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Design and Numerical Investigation of High-Performance Heat Exchangers Containing Triply Periodic Minimal Surface Lattice Structures †

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Abstract: This research explores the transformative realm of heat exchanger design, focusing on three different lattice types—gyroid, diamond, and SplitP. This study systematically investigates the impact of different cell sizes and wall thicknesses of the lattice structure on the performance of these innovative heat exchangers. The goal is to identify the design parameters of a high-performance heat exchanger with minimal fluid pressure loss but maximum heat transfer. Utilizing advanced computational simulations and modeling techniques, we delve into the intricate details of fluid dynamics within heat exchangers featuring distinct lattice geometries. By systematically adjusting lattice cell size and wall thickness, the research aims to identify the optimal configurations that maximize heat transfer efficiency while ensuring structural integrity. The analysis encompasses detailed examinations of fluid flow patterns, temperature changes, and pressure drops across the different lattice types. These complex heat exchangers were designed for additive manufacturing. The findings promise to guide the development of more efficient and customized heat exchangers, with implications for a wide range of applications where precise thermal management is paramount.

Keywords: additive manufacturing; heat exchanger design; triply periodic minimal surface; lattice structure; computational fluid dynamics

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1. Introduction

In the pursuit of advancing thermal engineering and optimizing heat exchanger performance, this investigation presents a comprehensive exploration of high-performance heat exchangers (HEXs). The integration of TPMS lattice structures represents a paradigm shift in heat exchanger engineering, offering unique geometric configurations that are not only aesthetically intriguing but also hold tremendous potential for enhancing heat transfer capabilities. Heat exchangers are crucial for efficient heat transfer between fluids, optimizing energy usage, controlling temperatures in processes, and enhancing overall system performance across various industrial and commercial applications. These devices facilitate the efficient exchange of thermal energy between two fluids, enabling the regulation of temperatures in various systems.

Currently, heat exchanger structures are usually constructed as spiral groove structures [1], which are created by tailor-welding a split structure or an array-distributed rectangular milling groove structure [2,3]. The channel becomes blocked during the welding process due to the uneven flow of the molten pool, and the residual stress after cooling may result in deformation or even fracture, which would impair engine performance. If the heat exchange efficiency of a heat exchanger with a milling groove construction needs to be increased, the heat exchanger's length must be extended. It is challenging to meet the standards for usage in new engines since the lengthening of the heat exchanger

increases its volume, weight, and heating time [1,4]. Another concern is the bulkiness of traditional designs, which can pose spatial constraints in certain applications. Additively manufactured lattice-based heat exchangers offer a transformative leap forward in thermal engineering, surpassing the limitations of traditional heat exchangers in several key aspects. One significant advantage lies in their design flexibility and complexity, enabled by additive manufacturing techniques [5].

Lattice structures in additive manufacturing represent a revolutionary approach to designing and constructing three-dimensional objects. The design consists of interconnected elements arranged in a repetitive manner, creating a visually distinct grid-like or web-like pattern [6,7]. These structures are known for their efficiency in material usage, offering a balance between strength and weight. The open design allows for an efficient load distribution, making lattice structures versatile solutions in engineering, design, and construction. These structures, characterized by interconnected geometric patterns, offer a unique combination of strength, lightweight properties, and material efficiency [6,8]. The intricate lattice structures, such as gyroid, diamond, or SplitP, allow for the precise customization of heat exchanger geometries, optimizing performance for specific applications. The additive manufacturing process also enhances efficiency by enabling the creation of complex structures with reduced material waste [9]. Furthermore, lattice-based designs exhibit superior heat transfer characteristics due to their increased surface area and enhanced fluid flow patterns. This results in improved overall efficiency, reduced fouling, and enhanced adaptability to variable operating conditions. The lightweight and compact nature of lattice-based heat exchangers further contributes to space saving and their ease of integration, making them a promising and advantageous alternative to traditional heat exchangers in various industrial, commercial, and residential applications [10,11].

Currently, the primary application of lattice structures is in their lightweight design; research on heat transfer using lattice structures as filling structures is still in its early stages. Theoretical and technological frameworks that are appropriate for evaluating heat transfer efficiency, choosing lattice structures, and designing heat and mass transfer methods under multi-field coupling are lacking. Further investigation into the macroscopic properties and heat transport properties of lattice systems is still required [12]. The objective of this research is to design, analyze, and numerically investigate the performance of heat exchangers featuring TPMS lattice structures. By employing advanced computational techniques and simulations, we aim to understand the intricate interplay between geometric parameters, fluid dynamics, and temperature distribution within these novel structures. The insights gained from this study will contribute to the development of high-performance heat exchangers tailored to the specific needs of optimizing energy efficiency and promoting sustainable practices.

