

Numerical Investigation of the Heat Transfer Rate and Fluid Flow Characteristics of Conventional and Triply Periodic Minimal Surface (TPMS)-Based Heat Sinks [†]

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Abstract: Heat sinks have been widely used in cooling systems due to their high heat transfer efficiency. In this study, the thermal performance and fluid flow characteristics of conventional and triply periodic minimal surfaces (TPMS)-based heat sinks were investigated through detailed computational fluid dynamics (CFD) simulations. The results indicate that the TPMS-based heat sink, particularly SplitP, exhibited the highest heat transfer rate at 0.0082 W, which is more than ten times the rate of the conventional design (0.00076 W). The Gyroid structure also showed impressive performance with a 0.0022 W heat transfer rate. Furthermore, the performance evaluation criterion (PEC) was used to quantify the effectiveness of each design in terms of heat transfer efficiency. The PEC values obtained were 1.00 for the conventional heat sink, 1.17 for the Gyroid heat sink, showing a 17% improvement, and 1.43 for the SplitP heat sink, showing a 43% improvement. The findings from our study will inform future heat sink design, contributing to the development of more efficient cooling solutions by emphasizing the critical role of PEC in performance evaluation.

Keywords: triply periodic minimal surface; computational fluid dynamics; heat transfer rate; Gyroid; SplitP; performance evaluation criterion



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1. Introduction

The development of various industries such as electronics, aerospace, automotive, and others requires the use of compact and high-performance heat dissipation equipment. If the heat generated is not efficiently dissipated, it will eventually lead to a decrease in device performance. This, in turn, drives the need for the design of more advanced heat sinks [1]. Conventional heat sinks commonly employ different types of fin surfaces, including plate-fin [2], cross-fin [3], and micro-channel [4] heat sinks. These traditionally manufactured heat sinks, however, are limited in their ability to machine complex designs at the microscale, which limits their cooling capacity and necessitates a large amount of space. As a result of the recent advancement in additive manufacturing, also known as 3D printing technology, researchers have begun to explore complex geometries that were previously unattainable using traditional manufacturing methods [5]. One particular type of design that has gained attention due to its compact design and impressive thermophysical properties [6] is the Triply Periodic Minimal Surface (TPMS).

TPMS, or a zero mean curvature surface, is a surface that is periodic in three directions and minimizes the surface area between given boundaries [7]. Cheng et al. explored the convective heat transfer capabilities of four distinct TPMS-solid configurations: Primitive, Gyroid, Diamond, and IWP. Their investigation revealed that the Primitive TPMS-solid structure exhibited superior heat transfer efficiency compared to the other designs [7]. Attarzadeh et al. [8] conducted a numerical study on the “Schwartz D” heat exchanger

design. The findings indicate that this design demonstrates high heat transfer rates while simultaneously maintaining a low-pressure decrease. Consequently, it possesses significant potential for various industrial applications. Moza et al. [6] have developed an experimental research procedure to assess the heat transfer effectiveness of compact heat exchangers made with TPMS structures. Their study also aims to explore the impact of different operating parameters. Ma et al. [9] conducted a study comparing pyramidal lattice, plate-fin, and a combined structure found the integrated structure outperforms individual structures but has the highest pressure drop. Wang et al. [10] introduced an innovative design termed the “lattice pin fin”, which integrates the features of traditional pin fins with lattice structures. When evaluating the thermal performance of this hybrid design, the findings indicated a marginal enhancement in heat transfer efficiency with the use of a lattice pin fin as opposed to a conventional solid pin fin. Hu and Gong used TPMS lattices to improve thermal conductivity and enhance heat transfer for thermal energy storage and management systems [11]. Al-Ketan et al. [12] investigated the performance of TPMS heat sinks under forced convection and the results showed that the Diamond heat sink had a convective heat transfer coefficient about 32% better than the Gyroid heat sinks.

Previous research has extensively analyzed conventional heat sinks, yet there is a lack of studies comparing their performance with that of TPMS-based heat sinks. Our study aims to address this gap by investigating and comparing the heat transfer rate and fluid characteristics of both conventional and TPMS-based heat sinks through detailed numerical investigation. This research is to provide a direct comparison, offering new insights into the factors that influence the heat transfer rate of these heat sink designs. The findings from our simulations will inform future heat sink design, contributing to the development of more efficient cooling solutions.

