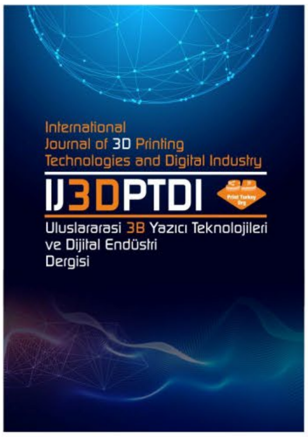

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AN INNOVATIVE METHODOLOGY TO DESIGN GYROID HEAT EXCHANGERS FOR METAL ADDITIVE MANUFACTURING

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ABSTRACT

This study demonstrates an innovative approach to the automatic design of compact gyroid heat exchangers using the advanced engineering software nTopology, which is based on implicit modeling technology. The aim is to provide a modern enhancement to traditional 'Shell and Tube' type heat exchangers. Utilizing functions in implicit modeling and parametric design features, complex internal gyroid structures can be used as an alternative heat transfer interface in 'Shell and Tube' type heat exchangers. The most striking aspect of the methodology is its ability to fully automate the design process. By consolidating specific parameters into a single function block and entering scalar values, a fast and flexible workflow is activated, automatically generating the final geometry. Gyroid structures with high thermal performance and fluid dynamics are automatically adapted for various volumes and geometries. These structures can improve the overall efficiency of heat exchangers and offer significant advantages, especially in specialized application areas such as aerospace and space industries. In the design and sizing process of the gyroid heat exchanger, if manufacturing is planned, it is necessary to pay attention to the design principles for metal additive manufacturing. In conclusion, this study demonstrates that the advanced engineering software known as nTopology can create a synergistic effect in the rapid and easy design of gyroid heat exchangers and in establishing the automation of the design process.

Keywords: Additive Manufacturing, Gyroid, Heat Exchanger, nTopology.

1. INTRODUCTION

Heat exchangers are used in a wide range of applications, including energy, chemical, food processing, and HVAC systems. These systems are designed to transfer energy efficiently. However, design and efficiency constraints imposed by traditional manufacturing methods may prevent these systems from reaching their full potential. In this context, additive manufacturing offers significant potential for heat exchangers [1].

Additive manufacturing methods provide design flexibilities that could be beneficial for various types of heat exchangers. For instance, research on different structures of heat exchangers, such as shell and tube, double tube, and compact heat exchangers, has focused on optimizing the design of heat exchangers. The designs of these systems can be customized through additive manufacturing to enhance performance and efficiency [2-8].

One study focused on a heat exchanger resembling a fractal tree and demonstrated that this design was thermally and hydrodynamically superior to traditional spiral tube exchangers [9]. This highlights the ability of additive manufacturing to create complex and efficient geometries.

In another study, a metal-polymer composite heat exchanger was developed for liquid cooling systems and was found to have similar performance to traditional radiators [10]. This result emphasizes the capacity of additive manufacturing to create complex designs that incorporate different materials like metal and polymer.

The thermal performance of heat exchangers produced by additive manufacturing was investigated in a study for three different air heat exchangers. Researchers demonstrated that factors like surface roughness and internal voids had a significant impact on performance [11]. This indicates that additive manufacturing could offer significant advantages in terms of heat transfer and thermal performance.

Furthermore, it has been observed that high-performance counterflow heat exchangers produced by additive manufacturing can prevent heat expansion problems and enable the creation of innovative new designs. For example, one study showed that an aluminum alloy heat sink exhibited a 50% increase in thermal properties compared to a traditional copper heat sink [12].

The applications of gyroid structures in heat exchangers are also noteworthy. One study stated that gyroid structures are effective in cooling gas turbine blades [13]. Whether located fully or partially within the channel, these structures can be effective in enhancing heat transfer and providing mechanical support. Additionally, the porosity of these structures can be adjusted, making them customizable for various applications [14].

The design method presented in this work represents a novel and innovative approach, and as such, it is not currently aligned with existing standards such as those from ISO or ASTM. However, our research into alternative designs for Gyroid heat exchangers, finite element analysis of these designs, parameters affecting manufacturability through metal additive manufacturing, and identification of key parameters influencing the performance of the heat exchanger could pave the way for the development of standards in this area. From this perspective, we believe that this method could serve as a preliminary step towards standardization efforts in the future.

