



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

Hiba Hameed Kareem^{1*}, Tawfeeq K. Al-Hamdi², Saad Najeeb Shehab³

¹ Department of Construction and Project Management, Mustansiriyah University, Baghdad, Iraq

^{2,3} Mechanical Engineering Department, College of Engineering, Mustansiriyah University, Baghdad, Iraq.

*Corresponding Author

Hiba Hameed Kareem

Department of Construction and Project Management, Mustansiriyah University, Baghdad, Iraq.

Article History

Received: 09.07.2025

Accepted: 03.08.2025

Published: 21.08.2025

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. C3 had the highest maximum thermal performance with the highest Nusselt number (38.4 at Re=1000) which is an enhancement of 123 with respect to the traditional design. The Thermal Performance Factor (TPF) of C3 had a maximum of 1.456 with Re= 600, which was the most appropriate ratio between heat transfer improvement and pressure drop. The temperature contours and velocity profiles showed that there is good dissipation of heat and flow dynamics with temperature differences that come with a 30-55 temperature range and velocity difference indicating the recirculation zones where efficacy of transferring heat occurred. The observations are very useful in designing advanced heat sinks that will have the potential of better thermal management in the electronic systems of high power. The work bridges the gap that has been there between experimental optimization and practical use that is geared towards the advancement of more efficient cooling technologies of contemporary electronics.

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

Cite this article:

Kareem, H. H., Al-Hamdi, T. K., Shehab, S. N., (2025). Numerical Study on Hydro-Thermal Performance Optimization of Mini-Channel Heat Sinks Using Surface Modification. *ISAR Journal of Science and Technology*, 3(8), 20-33.

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 enables scientists to model complex thermal processes and geometries difficult to experimentally test and gives informative information on 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. Studies are being done on experimental setups, numerical models, and comparative analysis in attempt to investigate different heat sink designs and their thermal hydraulic characteristics. H. A. Hussein [18] made a study based on numbers to evaluate the efficiency of multi-mini-channel heat sinks (MMCHS) having pin fins which were of a square structure. 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. Ghadhbhan 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 is aimed to fill the gaps by conducting an intensive CFD analysis of three novel-geometries of heat sinks. It aims at exploring their thermo performance in different environments and operating conditions and comparing the performance with conventional heat sink models to determine efficiency, scalability and cost. The anticipated input of this paper is to increase awareness of the thermal processes of heat sink designs and give empirical results, which would guide the development of the more effective thermal management of the electronic industry. The purpose of this paper is to fill in the gap between experiment optimization and practice and provide new

information, which will result in the major breakthrough in electronic devices cooling technologies.

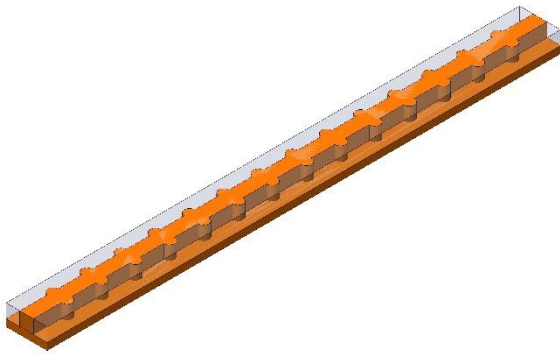
2. Numerical Modeling

2.1 Description of the Physical Model

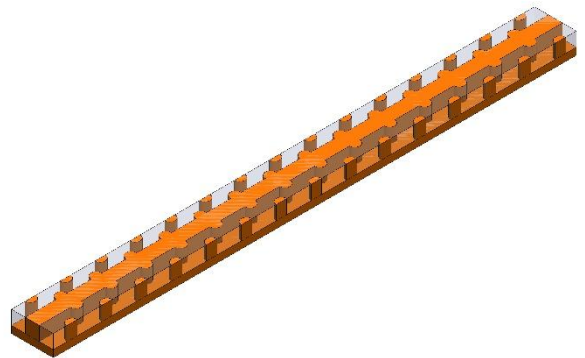
In this study, the physical model was created in order to compare the thermal performance of these innovative set ups of the heat sinks to determine the enhanced performance of the heat sink over the conventional one in terms of improving the amount of heat dissipation. The heat sinks in this case also consist of three innovative configurations with one conventional straight-fin structure to be compared to it, which is introduced in Figure 1. The construction of all the models was based on a single fin, and the advantage on this was that because of symmetry on either side, it would help in the process of simulating in the ANSYS environment.

The thermal conductivity of the heat sink materials is assumed to be homogeneous to ensure that its thermal conductivity is high so as to conduct the heat effectively. 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.

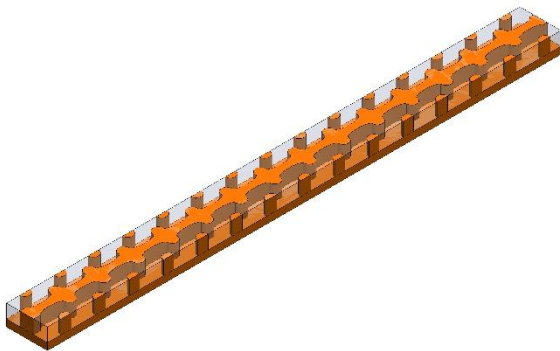
This technique enables the comprehensive comparison of the thermal performance for various heat sink geometries and also indicates the possibility for enhancement by geometric modification. Results derived by the numerical simulation are to be used to guide the heat sink designs for the purpose of optimizing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



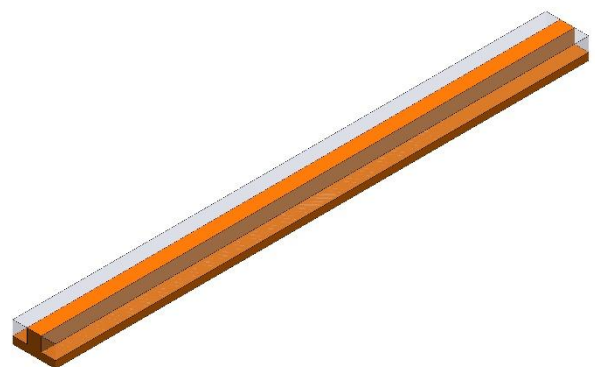
a) Configuration 1 (C1)



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. A fine resolution of 1,464,750 nodes was used and contained in the mesh to allow the thorough study of both the thermal and flow phenomena in the different heat sink configurations.