2. Design of the Lattice Structure Parametric Model

Parametric design is an innovative approach to designing objects, structures, or systems where the relationships between various elements are defined by parameters, enabling flexibility, adaptability, and efficient iteration [13]. In parametric design, mathematical equations, algorithms, or logical rules are utilized to create a set of parameters that govern the form, size, and relationships within a design. Such a parametric design model was developed to create twelve different heat exchangers (HEXs)—Table 1. There are many lattice structures available to design. Among them, the most suitable three lattice types for HEX design—gyroid, spiltP, and diamond—were selected. All of the lattices are structurally unique and they represent unique HEXs—Figure 1. The parametric design was created using nTop software (Version 4.4.2) in such a way that by changing a few parameters, different combinations of HEXs can be designed. This parametric design helped to save time on repetitive tasks and automate the HEX investigation process.

Table 1. Combinations of twelve different HEXs with specifications.

HEX ID	Lattice Types	Wall Thickness	Unit Cell Size (L = W = H)
G210	Gyroid	2	10
G215	Gyroid	2	15
G310	Gyroid	3	10
G315	Gyroid	3	15
S210	SplitP	2	10
S215	SplitP	2	15
S312	SplitP	3	12
S315	SplitP	3	15
D210	Diamond	2	10
D215	Diamond	2	15
D310	Diamond	3	10
D315	Diamond	3	15

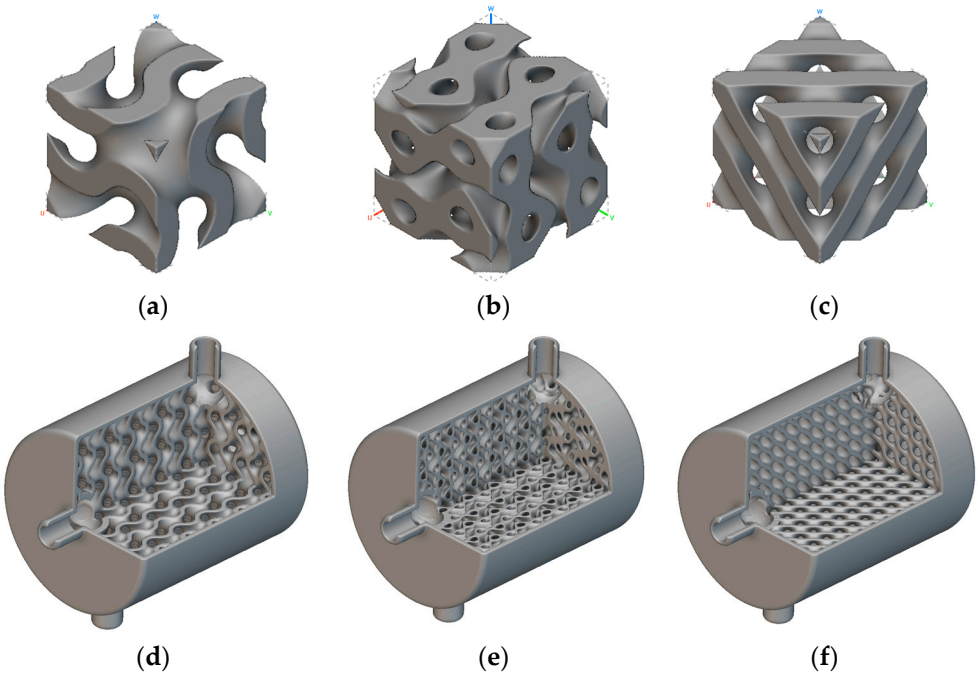


Figure 1. The unit cell of the three lattices. (**a**) Gyroid; (**b**) SplitP; and (**c**) Diamond. HEX design using the three different lattices: (**d**) Gyroid; (**e**) SplitP; and (**f**) Diamond.

