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INVESTIGATION OF LAMINAR STEADY AND UNSTEADY FLOWS IN GYROID TPMS STRUCTURES

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ABSTRACT

This study presents an extensive computational fluid dynamics (CFD) investigation of the airflow behavior within Gyroid Triply Periodic Minimal Surface (TPMS) structures, focusing on both laminar steady and unsteady flow conditions. Using representative elementary volume (REV)-scale simulations, the pressure drop characteristics across these porous structures are examined. Three porosity levels of 50%, 60%, and 70% are analyzed to understand the effect of porosity on flow behavior and pressure drop. The results demonstrate that increased porosity significantly influences the hydraulic Reynolds number. For the 50% porosity structure, steady laminar flow is maintained at hydraulic Reynolds numbers up to 70, while the 70% porosity structure allows steady laminar flow at Reynolds numbers as high as 210. Additionally, flow fluctuation intensity within the Gyroid structure is quantified by measuring velocity fluctuations in the flow direction. These findings offer critical insights into the design and optimization of Gyroid TPMS structures for engineering applications.

Keywords: Gyroid, REV scale, Pressure drop, Laminar flows

NOMENCLATURE

ΔP	$[Pa]$	pressure drop
D_h	$[m]$	hydraulic diameter
ϕ	[-]	porosity
V	$[m^3]$	total volume
A	$[m^2]$	wetted surface area
ρ	$[kg/m^3]$	fluid density
u_s	$[m/s]$	superficial velocity
μ	$[Pa \cdot s]$	dynamic viscosity
$\mathrm{Re_h}$	[-]	hydraulic Reynolds number
I	[-]	flow fluctuation intensity
u'_{rms}	$[m/s]$	root-mean-square of fluctuations
$\bar{u}$	$[m/s]$	mean velocity

1. INTRODUCTION

Triply Periodic Minimal Surface (TPMS) structures, particularly the gyroid structure, are mathematically-defined surfaces that exhibit three-dimensional periodicity while maintaining zero mean curvature. Triple periodicity in a gyroid TPMS structure refers to its repeating pattern in three independent spatial directions, meaning it extends infinitely and uniformly along the x, y, and z axes. This creates a continuous, interconnected, and periodic minimal surface without boundaries or edges. A key advantage of gyroid structures is their high surface-area-to-volume ratio, making them highly suitable for applications such as heat exchangers [1], catalysis [2], and membrane reactors [3], where efficient mass and heat transfer are essential. Understanding the flow characteristics within gyroid structures is crucial for optimizing their performance in various engineering applications, as flow characteristics directly influence pressure drop, transport phenomena, and overall system efficiency. In applications such as fluid mixing, filtration, and energy conversion, precise knowledge of the flow dynamics enables better design and operational control, ensuring enhanced performance and durability. For instance, in energy conversion systems, gyroid structures are increasingly explored for their role in fuel cells and batteries [4] where their topology enhances reactant distribution, improves electrochemical performance, and facilitates effective heat dissipation. This study presents an investigation of laminar airflow behavior within a gyroid structure, providing insights into its hydrodynamic characteristics and potential engineering applications.

In our prior research, we conducted a computational fluid dynamics (CFD) study to examine the air flow dynamics within Schwarz-D triply periodic minimal surface (TPMS) structures. The investigation primarily focused on evaluating pressure drop characteristics at both the full-scale and representative elementary volume (REV) scale. The findings revealed a good correlation between the simulated pressure drops and experimental measurements. Furthermore, the REV-scale simulations exhibited close agreement with both experimental data from the literature and full-scale CFD predictions, demonstrating their reliability in capturing fluid dynamic behavior within TPMS structures [5], [6].

Building on these findings, the present study extends the investigation of airflow within a Gyroid TPMS structure, utilizing only REV scale simulations. Through single-phase CFD simulations under both laminar steady and unsteady flow conditions, this work aims to predict pressure drop and analyze the influence of porosity on fluid flow characteristics. Unlike prior study, for laminar unsteady simulations, flow fluctuation intensity is calculated within the Gyroid structure's flow domain by measuring air velocity fluctuations in main flow direction at ten probes placed at different locations in the domain. These analyses provide a deeper understanding of airflow behavior in Gyroid TPMS structures, offering valuable insights into their fluid dynamic performance under varying flow conditions. This paper aims to explore the significance of gyroid structures and their potential in optimizing performance in the field of chemical engineering.