The equations that are governing include a set of partial differential equations pertaining to continuity, momentum and energy and as defined 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 first parameter that determines the efficacy of system and cooling performance of the heat sinks is the effective thermal resistance (R_{th}). A lower value is linked to an increment in system efficiency. The heat transfer coefficient and R_{th} that was applied in thermal analysis is represented in Equations (6) and (7). Determination of the friction factor is calculated through Equation (9) as well as the Reynolds number is calculated through 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 is a ratio that determines the increase of efficiency of the heat transfer at the additional resistance brought about by the new structure of the heat sink [31]. When TPF value is higher than one, the merits of enhanced heat transfer overcomes the demerits due to the increased pressure drop [32]. This experiment is crucial in the determination of whether the modifications in the design such as the fin arrangements or introduction of new materials is associated with a net increase in the efficiency of the thermal management. The TPF can be stated as below:

$$TPF = \frac{Nu_{av}}{Nu_{av,0}} \left/ \left(\frac{\Delta P}{\Delta P_0} \right)^{\frac{1}{3}} \right. \quad (10)$$

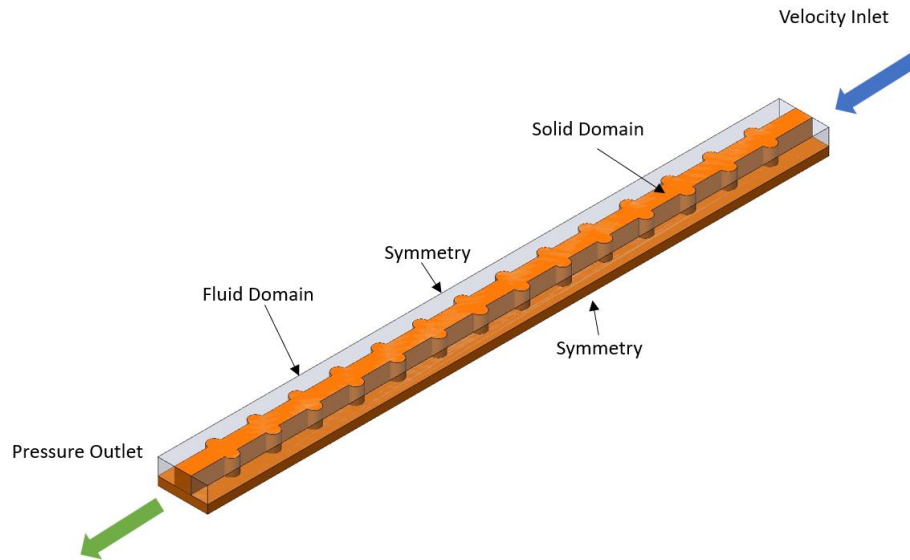


Fig. 2: Schematic of Boundary Conditions Applied in Heat Sink Simulations.

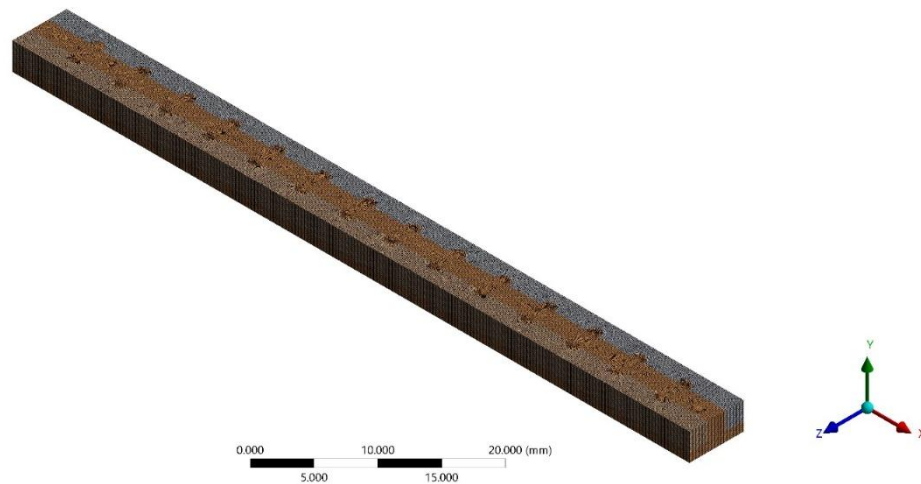


Fig. 3: Mesh Configuration for Heat Sink Computational Model.

3. Results and Discussion

Here, the results gotten by the experiments and the simulations shall be compared to find out the performance of the various configurations of the heat sinks over the various operating conditions. As indicated by the findings of the simulation using computational fluid dynamics (see Figure 4), the thickness of the fins and the Reynolds number have a lot of mean in the heat transfer performance of heat sinks. We have set the fin thicknesses at 1 mm, 1.5 mm and 2 mm, and the Nusselt number is found to be rising with the fin thickness that shows the thermal advantages of higher levels of convective heat transfer surfaces. As an illustration, we see that at $Re=200$, the values of Nu of 1 mm fins are 7.48 compared to those at 2 mm fins of 10. This is observed at larger values of the Reynolds numbers and the value of Reynolds number of 2 mm fins is 22 at $Re=1000$ compared to 17.2 at 1 mm fins. Figure 5 in this way shows that the Reynolds number (Re) increases; the factor of friction (f) decreases with varying fin thickness (1 mm, 1.5 mm, and 2 mm). The crustal factors of friction of these thicknesses are 0.466, 0.639 and 0.977 respectively that means that the thicker the fins, the more resistance there is to the flow. These values drop to 0.17, 0.23, and

0.374 as the Reynolds number size increases to 1000 with a consistent decrease in the value of these parameters across all the fin sizes. This trend indicates that although the extra weight to be supported by more thickening of the fins can help to enhance the heat transfer through these effects by creating more surface area, there are additional frictional losses on the system as well. Reduction in friction factor, therefore, with increase in Reynolds number is an indication that, at high flow velocity, the negative influence of increased fin-thickness on the hydraulic resistance is partially counteracted. Figure 6 demonstrates the Thermal Performance Factor (TPF) of heat sinks of various fin thicknesses (1 mm, 1.5 mm and 2 mm) at various Reynolds number (Re). The TPF values of ratio between heat transfer enhancements to the penalty factor of pressure drop usually increase with fin thickness and Reynolds number. Of particular concern is the 1.5 mm fins which exhibits the highest linear improvement in TPF and is found throughout the range of fins in the 1.021 at $Re=200$ up to 1.269 at $Re=1000$. This is the best balance in performance under the best tradeoff between the fluid resistance and the heat transfer efficiency. This is less spectacularly enhanced in the 2 mm fins, which have the early lead value, $Re=200$ of 1.017, reaching the

value of 1.185 at $Re=1000$, at higher flow rates. This finding indicates that the larger fin size has the potential of enhancing the heat transfer but the pressure drop increase that is associated with it may limit the total effectiveness of the whole performance at higher flow rates. It is shown in the simulation that the 1.5 mm fin thickness gives the highest performance in terms of thermal performance as the value of TPF shows the best value. 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. According to figure 8 C2 and C3 have a significantly higher value of friction factors than C1 and T, maxing at $Re=200$ with a value of 2.48 and 2.13 respectively. This indicates that there is an enhanced ratio of flow resistance in the more demanding setups. As indicated in figure 9, C2 and C3 possess higher values of TPF at higher friction factor at the mid-Reynolds numbers, i.e. higher representation of balance between heat transfer increase and flow resistance. Its maximum in the TPF of C3 is at $Re=600$ at value 1.456 which corresponds to optimum performance within the rate of flow.