2. Materials and Methods

2.1. Heat Sink Design

The traditional heat sink was created with SOLIDWORKS 2021, chosen for its capabilities in conventional thermal management designs. In contrast, heat sinks based on TPMS structures, specifically Gyroid and SplitP configurations, were developed using nTopology software. These structures are known for their complex geometries that optimize surface area and enhance heat transfer rate. Both conventional and TPMS-designed heat sinks have the same volume with dimensions of 10 mm by 10 mm (Figure 1). Both heat sink designs are made of aluminum due to its excellent thermal conductivity and lightweight nature, crucial for efficient heat dissipation. Below the heat sink, where a thermal load is applied, a copper chip facilitates efficient heat conduction from the heat source. Following the design phase, the complex scaffold designs were converted into computational models using a tetrahedral unstructured mesh.

2.2. Governing Equations

For a steady state, three-dimensional model, the governing equation for continuity, momentum, and energy, respectively, are presented below [13]:

$$\frac{\partial u_i}{\partial x_i} = 0 \quad (1)$$

$$\frac{\partial (u_i u_j)}{\partial x_j} = -\frac{\partial \bar{p}}{\partial x_i} + \nu \nabla^2 u_i + \frac{\partial}{\partial x_j} \left(-\overline{u_i' u_j'} \right) \quad (2)$$

$$\frac{\partial (T u_j)}{\partial x_j} = \alpha \nabla^2 T + \frac{\partial}{\partial x_j} \left(-\overline{u_i' \theta} \right) \quad (3)$$

A Realizable k - ϵ model is used due to its accurate results at a relatively low computational cost [14]. The equations for turbulent kinetic energy and turbulent dissipation rate, respectively, are provided below:

$$\frac{\partial}{\partial x_j}(\rho k u_j) = \frac{\partial}{\partial x_j} \left[\left(\mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_j} \right] + G_k + G_b - \rho \epsilon - Y_M + S_k \quad (4)$$

$$\frac{\partial}{\partial x_j}(\rho \epsilon u_j) = \frac{\partial}{\partial x_j} \left[\left(\mu + \frac{\mu_t}{\sigma_\epsilon} \right) \frac{\partial \epsilon}{\partial x_j} \right] + C_1 \rho S \epsilon - \rho C_2 \frac{\epsilon^2}{k + \sqrt{\epsilon \nu}} - C_{1\epsilon} \frac{\epsilon}{k} C_{3\epsilon} G_b + S_\epsilon \quad (5)$$

where u , $\bar{p}$, ν , T , α , $\overline{u_i' u_j'}$, k , ϵ , μ_t denotes the average velocity, average pressure, kinematic viscosity, temperature, thermal diffusivity, Reynolds stress, turbulent kinetic viscosity, dissipation and eddy viscosity, respectively. The model constant $C_{1\epsilon}$, C_2 , σ_k , σ_ϵ have values of 1.44, 1.9, 1, and 1.2, respectively. Also

$$C_1 = \max \left[0.43, \frac{\eta}{\eta + 5} \right], \quad \eta = S \frac{k}{\epsilon}, \quad S = \sqrt{2 S_{ij} S_{ij}} \quad (6)$$

The Reynolds number is calculated using the following equation [12]

$$Re = \frac{\rho u L}{\mu} \quad (7)$$

where ρ , u , L and μ are the density of air, inlet velocity, characteristic length, and dynamic viscosity, respectively.

