

Topology-dependent fluid transport in gyroid and diamond TPMS bone scaffolds: a comparative CFD study of hydraulic resistance and permeability

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Abstract: The fluid-transport characteristics of porous scaffolds play a critical role in bone tissue engineering (BTE) by governing nutrient delivery, oxygen transport, metabolic waste removal, and the hydrodynamic environment experienced by cells. Triply periodic minimal surface (TPMS) architectures offer interconnected and continuous pore networks with considerable potential for regulating these transport phenomena. However, their hydraulic performance is strongly dependent on topology. This study presents a comparative computational fluid dynamics (CFD) investigation of Gyroid and Diamond TPMS scaffolds to elucidate the influence of topology on pressure distribution, velocity characteristics, hydraulic resistance, and permeability. The porosity (ϵ) was calculated as 84.5% for the Gyroid scaffold and 80.8% for the Diamond scaffold. Both architectures were evaluated under identical computational conditions, with water entering the scaffold at 0.002 m s^{-1} and 37°C . The Reynolds number was used to characterize the flow regime, while Darcy's law was employed to quantify scaffold permeability. A grid-independence analysis demonstrated numerical convergence at approximately 2–3 million elements, confirming that mesh refinement produced only minor changes in the predicted flow characteristics. The simulations revealed distinct topology-dependent flow behaviour. The Diamond scaffold exhibited stronger local flow acceleration, with a maximum velocity of approximately 0.2933 m s^{-1} , whereas the Gyroid scaffold produced a lower maximum velocity of approximately 0.1489 m s^{-1} and a more uniformly distributed flow field. Despite its lower peak velocity, the Gyroid architecture demonstrated substantially greater permeability, reaching $8.527 \times 10^{-9} \text{ m}^2$ compared with $2.862 \times 10^{-9} \text{ m}^2$ for the Diamond scaffold, corresponding to approximately a threefold increase in permeability. The continuous and smoothly interconnected Gyroid topology promotes more uniform flow and reduced hydraulic resistance, resulting in enhanced scaffold-scale fluid transport.

Keywords: Triply Periodic Minimal Surface, computational fluid dynamics, bone scaffold.

1. Introduction

The regeneration of bone defects remains a major challenge in orthopaedic and regenerative medicine because the intrinsic healing capacity of bone may be insufficient for large defects. Even though autologous bone grafts represent a successful treatment option, their use is restricted due to complications or limitations associated with the harvesting of donor tissues[1]. The above-stated issues have stimulated the development of tissue engineering technologies which are used for the creation of scaffolds that serve as temporary

structures and help in providing a support for the cells that attach, proliferate, grow blood vessels, create an extracellular matrix, and repair the bone tissues[2,3]. The challenge is to have an effective bone scaffold achieve the mechanical stability, yet at the same time, provide interconnected pores for the purpose of allowing the passage of cells, blood vessels, nutrients, oxygen, and other metabolic waste products[4,5]. This becomes complicated because pore interconnectivity, porosity, mechanical strength, and the transport of fluids are tightly intertwined. Although conventional strut-type lattice structures can provide desired porosity and mechanical properties, these structures may lead to irregular pore geometry and flow distribution due to the use of discrete elements with sharp intersections[6,7].

Architecture incorporating triply periodic minimal surface (TPMS) has emerged as an efficient choice for the development of scaffold materials that can mimic natural bone tissue by providing continuous, smooth, and well-interconnected 3D porous structure[8,9]. In contrast to the traditional lattices made of struts, TPMS - structures produce continuous curved channels of the material and thus lack sharp intersections[10]. Mathematical modeling of these structures enables the systematic control over their porosity and pore geometry. Therefore, the following parameters can be controlled in one TPMS architecture: fluid transport and permeability, surface area, pore interconnectivity, and mechanical properties[11]. Out of the various TPMS designs, Gyroid and Diamond models are of great interest because of their different designs of channel networks enabling different flow characteristics. Fluid transport within porous scaffolds is essential because convective flow facilitates the delivery of nutrients and oxygen for removal of metabolic waste. Because it is the transport of nutrients and oxygen that primarily happens as a result of the flow through the pore network, influencing the local hydrodynamics[12]. Thus, it is inadequate to analyze the quality of scaffolds merely in terms of their porosity and mechanical properties.

Several other factors must be taken into account, including pressure distribution, velocity field, pressure loss, hydraulic resistance, and permeability, which provide some additional information on how well fluids flow in a porous structure[13]. Internal topology plays a key role in the relationship between the above-listed parameters and fluid dynamics since the shape, size, and direction of pore constrictions, or even pore shape influence the local velocity profile and pressure[14]. As a result, two scaffolds may have the same level of porosity, but different fluid-transport properties.

The use of computational fluid dynamics (CFD) supplies a suitable tool to investigate such challenging fluid flow phenomena, and correlates the architecture of scaffolds to the hydraulic performance[15–17]. Here, the Reynolds number will be utilized to characterize the flow regime, while the permeability of the scaffold is determined from the pressure drop across the porous medium through Darcy's law[18]. Simulation conditions are kept the same between both structures so that experimental results are comparable. Water enters the computational domain at a speed of 0.002 m s^{-1} and temperature of 37°C with scaffold walls described as no slip condition and free outflow set at the outlet[19,20]. Using the same conditions leads to having the differences in the flow behavior linked to the architectural properties of both scaffold topologies.

Even with the growing use of TPMS designs in the field of tissue engineering, an important question with regards to the relation of topology and hydraulic transport efficacy remains unanswered[21]. A topology with high maximum velocity does not necessarily provide good fluid transport on the scaffold scale as strong local acceleration is often associated with high pressure losses and resistance[22]. Also, it may be the case that uniformity of the flow field leads to lower hydraulic resistance as well as enhanced permeability. Thus, a detailed comparison of TPMS scaffolds should take into account several hydraulic parameters instead of only velocity or pressure[23]. This point is essential with regards to Gyroid and Diamond architectures because they have different channel shapes and respectively may create different pressure and velocity fields[24].