Overall, the design flexibility and capacity to create complex geometries offered by additive manufacturing have the potential to significantly improve the efficiency and performance of heat exchangers. However, more research and optimization work is required to fully discover the potential of this technology in heat exchanger design.

As no physical manufacturing was conducted within the scope of this study, testing the additive manufacturing parameters was not feasible. However, the dimensioning of the design has been carried out considering the capabilities of the EOS M290 aluminum metal additive manufacturing printer. The geometry of the designed heat exchanger has been verified in the printer's software for manufacturability without any detected errors, and it has been confirmed that the gyroid internal structure can support itself without the need for additional support material. With this information, we would like to indicate that the design is suitable for additive manufacturing and that further research will continue in this direction.

2. MATERIALS AND METHODS

In this study, a methodology is presented for designing gyroid heat exchangers with complex internal structures, utilizing the advantages of implicit modeling.

The methodology presented in our study addresses the limitations of traditional CAD modeling by offering significant time savings and increased flexibility in design processes. Notably, this method provides a substantial alternative to conventional Shell and Tube heat exchangers by automatically generating gyroid structures with a high heat transfer interface area and complex internal geometry.

At the beginning of the heat exchanger design process, geometries formed from implicit bodies are used. Most functions in the nTopology software operate based on this type of input data [15]. The cylinder and two spheres shown in Figure 1a are positioned concentrically with equal radius at the cylinder's start and end points. These common radius values and the length of the cylinder are defined as variables and can be changed parametrically. In the automation process, when the radius and length parameters are modified, the design is automatically updated. The diameters and distances of the fluid inlet and outlet pipes shown in Figure 1b are also defined to be parametrically alterable. Rules can be set between variables, such as one radius being twice the size of another. Based on these definitions, the relationships between variables defined by the designer can indirectly affect other dimensions. The more complex and accurate the parametric relationships, the more flawless and advanced the automation process for creating the final design will be.

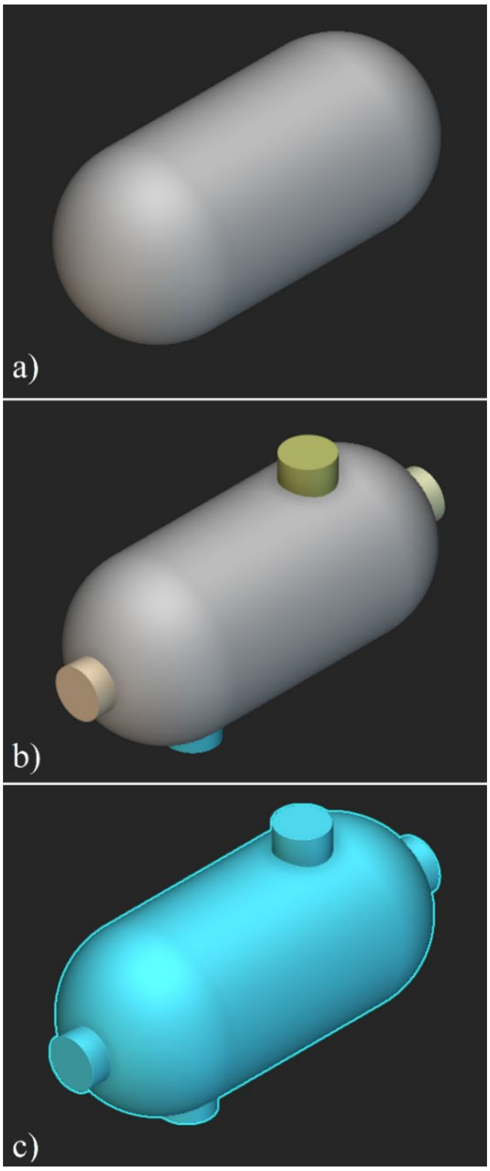

Figure 1. a) Implicit Bodies (Two Sphere and One Cylinder) b) Inlets and Outlets c) Single Implicit Body.

In Figure 2a below, the 'Shell' function capable of forming a shell structure is used [16]. This function takes the implicit geometry representing the internal volume as input, and the thickness of the formed shell is defined as a variable for design automation. The 'direction' parameter of the function is selected as 'outward,' and an offset operation is performed. The shell structure is shown in gray in Figure 2a. The area shown in blue in Figure 2b is where heat transfer will occur.

