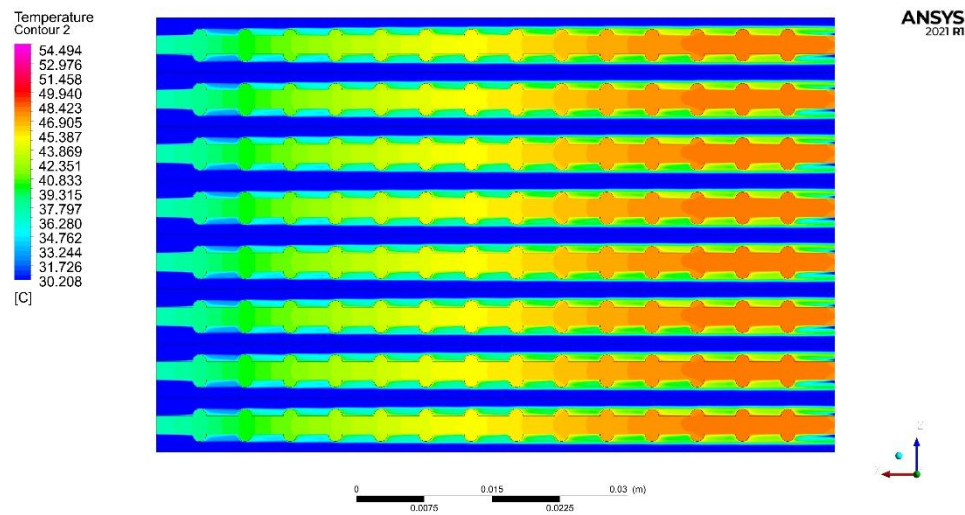
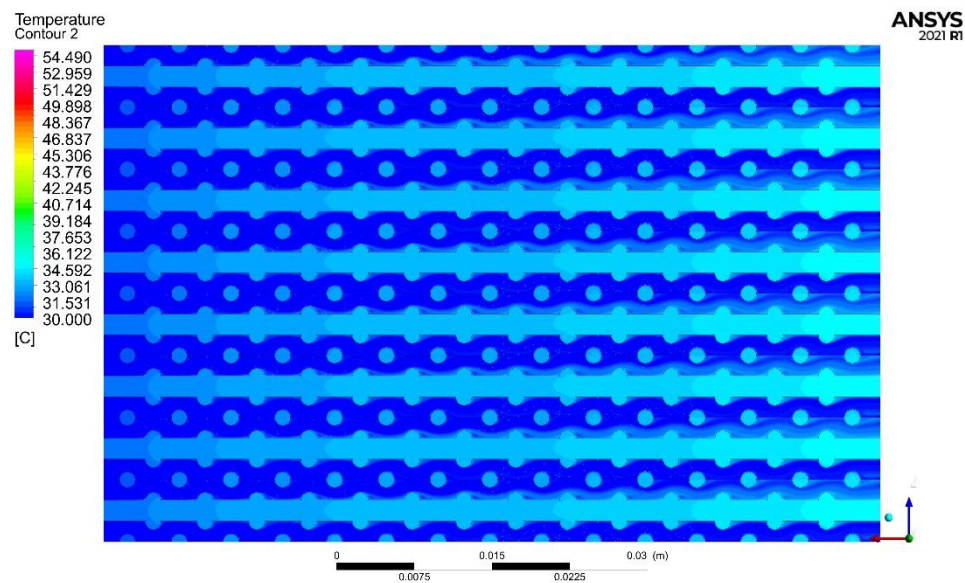


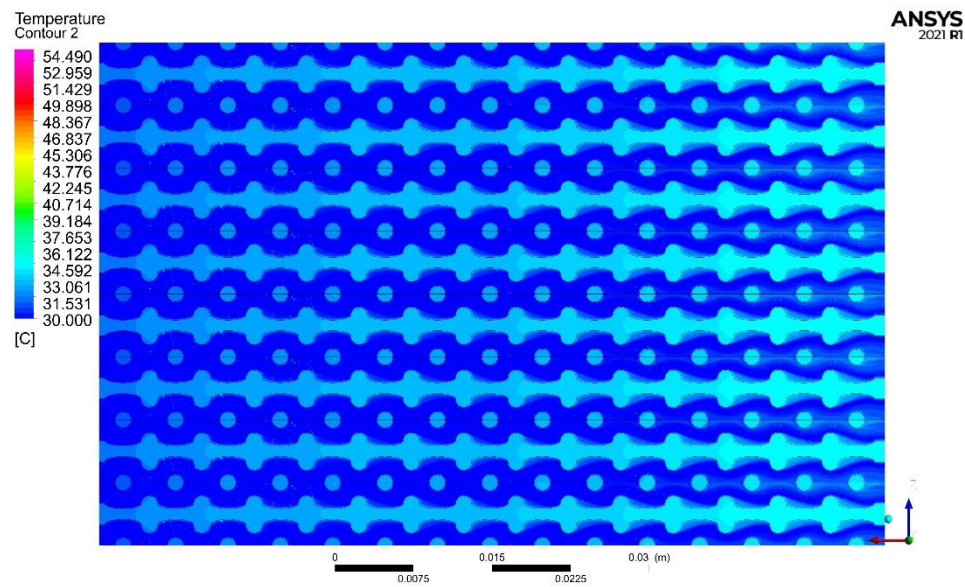
Fig. 9: Thermal Performance Factor for Heat Sink Configurations Across Varying Reynolds Numbers.