This study makes a comparative analysis of Gyroid and Diamond TPMS scaffolds in relation to their fluid-transport properties. Calculated values and trends such as pressure distribution, pressure gradient, velocity fields, hydraulic characteristics, and permeability are analyzed under similar conditions. Furthermore, the grid independence test is conducted to prove the reliability of the employed numerical methods. In this study, it has been shown that the two architectures have different flow characteristics, where the flow in the Diamond architecture is stronger than the one in the Gyroid architecture. It must be

mentioned that the value of the calculated permeability for Gyroid scaffold is $3.879 \times 10^{-9} \text{ m}^2$, while the value of the same parameter for Diamond architecture is considerably smaller and equals $1.301 \times 10^{-9} \text{ m}^2$. The results obtained can be used to select architectural designs for TPMS bone scaffolds requiring proper operation of the flows within the scaffold.

2. Mathematical formulations

To define a TPMS, a trigonometric level-set-based blending function is employed to continuously interpolate between two distinct TPMS topologies. The gyroid and diamond TPMS geometries are mathematically defined by [8,25].

$$\text{Gyroid: } f(x, y, z) = \cos(\omega_x x) \sin(\omega_y y) + \cos(\omega_y y) \sin(\omega_z z) + \cos(\omega_z z) + \sin(\omega_x x) = C \quad (1)$$

$$\text{Diamond: } f(x, y, z) = \cos(\omega_x x) \cos(\omega_y y) (\omega_z z) - \sin(\omega_x x) \sin(\omega_y y) \sin(\omega_z z) = C \quad (2)$$

The wave vectors along three coordinate (x, y, and z) directions are defined as $\omega_x = 2\pi\alpha$, $\omega_y = 2\pi\beta$, and $\omega_z = 2\pi\gamma$ respectively, where α , β , and γ denote the cyclicity limits of the TPMS geometries. Those limits are determined on the number of unit cells N along with coordinate each spatial direction and the conforming unit cell size L, as presented as $\alpha = \frac{N_x}{L_x}$, $\beta = \frac{N_y}{L_y}$, and $\gamma = \frac{N_z}{L_z}$. where N_x , N_y , and N_z represent the number of unit cells along the x, y, and z directions, respectively, and L_x , L_y , and L_z denote the corresponding domain lengths. Substituting these expressions into the wave vector definitions yields $\omega_x = 2\pi \left(\frac{N_x}{L_x} \right)$, $\omega_y = 2\pi \left(\frac{N_y}{L_y} \right)$, and $\omega_z = 2\pi \left(\frac{N_z}{L_z} \right)$. The continual value C defines the external of each TPMS comparison and was methodically familiar to achieve aim scaffold porosities.

The Reynolds number (Re) was calculated to characterize the flow regime within the porous TPMS scaffold using the following relationship:

$$Re = \frac{\rho \cdot u \cdot D_p}{\mu} \quad (3)$$

Where, Re is the dimensionless, ρ is the fluid density ($\text{kg} \cdot \text{m}^{-3}$), u is the superficial fluid velocity ($\text{m} \cdot \text{s}^{-1}$), D_p is the maximum pore diameter (m), and μ is the viscosity of the fluid ($\text{Pa} \cdot \text{s}$). This dimensionless parameter is used to determine the dominant flow regime and assess whether the fluid flow through the scaffold is predominantly laminar or turbulent.

The permeability of the TPMS geometry can be determined using Darcy's law as:

$$K = \frac{u \cdot \mu \cdot L_T}{\Delta P} \quad (4)$$

Wherever, K is the scaffold permeability m^2 , L_T is the scaffold height (m), and ΔP is the pressure drop across the scaffold (Pa). The permeability coefficient quantifies the capacity of the porous scaffold to allow fluid transport through its interconnected pore network.

$$\text{Porosity } (\varepsilon) = \left(\frac{V_v}{V_t} \right) \times 100 \quad (5)$$

Where, V_v is Volume of void space (the "empty" space or pores inside the material) and V_t is Total or bulk volume (the total volume of the material, including both solids and voids).

$$\text{Pressure drop } (\Delta P) = P_{in} - P_{out} \quad (6)$$

Where, P_{in} is inlet pressure and P_{out} is pressure outlet.

2.1 Thermophysical and properties of PLA

The PLA used in the numerical analysis had a density of $1240 \text{ kg} \cdot \text{m}^{-3}$, a specific heat capacity of $1800 \text{ J} \cdot \text{kg}^{-1} \cdot \text{K}^{-1}$, and a thermal conductivity of $0.13 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$. Its mechanical properties included a Poisson's ratio of 0.36 and a Young's modulus of $3.5 \times 10^9 \text{ Pa}$. These thermophysical and mechanical properties were used to define the PLA scaffold material in the numerical simulations.

2.2 Boundary conditions and computational domain of diamond and gyroid TPMS scaffolds

Figure 1 shows the computational fields and boundary conditions applied for the Gyroid and Diamond TPMS structures. Both structures were tested under identical conditions so that a direct assessment of the two structures could be completed. Fluid enters through the top inlet region at the speed of $0.002 \text{ m} \cdot \text{s}^{-1}$ and temperature of 37°C at the dimension of diameter 12 mm, thickness of 0.5 mm, height is 22 mm, and cell size of $4 \times 4 \times 4 \text{ mm}$. The porosity (ϵ) was calculated as 84.5% for the Gyroid scaffold and 80.8% for the Diamond scaffold, corresponding to solid fractions of 15.5% and 19.2%, respectively. After that fluid flows through the interconnected porous network, where different TPMS structures influence the flow. A free-outflow boundary condition was applied in the outlet region to let fluid exit from the TPMS structure without additional pressure conditions. The sides of TPMS structure acted as no-slip walls that simulate the interaction of fluid and PLA scaffold. Keeping the same boundary conditions for both structures allow reverting observed differences in the flow to the differences in geometry of Gyroid and Diamond geometries.

