Thermo-hydraulic performance of uniform and hybrid Triply Periodic Minimal Surfaces (TPMS) heat exchangers

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Abstract: Triply Periodic Minimal Surfaces (TPMS) geometries are remarkable solutions for achieving optimal heat transfer performance in industries where space-efficient cooling solutions are required. Utilizing these additively manufactured geometries in Heat Exchanger (HX) applications involves a trade-off between maximizing heat transfer and minimizing pressure drop. While prior studies mostly focused on uniform TPMS-based HXs, this research investigates the thermo-hydraulic performance of both uniform (Gyroid, Diamond D, and FRD) and hybrid (Gyroid-FRD, Diamond D-Gyroid, and Diamond D-FRD) TPMS-based HXs. In this study, TPMS geometries were generated via LattGen, and design setup and Computational Fluid Dynamics (CFD) simulation were conducted using Ansys Fluent 2023 R2. All geometries were generated at 30% relative density, and hybrid transitions were achieved via the Sigmoid function. A k-epsilon turbulence model was employed for CFD analysis, and the model was validated against existing literature. Results illustrate that the FRD HX exhibits the best temperature change performance, corresponding to a 13.9 [K] increase in temperature, while introducing a 239.58 [Pa] pressure drop. Among hybrids, Diamond D-FRD HX enabled 13.82 [K] temperature change, improving base uniform FRD flow resistance by 62.5%. The investigation reveals that hybridization can yield an intermediate of thermo-hydraulic performance characteristics from their uniform base structures.

Keywords: Triply Periodic Minimal Surfaces, Hybridization, Heat exchangers, Computational Fluid Dynamics

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1. Introduction

High-performance heat transfer is crucial in the oil and gas, automotive, aerospace, and electronics industries - including direct-to-chip liquid cooling - where space-efficient cooling solutions are required. Thermal energy management relies on heat exchangers (HXs), where their design involves a trade-off between maximizing surface area for heat transfer and minimizing pressure drop across the system [1].

From a manufacturing perspective, conventional methods like casting or milling have long been standard practice, although they are often incapable of facilitating the fabrication of intricate geometries. As an alternative, the emergence of Additive Manufacturing has overcome the fabrication challenges, opening new horizons to harness complex structures, such as Triply Periodic Minimal Surfaces (TPMS) in developing highly efficient HXs [2].

TPMS geometries, known for their complex structures, are mathematically defined surface-based lattices, categorized as sheet-based or solid-network-based geometries [3]. Generally, TPMS structures are renowned for their high energy absorption capabilities, material efficiency, and high surface area-to-volume ratio, making them more advantageous in comparison with common finned or tubular HXs. These structures are frequently configured as uniform, functionally graded, and hybrid, each tailored to suit specific applications [4].

The use of TPMS structures in heat management applications is rapidly evolving in parallel with advancements in additive manufacturing. Kwasi-Effah et al. [1] explored the thermo-hydraulic performance of various uniform sheet-based TPMS geometries, including novel G-Prime 2, which showed high thermal efficiency at the expense of increased pressure drop. Sheet-based and solid-network-based uniform TPMS structures are studied in free convection research on heat sinks by Baobaid et al. [5]. It is demonstrated that the employment of TPMS geometries outperforms conventional commercial heat sink performance by a substantial margin. Qian et al. [6] investigated the benefits of combining two TPMS structures, Gyroid and Diamond, to design a TPMS HX using the field synergy principle. To merge the two geometries, a weighted average of one-dimensional coordinates was used for the transition. Results showed that the hybrid HX exhibited significant improvements, both in the efficiency of the heat transfer and compactness.

Extensive research has been conducted on the mechanical and thermal behaviour of TPMS structures and their applications in heat sinks and HXs. However, most thermo-hydraulic studies emphasize the uniform and functionally graded geometries, while the hybrid design remains largely unexplored. This research gap reveals a promising opportunity to study the thermo-hydraulic efficacy of merged TPMS-based HXs. The objective of this study is to investigate the thermo-hydraulic behaviour of hybrid TPMS HXs by comparing them with uniform sheet-based base geometries. This Computational Fluid Dynamics (CFD) study aims to broaden the understanding of hybrid TPMS geometries and assess their potential suitability for industries requiring compact and efficient HXs.