2. METHODOLOGY

The flow characteristics within Gyroid TPMS structures were analyzed using CFD simulations. The Gyroid TPMS structures were generated in Autodesk Fusion 360 and exported as STL files, which were then imported into STAR-CCM+ for CFD analysis. Three distinct Gyroid TPMS structures with porosities of 50%, 60%, and 70% were selected for investigation, allowing for a systematic study of how increasing porosity affects the flow characteristics such as pressure drop, velocity distribution, and flow fluctuations. To ensure geometric consistency and isolate the effect of porosity, the unit cell size (UCZ) was kept at a constant value of 3 mm across all cases.

The CFD simulations were conducted using air as the working fluid under both steady and unsteady laminar flow conditions to capture air flow behavior relevant to low-Reynolds number regimes. The simulations were performed at the REV scale, utilizing a computational domain composed of two repeating unit cells. Periodic boundary conditions were applied on the 4 sides to emulate an infinitely repeating Gyroid structure. This CFD simulation approach significantly reduces computational cost and resource requirements compared to full-scale CFD simulations, while still capturing the essential transport phenomena within the porous structure. By focusing on the REV scale, the analysis remains physically representative and computationally efficient, making it particularly suitable for parametric studies of flow behavior in complex geometries such as Gyroid TPMS structures.

First, the Reynolds number threshold beyond which a steady laminar flow model is no longer applicable was identified. Then, laminar unsteady CFD simulations were conducted to evaluate the unsteady flow within the flow domain. To confirm the onset of transition, flow fluctuation intensity was computed based on velocity fluctuations along the flow direction. This analysis was carried out using 10 probes placed at different locations within the flow domain to capture localized variations and assess early-stage flow fluctuation intensity.

2.1. CFD Simulation Setup

The REV-scale simulation setup for single-phase flow through the Gyroid TPMS structure with 50% porosity and a UCZ of 3 mm is depicted in Figure 1. The computational domain was created as a rectangular box, with a length six times the UCZ and a width equal to the UCZ, as shown in Figure 1. To define the flow region for the CFD simulation, the Gyroid structure was subtracted from the rectangular domain.

As illustrated in Figure 1, periodic boundary conditions were applied on all four lateral walls in the REV setup, while velocity inlet and pressure outlet boundary conditions were assigned at the inlet and outlet, respectively. The simulations were conducted using air with a constant density, flowing through the Gyroid TPMS structure under both steady and unsteady laminar conditions. A laminar, segregated flow model was employed for all CFD simulations.

To assess the pressure drop after the CFD simulation, two plane surfaces, P1 and P2, were positioned 3 mm apart, as shown in Figure 1. For steady laminar flow, the pressure drop ($\Delta P = P1 - P2$) was obtained by computing surface-averaged pressure reports at these planes during post-processing. For unsteady laminar flow, the pressure drop was measured as the temporal evolution of the space- and time-averaged pressure drop at the same plane surfaces, P1 and P2. This simulation framework was implemented for all cases with 50%, 60%, and 70% porosity.

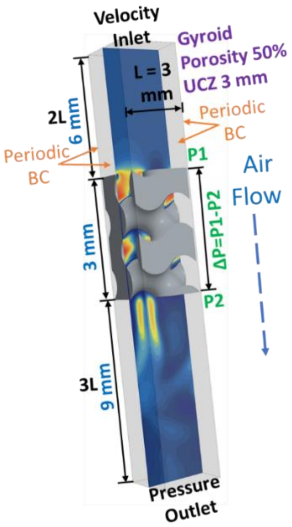

Figure 1. CFD setup for Representative Elementary Volume (REV) scale simulation.

2.2. Meshing

As depicted in Figure 2, the polyhedral mesh was generated using the automated meshing tool of STAR-CCM+ after defining the flow domain. A global base mesh size of 0.36 mm was chosen to ensure adequate resolution for capturing essential flow characteristics. To accurately model boundary layer effects and resolve near-wall regions, nine prism layers were incorporated, with a total thickness equivalent to 20% of the base size. A volume growth rate of 1.2 was applied to maintain a smooth cell size transition and ensure high mesh quality across the flow domain. Furthermore, a volumetric control mesh was introduced around the Gyroid Structure, with a base size set to 10% of the global mesh size, improving the mesh resolution to accurately capture the air flow within the structure. The final mesh contained approximately 2.5 million polyhedral cells for the simulation case with 50% porosity.