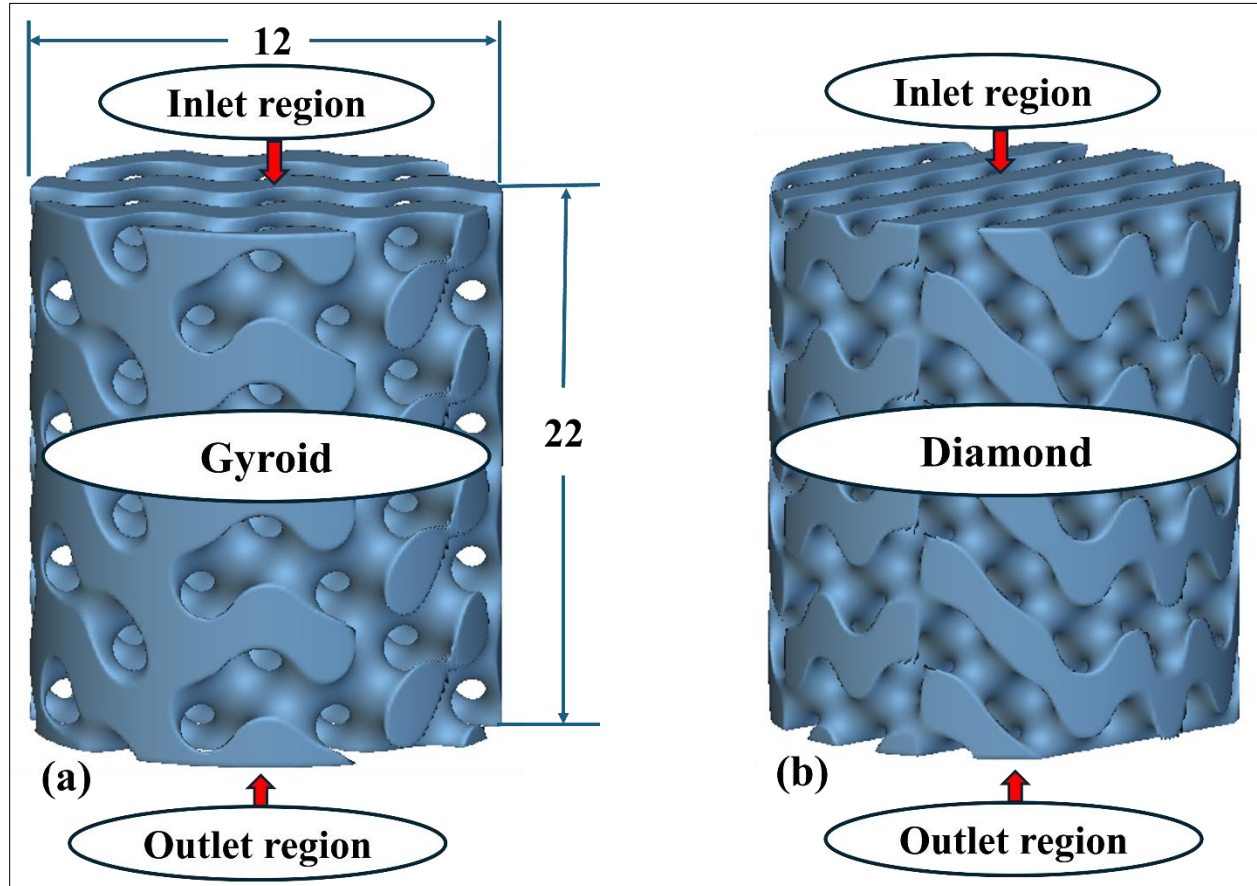


Figure 1. Boundary condition (a) Gyroid and (b) Diamond TPMS structures

2.3 Numerical validation

The numerical validation of the calculated permeability in Gyroid and Diamond TPMS scaffolds has been shown in **Figure 2** with the reference results obtained from Zhang Yu and Paolo Colombo. The results presented in the indicate that the predicted permeability in this study closely corresponds to the values in the source of information obtained from Zhang Yu and Paolo Colombo. In case of the Gyroid method, the permeability of $1.50 \times 10^{-10} m^2$ obtained in this study was increased to $8.53 \times 10^{-10} m^2$, which indicates a small relative error. Talking about the Diamond method, the value of permeability predicted earlier as $2.86 \times 10^{-10} m^2$ matches the reference data exactly with a relative error, which is highly significant. Observation of the reduced disparity in the Diamond structure demonstrates excellent agreement between the implementation of the numerical approach and the published benchmark.