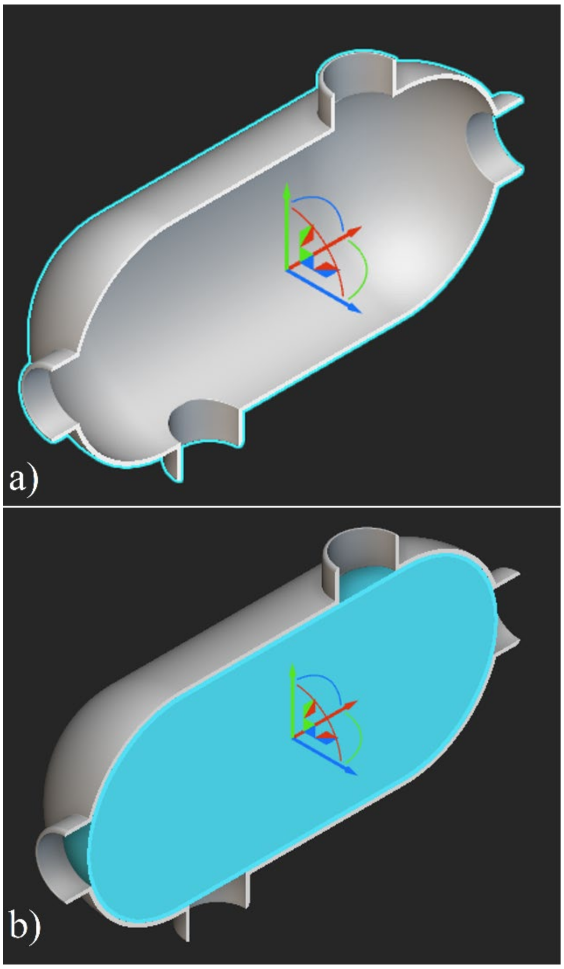

Figure 2. a) Shell Body b) Area of Heat Transfer

In Figure 3a below, plenum regions are formed at pipe entrances and exits to reduce pressure losses. The dimensions of the plenum regions are related to the diameters of the pipes they are in. Since the plenum dimensions are defined as variables, they are automatically updated in response to changes in pipe diameter and position. The fluid entering the plenum regions proceeds into the area shown in yellow in Figure 3b, where heat transfer will occur. The 'Walled TPMS' function is used for this area [17]. This function offers the opportunity to design a gyroid structure as an interface for heat transfer. The function accepts parameters such as the dimensions of gyroid unit cells, the thickness of the gyroid interface, and the type of TPMS as inputs. These parameters become part of design automation when defined as variables, and the design is updated within seconds when the parameters are changed.

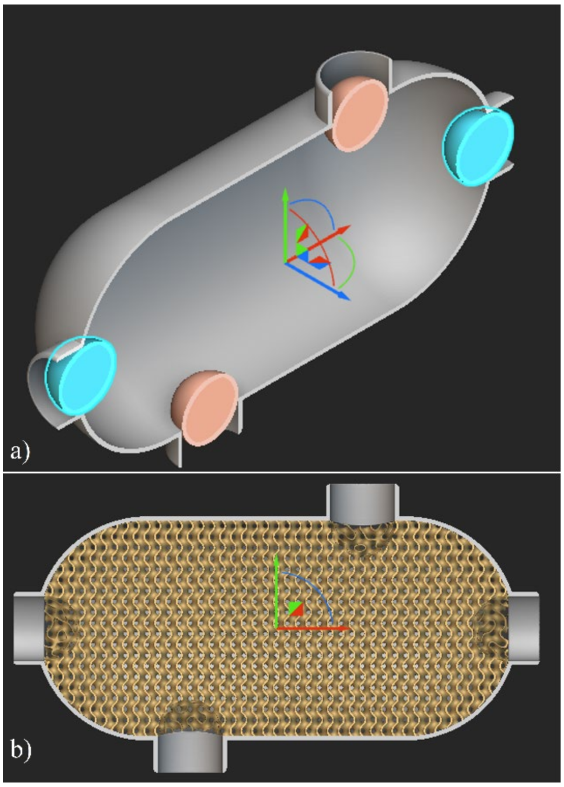

Figure 3. a) Plenums b) Walled TPMS

In Figure 4a below, based on the gyroid-type minimal surface forming the heat transfer interface, the volume of the cold fluid is derived. This volume is represented in blue. There is complete geometric compatibility, as can be seen from the cross-sectional view of the cold fluid volume. The volume of the hot fluid derived in the same manner is represented in pink in Figure 4b. In Figure 4c, the interface where heat transfer occurs between fluids and its grid structure are shown. The resulting hot and cold fluid geometries are completely independent of each other and will automatically update when parameters change. The independence of the fluid geometries provides the geometry necessary for CFD analysis.