Figure 10 shows the temperature patterns of the various designs of the heat sinks at the simulation stage. The heat sinks vary in temperature between around 30 °C and 55 °C. Blue to red color gradient depicting how cold parts that are in the inlet side change to hot ones that are in the outlet side reflect how the required heat is effectively dissipated. This image proves that the heat sink is able to keep the temperatures down despite increasing the operational conditions to provide optimum performance of electronic components. These observations confirm the usefulness of the design in extraction of heat, necessary in power consuming applications. Figures 11 and 12 show the general imagery of the dynamics of fluids in the heat sink channels that are depicted by their velocity figures. Figure 11 suggests that the velocities are heterogeneous across the channels in that there are between 0.000 m/s and over 0.500 m/s, which indicates that there are considerable flow variation and hotspots of the fluid to accelerate or decelerate. Representation of the Figure 12 in terms of streamlines provides a detailed understanding of the the nature of the flow and how the fluid flows around the obstruction in the channels. Particularly, it is important that there are vortex patterns near the fins, which are the recirculation regions, which may affect the heat transfer efficiency and the mixing of the fluid. General knowledge of the flow patterns in the heat sinks is useful in the identification of the areas where they can be better to enhance the thermal efficiency and reduce the flow resistance. The results clarify the prevailing forces of the fin designs, flow scenarios on the thermal and hydraulic performance of the heat sinks, and offer valuable details to the best heat sink design, to be used in real-life.

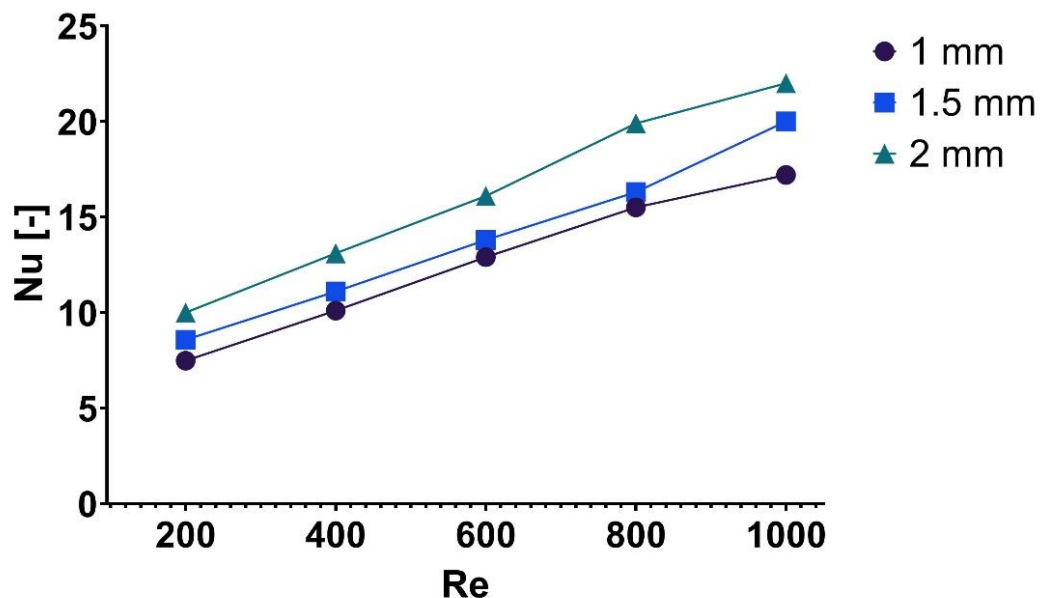


Fig. 4: Reynolds Number and Nusselt Number Variation for Various Fin Thicknesses.

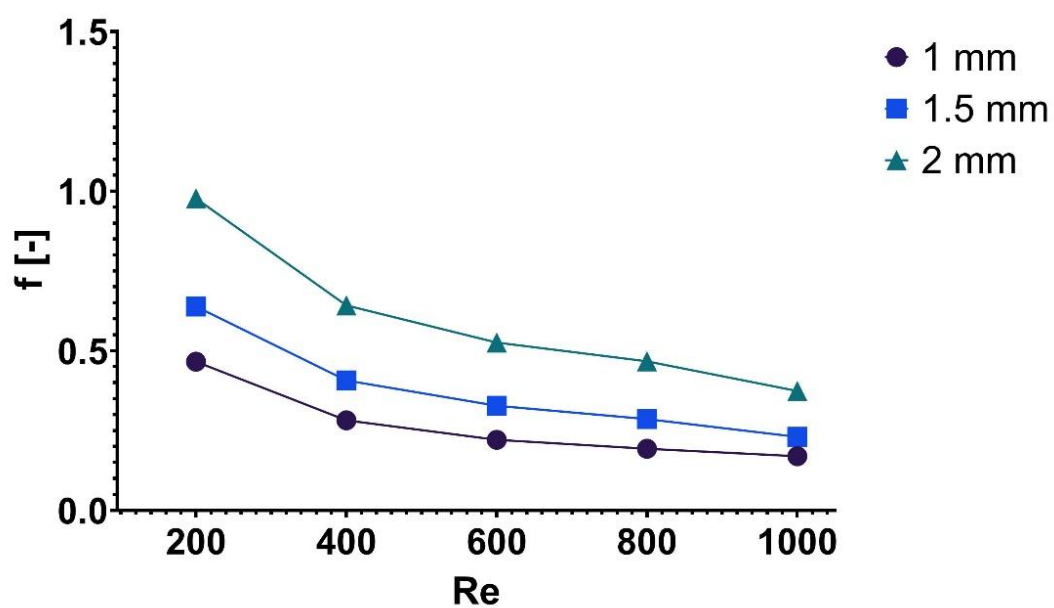


Fig.5: Friction Factor for Different Fin Thicknesses as a Function of Reynolds Number.