2. Materials and methods

2.1. TPMS geometry theory and generation

TPMS geometries are mathematically defined periodic structures, classified into solid-network and sheet-based categories. A unit cell is the smallest three-dimensional volume of these geometries, periodically repeated in all directions. The mathematical expression of a TPMS geometry is given in Equation 1:

$$f(x, y, z) = c \quad (1)$$

where f is the scalar function of three-dimensional coordinates and c is the iso-value. The value of c governs the TPMS geometry by setting field thresholds to generate sheet-based or solid-based structures. TPMS morphologies used in this study are uniform and hybrid. Hybridization was achieved utilizing the Sigmoid function as a spatial weight to smoothly merge two uniform TPMS structures. Equation 2 represents a hybridized TPMS function:

$$f(x, y, z)_{hybrid} = \big(1 - S(x)\big) f_1(x, y, z) + S(x) f_2(x, y, z) \quad (2)$$

where f_{hybrid} is the hybrid function, and f_1 and f_2 represent the scalar fields of the two uniform TPMS geometries. $S(x)$ is a spatial weight function, known as the Sigmoid function, with values between 0 and 1. The Sigmoid function $S(x)$ is defined in Equation 3:

$$S(x) = \frac{1}{1 + e^{-kg(x)}} \quad (3)$$

where k controls the transition sharpness, and $g(x)$ determines the transition shape. In this study, TPMS geometries were generated using LattGen, a Matlab-based tool for creating TPMS lattice structures. The investigated geometries included uniform Gyroid (G), Diamond-D (D), FRD (F), and hybrid structures D-G, G–F, and D–F. Table 1 presents the mathematical expressions corresponding to each structure. Each geometry was composed of a 10×10×10 mm^3 unit cell, and the overall geometry is 30×10×10 mm^3, indicating three unit cells aligned along the flow direction. Thickness was tailored to achieve a relative density of 30% in all geometries. Relative density is defined as the ratio of solid volume to the total geometry volume. For hybridization, $g(x)$ was linear, and k was set to 10 for a smooth transition. The STL files generated by LattGen were then imported into Ansys SpaceClaim 2023 R2 for geometry cleanup and setup.

Table 1. TPMS geometries' mathematical representation

TPMS geometry	Mathematical equation
Gyroid (G)	$cos(x)\sin(y) + \cos(y)\operatorname{sinz}(z) + \cos(z)\sin(x) = c$
Diamond-D (D)	$\sin(x)\sin(y)\sin(z) + \sin(x)\cos(y)\cos(z) + \cos(x)\sin(y)\cos(z) + \cos(x)\cos(y)\sin(z) = c$
FRD (F)	$4(\cos(x)\cos(y)\cos(z)) - (\cos(2x)\cos(2y) + \cos(2x)\cos(2z) + \cos(2y)\cos(2z)) = c$

2.2. Mesh generation

Fault-tolerant meshing was performed using Ansys Fluent 2023 R2. Hexcore volume fill was used for fluid region discretization, and polyhedral cells were assigned to the TPMS geometry and heat source. A target skewness of 0.75 was maintained. Furthermore, five boundary layers were applied to all zones. By reducing the minimum and maximum cell sizes, mesh refinement was achieved, as shown in Table 3.

2.3. CFD simulation

The CFD analysis was conducted using Ansys Fluent 2023 R2. The energy model was enabled for heat transfer analysis, employing the Realizable k-epsilon turbulence model with enhanced wall treatment. The default model constants were also kept. Water was considered the working fluid, and aluminum was assigned to HXs and the heat source. Boundary conditions are illustrated in Table 2.

Table 2. Boundary conditions

Boundary	Type	Value
Inlet	Velocity inlet	0.03 m/s
Outlet	Outflow	-
Heat Source	Constant temperature	343.15 K
Enclosure (side walls)	Adiabatic	-

The main objective of the CFD analysis was to investigate temperature change ($\Delta T = T_{out} - T_{in}$) and pressure drop ($\Delta P = P_{in} - P_{out}$) of each TPMS geometry functioning as an HX where T_{out}, T_{in}, P_{out}, P_{in} denote the outlet temperature, inlet temperature, outlet pressure, and inlet pressure, respectively.