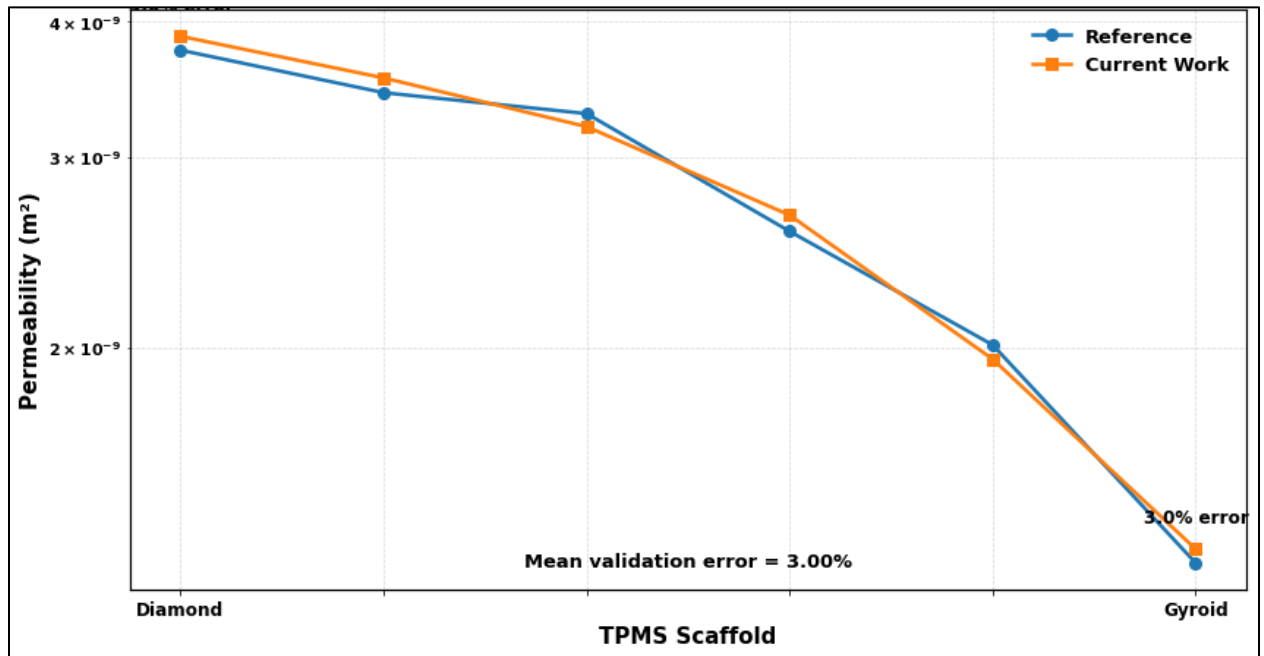


Figure 2. Numerical validation of TPMS scaffold permeability from Zhang Yu and Paolo Colombo [26]

2.4 Grid independence analysis

The grid independence study shows that the numerical solutions for the Diamond and Gyroid TPMS scaffolds become practically unaffected by further mesh refinement shown in the **Figure 3**. In particular, for the Diamond TPMS, the highest velocity initially increases fast with mesh refinement at the coarser levels until it becomes stable at around 0.09595 m/s while the pressure drop continuously stabilizes at about 15.37 Pa. Further refinement beyond around 3-4 million elements hardly changes these characteristics; for instance, the pressure drop virtually does not change from 15.35 Pa at 3 million elements to 15.37 at 6 million elements, which corresponds to a variation of around 0.13%. The same can be said about the maximum velocity, which also changes by about 0.05% in the mentioned range. The Gyroid TPMS shows similar convergence behavior, where the maximum velocity becomes about 0.1287 m/s, and the pressure drop is around 5.16 Pa. Also, the pressure drop does not change much, going from about 5.15 to 5.16 Pa, which

corresponds to only 0.19%. Thus, the findings indicate that additional mesh refinement does not substantially alter the main flow characteristics. Therefore, the optimal mesh has been identified to be grid independent and providing a good compromise between numerical accuracy and computational effort in the subsequent CFD process.

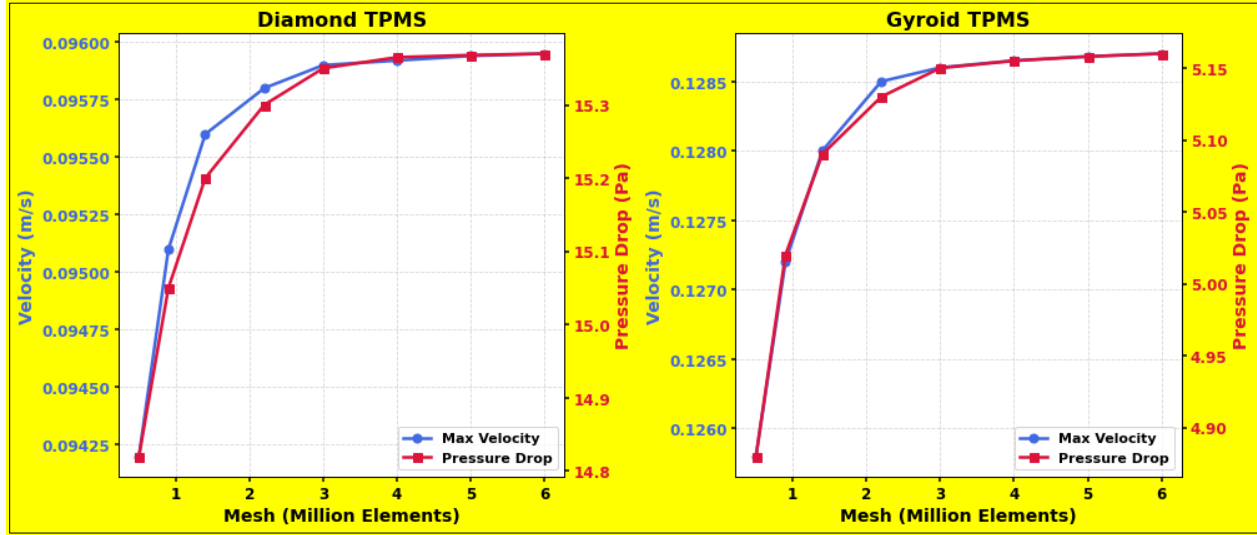


Figure 3. Grid independence and mesh convergence analysis

3. Results and discussion

3.1 Pressure distribution

3.1.1 Pressure distribution of the diamond TPMS scaffold: **Figure 4** depicts the pressure distribution in the Diamond TPMS structure. The irregular pressure profile is due to the variation of flow direction and the increase/ decrease of the pore size. From the pressure profile, pressures in the Diamond TPMS are calculated to be within the interval -11.81 to 15.37 Pa, where the majority of green areas correspond to the reference pressures, blue regions relate to lower pressures and localized high-pressure areas demonstrate positive pressures.

The intricate curves and many channels of the Diamond architecture create a continuous change in fluid momentum, which results in localized pressure changes on the surface of the scaffold. Such changes in pressure are crucial in bone tissue engineering through the aspects of fluid transportation in porous structures and the effect of mechanical and biochemical signals received by cells. In essence, the Diamond TPMS shows that a strongly interlinked pressure distribution field exists but is heterogeneously arranged throughout the 3D structure.