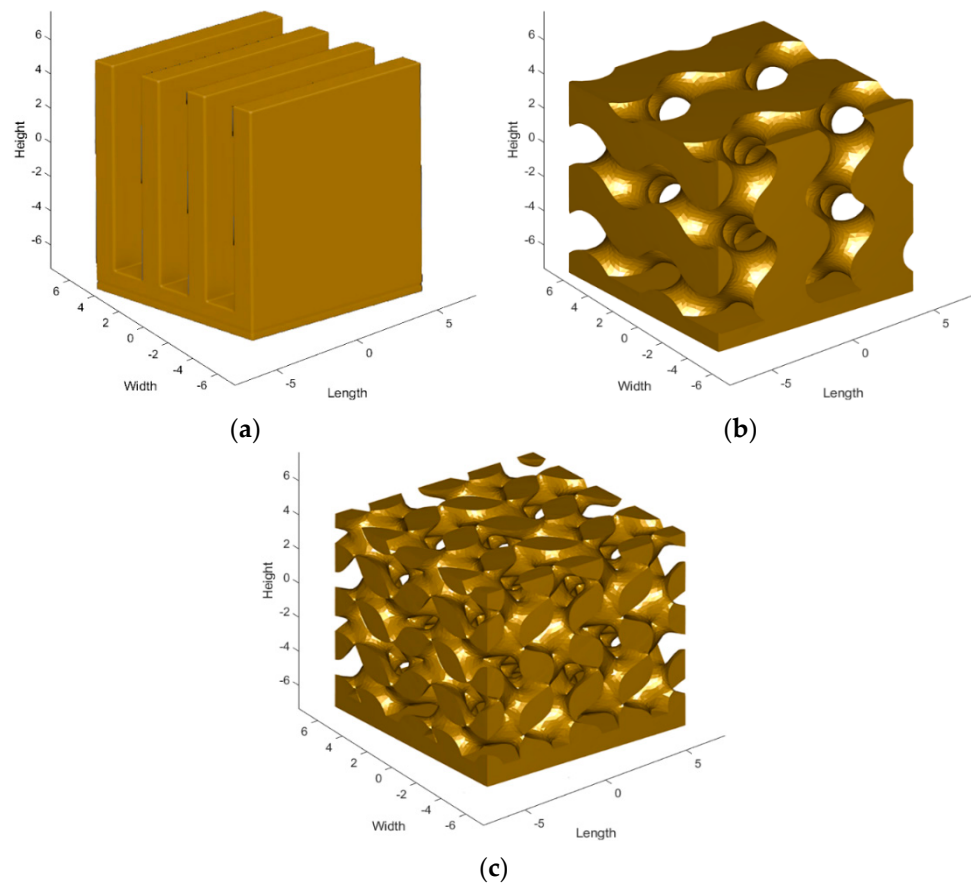


Figure 1. (a) Conventional heat sink, (b) Gyroid heat sink, (c) SplitP heat sink.

2.3. Boundary Conditions

In this study, an air velocity of 10 m/s is applied to represent the incoming flow at the inlet boundary. The side and upper walls are treated as symmetrical boundaries, ensuring no heat or mass transfer occurs through these surfaces. On the copper chip, a heat load of 10 W is applied to simulate the heat generation within the component. The inlet air temperature is set at 298 K, reflecting the initial thermal conditions of the airflow entering the domain. Figure 2 shows the boundary conditions.

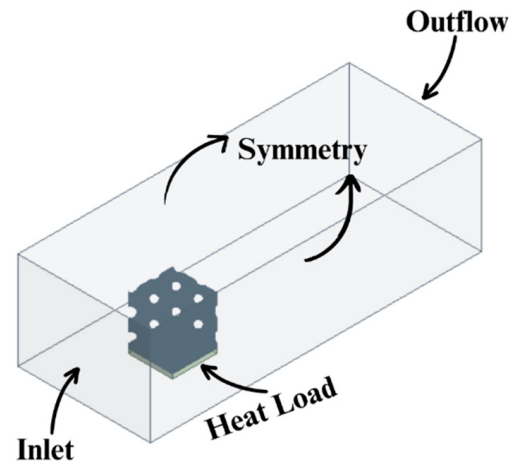


Figure 2. Boundary conditions on heat sink.

2.4. Discretization and Numerical Schemes

This study utilizes the Finite Volume Method (FVM) as the primary approach to simulate fluid flow. In order to ensure grid independence, a mesh sensitivity analysis was conducted with element sizes of 0.35, 0.50, and 0.75 mm. The results showed that a mesh size of 0.50 mm led to minimal variation in pressure drop (<2%), confirming grid independence for subsequent simulations. To effectively model the turbulent aspects of the flow, the Realizable k - ϵ model was applied, providing reliable predictions, especially in complex flow conditions. A coupled scheme was employed to solve the momentum and pressure equations simultaneously, which enhances the overall stability and efficiency of the computational process. The spatial discretization of the energy equation was handled using a second-order upwind scheme, ensuring greater accuracy in capturing temperature variations. For the momentum and pressure equations, a first-order upwind scheme was used. Although it offers less accuracy than higher-order methods, this choice ensures robust and stable solutions, particularly in regions with sharp gradients and complex flow patterns. This combination of numerical schemes effectively balances the computational efficiency with the need for precise and reliable simulation results.