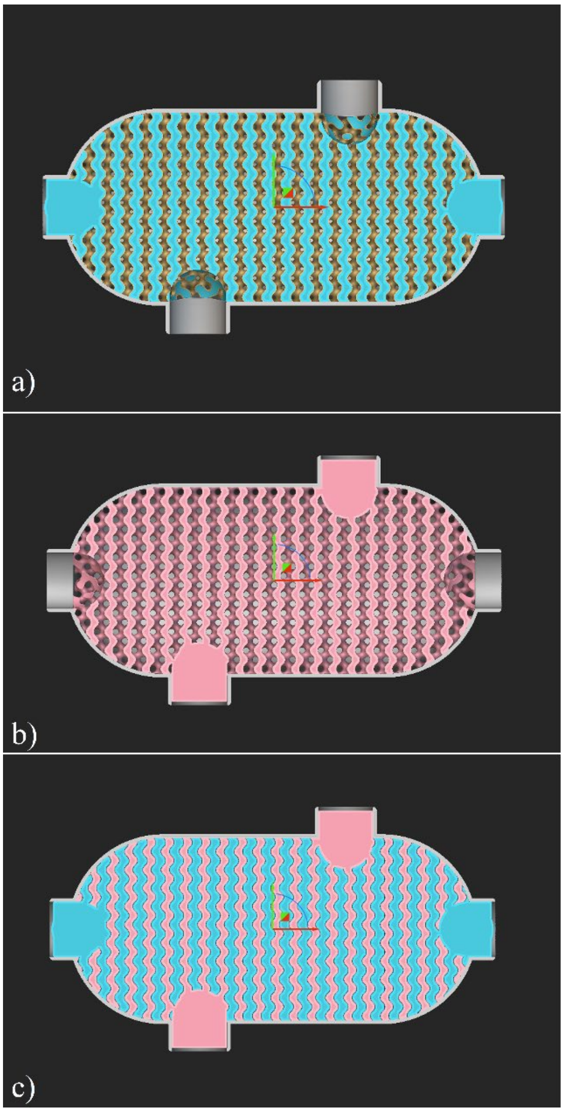

Figure 4. a) Cold Fluid b) Hot Fluid c) Section of Heat Transfer Area

To prevent fluids from mixing with each other, special geometries represented in green, as shown in Figure 5a, need to be created. The primary purpose of the baffle geometries is to seal the openings where the other fluid is present in the pipes where one fluid enters and exits. Baffle geometries have a unique structure and are always fully compatible with other design parameters, such as pipe diameter, plenum region, and the geometry of the gyroid interface. Thus, no extra workload will be needed for baffle designs during design iterations. Moreover, since the thickness of the baffle is defined as a variable, the thickness value can easily be updated.

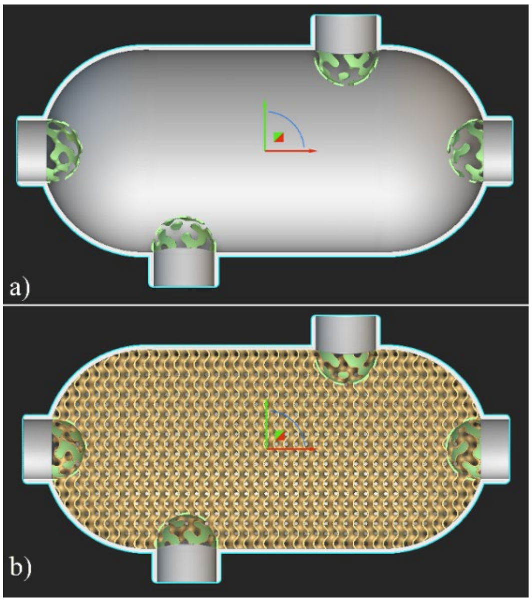

Figure 5. a) Baffles b) Heat Transfer Area with Baffles

In the cross-sectional view in Figure 6a, the baffle geometry and the volume filled by the cold fluid are seen together. The baffle geometries that prevent the cold fluid from mixing with the hot fluid are clearly visible since the volume where the hot fluid should be is not rendered. In Figure 6b, a close-up cross-sectional view shows the full compatibility of the heat transfer interface and baffle geometries with the complex internal structure.