The CFD model was validated against the experimental results reported by Tang et al. [7]. The developed model predicted the temperature difference through the same HX of the experiment with an approximate error of 10%.

To ensure the reliability of the CFD results, a mesh sensitivity study was conducted, which is summarized in Table 3. The criterion was to maintain ΔT and ΔP changes below 1% between the medium and fine mesh. The ΔT and ΔP reported in Table 3 correspond to the fine mesh that passed the mesh sensitivity criterion as the final mesh.

Table 3. Mesh sensitivity study (NC: Number of Cells)

Heat exchanger	Coarse NC	Medium NC	Fine NC	ΔT [K]	ΔP [Pa]
G	216,768	889,262	1,341,052	10.67	46.22
D	197,724	304,489	509,204	12.47	45.05
F	1,122,488	1,446,129	2,213,395	13.9	239.58
D-G	373,410	670,820	972,613	11.05	64.27
G-F	729,710	1,619,787	2,276,457	12.64	85.14
D-F	446,056	1,058,623	1,336,685	13.82	89.68

The hydraulic diameter (D_h), Reynolds number (Re), average convective heat transfer coefficient (h_{avg}), and Nusselt number (Nu) were calculated using Equations 4 to 7:

$$D_h = \frac{4V_S}{A_S} \tag{4}$$

$$Re = \frac{\rho U D_h}{\mu} \tag{5}$$

$$h_{avg} = \frac{\rho U A_1 C_p \Delta T}{A_2(T_w - T_f)} \tag{6}$$

$$Nu = \frac{h_{avg} D_h}{k} \tag{7}$$

where V_S denotes TPMS geometry void (fluid) volume, and A_S represents its wet surface area. ρ refers to water density, while U indicates the inlet cross-sectional velocity. The dynamic viscosity of water is denoted as μ. A_1 and A_2 correspond to the inlet cross-section area and heat source surface area, respectively. C_p stands for water's specific heat capacity. T_w is the heat source temperature, and T_f is the average of T_{out} and T_{in}. k is also the thermal conductivity of water.

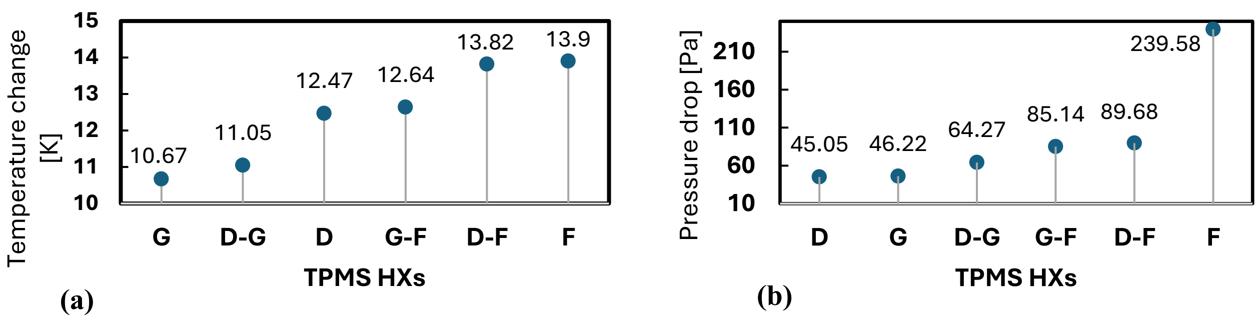

Figure 1. (a) Temperature change across TPMS HXs; (b) Pressure drop across TPMS HXs