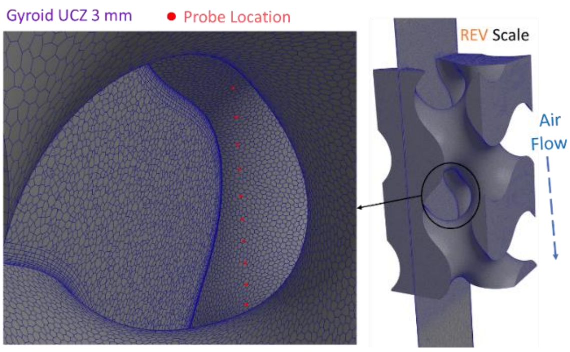

Figure 2. REV-scale polyhedral mesh with prism layers and designated probe locations for flow fluctuation intensity measurement.

As shown in Figure 2, ten probe locations were placed within the computational domain to measure velocity over time during the laminar unsteady simulations. At each probe location, the velocity component in the main flow direction (z-direction) was recorded at each time step. The velocity values at each probe location were then averaged over the simulation time to obtain a representative mean velocity for each specific location. This averaged velocity data was subsequently used to calculate the flow fluctuation intensity, which serves as a key indicator for assessing the presence of flow fluctuations within the domain. By analyzing the flow fluctuation intensity, this study was able to confirm whether the flow remained steady or exhibited unsteady behavior across the Gyroid TPMS structures.

Pre-processing, simulation, and post-processing were performed with Simcenter STAR-CCM+ (version 2302, Siemens Product Lifecycle Management Software Inc., Plano, TX, USA). The numerical simulations were run on a parallel computing system at the Max Planck Research Institute in Magdeburg, which featured 11th Gen. Intel Core i7-11700 processors operating at 2.50 GHz, each equipped with 64 GB of RAM.

2.3. Flow Properties

The hydraulic diameter is a generalized measure of length scale, independent of specific geometric details. It is calculated from the total surface area and the porosity of the structure.

$$D_h = \frac{4\phi V}{A}$$

where D_h is the hydraulic diameter, ϕ is the porosity, V is the total volume and A is the wetted surface area. The Reynolds number ($\mathrm{Re_h}$) is defined using the hydraulic diameter D_h as:

$$\mathrm{Re_h} = \frac{\rho u_s D_h}{\mu\phi},$$

where $\mathrm{Re_h}$ is the Reynolds number based on hydraulic diameter, ρ is the fluid density, u_s is the superficial velocity and μ is the dynamic viscosity.

Flow fluctuation intensity is one of the most straightforward and widely used methods for quantifying the magnitude of temporal velocity variations relative to the mean flow velocity in fluid dynamics. It serves as a non-dimensional indicator that reflects the degree of unsteadiness or turbulence in the flow field. In the context of laminar unsteady simulations, where the flow may exhibit periodic or aperiodic fluctuations even in the absence of turbulence, flow fluctuation intensity provides a clear and quantifiable measure of how much the instantaneous velocity deviates from its time-averaged value. This metric is particularly useful in characterizing transitional or turbulent behaviors that are not captured by steady-state simulations.

Mathematically, the flow fluctuation intensity is computed by taking the root mean square of the fluctuating component of the velocity defined as the difference between the instantaneous velocity and the mean velocity and dividing it by the mean velocity itself, typically expressed as:

$$I = \frac{u'_{rms}}{\bar{u}}, \qquad u'_{rms} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(u'_i)^2}$$

where u'_{rms} is the root-mean-square of the fluctuations and $\bar{u}$ is the mean velocity.

3. RESULT AND DISCUSSION

In the CFD simulation of airflow through Gyroid TPMS structures, the behavior of the flow was initially evaluated using a laminar steady-state model. For the structure with 50% porosity, the simulations demonstrated good convergence characteristics, with continuity residuals falling below the threshold of 10^{-6} for hydraulic Reynolds numbers up to 70. However, when the hydraulic Reynolds number exceeded this limit, the steady-state model failed to converge, and oscillatory residual patterns began to emerge, indicating the breakdown of the steady flow assumption and the onset of unsteady flow behavior. This transition suggests that beyond the hydraulic Reynolds number of 70, the flow becomes time-dependent, necessitating the use of a laminar unsteady model to accurately resolve the evolving flow field.

Similarly, for the Gyroid structure with 60% porosity, the laminar steady model remained effective and well-converged, maintaining residuals below 10^{-6} up to a hydraulic Reynolds number of approximately 120. A comparable trend was observed for the 70% porosity Gyroid structure, where steady-state simulations remained stable and continuity residual converged below 10^{-6} up to the hydraulic Reynolds number of 210. Beyond these limits, oscillatory residuals emerge, signifying the transition to unsteady flow.