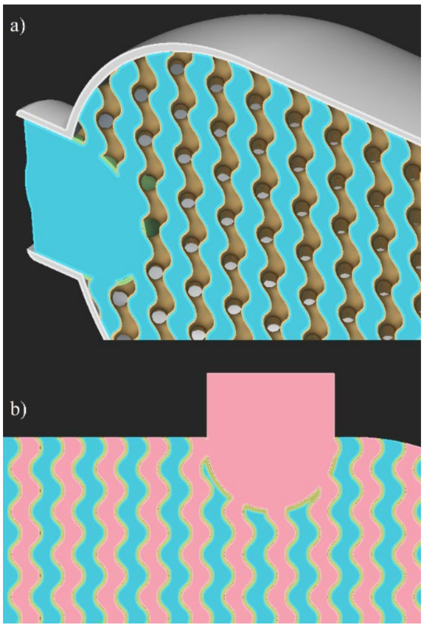

Figure 6. a) Cross-Sectional View of Baffle Geometry and Cold Fluid b) Geometric Compatibility Between the Gyroid Structure and Baffle Geometry

In Figure 7a below, an isometric view of the gyroid structure and cold fluid represented in gray is given. An isometric view for the hot fluid is similarly created in Figure 7b. The complex grid structure formed by the fluid volumes together is clearly seen in Figure 7c.

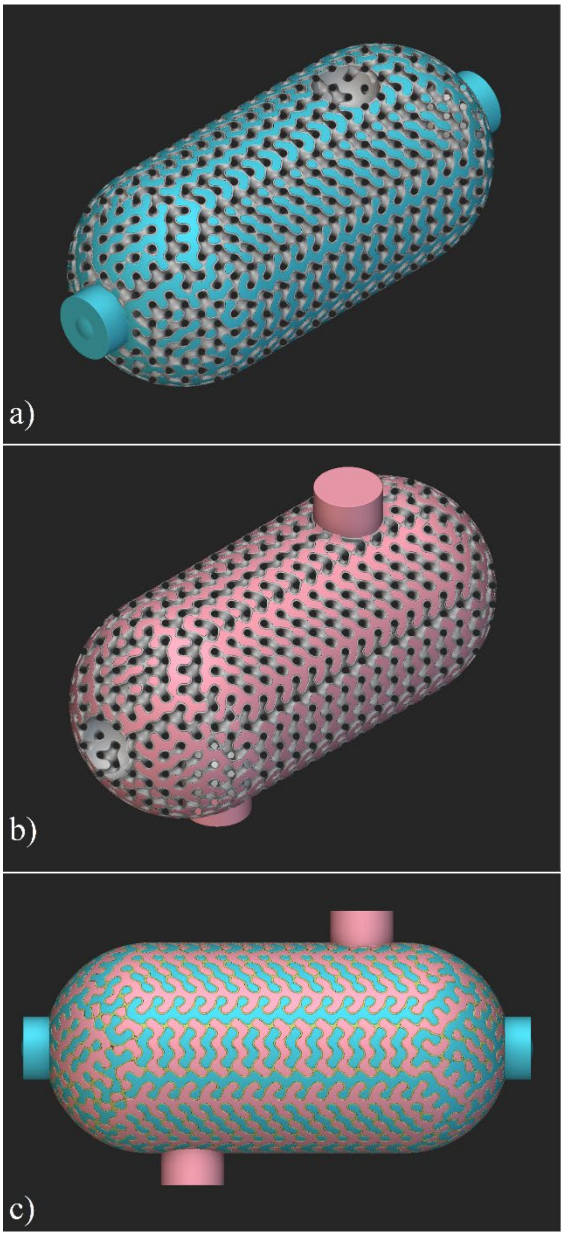

Figure 7. a) Gyroid structure with Cold Fluid b) Gyroid Structure with Hot Fluid c) General View of Fluid Volumes

In Figure 8 below, different views of the final design are provided. The metallic gray surfaces closed by the baffle geometries that prevent the fluids from mixing with each other have been checked in different views and sections and are fully compatible with the complex gyroid structure.