a) C1

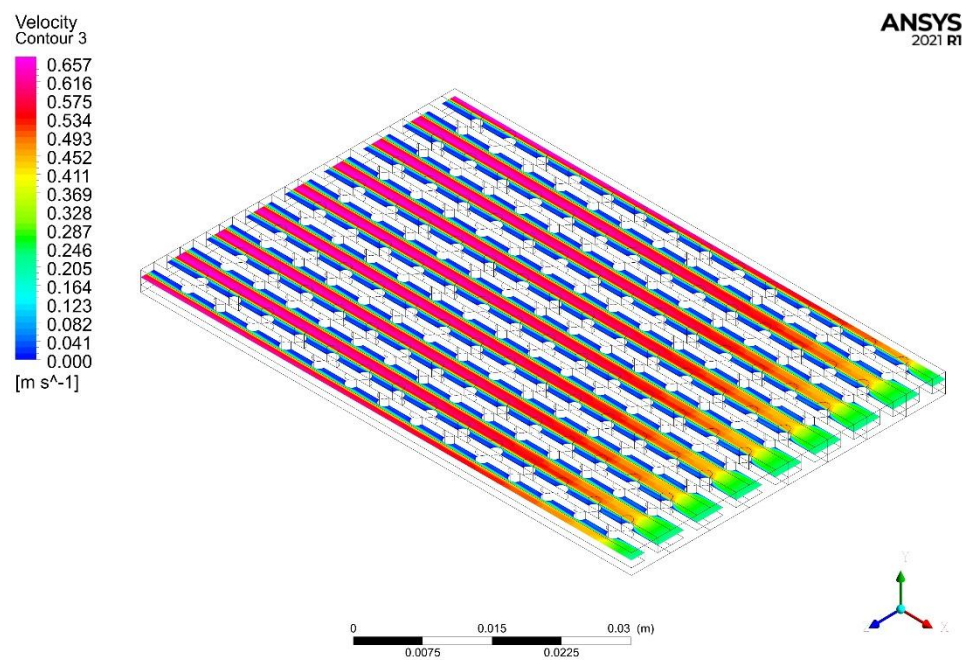


b) C2

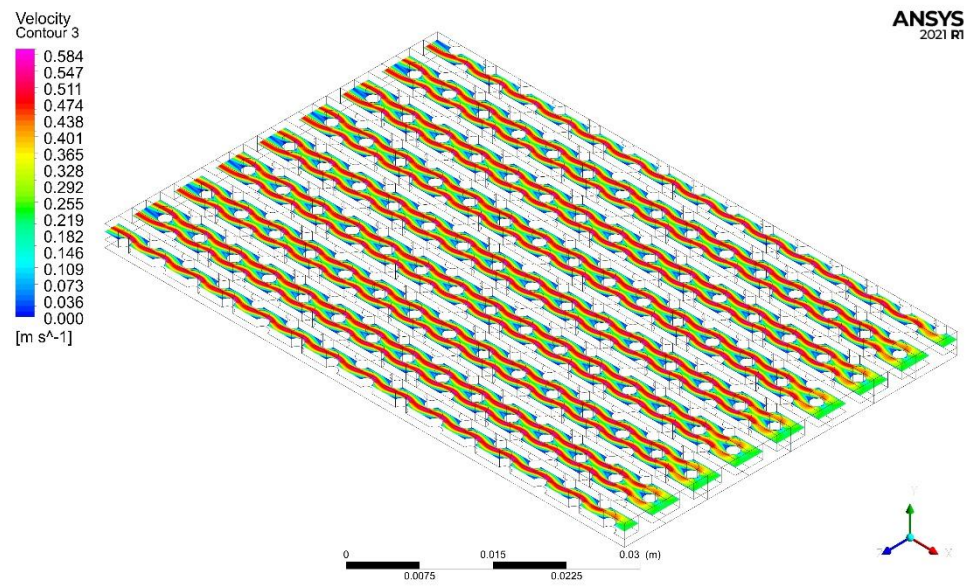


c) C3

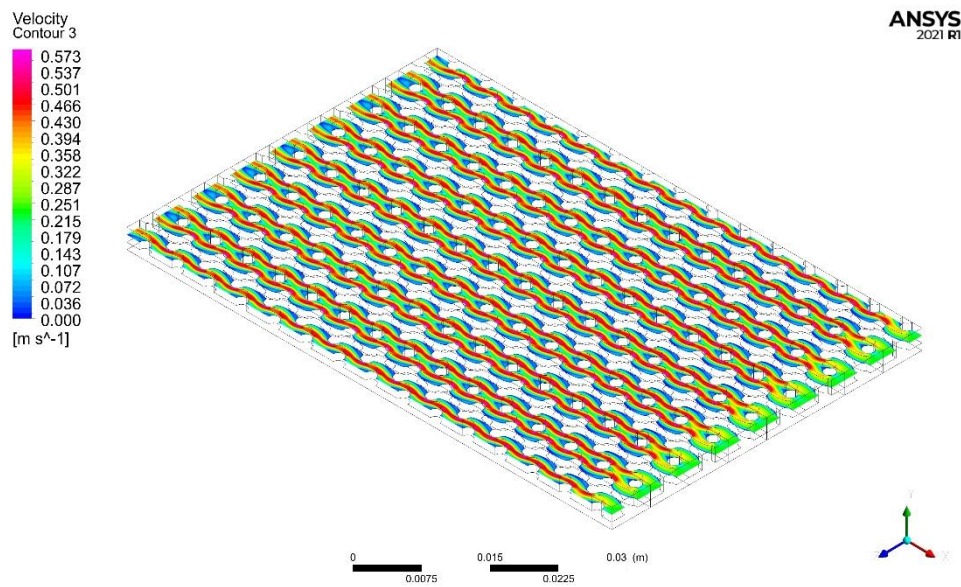
Fig. 10: Temperature Distribution in Heat Sink Designs under Various Operating Conditions.