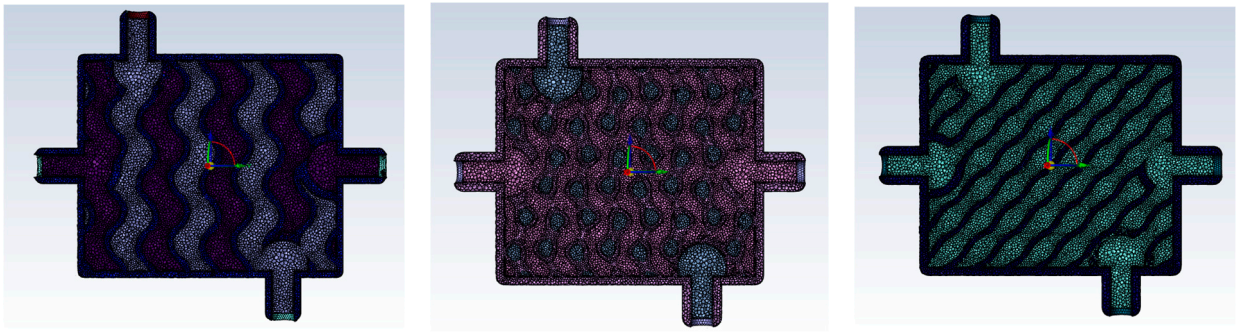
3. Numerical Investigation

3.1. Exporting Mesh from nTop

Two different approaches were followed to generate and export mesh from nTop, namely surface mesh and volume mesh. For comparatively simple lattices, like gyroid, surface mesh was used. For comparatively complex lattices, like splitP and diamond, the volume mesh approach was used with a robust tetrahedral meshing option to solve complex volume surfaces. The initial boundary conditions were also defined in nTop using the FE boundary body and FE boundary flood fill approach. Finally, three meshes—shell, cold fluid, and hot fluid with boundary lists—were exported.

3.2. Importing Mesh to Ansys and Generating Volume Mesh

The ANSYS fluent (with fluent meshing) tool was incorporated for the heat transfer analysis. The float-tolerant meshing option was used to proceed with the volume meshes—Figure 2. Surface mesh target skewness was selected as 0.8 and 0.04 for the volume mesh improved limit. Mesh checking was carried out, and mesh improvement was performed at a limit of 0.1.

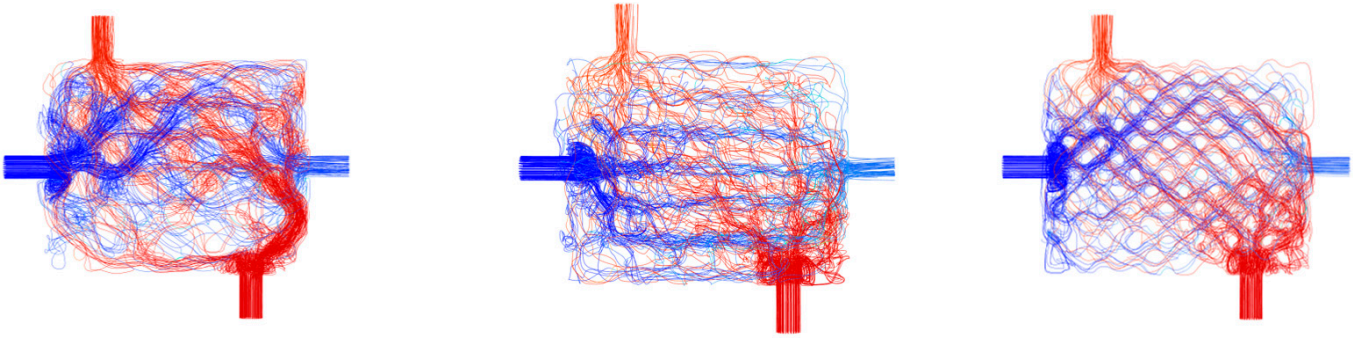


(**a**) (**b**) (**c**)

Figure 2. Section view of the volume meshes generated on Ansys Fluent. (**a**) Gyroid; (**b**) splitP; and (**c**) diamond.

3.3. Heat Transfer Analysis

The K-epsilon model was used for the analysis with the "energy on" condition. Other boundary conditions were set accordingly. The inlet temperature of cold fluid was 12 °C, and the inlet temperature of hot fluid was 90 °C. Water liquid was used as a fluid, and aluminum was used as a HEX material. The path lines (Figure 3) of the cold and hot fluids were investigated after completing the iteration.



(**a**) (**b**) (**c**)

Figure 3. Path lines of the fluid flow within three HEXs: (**a**) gyroid; (**b**) splitP; and (**c**) diamond.

4. Results and Discussion

4.1. Heat Transfer Against Different Lattic Types, Sizes, and Wall Thicknesses

Numerical investigations were carried out on twelve different HEX samples, keeping the conditions of temperature, pressure, velocity, and other parameters the same. The temperature contours (Figure 4) of all HEX samples were drawn from the investigation using Ansys Fluent.