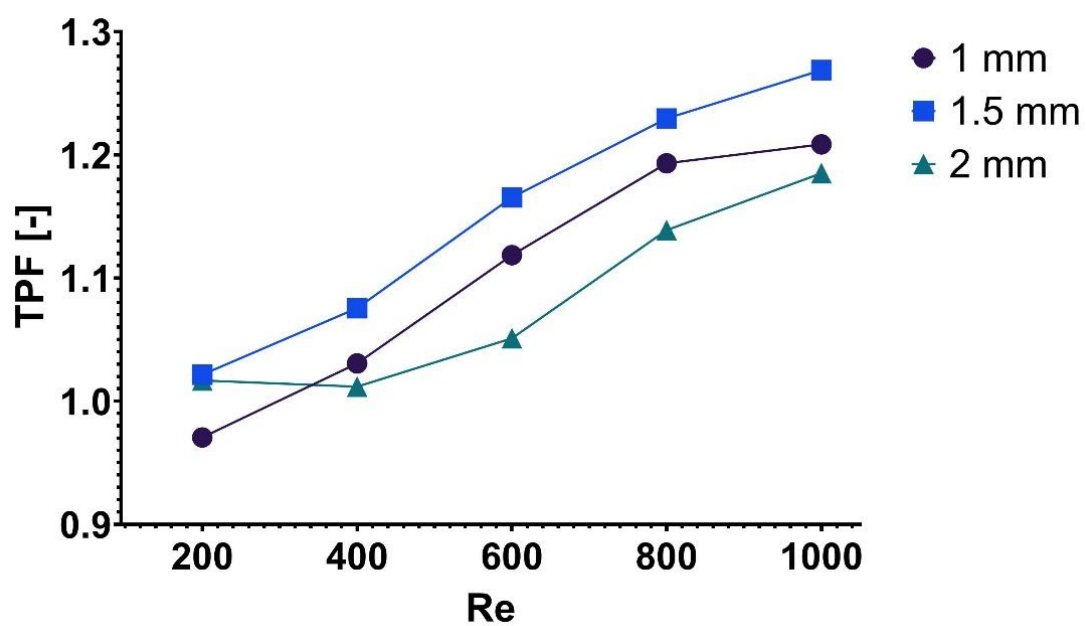


Fig. 6: Thermal Performance Factor (TPF) Across Different Reynolds Numbers for Varied Fin Thicknesses.

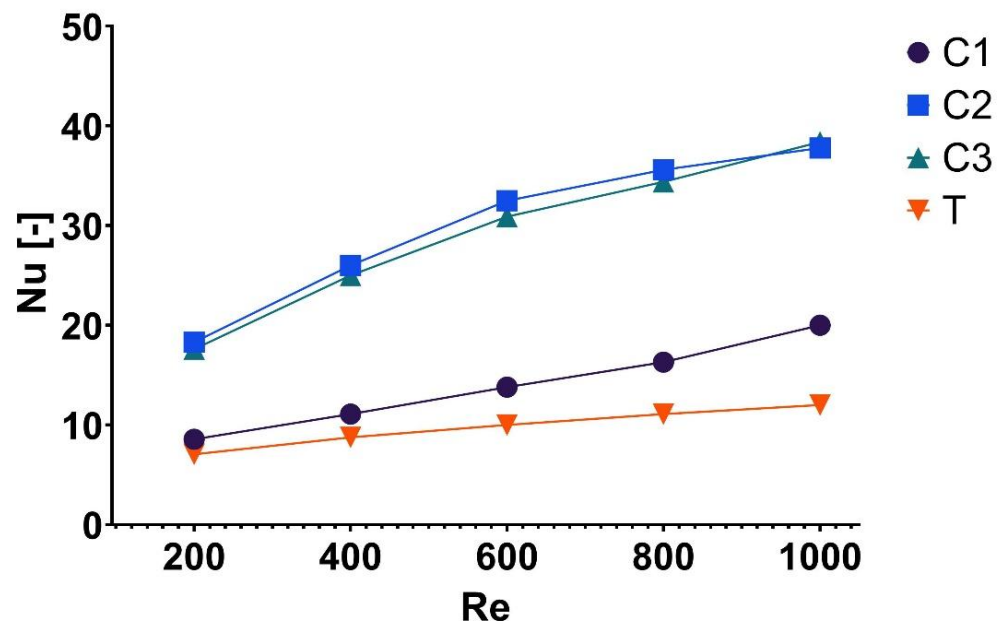


Fig. 7: Relationship between Nusselt Number and Reynolds Number for Different Designs of Heat Sinks.

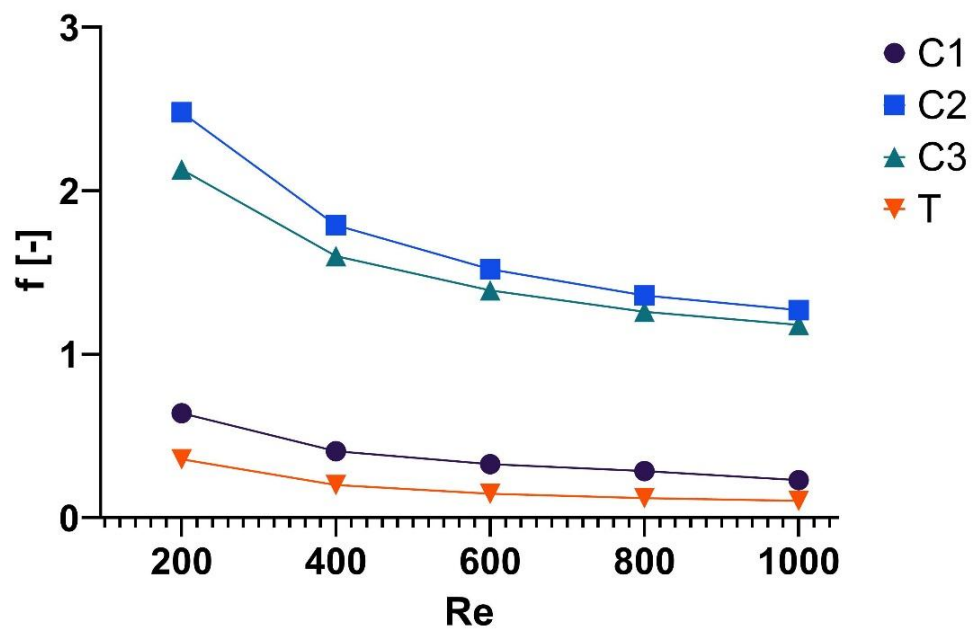


Fig. 8: Friction Factor Across Different Reynolds Numbers for Various Heat Sink Configurations.