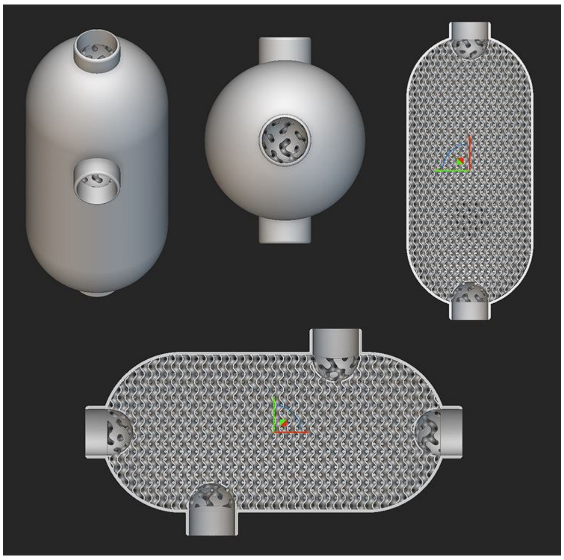

Figure 8. Different Views of the Gyroid Heat Exchanger

All the workflow followed in this methodology can be converted into a single function block. This transformation is a technique that provides automation in the design process and is seen in Figure 9 below. When new dimensions related to the design are entered as variables in the created function block, the entire workflow is automatically repeated with the new parameter values, and the new geometry of the gyroid heat exchanger can be automatically produced within seconds.

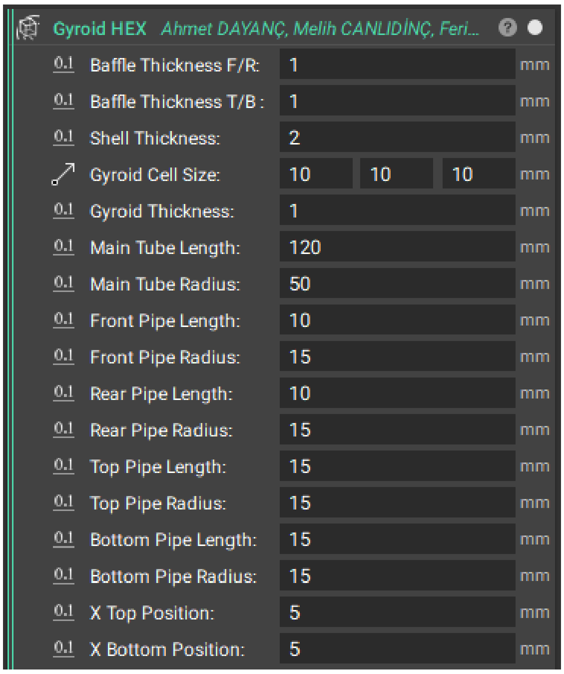

Figure 9. Function block

3. RESULTS

In conclusion, this study shows that automation and parametric design can be effectively used in the design of gyroid-type heat exchangers. The ability to automate the design process provides significant time savings, especially during the prototyping phase and for generating design variations for performance tests. Furthermore, the complexity of the automation process depends on the number of parameters and the correct definition of complex parametric relationships, offering great flexibility to the designer. One of the significant advantages of implicit modeling technology is that it allows for the easy design of complex gyroid structures, which have advantages in terms of thermal performance and fluid dynamics. Gyroid minimal surfaces, in particular, offer maximum heat transfer surface in minimum volume and perfectly separate hot and cold fluids with a thin interface, significantly enhancing the efficiency of such heat exchangers. When design rules for additive manufacturing are followed and effective heat transfer materials like aluminum or copper are considered, the design is thought to be practically as well as theoretically applicable. Using different TPMS types in the complex internal geometry of the design and selecting different materials will directly affect heat transfer [18]. Different variations that can be produced with additive manufacturing can be tested under specific conditions, and their performances can be compared. This study offers a research area to optimize the performance of heat exchangers, and its effectiveness in real-world applications depends on factors such as material selection, parameter values, manufacturing tolerances, and the limitations of additive manufacturing methods. These factors point to important considerations for future research.

This study focuses on the design methodology of Gyroid heat exchangers and does not include the manufacturing or experimental phase at this stage. Therefore, we are unable to present experimental results and analyses for comparison with other heat exchangers measured in the literature. We recognize the importance of this aspect and plan to develop a research project that will secure the necessary funding for the manufacturing and testing phases in our future work, allowing us to compare our results with previous research. We believe that this study provides a foundational basis for future advancements in this field and is valuable in this respect.

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