The outlet temperature and pressure of cold and hot fluids from different HEX samples were taken (Table 2) to record the data. Data were taken from the contour drawn on the center plane of each HEX sample. The same position and procedure were followed when recording the data for a better comparison result. A special case occurs in the S310 HEX design. The fluid zones were not connected together for this size. For this reason, the unit cell size was enlarged to achieve the optimum design, and a unit cell size of 12 × 12 × 12 was found to be the optimum unit cell, which can fulfill all criteria as a HEX with a 3 mm wall thickness.

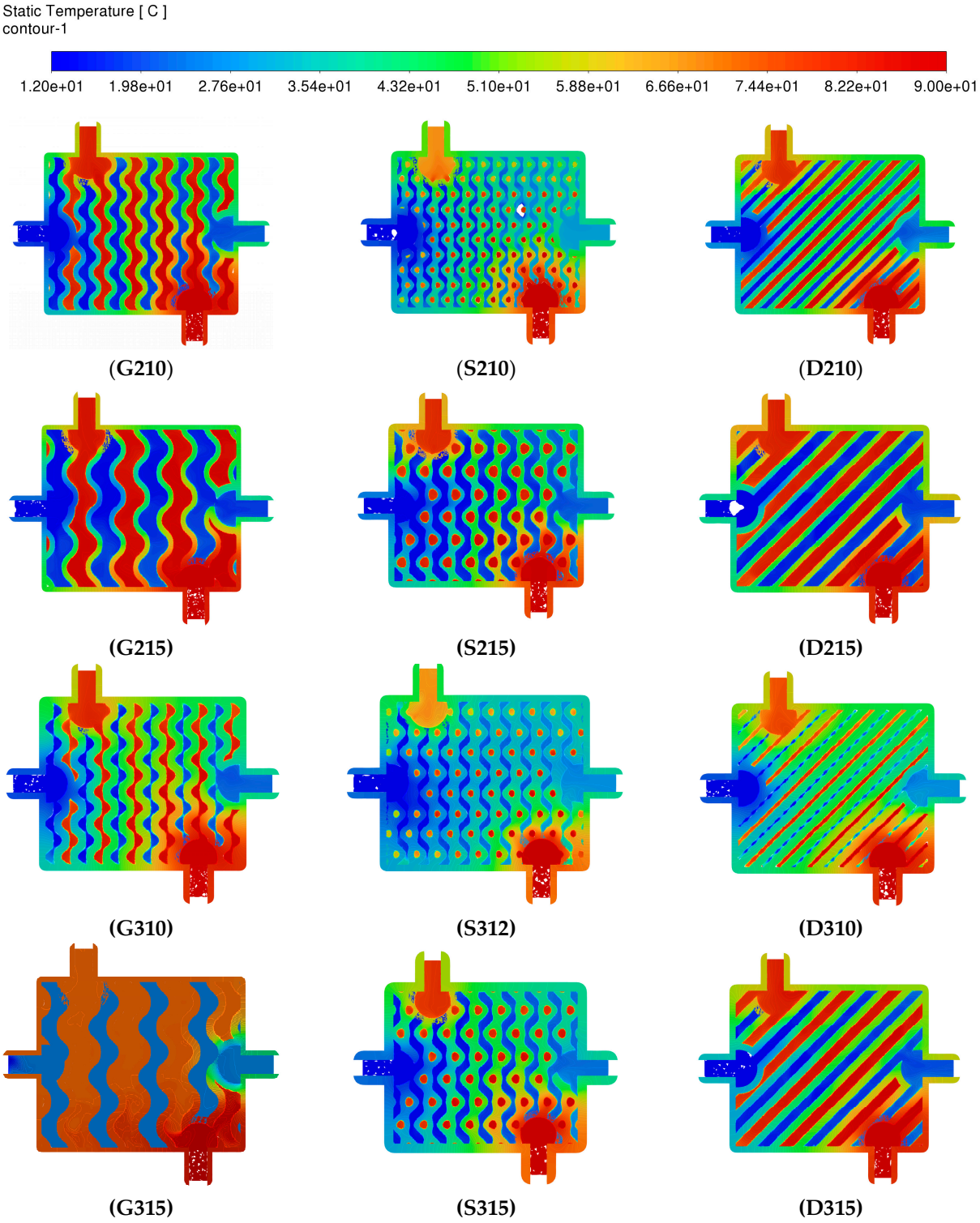


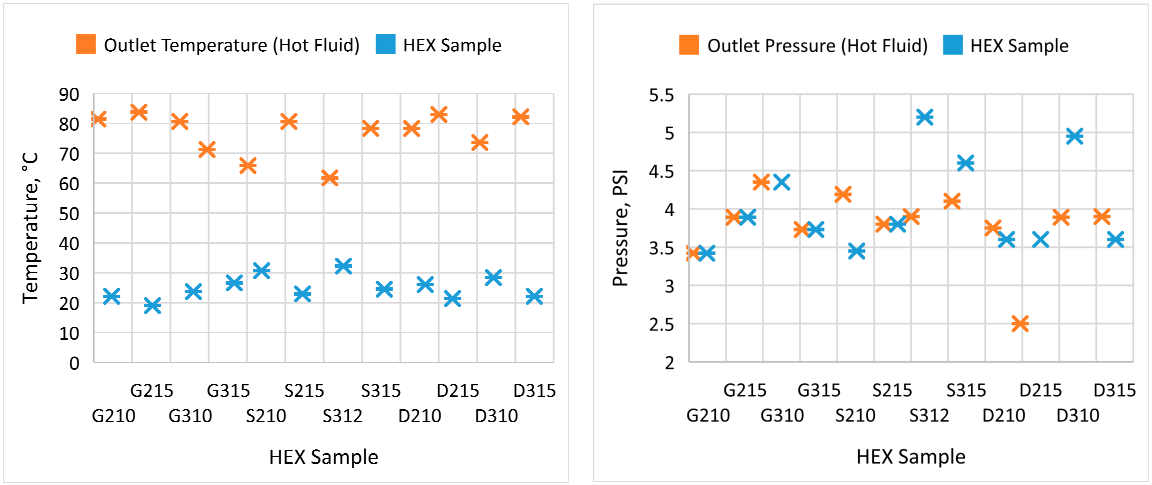
Figure 4. Temperature contours of different HEX samples.

Table 2. Outlet temperature and pressure of hot and cold fluids.

HEX Sample	Outlet Temperature of Hot Fluid (°C)	Outlet Temperature of Cold Fluid (°C)	Outlet Pressure of Hot Fluid (PSI)	Outlet Pressure of Cold Fluid (PSI)
G210	81.42	22.14	3.42	3.42
G215	83.76	19.01	3.89	3.89
G310	80.64	23.7	4.35	4.35
G315	71.27	26.62	3.73	3.73
S210	65.86	30.72	4.19	3.45
S215	80.64	22.92	3.8	3.8
S312	61.76	32.27	3.9	5.2
S315	78.32	24.49	4.1	4.6
D210	78.3	26.04	3.75	3.6
D215	82.98	21.35	2.5	3.6
D310	73.6	28.38	3.89	4.95
D315	82.2	22.14	3.9	3.6

4.2. Comparative Analysis of the Outlet Temperature and Pressure from Different HEX Samples

Two different charts were plotted using the data found from the investigation of temperature and pressure changes during the HEX operation. Figure 5 represents the comparative result of temperature changes, and the comparative results of pressure over time for both hot and cold fluid flows.



(**a**) (**b**)

Figure 5. Outlet temperature (**a**) and pressure (**b**) of different HEX samples.

Temperature directly influences the heat transfer process, affecting the efficiency of the exchange between hot and cold fluids. The temperature differential between the inlet and outlet of the fluids plays a critical role in determining the overall effectiveness of heat transfer. Simultaneously, pressure conditions impact fluid flow rates, which are integral to the heat exchange process. To achieve the best performance of a HEX, an optimum design is required that can achieve high-temperature exchange while maintaining a low-pressure drop. From the above numerical investigation, the S312 HEX sample shows the best performance considering temperature change and pressure drop.

5. Conclusions

This study underscores the paramount importance of considering both temperature and pressure factors in determining the optimal performance of heat exchangers (HEXs). The temperature differentials between the inlet and outlet directly influence the efficiency of heat transfer, while pressure conditions play a crucial role in the fluid flow rates that are integral to the heat exchange process. This article emphasizes the need for an optimum

design that achieves high-temperature exchange while maintaining a low-pressure drop. Through a meticulous numerical investigation, HEX sample S312 emerges as the standout performer, exhibiting the highest temperature exchange point and the lowest pressure loss point when compared to the other options. The findings highlight the significance of a comprehensive approach to HEX design, taking into account both temperature and pressure considerations to achieve the best possible performance and efficiency in various industrial applications.

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