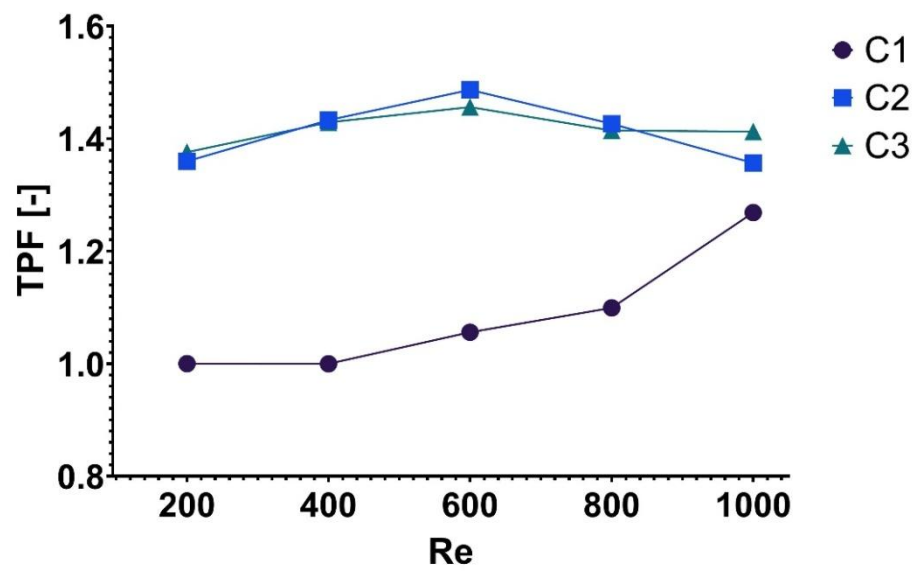
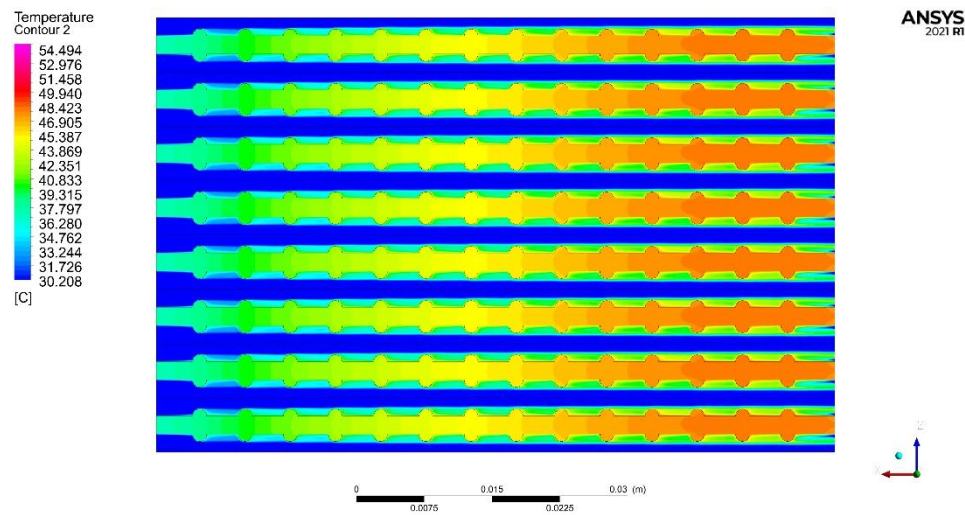
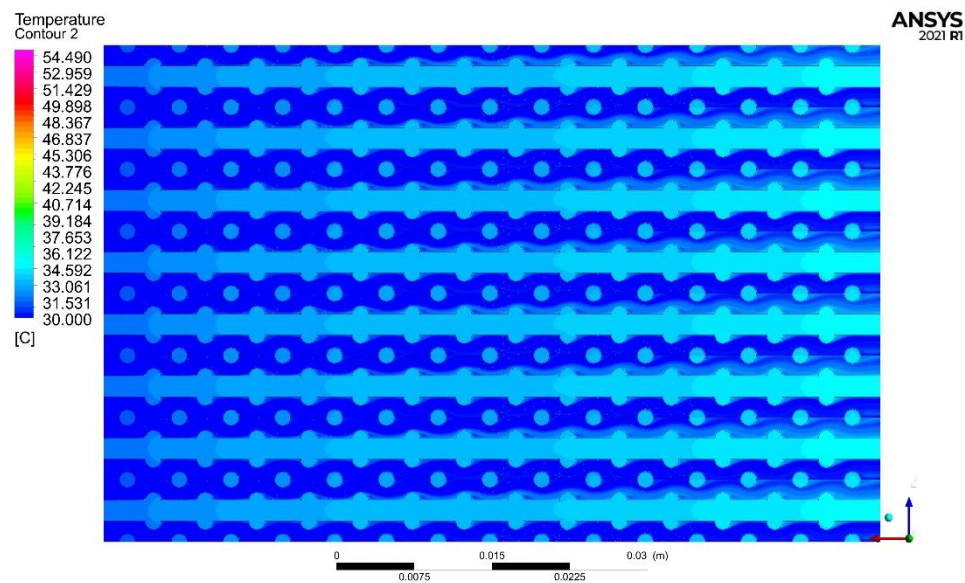


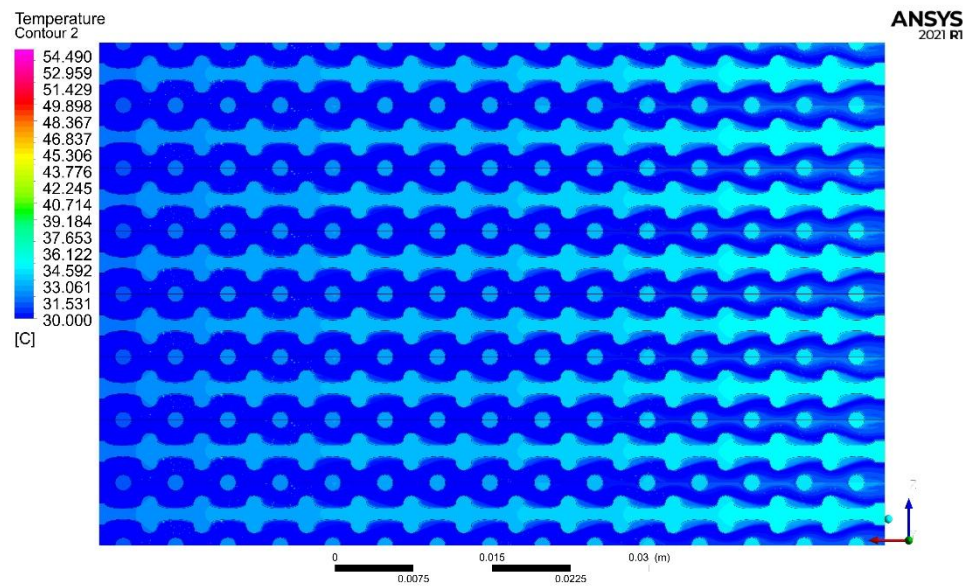
Fig. 9: Thermal Performance Factor for Heat Sink Configurations Across Varying Reynolds Numbers.



