

Magnetic Resonance Velocimetry-Based Analysis of Secondary Flow Structures and Flow Development in a Gyroid Channel for Small Modular Reactor Heat-Transfer Applications

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1. Introduction

The growing demand for low-carbon energy has increased interest in small modular reactors (SMRs) as compact and flexible energy systems. Their compact configurations require thermal-hydraulic components with high heat-transfer performance within limited volumes. Triply periodic minimal surface (TPMS) structures have therefore received attention as potential compact heat-transfer structures because their high specific surface area and interconnected three-dimensional passages can provide enhanced thermal performance [1]. Among these structures, the Gyroid geometry is particularly promising because it provides continuous flow passages with smoothly varying curvature. Recent advances in metal additive manufacturing have further expanded the applicability of TPMS structures to advanced energy and nuclear systems [2].

Previous investigations of Gyroid-based heat exchangers have primarily evaluated macroscopic parameters, including pressure drop, friction factor, and heat-transfer performance. For example, Li et al [3]. reported that a Gyroid structure exhibited approximately half the friction factor and 1.4 times higher Nusselt number than a printed circuit heat exchanger. However, such integral performance metrics do not fully explain the underlying transport mechanisms. The continuously varying geometry of a Gyroid channel can induce local acceleration and deceleration, flow redistribution, transverse motion, and secondary-flow structures. These local flow characteristics affect mixing and thermal-boundary-layer development and consequently influence heat-transfer performance. Quantitative measurements of the internal three-dimensional velocity field are therefore needed to identify geometry-induced flow structures and provide experimental data for validating computational fluid dynamics (CFD) models.

Magnetic resonance velocimetry (MRV) enables non-invasive measurement of time-averaged, three-dimensional, three-component velocity fields in optically inaccessible or geometrically complex channels [4]. Unlike optical velocimetry, MRV does not require optical access or refractive-index matching and is not affected by refraction at fluid–solid interfaces. MRV has also been applied to characterize secondary flows and

turbulent kinetic energy in other geometrically complex, opaque internal passages relevant to compact heat-transfer components [5]. Accordingly, MRV is suitable for resolving internal flow structures in TPMS channels.

In this study, MRV was used to measure the three-dimensional velocity field in a Gyroid flow channel at Reynolds numbers of 1000, 1500, and 2000, providing an experimental basis for CFD validation and for improving the understanding of flow behavior in Gyroid-based thermal-fluid systems. In porous media with continuously curved passages, such as the Gyroid structure, the flow regime has been reported to become fully turbulent for Re above 300, in contrast to the substantially higher transition Reynolds number of straight channels [6]. Accordingly, all three flow conditions investigated in this study correspond to the turbulent flow regime. The measured fields were compared to identify characteristic flow structures and their dependence on Reynolds number.

2. Methods

2.1 Definition of Gyroid Geometry

The Gyroid structure was defined using a mathematical level-set function representing a TPMS. The Gyroid surface is expressed as

$$f(x, y, z) = \sin(kx) \cos(ky) + \sin(ky) \cos(kz) + \sin(kz) \cos(kx) = C \quad (1)$$

Where

$$k = \frac{2\pi}{L} \quad (2)$$

with L denoting the unit-cell period and C defining the isovalue of the Gyroid surface. Unlike the isosurface defined by $f(x,y,z)=C$, which represents a two-dimensional boundary, inequality conditions applied to the level-set function define volumetric domains. As illustrated in Fig. 1, the level-set representation can be used to construct different TPMS configurations depending on how the function value is used to define the solid and fluid regions. Based on these conditions,

TPMS structures can generally be classified as solid-type or sheet-type configurations.

In the solid-type configuration, the level-set function divides the domain into a single connected fluid region and a solid region,

$$\Omega(x, y, z) = \begin{cases} \text{Solid,} & \text{if } f(x, y, z) > C \\ \text{Fluid,} & \text{if } f(x, y, z) \leq C \end{cases} \quad (3)$$

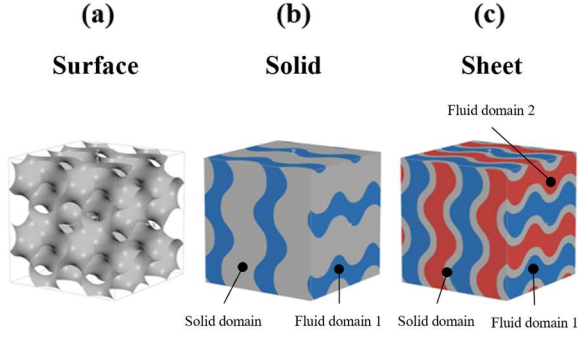


Fig. 1. Schematic representation of the Gyroid geometry: (a) Gyroid minimal surface, (b) solid-type and (c) sheet-type configuration