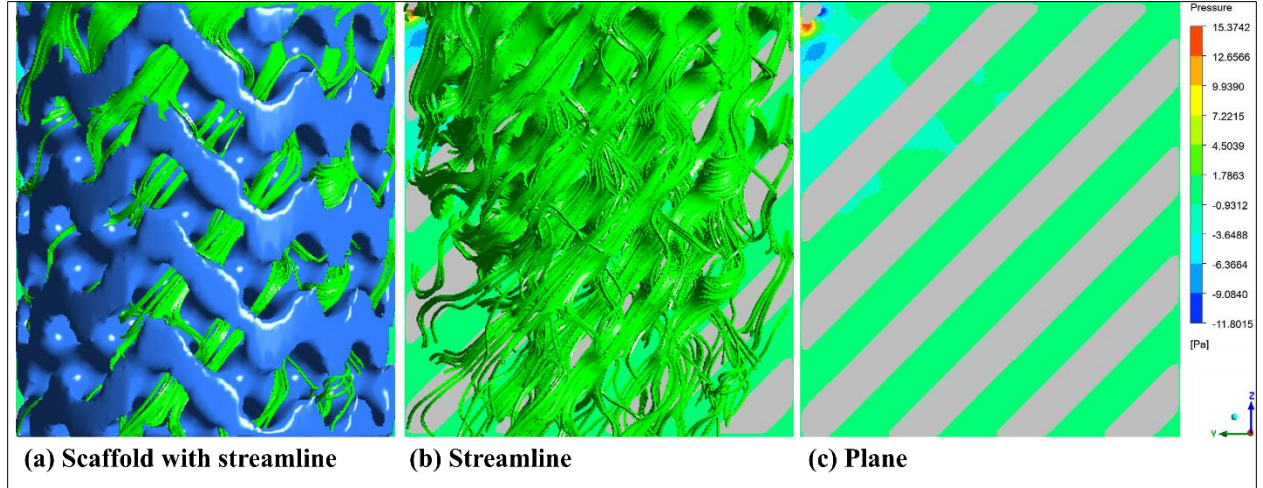


Figure 4. Numerical analysis of pressure gradients in the diamond TPMS architecture

3.1.2 Pressure distribution characteristics of the gyroid TPMS scaffold: The simulated pressure mapping of Gyroid TPMS scaffold is presented in **Figure 5**. The pressure field appears to be distributed differently across the entire interconnected network of Gyroid pores, where the range observed was -11.05 to 5.16 Pa. The green regions show the pressure being around the nominal value. The blue regions display lower pressure zones. Yellow and orange regions, as well as localized red regions, reflect higher pressures generally because their position coincides with the place where the flow meets the obstacles.

The Gyroid architecture is represented by the ongoing and easily bent channels that allow for gradual changes in the flow direction, thus creating more or less uniform pressure gradients in the scaffold. The streamlines illustrate effective fluid penetration and continuous distribution of the fluid throughout the pores. Such pressure variations are essential for bone tissue engineering because they affect fluid perfusion, transport of nutrients, and local mechanical conditions experienced by cells. Thus, the Gyroid TPMS represents a system with a big degree of interconnection of flow paths, which contain localized pressure gradients due to the constrictions and curvatures of the pores.

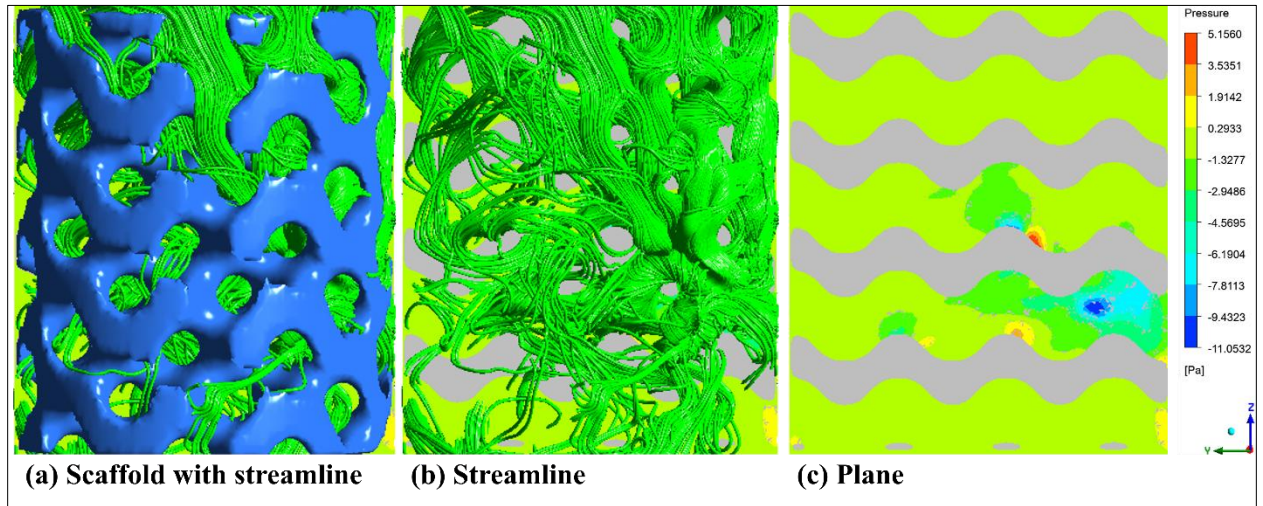


Figure 5. Numerical evaluation of pressure gradients in the gyroid TPMS architecture

3.1.3 Comparative analysis of pressure drop and hydraulic resistance: The analysis of pressure drops from **Figure 6** shows that there is a significant difference in hydraulic resistance between the Diamond TPMS and the Gyroid TPMS. The pressure drop in Diamond TPMS is equal to about 15.37 Pa according to **Figure 6** (a), which is obviously higher than 5.16 Pa in Gyroid TPMS. This means that Diamond TPMS causes greater resistance to fluid flow and results in higher pressure gradient being required for the fluid movement. The respective pressure gradient curves in **Figure 6** (b) reflects this tendency. Indeed, the local pressure decreases with the increase in normalized length for both TPMS types reaching about 0 at the outlet. But the pressure gradient for Diamond TPMS appears to be much steeper than for that in the case of Gyroid TPMS. Thus, high-pressure drop-in Diamond TPMS should be caused by the complexity of its pores and the presence of high level of flow redirection as a result of which hydraulic resistance being created is higher than in the case of the Gyroid TPMS.