a) C1

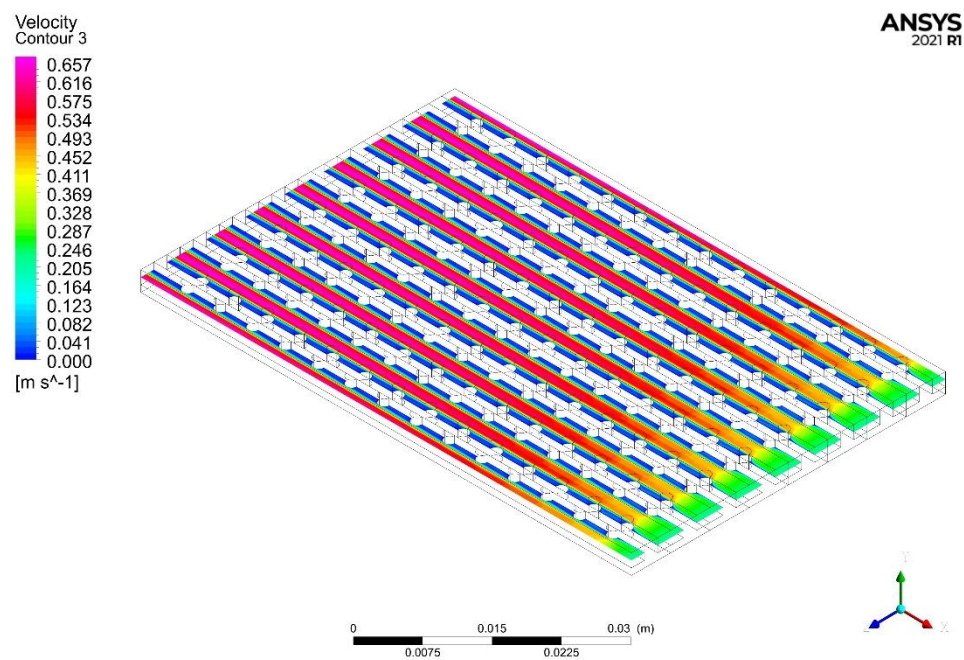


b) C2

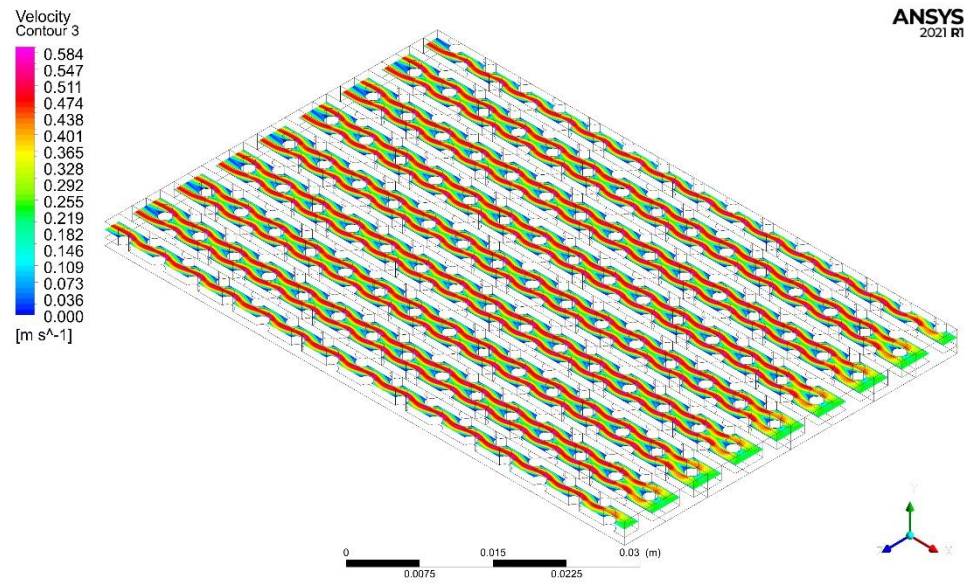


c) C3

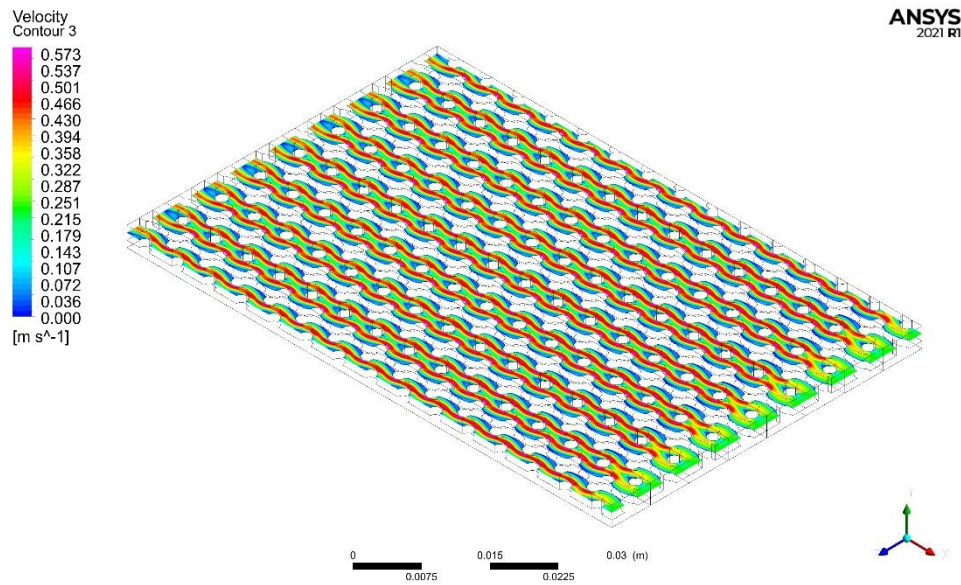
Fig. 10: Temperature Distribution in Heat Sink Designs under Various Operating Conditions.