As illustrated in Fig. 1(b), the solid-type configuration consists of one interconnected fluid domain and one solid domain, with the Gyroid surface defining the interface between them. This configuration is commonly used for single-fluid cooling applications because the interconnected fluid passage provides a continuous flow path throughout the structure.

In contrast, the sheet-type configuration defines a solid wall around the TPMS surface and separates the domain into two independent fluid regions,

$$\Omega(x, y, z) = \begin{cases} \text{Fluid 1,} & \text{if } f(x, y, z) \leq C_1 \\ \text{Solid,} & \text{if } C_1 < f(x, y, z) < C_2 \\ \text{Fluid 2,} & \text{if } f(x, y, z) \geq C_2 \end{cases} \quad (4)$$

As illustrated in Fig. 1(c), the sheet-type configuration forms a finite-thickness solid wall around the Gyroid surface, thereby separating the structure into two independent and non-intersecting fluid domains. This configuration is therefore suitable for heat-exchanger applications in which two fluids exchange heat across the solid wall without direct mixing.

In this study, a solid-type Gyroid with $C = 0.53775$ was fabricated and used as the test specimen, with a unit-cell period of $L = 13$ mm, so that the width, depth, and height of a single unit cell are each 13 mm. The sheet-type configuration forms two fluid regions that remain completely separated from one another; from the perspective of a single fluid region, however, there is no difference between the case in which the opposing region is fluid and the case in which it is solid. Consequently, in terms of momentum transport, the flow behavior within one channel of the sheet-type configuration is identical to that within a solid-type Gyroid channel of the same geometry. For this reason, the present experimental and computational study adopted the solid-type configuration, which is geometrically simpler while remaining physically representative.

2.2. Test section and flow loop

The test sections were fabricated using non-magnetic Clear Resin on a Formlabs Form 4 masked stereolithography 3D printer. Each Gyroid array was enclosed within a square duct, with flanges installed at both ends to allow connection to the flow loop. The Gyroid unit cells were arranged in a 3×3 configuration in the transverse plane. Two Gyroid test sections were connected in series, forming a total of 26 unit cells in the streamwise direction. Non-magnetic polymer components were used for mechanical fastening, while O-rings were installed at the joints to prevent leakage. Mechanical interlocking features were additionally incorporated to maintain the alignment of adjacent sections during assembly. Fig. 2 presents a schematic diagram of the Gyroid test section.

A closed-loop water-circulation system comprising a reservoir, pump, flow meter, temperature circulator, flow-conditioning section, and Gyroid test section was constructed, as illustrated in Fig. 3. The flow-conditioning section, consisting of an expansion region, honeycomb, and contraction, was installed upstream of the test section to provide a uniform inlet flow. The expansion and contraction sections were fabricated from polymethyl methacrylate (PMMA), while the honeycomb was fabricated from acrylonitrile butadiene styrene (ABS). These non-metallic polymer materials were selected to minimize potential magnetic

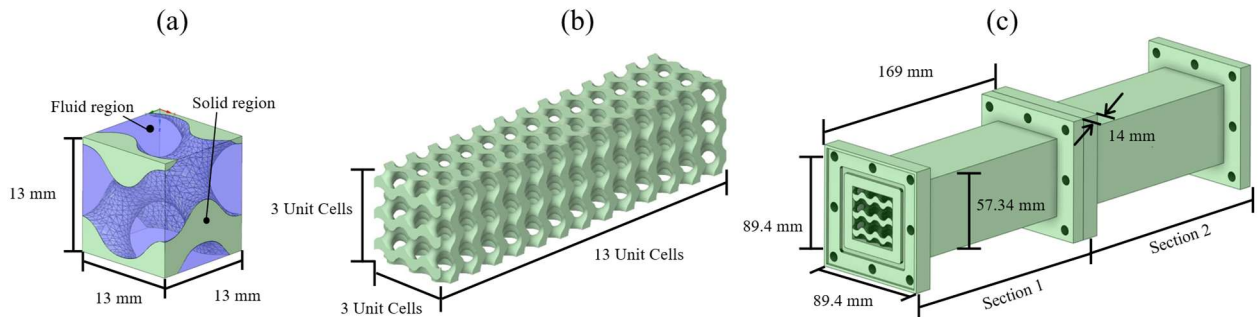


Fig. 2. Schematic diagram of the Gyroid test section: (a) One unit cell, (b) Unit cell array in a test section, (c) total test section figure.