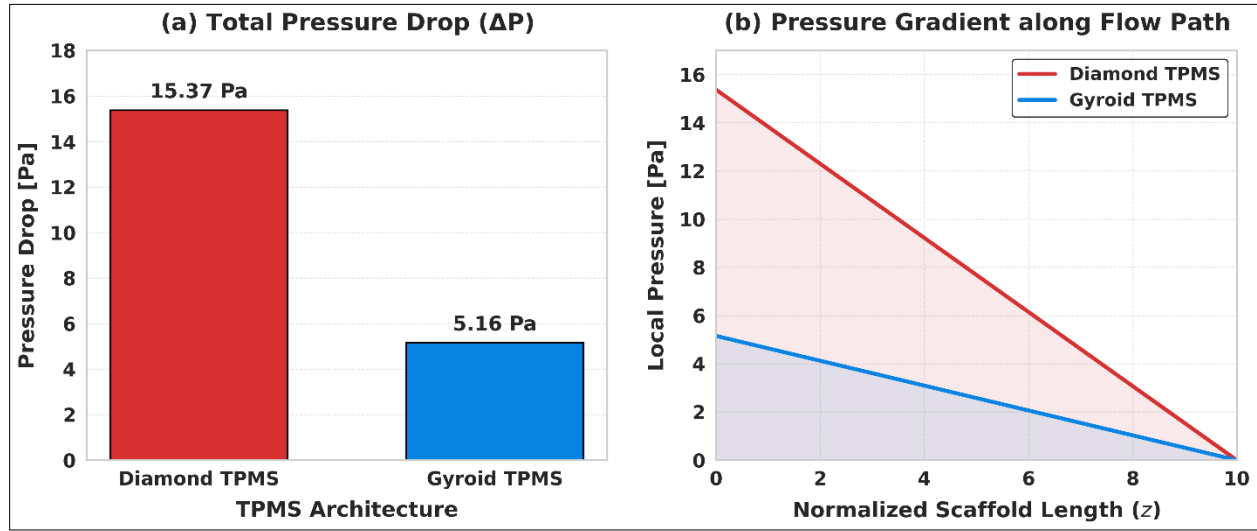


Figure 6. Pressure gradient and flow resistance characteristics of TPMS architectures

3.2 Velocity distribution

3.2.1 Velocity distribution characteristics of the diamond TPMS scaffold: The simulated velocity distribution including the Diamond TPMS scaffold is presented in **Figure 7**. The velocity characteristics of the flow appear to be distinctly heterogeneous, owing to the complex structure of the pore network in the Diamond topology. The velocity values in this context might vary from approximately 0 to $0.293 \text{ m}\cdot\text{s}^{-1}$. The largest share of blue regions in the illustrated velocity map represents those areas with low velocities, while the territory with averaged velocities is shown with green colors in the color spectrum.

At narrow pore openings and points of constriction, speed increases, while wider pore areas and the expanding flow regions have reduced speeds. The streamlines confirm the fact that the Diamond design facilitates constant changes in flow direction and has a great deal of interaction between the fluid and scaffold. The spatial differences in speeds matter for bone tissue engineering because they affect the delivery of nutrients, the flow of fluids, and the hydrodynamic stimulation of cells in the area. Thus, the Diamond TPMS displays an interconnected flow field with speed increase at narrower pore sections.

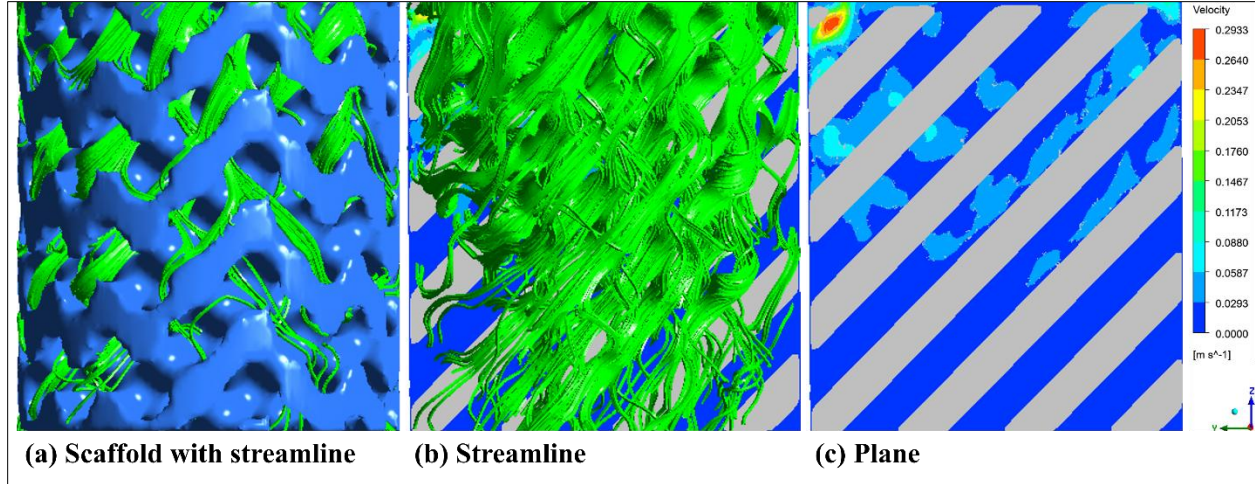


Figure 7. Numerical analysis of fluid flow velocity in the diamond TPMS architecture

3.2.2 Velocity distribution and flow characteristics of gyroid TPMS: The velocity distribution pattern of the Gyroid TPMS scaffold depicts a continuous and uniform fluid flow through the porous structure. **Figure 8** (a-c) shows that the streamlines follow the complex and interconnected Gyroid channels leading to speed changes due to variations in the pore size and flow direction. The contour lines of velocities range from almost 0 to 0.1489 m/s, thus higher speeds appear at the narrow pore areas where the water is accelerated, while lower velocities are found in wider areas. All in all, Gyroid structure provides uniform supply ability of fluids and interconnected flows, which contributes to the transportation of nutrients and oxygen. The more uniform flow distribution may be advantageous for nutrient transport and hydrodynamic stimulation in bone tissue engineering applications; however, these biological effects require experimental validation.