a) C1

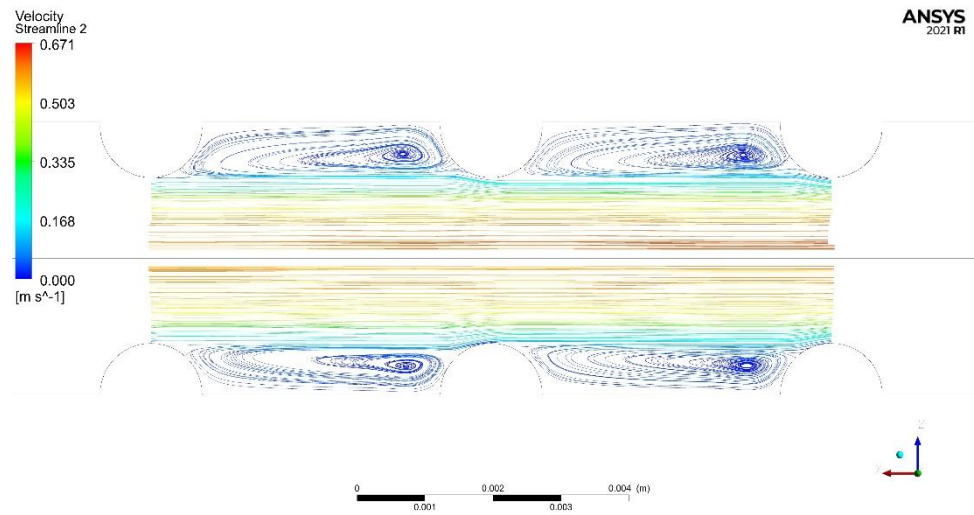


b) C2

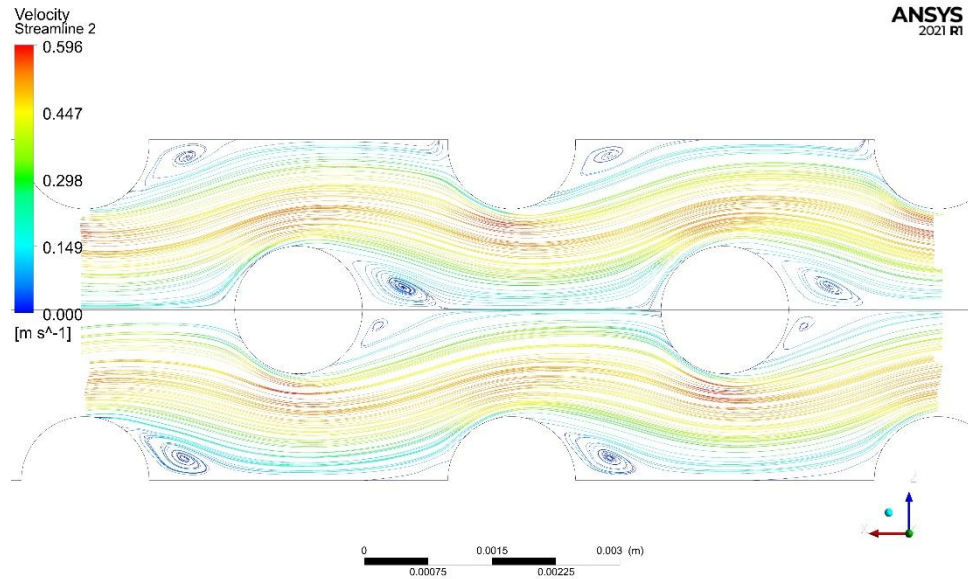


c) C3

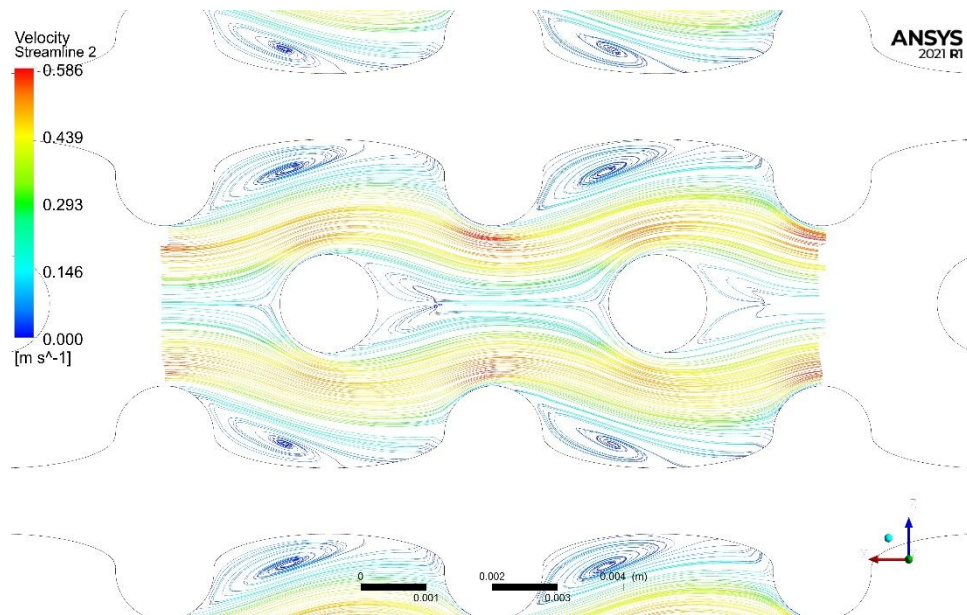
Fig. 11: Velocity Distribution in Heat Sink Channels.



a) C1



b) C2



c) C3

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

4. Conclusion

In this research, the thermal performance of the new designs in heat sinks was fully investigated through the running of the Computational Fluid Dynamics simulations to attain the optimized fluid flow and heat transfer performance under different operating conditions. It supported the enhanced performance of the 1.5 mm thickness fin design which exhibited the best balance of the heat dissipation and pressure drop with an increase in the Thermal Performance Factor (TPF) of a peak of 26.9% at the operating condition of $Re = 1000$. Compared to the standard model, outstanding improvement of the heat transfer efficiency in the new designs was achieved with the most efficient combination of the

new designs having Nusselt number that was 38.4 percent higher than the standard model. This type of information is also very important since it sheds light on interactions between fin shape, flow dynamics, and heat performance maintaining that certain modifications to the design can cause extraordinary heat sink performance improvements.

Overall, the work does not only contribute to the heat sink and its management in small electronic devices but also preconditions the future development of heat sink technology. The world has to keep technologically advancing because of the increased thermal demand of the new electronic components and systems.