To appropriately capture the unsteady characteristics of the flow in these regimes, laminar unsteady simulations were carried out. Specifically, for the 50% porosity structure, unsteady simulations were performed for hydraulic Reynolds numbers ranging from 80 to 100. For the 60% and 70% porosity structures, the unsteady simulations covered hydraulic Reynolds number ranges of 130 to 150 and 220 to 240, respectively. These simulations enabled the resolution of transient flow phenomena that could not be captured under steady assumptions. Furthermore, the presence of unsteady airflow was validated through the quantification of flow fluctuation intensity, confirming the necessity of time-dependent model to accurately characterize the fluid dynamics within the TPMS structures at relatively high hydraulic Reynolds numbers.

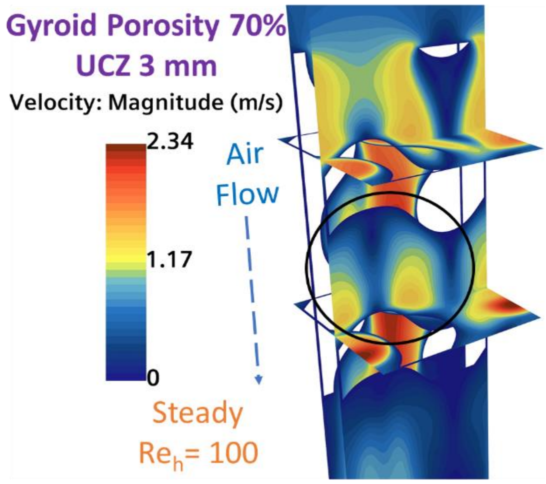

Figure 3(a). Velocity profile for steady laminar CFD simulations at Re$_h$ =100.

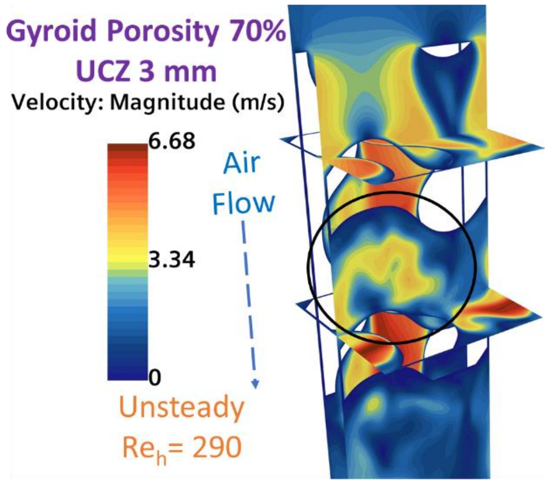

Figure 3(b). Velocity profile for unsteady laminar CFD simulations at Re$_h$ = 290.

Figure 3 presents a comparative analysis of the velocity magnitude within a gyroid triply periodic minimal surface structure at different hydraulic Reynolds numbers: 100 (steady flow) and 290 (unsteady flow). At the lower hydraulic Reynolds number (top) the flow exhibits a quite uniform velocity profile throughout the structure, with relatively low maximum velocities. In contrast, at the higher hydraulic Reynolds number (bottom), the flow becomes fluctuating. Notably, within the black circled region, representing a specific section of the gyroid unit cell, the velocity magnitude increases substantially under unsteady flow conditions. This suggests the onset of inertial effects and potentially localized flow acceleration within the Gyroid geometry as the Reynolds number rises, leading to a more dynamic airflow behavior compared to the lower Reynolds number.

Figure 4 shows the variation in pressure drop as a function of the hydraulic Reynolds number (Re_h) for a gyroid structure at different porosities (ϕ), considering either steady or unsteady laminar flow conditions. The results indicate a clear dependence of pressure drop on both porosity and hydraulic Reynolds number. At a given Re_h, a decrease in porosity leads to a significant increase in pressure drop due to the reduced flow passage and enhanced flow resistance. As a consequence, the structure with ϕ=50% exhibits the highest pressure drop, followed by ϕ=60% and ϕ=70%, in both steady and unsteady flow cases. Moreover, as Re_h increases, the pressure drop rises non-linearly due to the increasing inertial effects, which intensify the flow resistance through the porous Gyroid structure.