3. Validation Study

To validate the results, a comparison was made between the Nusselt number (Nu) and Reynolds number (Re) obtained in the present study with those reported by Khalid et al. [13], who conducted a study on Gyroid-based TPMS heat sinks. As illustrated in Figure 3, the findings from the present study closely match the study by Khalid et al. [13]. This close agreement demonstrates the accuracy and reliability of the computational method used in this study.

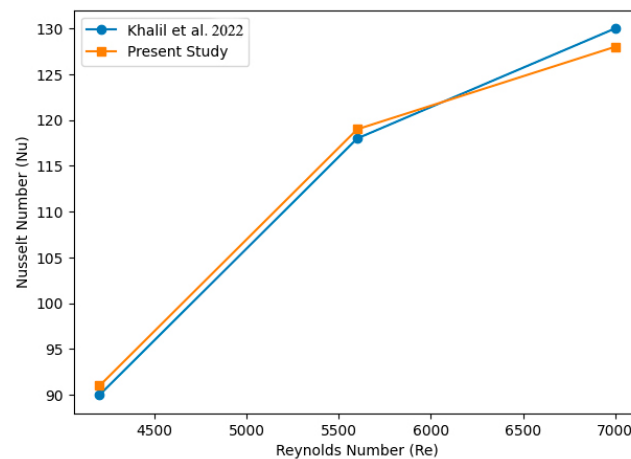


Figure 3. Validation study comparing Re vs. Nu [13].

4. Performance Parameter

The performance of the heat sinks was assessed using the Performance Evaluation Criterion (PEC), which takes into account both the heat transfer and pressure drop characteristics. The PEC is calculated using the following formula [15]:

$$PEC = \frac{Nu / Nu_{ref}}{\left(\Delta p / \Delta p_{ref} \right)^{1/3}} \quad (8)$$

$$Nu = \frac{hL}{k} \quad (9)$$

where Nu , Δp , h , and k are the Nusselt Number, pressure drop, heat transfer coefficient, and thermal conductivity of fluid, respectively. The reference values (Nu_{ref} and Δp_{ref}) are taken from the conventional heat sink.

5. Results and Discussion

In this analysis, the performance of conventional and TPMS-based heat sinks was compared using CFD results for velocity, pressure, and temperature distributions. All figures represent the XY-plane at the mid-height of the heat sinks. This plane was selected to provide a clear view of the flow and thermal characteristics across the main section of interest. In Figure 4a, the conventional heat sink airflow velocity sharply increases as it encounters the heat sink's frontal surface, with significant deceleration noted as the flow separates at the leading edge, creating a low-velocity wake region behind the heat sink. The peak velocity is observed at approximately 12.431 m/s at the edges where the flow reattaches, indicating significant recirculation and wake formation. Conversely, in Figure 4b, the Gyroid heat sink exhibits a more gradual acceleration of airflow through its structure, with velocities peaking at about 15.09 m/s in the narrower passages between the Gyroid curves. This higher peak velocity suggests enhanced mixing and more efficient heat transfer due to the increased surface area interaction. In Figure 4c, the SplitP heat sink demonstrates a complex flow pattern, with the maximum velocity reaching approximately 12.80 m/s. The flow within the SplitP structure appears to be more controlled, reducing the extent of wake regions compared to the conventional design, while still achieving significant local velocity increases around its features.