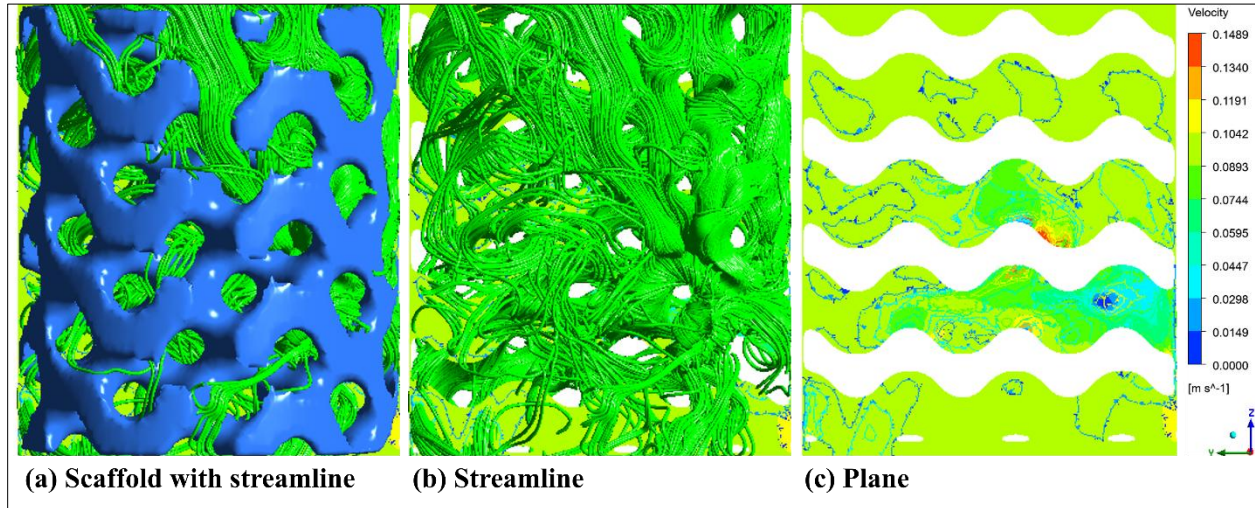


Figure 8. Hydrodynamic behavior of gyroid TPMS scaffolds for bone regeneration

3.2.3 Comparative analysis of velocity distribution: According to the velocity analysis in **Figure 9** (a), the Diamond TPMS architecture exhibits a maximum velocity of 0.2933 m/s, 1.97 times greater than 0.1489 m/s attained in case of the Gyroid TPMS architecture, thus indicating the higher local flow acceleration. Figure 9 (b) shows higher velocity distributed over much broader range of values of approximately 0.30 m/s, with a distinct higher tail, which illustrates much better spatial distribution and high flow region presence. On the contrary, Gyroid TPMS has the narrower velocity distribution around 0.05–0.08 m/s, thus meaning that the flow is perfectly uniform. Thus, while the Diamond TPMS enables more intense local flow acceleration, the Gyroid TPMS gives a uniform flow transfer, thus revealing a trade-off between intensity and uniformity of the flow in TPMS.

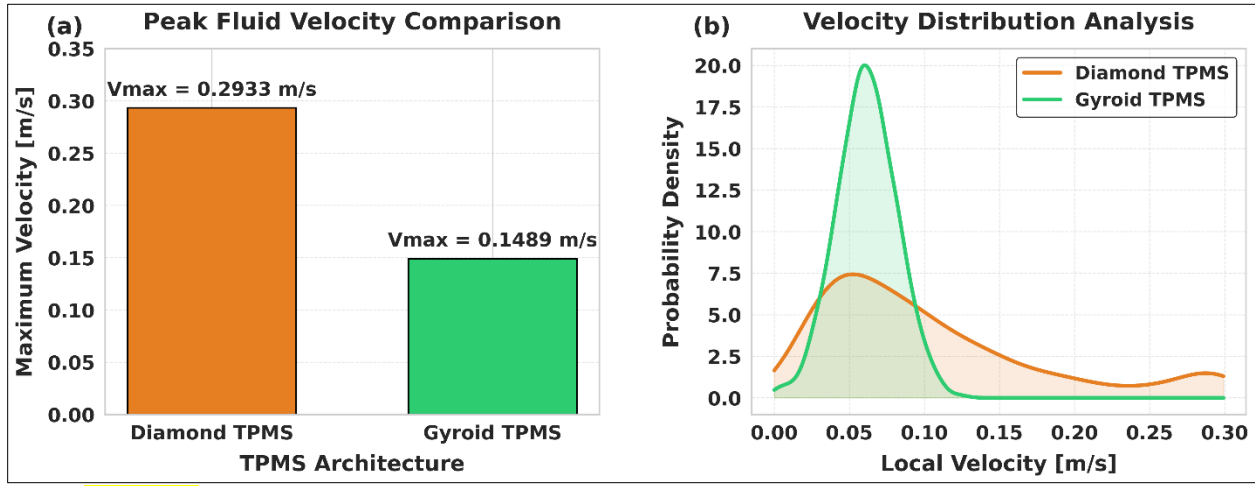


Figure 9. Computational domain and boundary conditions used for CFD simulations

3.3 Permeability comparison of diamond and gyroid TPMS scaffolds

The permeability results reveal a substantial difference in the hydraulic transport performance of the Diamond and Gyroid architectures are shown in the **Figure 10**. The permeability value for Diamond TPMS was found to be $2.862 \times 10^{-9} \text{ m}^2$, whereas the Gyroid TPMS had a much higher value of $8.527 \times 10^{-9} \text{ m}^2$, which means that the permeability of Gyroid TPMS was around 2.98 times higher, or close to 198% more than that of the Diamond TPMS scaffold. Therefore, it can be said that the higher permeability suggests lower hydraulic resistance of the Gyroid TPMS and better fluid transport through the pore network of this scaffold. On the contrary, the relatively lower permeability of Diamond TPMS indicates the greater flow resistance probably due to the fact that there are more complicated pore constrictions and flow redirection in its structure. Hence, the Gyroid architecture provides superior bulk permeability and more spatially uniform flow, whereas the Diamond architecture produces stronger local flow acceleration but greater hydraulic resistance.