susceptibility effects. Water temperature was maintained at 25C, and the volumetric flow rate was monitored upstream of the test section. To minimize electromagnetic interference during MRI measurements, the pump, reservoir, flow meter, and temperature circulator were located outside the MRI room, whereas the test section and flow-conditioning components were positioned near the scanner. Each test section was placed at the center of the MRI bore and measured under the three flow conditions described in Section 2.3.

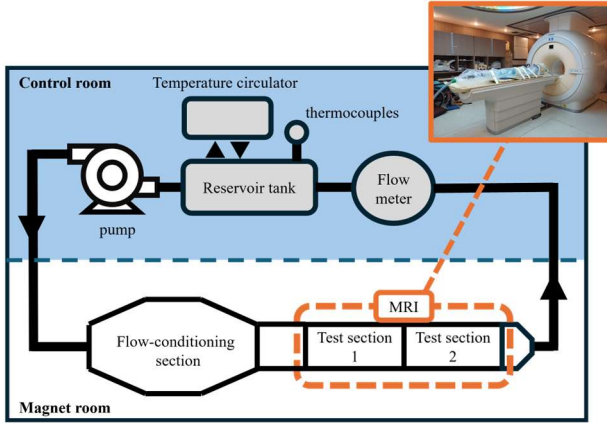


Fig. 3. Schematic diagram of the experimental flow loop

2.3. Flow conditions

Three flow conditions were investigated at Reynolds numbers of $Re=1000$, 1500 , and 2000 . The Reynolds number was defined using the hydraulic diameter of the Gyroid channel and the mean flow velocity. All experiments were conducted using a 20mM copper sulfate ($CuSO_4$) aqueous solution, used to enhance the MRI signal, maintained at 25C. Owing to the dilute $CuSO_4$ concentration, the fluid properties were approximated by those of water 25C, and the corresponding density and dynamic viscosity are listed in Table I.

Table I: Flow parameters

Conditions	Value
Working fluid	20mM $CuSO_4$ solution
Reynolds number	1000/1500/2000
Volumetric flow rate [LPM]	5.35 / 8.1 / 10.8
Temperature [$^{\circ}C$]	25
Density[kg/m ³]	997.05
viscosity[$\mu Pa \cdot s$]	890.02
Prandtl number	6.14

2.4. MRI setup

Three-directional phase-contrast MRI measurements were performed to obtain the velocity field within the Gyroid test section. Velocity encoding was independently applied along the x -, y -, and z -directions, and the corresponding velocity components were reconstructed voxel-wise within the measurement volume. The velocity component along each encoding direction was calculated from the phase difference between the velocity-encoded measurements as

$$u_i(x) = \frac{\Delta\phi_i(x)}{\pi} VENC_i, \quad i = x, y, z. \quad (5)$$

where u is the velocity component along the encoding direction, $\Delta\phi$ is the measured phase difference, and $VENC$ is the velocity encoding value [7].

Measurements were conducted using a 3.0 T Achieva TX MRI scanner (Achieva, Philips, Netherlands) at the Ochang campus of the Korea Basic Science Institute. MRI measurements were sequentially acquired under pump-on, pump-off, and pump-on conditions. The pump-off acquisition was used to correct for background signal and noise by subtracting it from the pump-on data, thereby removing background-induced errors and improving the accuracy of the measured velocity field, while the repeated pump-on acquisition was used to evaluate the repeatability of the measured velocity field. The imaging and flow-encoding parameters are summarized in Table II.