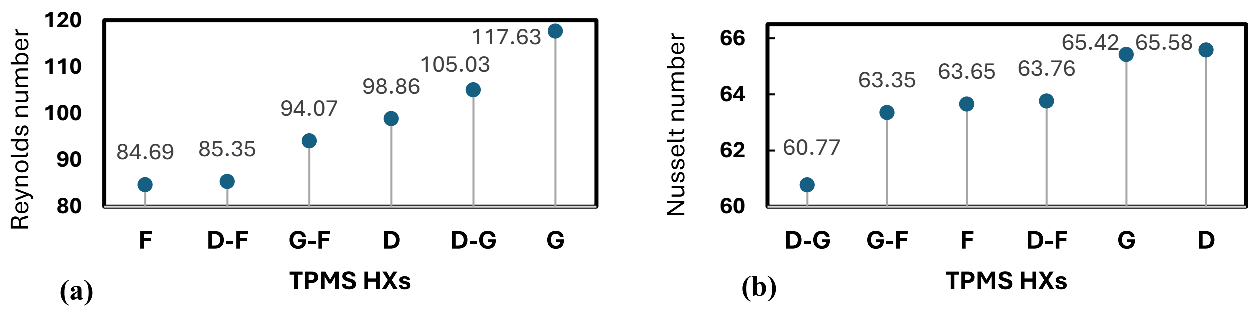

Figure 2. (a) TPMS HXs Reynolds number; (b) TPMS HXs Nusselt Number

3. Results and discussion

The temperature change and pressure drop across the studied TPMS HXs are illustrated in Figure 1. The uniform FRD geometry achieved the highest temperature change of 13.9 [K], exhibiting a 239.58 [Pa] pressure drop, indicating maximum flow resistance while demonstrating efficient heat transfer. In contrast, the Diamond D structure showed the lowest pressure drop (45.05 [Pa]) with a moderate temperature change of 12.47 [K]. Diamond D-FRD and Gyroid-FRD presented the best heat transfer performance among hybrid geometries, with pressure drops of 89.68 [Pa] and 85.14 [Pa], and temperature changes of 13.82 [K] and 12.64 [K], respectively.

The Reynolds and Nusselt numbers for TPMS HXs are illustrated in Figure 2. Superior convection performance was observed in the Diamond D and Gyroid geometries, with Nusselt numbers of 65.58 and 65.42, respectively. It was observed that in hybrid HXs, placing the uniform side of the geometry with a higher Nusselt number adjacent to the heat source enhances the temperature change. Lowest Reynolds number, 84.69, belonged to the FRD structure, indicating its smaller hydraulic diameter and narrower flow paths, which led to a pressure drop of 239.58 [Pa], the highest of all HXs investigated. Among hybrid TPMS geometries, Diamond D-FRD had the best convection performance with a Nusselt number of 63.76.

In terms of temperature change, all the hybrid HXs exhibited intermediate performance relative to their base geometries, confirming the expectation. However, regarding pressure drop, the Diamond D-Gyroid hybrid showed higher flow resistance than both of its parent structures. In contrast, the Gyroid-FRD and Diamond D-FRD hybrids demonstrated intermediate pressure drops, aligning more closely with the expected trend. Furthermore, when comparing the Diamond D and FRD structures, the Diamond D-FRD hybrid exhibited a temperature change that deviated by only 1% from that of the FRD, while it reduced the FRD pressure drop by 62.5%, indicating a significant improvement in flow resistance, a desirable outcome for heat exchanger applications.

4. Conclusion

This study investigated the thermo-hydraulic performance of uniform and hybrid TPMS-based HXs using CFD analysis. Among the examined geometries, the uniform FRD exhibited the highest thermal efficiency but also the greatest pressure drop. In most cases, hybrid structures demonstrated intermediate performance of their respective base geometries. However, the Diamond D-Gyroid deviated from this trend, showing a higher pressure drop than both of its base structures. Other hybrids, such as Diamond D-FRD and Gyroid-FRD, showed intermediate temperature changes with well-balanced pressure drops. These results suggest that hybridization of TPMS geometries can yield intermediate thermo-hydraulic performance of their respective base geometries, although each configuration should be evaluated for its intended application. The findings from this study support further exploration of tailored TPMS morphologies to achieve optimized thermo-hydraulic performance.

5. Statement on generative artificial intelligence (AI) usage

In the preparation of this manuscript, ChatGPT was used solely for language editing purposes. The tool was applied to grammar refinement and clarity improvements, and all AI-generated content has been thoroughly reviewed and edited by the authors to ensure originality and accuracy. We, the authors, affirm full authorship of the final text and accept complete responsibility for its content.

6. References

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