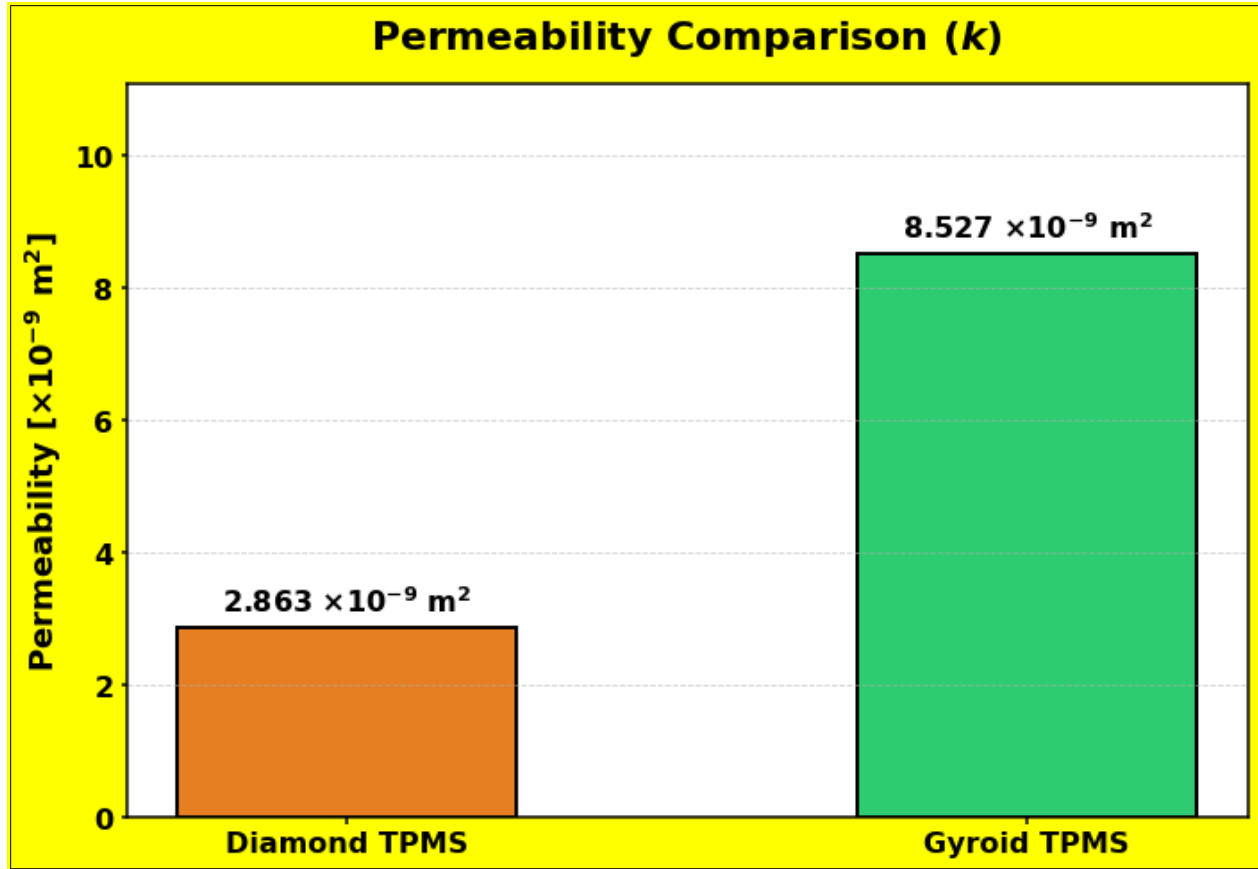


Figure 10. Hydraulic transport performance of TPMS architectures

Conclusion

This research examined the fluid-transport properties of Gyroid and Diamond TPMS scaffolds used in bone tissue engineering applications using computational fluid dynamics analysis. At the porosity (ϵ) of 84.5% for the Gyroid scaffold and 80.8% for the Diamond scaffold. The effect of TPMS topology on pressure distribution, velocity parameters, hydraulic resistance, and permeability was analyzed under the same boundary conditions. The grid independence test explained that the numerical solutions reached an adequate stability at about 2–3 million elements which indicated that higher degree of refinement of the mesh resulted in limited changes of the predicted velocities and pressure drop.

The research results indicated that there are significant disparities with regard to the hydrodynamic performance of the two TPMS models in question. The Diamond architecture had a more intense local flow acceleration, with the highest speed being around 0.293 m s^{-1} . The Gyroid design had a smaller maximum velocity of approximately 0.1489 m s^{-1} . At the same time, the distribution of speed inside the Gyroid model was more homogeneous than that in the Diamond architecture due to the continuous and uniformly interconnected pores of the structure. At the same time, the Diamond model had the highest variation of speed owing to the pore constrictions and changes in the flow direction. An important outcome of this study is that the maximum value of local velocity is not sufficient to describe the fluid-transport performance of the TPMS scaffold.

While Diamond had significantly higher local flow rates, Gyroid topology had significantly higher permeability levels. The calculated permeability of Gyroid was calculated to be $8.527 \times 10^{-9} \text{ m}^2$,

and compared to Diamond's $2.862 \times 10^{-9} \text{ m}^2$, the Gyroid scaffold has around 2.98 times higher permeability. This finding indicates that the Gyroid architecture, with its continuous curvature and connected flow ways, has a more efficient bulk fluid transport mechanism, whereas the complex flow reorientation and pore constrictions of Diamond architecture lead to greater hydraulic resistance.

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