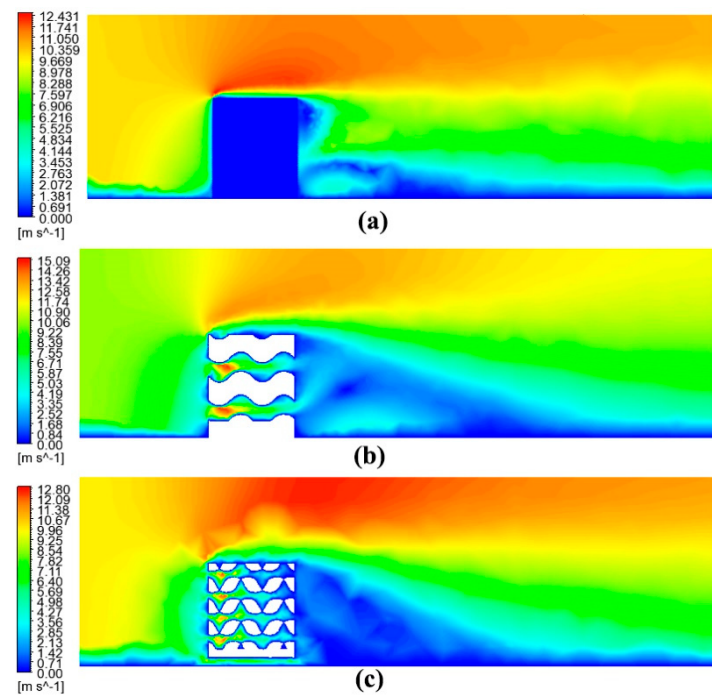


Figure 4. Velocity contours of (a) Conventional heat sink, (b) Gyroid heat sink, (c) SplitP heat sink.

The pressure contours reveal the distinct pressure profiles associated with each heat sink design. In Figure 5a, the conventional heat sink has the high-pressure region at the leading edge (approximately 63.485 Pa) and rapidly transitions to lower pressures downstream, with significant pressure drops highlighted in blue. This sharp gradient indicates strong resistance to airflow, leading to potential inefficiencies in heat dissipation. In contrast, Figure 5b shows the Gyroid heat sink reaches a higher maximum pressure of about 128.93 Pa but demonstrates a more evenly distributed pressure drop along its structure. This suggests a less restrictive flow path, allowing for smoother pressure transitions and potentially better overall performance. In Figure 5c, the SplitP heat sink also achieves a high maximum pressure of 116.11 Pa, similar to the Gyroid design. The pressure drop across the SplitP structure is more moderate compared to the conventional design, indicating that the flow resistance is managed more effectively, likely due to the distributed nature of the pressure transitions. These observations underline the advantages of TPMS-based designs in reducing pressure losses and maintaining a more stable pressure environment conducive to efficient cooling.

In Figure 6a, the conventional heat sink shows a significant thermal gradient, with temperatures ranging from a high of 350.702 K near the heat source to a low of around 297.150 K at the far end of the heat sink. This steep gradient indicates limited thermal distribution and highlights the inefficiency in spreading the heat across the heat sink's surface. In Figure 6b, the gyroid heat sink shows the temperature distribution which is more homogeneous, with peak temperatures slightly higher at 360.96 K but spreading more uniformly through the structure. This suggests improved heat dissipation capabilities due to enhanced surface interaction with the airflow. In Figure 6c, the SplitP heat sink also demonstrates a more even temperature profile, with maximum temperatures reaching 345.67 K. The temperature contours indicate that the SplitP design effectively spreads heat away from the source, maintaining lower average temperatures throughout the structure. These findings affirm that the TPMS-based Gyroid and SplitP designs offer superior thermal management compared to the conventional heat sink, likely due to their complex geometries facilitating better heat exchange and distribution.

The trends observed in Figures 4–6 are primarily due to the differences in geometric complexity and surface area of the heat sinks. The conventional heat sink has a straight-

forward structure, resulting in significant flow separation and a large wake region with high pressure at the front and lower heat transfer efficiency. The gyroid heat sink, with its complex, wavy design, enhances mixing and turbulence, leading to more uniform velocity and temperature distributions, and reduced high-pressure zones due to better flow reattachment. The SplitP heat sink further maximizes these effects with its highly complex structure and increasing surface interactions, promoting extensive turbulence and mixing, and providing even more efficient heat transfer, evidenced by lower and more uniform temperature distributions and highly variable pressure fields.