References

- [1] W. Dong, X. Zhang, B. Liu, B. Wang, and Y. Fang, "Research progress on passive enhanced heat transfer technology in microchannel heat sink," *International Journal of Heat and Mass Transfer*, vol. 220, p. 125001, 2024.
- [2] L. Du and W. Hu, "An overview of heat transfer enhancement methods in microchannel heat sinks," *Chemical Engineering Science*, vol. 280, p. 119081, 2023.
- [3] H. M. Maghrabie *et al.*, "Microchannel heat sinks with nanofluids for cooling electronic components: Performance enhancement, challenges, and limitations," *Thermal Science and Engineering Progress*, vol. 37, p. 101608, 2023.
- [4] K. Rezk, M. A. Abdelrahman, A. A. A. Attia, and M. Emam, "Thermal control of temperature-sensitive electronic components using a vapor chamber integrated with a straight fins heat sink: An experimental investigation," *Applied Thermal Engineering*, vol. 217, p. 119147, 2022.
- [5] R. Kothari, S. K. Sahu, S. I. Kundalwal, and P. Mahalkar, "Thermal performance of phase change material-based heat sink for passive cooling of electronic components: An experimental study," *International Journal of Energy Research*, vol. 45, no. 4, pp. 5939-5963, 2021.
- [6] A. Kumar, R. Kothari, S. K. Sahu, and S. I. Kundalwal, "Thermal performance of heat sink using nano-enhanced phase change material (NePCM) for cooling of electronic components," *Microelectronics Reliability*, vol. 121, p. 114144, 2021.
- [7] A. Kumar, R. Kothari, S. K. Sahu, and S. I. Kundalwal, "A comparative study and optimization of phase change material based heat sinks for thermal management of electronic components," *Journal of Energy Storage*, vol. 43, p. 103224, 2021.
- [8] M. M. Souby, M. H. S. Bargal, and Y. Wang, "Thermohydraulic performance improvement and entropy generation characteristics of a microchannel heat sink cooled with new hybrid nanofluids containing ternary/binary hybrid nanocomposites," *Energy Science & Engineering*, vol. 9, no. 12, pp. 2493-2513, 2021.
- [9] X. Zhang, Z. Ji, J. Wang, and X. Lv, "Research progress on structural optimization design of microchannel heat sinks applied to electronic devices," *Applied Thermal Engineering*, vol. 235, p. 121294, 2023.
- [10] M. M. A. Baig, S. F. Hassan, N. Saheb, and F. Patel, "Metal matrix composite in heat sink application: Reinforcement, processing, and properties," *Materials*, vol. 14, no. 21, p. 6257, 2021.
- [11] Z.-Q. Yu, M.-T. Li, and B.-Y. Cao, "A comprehensive review on microchannel heat sinks for electronics cooling," *International Journal of Extreme Manufacturing*, vol. 6, no. 2, p. 022005, 2024.
- [12] B. Dash, J. Nanda, and S. K. Rout, "The role of microchannel geometry selection on heat transfer enhancement in heat sinks: A review," *Heat Transfer*, vol. 51, no. 2, pp. 1406-1424, 2022.
- [13] I. Zahid *et al.*, "Thermal performance analysis of various heat sinks based on alumina NePCM for passive cooling of electronic components: an experimental study," *Energies*, vol. 15, no. 22, p. 8416, 2022.
- [14] S. S. Thakar, S. Nambiar, G. A. Chandavarkar, and S. S. Prabu, "Investigation of impingement cooling on a heat sink using CFD simulation," *Materials Today: Proceedings*, vol. 46, pp. 8753-8760, 2021.
- [15] J. Gao, Z. Hu, Q. Yang, X. Liang, and H. Wu, "Fluid flow and heat transfer in microchannel heat sinks: Modelling review and recent progress," *Thermal Science and Engineering Progress*, vol. 29, p. 101203, 2022.
- [16] Y. Li, S. Roux, C. Castelain, Y. Fan, and L. Luo, "Design and optimization of heat sinks for the liquid cooling of electronics with multiple heat sources: a literature review," *Energies*, vol. 16, no. 22, p. 7468, 2023.
- [17] B. M. Nafis, R. Whitt, A.-C. Iradukunda, and D. Huitink, "Additive manufacturing for enhancing thermal dissipation in heat sink implementation: a review," *Heat Transfer Engineering*, vol. 42, no. 12, pp. 967-984, 2021.
- [18] H. A. Hussein, "Numerical hydrothermal evaluation of heat transfer in a multi-mini-channel heat sink: Effect of square pin fins," *Results in Engineering*, vol. 20, p. 101403, 2023/12/01/ 2023.
- [19] H. Xiao, Z. Liu, and W. Liu, "Conjugate heat transfer enhancement in the mini-channel heat sink by realizing the optimized flow pattern," *Applied Thermal Engineering*, vol. 182, p. 116131, 2021/01/05/ 2021.
- [20] M. W. Uddin and N. S. Sifat, "Comparative study on hydraulic and thermal characteristics of minichannel heat sink with different secondary channels in parallel and counter flow directions," *International Journal of Thermofluids*, vol. 17, p. 100296, 2023/02/01/ 2023.
- [21] Y. Wang, G. Xia, R. Li, Q. Li, and Z. Yan, "Heat transfer enhancement in porous wall mini-channel heat sinks utilizing electric field: An experimental study," *International Journal of Heat and Mass Transfer*, vol. 203, p. 123803, 2023/04/01/ 2023.
- [22] Y. Wang, G. Xia, Z. Yan, and Q. Li, "Numerical study of bionic parallel mini-channel heat sink applied to the cooling of a linear Fresnel photovoltaic system," *International Journal of Heat and Mass Transfer*, vol. 195, p. 123130, 2022/10/01/ 2022.
- [23] S. Wu, K. Zhang, G. Song, J. Zhu, and B. Yao, "Experimental study on the performance of a tree-shaped mini-channel liquid cooling heat sink," *Case Studies in Thermal Engineering*, vol. 30, p. 101780, 2022/02/01/ 2022.
- [24] A. Tikadar, S. K. Oudah, T. C. Paul, A. S. Salman, A. K. M. M. Morshed, and J. A. Khan, "Parametric study on thermal and hydraulic characteristics of inter-connected parallel and counter flow mini-channel heat sink," *Applied Thermal Engineering*, vol. 153, pp. 15-28, 2019/05/05/ 2019.
- [25] H. A. Hussein, "A simulation study of thermal and hydraulic characteristics mini-channel circular heat sink: Effect of L-

- shaped multi-channel arrangement on flow maldistribution," *Case Studies in Thermal Engineering*, vol. 65, p. 105655, 2025/01/01/ 2025.
- [26] V. Nagendra, B. Jagadish, and C. S. Kumar, "Numerical Assessment of the ribs effect on the thermo hydraulic performance of a counter flow mini channel with secondary channels," *Applied Thermal Engineering*, vol. 266, p. 125718, 2025/05/01/ 2025.
- [27] A. Dixit, R. Maithani, and S. Sharma, "Enhancing electronic system cooling: exploring minichannel heat sink solutions," *Journal of Thermal Analysis and Calorimetry*, pp. 1-51, 2025.
- [28] F. N. Ghadhbhan and H. M. Jaffal, "Numerical investigation on heat transfer and fluid flow in a multi-minichannel heat sink: Effect of channel configurations," *Results in Engineering*, vol. 17, p. 100839, 2023/03/01/ 2023.
- [29] B. Manvi, J. Tawade, M. Biradar, S. Noeiaghdam, U. Fernandez-Gamiz, and V. Govindan, "The effects of MHD radiating and non-uniform heat source/sink with heating on the momentum and heat transfer of Eyring-Powell fluid over a stretching," *Results in Engineering*, vol. 14, p. 100435, 2022/06/01/ 2022.
- [30] E. Hosseinirad and M. Khoshvaght-Aliabadi, "Proximity effects of straight and wavy fins and their interruptions on performance of heat sinks utilized in battery thermal management," *International Journal of Heat and Mass Transfer*, vol. 173, p. 121259, 2021/07/01/ 2021.
- [31] H.-l. Liu, D.-h. Qi, X.-d. Shao, and W.-d. Wang, "An experimental and numerical investigation of heat transfer enhancement in annular microchannel heat sinks," *International Journal of Thermal Sciences*, vol. 142, pp. 106-120, 2019/08/01/ 2019.
- [32] R. Zheng, Y. Wu, Y. Li, G. Wang, G. Ding, and Y. Sun, "Development of a hierarchical microchannel heat sink with flow field reconstruction and low thermal resistance for high heat flux dissipation," *International Journal of Heat and Mass Transfer*, vol. 182, p. 121925, 2022/01/01/ 2022.