a) C1

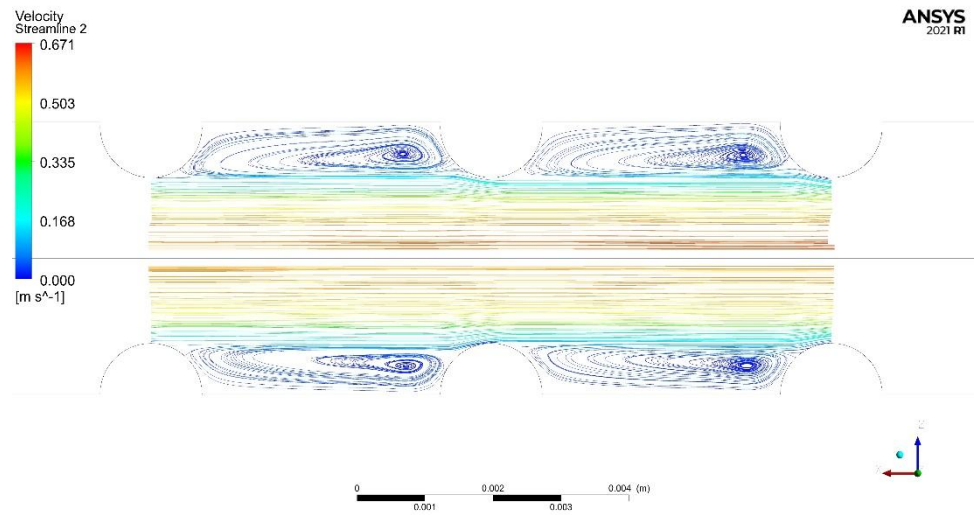


b) C2

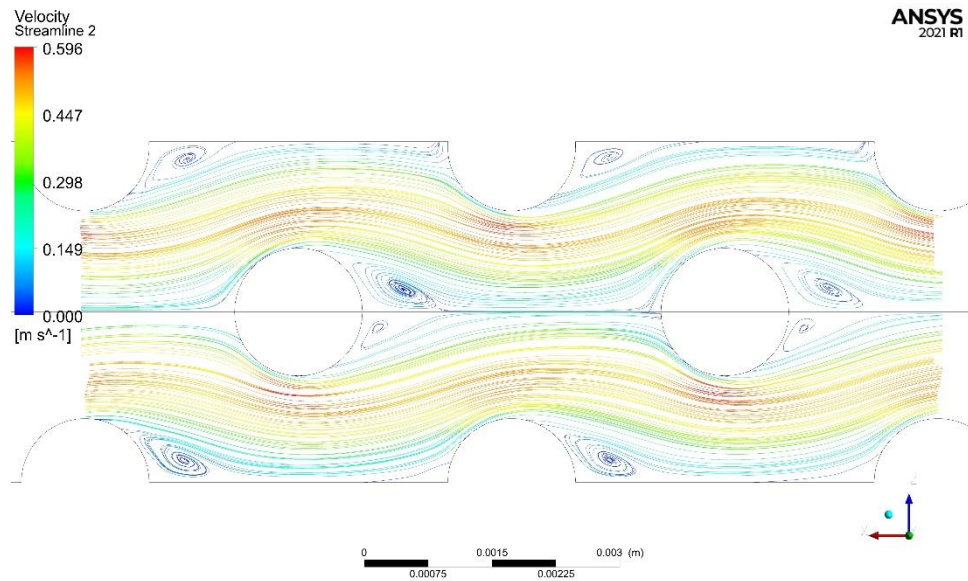


c) C3

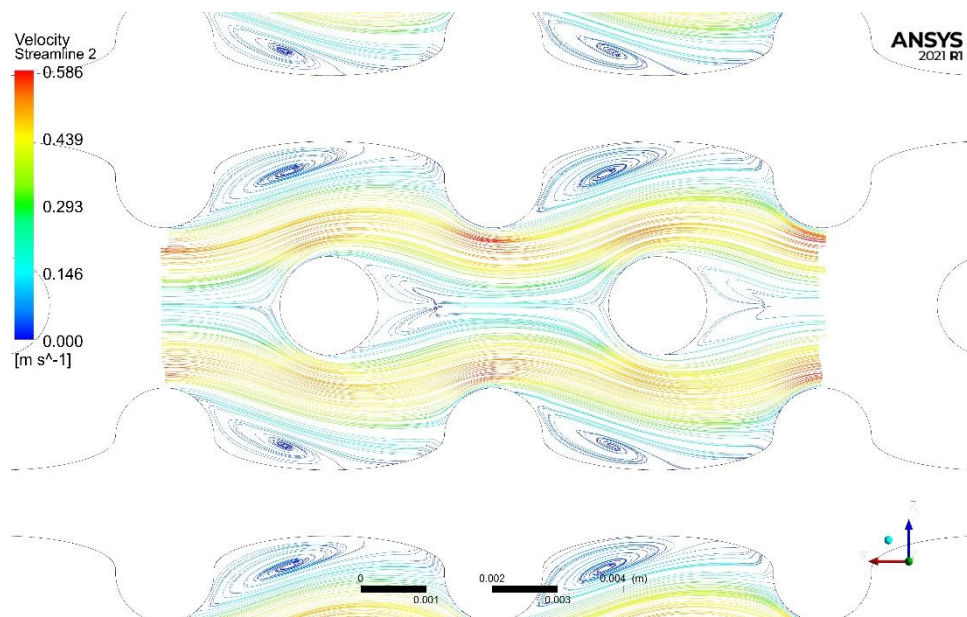
Fig. 11: Velocity Distribution in Heat Sink Channels.



a) C1



b) C2



c) C3

Fig. 12: Streamline Patterns in Heat Sink Flow Analysis.

4. Conclusion

This research completely studied the thermal performance of the new heat sink designs by performing Computational Fluid Dynamics simulations to achieve the optimized fluid flow and heat transfer efficiency for varying operating conditions. It confirmed the improved performance of the 1.5 mm thickness fin design, which showed the ideal balance between heat dissipation and pressure drop with an enhancement in the Thermal Performance Factor (TPF) by a maximum of 26.9% at the operating condition $Re = 1000$. The new designs showed an outstanding enhancement in heat transfer efficiency when contrasted with the standard

model, with the most effective setup having a Nusselt number 38.4% higher than the standard model's. Such information is crucial because it sheds light on the interaction between fin shape, flow dynamics, and heat performance, suggesting that specific changes to the design can lead to spectacular heat sink efficiency enhancement.

Overall, this work not only enhances the understanding of thermal management in small electronic devices but also lays the basis for future heat sink technology development. Continued technological innovation is necessary to keep pace with the escalating thermal demand of modern electronic components and systems.

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