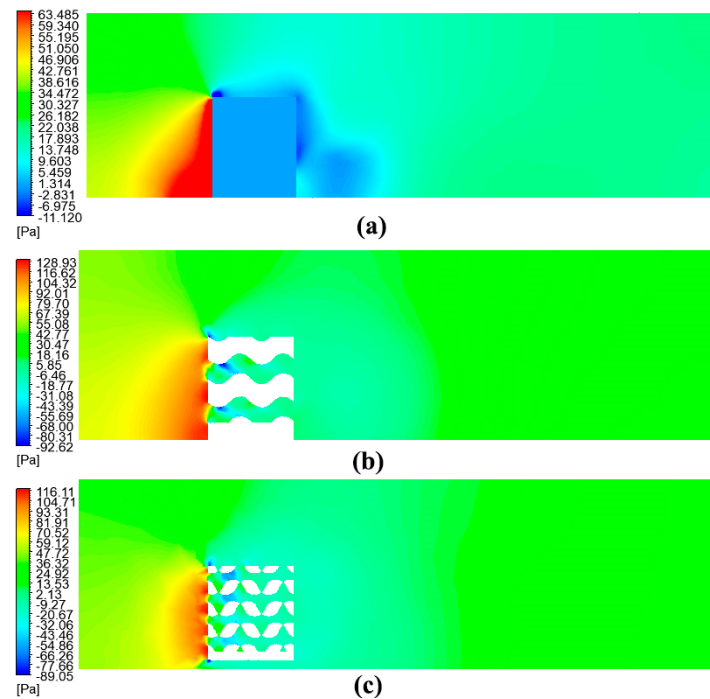


Figure 5. Pressure contours of (a) Conventional heat sink, (b) Gyroid heat sink, (c) SplitP heat sink.

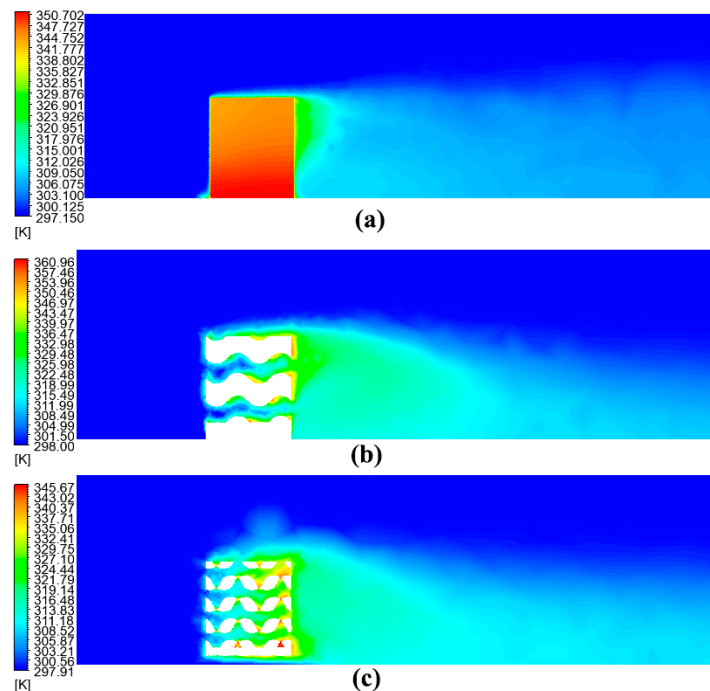


Figure 6. Temperature contours for (a) Conventional heat sink, (b) Gyroid heat sink, (c) SplitP heat sink.

In Figure 7, each bar represents the heat transfer rate in watts (W) for its respective structure type for heat sink design. The Conventional structure demonstrates the lowest heat transfer rate at 0.00075898 W. The Gyroid structure, known for its complex, periodic architecture, shows a moderate increase in heat transfer rate to 0.00223533 W. Notably, the SplitP structure exhibits the highest heat transfer rate, reaching 0.00823763 W. This significant enhancement in heat transfer for the SplitP structure suggests a superior thermal performance, likely due to its optimized design facilitating better heat conduction.

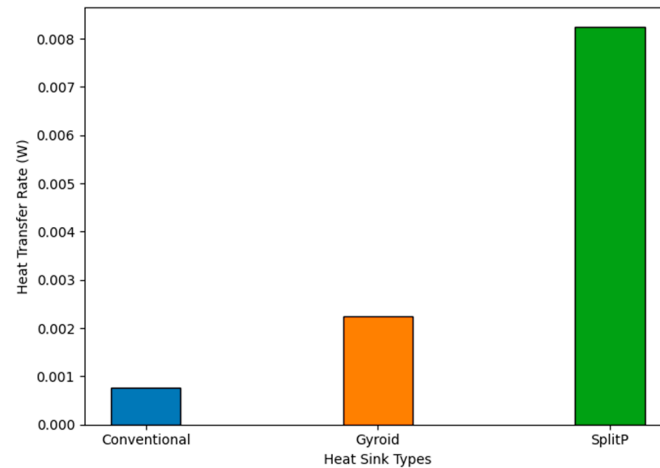


Figure 7. Heat sink type vs. Heat transfer rate.