Table II: Imaging parameters

Parameters		Value
MRI system		Philips Achieva 3.0T TX
Field of view [mm]		$48 \times 48 \times 192$
Voxel size [mm]		$0.4 \times 0.4 \times 0.4$
Repetition time/ Echo time [ms]	Re = 1000	5.6 / 3.6
	Re = 1500	5.4 / 3.4
	Re = 2000	5.3 / 3.3
VENC [cm/s]	Re = 1000	20 / 20 / 30
	Re = 1500	30 / 30 / 45
	Re = 2000	40 / 40 / 55
Flip angle of excitation [$^{\circ}$]		15
Flow compensation		On
Pump condition		On / Off / On
Matrix size (x,y,z)		$120 \times 120 \times 480$
Effective matrix size (x,y,z)		$97 \times 97 \times 423$
Number of signal averages		4

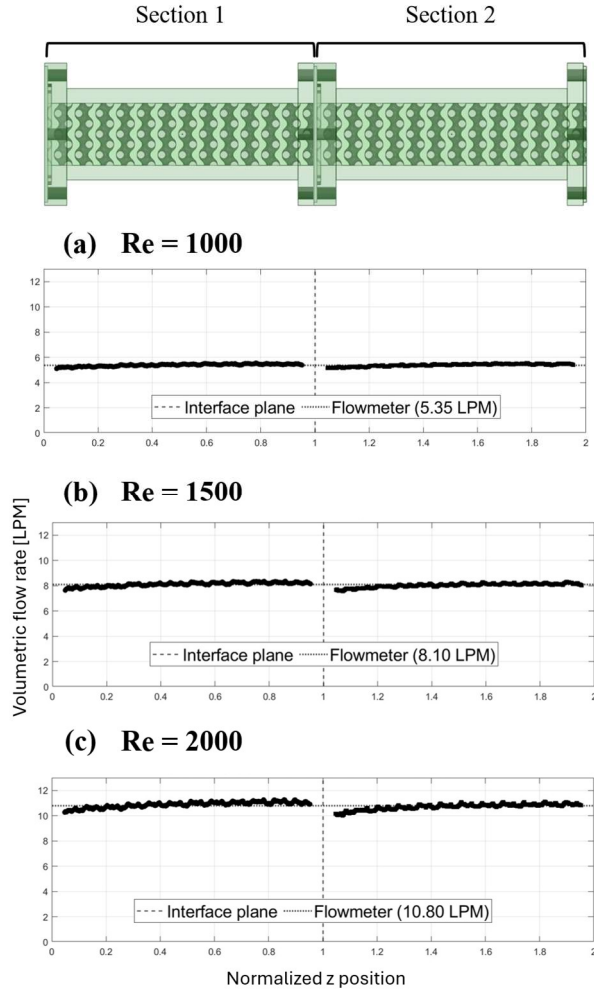


Fig. 4. Streamwise distribution of volumetric flow rate from MRV velocity field for (a) $Re=1000$, (b) $Re=1500$, (c) $Re=2000$.

3. Results and Discussion

3.1 Flow-rate validation of MRV measurements

The accuracy of the MRV measurements was assessed by comparing the volumetric flow rate reconstructed from the measured velocity field with the flow rate measured by the flow meter. For incompressible steady flow, the volumetric flow rate should be conserved along the streamwise direction. The flow rate through each cross-sectional plane was therefore calculated by integrating the streamwise velocity component over the fluid region:

$$Q(z) = \sum_{i \in A_f(z)} u_z(x_i, y_i, z) \Delta A \quad (6)$$

where $Q(z)$ is the reconstructed volumetric flow rate at the streamwise location z , u_z is the streamwise velocity component, $A_f(z)$ denotes the fluid area of the cross-

section, and ΔA is the in-plane voxel area.

To reduce the influence of measurement degradation near the MRV coil boundaries and at the interface between the two connected test sections, the upstream and downstream 10 voxel layers of each test section were excluded from the quantitative evaluation. Fig. 4 compares the cross-sectionally reconstructed flow rate with the reference flowmeter value along the two test sections.

For all three cases, the reconstructed flow rate was lower near the coil-edge regions and recovered toward an approximately constant value in the central measurement region. This trend indicates a reduced reliability near the edges of the measurement field of view, potentially associated with gradient nonlinearity and reduced local SNR. Nevertheless, the reconstructed flow rates agreed with the flowmeter measurements within maximum deviations of 4.55%, 6.66%, and 7.04%, for $Re = 1000$, 1500, and 2000, respectively. These results demonstrate that the present MRV measurements provide quantitatively consistent velocity fields over the central region of the Gyroid test section.

3.2 Flow development length analysis

Because the Gyroid unit-cell array is periodic in the streamwise direction, the internal flow field is expected to approach a periodically fully developed state after passing through a finite number of unit cells, analogous to the entrance development of conventional internal flows.