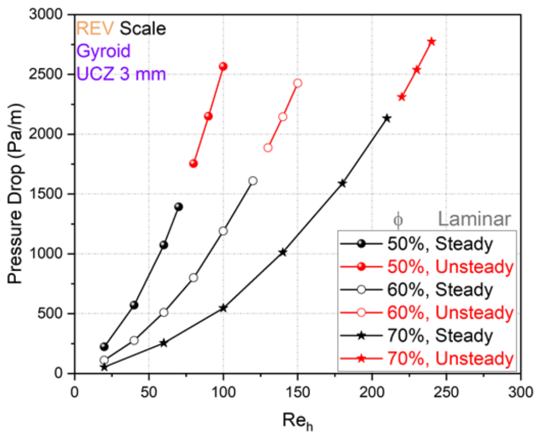

Figure 4. Pressure drop comparisons in gyroid structures (50–70% porosity) for steady or unsteady laminar CFD simulations.

The onset of unsteadiness occurs at progressively lower Re_h as porosity decreases, indicating a stronger influence of structural confinement on flow stability. These findings emphasize the critical role of porosity in controlling pressure drop characteristics and the transition between steady and unsteady laminar airflows in porous Gyroid structures.

Figure 5 presents the variation in flow fluctuation intensity (%) with the hydraulic Reynolds number for structures with different porosities (50%, 60%, and 70%). The results indicate that flow fluctuation intensity generally increases with increasing Reynolds number, marking the transition from laminar steady flow to unsteady flow. At lower Re_h, the intensity remains minimal, suggesting a stable laminar flow. However, as Re_h increases, a significant rise in flow fluctuation intensity is observed, indicating the onset of transitional flow.

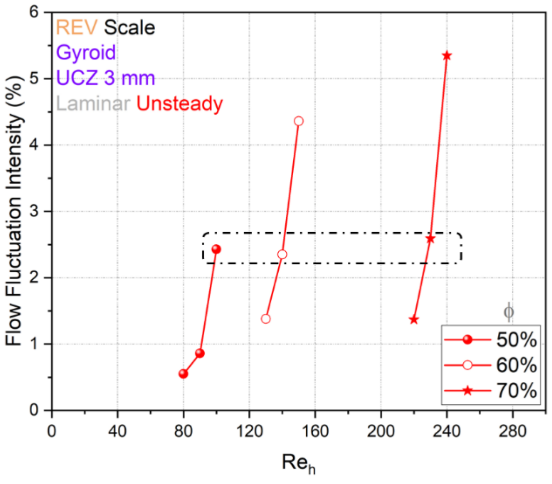

Figure 5. Flow fluctuation intensity vs. hydraulic Reynolds number for various structural porosities, with a rectangular dotted line indicating nearly identical values across different Reynolds numbers.

For instance, in the 50% porosity case, the flow fluctuation intensity is 0.5% at a hydraulic Reynolds number of 80, whereas at 100, it increases sharply to 2.5%. This steep rise in flow fluctuation intensity within the Re_h range of 80–100 clearly signifies the transition from a steady to an unsteady airflow state. Additionally, porosity plays a crucial role in shaping flow fluctuation characteristics. A higher porosity (70%) leads to a greater increase in flow fluctuation intensity within a hydraulic Reynolds number increment of just 20, compared to lower porosities (50% and 60%). This is because a more open structure enhances flow interactions and promotes flow instability.

The dotted-line rectangular box in the figure highlights an interesting phenomenon where different Reynolds numbers exhibit nearly identical flow fluctuation intensity values. This suggests that variations in porosity can shift the transition points between laminar and unsteady flow. Such findings imply that porosity modifications can be strategically employed to control the flow regime based on different engineering application requirements. Thus, by optimizing porosity and unit cell size, this structure could be specifically tailored for target applications, such as filtration, heat exchangers, and chemical reactors, where a precise control over the flow regime is essential.

4. CONCLUSIONS

This study conducted a comprehensive CFD analysis of fluid flow through Gyroid TPMS structures under laminar steady and unsteady flow conditions, focusing on pressure drop and flow fluctuation intensity in REV scale configurations. The results demonstrate that while the laminar steady model provides accurate predictions of pressure drop for Reynolds numbers up to approximately 70 in the 50% porosity case, this threshold extends to 210 for the 70% porosity case, highlighting the influence of structural porosity on flow resistance.

The evaluation of flow fluctuation intensity under laminar unsteady conditions reveals a similar increase with hydraulic Reynolds number, indicating the transition from laminar steady to unsteady flow. For the 50% porosity case, a sharp rise in flow fluctuation intensity within the range of Re_h=80–100 marks the onset of flow instability. These findings provide valuable insights for the design and optimization of TPMS-based porous structures in engineering applications where pressure drop, permeability, and flow stability must be carefully balanced. The study underscores the importance of porosity selection in tailoring flow characteristics, contributing to improved performance and efficiency in industrial and scientific applications involving porous media.

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