The performance evaluation criterion (PEC) was used to quantify the effectiveness of each design in terms of heat transfer efficiency. The PEC values obtained were 1.00 for the conventional heat sink, 1.17 for the Gyroid heat sink, and 1.43 for the SplitP heat sink shown in Figure 8. The conventional heat sink, with a PEC value of 1.00, serves as the baseline for comparison. The Gyroid heat sink, with its complex, interconnected structure, achieved a PEC value of 1.17, indicating a 17% improvement in performance over the conventional design. This enhancement is attributed to the Gyroid's increased surface area and improved flow mixing, which facilitate more efficient heat transfer. The SplitP heat sink demonstrated the highest performance with a PEC value of 1.43, signifying a 43% improvement over the conventional heat sink. The superior performance of the SplitP design is due to its highly complex structure, which maximizes surface interactions and induces greater turbulence, thereby enhancing heat dissipation. These findings highlight the significant advantages of using advanced geometrical structures like Gyroid and SplitP over conventional designs for thermal management applications.

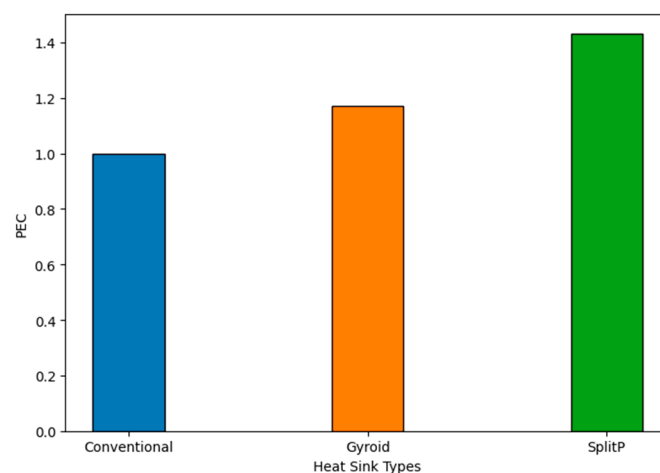


Figure 8. Heat sink type vs. PEC.

6. Conclusions

In this study, the thermal performance and fluid flow characteristics of conventional and TPMS-based heat sinks were investigated through detailed CFD simulations. Our results indicate that TPMS structures, specifically the Gyroid and SplitP configurations, significantly enhance heat transfer efficiency and fluid dynamics compared to traditional heat sink designs. The SplitP heat sink exhibited the highest heat transfer rate at 0.0082 W, which is more than ten times the rate of the conventional design (0.00076 W). This significant enhancement is attributed to the SplitP structure's complex geometry, which promotes greater fluid mixing and turbulence. The Gyroid structure also showed impressive performance with a heat transfer rate of 0.0022 W, demonstrating the potential of TPMS designs in applications where efficient thermal management is critical.

In addition to thermal performance, the fluidic characteristics were also evaluated. The TPMS-based designs exhibited higher fluid velocities and enhanced mixing, which contributed to the improved heat transfer rates. However, these designs also resulted in increased pressure drops due to their complex geometries. The SplitP heat sink showed a significant pressure drop, indicating the need for further optimization to balance pressure drop and heat transfer efficiency. Temperature distributions across the TPMS structures were more uniform, reducing hotspots and enhancing overall thermal management.

The performance evaluation criterion (PEC) values further validated these findings, with PEC values of 1.17 and 1.43 for the Gyroid and SplitP designs, respectively, compared to 1.00 for the conventional design. These values correspond to performance improvements of 17% and 43% for the Gyroid and SplitP designs, respectively. These findings highlight the significant advantages of using advanced geometrical structures like Gyroid and SplitP over conventional designs for thermal management applications, emphasizing the importance of PEC as a key parameter in evaluating heat sink performance.

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