Following the concept of periodic fully developed flow and subsequent research applying it [8], the flow development in the present Gyroid structure was evaluated using two independent and complementary indicators: (i) the unit-cell-averaged axial velocity and (ii) the shape of normalized axial velocity profiles at identical phase locations in successive unit cells.

The first indicator provides a quantitative convergence criterion based on the variation of the volume-averaged axial velocity between adjacent unit cells. The second indicator provides a qualitative, shape-based cross-validation by examining whether the normalized cross-sectional velocity distribution becomes repeatable among successive unit cells.

3.2.1 Unit-cell-averaged axial velocity

A unit cell was considered periodically developed when the unit-cell-averaged axial velocity converged between adjacent unit cells within a prescribed tolerance. The unit-cell-averaged axial velocity was obtained from the MRV velocity field by area-weighting the cross-sectional mean axial velocity, $\bar{u}$, with the fluid cross-sectional area, $A(z)$, determined from the fluid mask:

$$\bar{U}_{cell} = \frac{\int_{z_{in}}^{z_{out}} \bar{u}(z) A(z) dz}{\int_{z_{in}}^{z_{out}} A(z) dz} \quad (7)$$

Fig. 5 shows the variation of the unit-cell-averaged axial velocity as a function of unit-cell number. For all cases, the velocity variation between the first and second unit cells decreased substantially toward the third unit cell, after which the variation became nearly linear and progressively weaker. This behavior indicates that the inlet-affected flow field is progressively adjusted by the periodic Gyroid geometry before approaching a repeatable state.

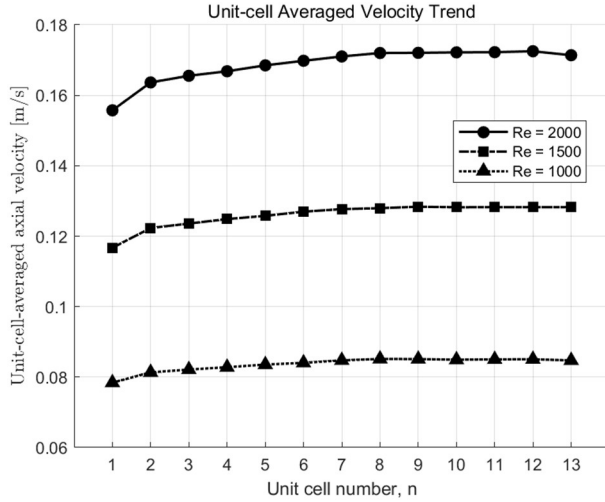


Fig. 5. Evolution of the unit-cell-averaged axial velocity along the Gyroid channel for Re = 1000, 1500, and 2000.

Table III summarizes the onset cell number of periodic development obtained using different convergence tolerances. For $\epsilon = 2\%$, all three cases converged at the same location, namely, $n_{\text{periodic}} = 2$.

Thus, under a practically relevant convergence criterion, the periodically developed state was reached after approximately two Gyroid unit cells, independent of the flow condition. A flow-rate-dependent trend was observed when the more stringent criterion of $\epsilon = 1\%$ was applied. The highest-flow-rate condition, Re=2000, reached convergence at unit cell 5, whereas Re=1500 and Re=1000 converged at unit cells 4 and 2, respectively. This trend indicates that the approach to a highly converged periodic state becomes slower as the imposed flow rate increases.

For the strictest criterion, $\epsilon=0.5\%$, Re=1500 and Re=1000 maintained convergence from unit cell 7 onward. In contrast, Re=2000 did not satisfy the persistent convergence criterion within the available measurement domain. This result is attributed to the fact that, particularly for the highest-flow-rate case, the 0.5% criterion approaches the expected uncertainty level of the MRV-derived velocity field. At elevated flow rates, the measurement quality can be affected by reduced signal-to-noise ratio, enhanced intravoxel velocity variation, and stronger sensitivity of the calculated mean velocity to mask and registration errors. Therefore, the failure to satisfy the 0.5% threshold for Re=2000 does not necessarily indicate that the flow remains physically undeveloped throughout the measured region.

Table III: Unit-cell number at the onset of periodic development determined using different convergence tolerances for Re = 1000, 1500, and 2000.

ϵ (tolerances)	Re = 1000	Re = 1500	Re = 2000
5.0%	1	2	2
2.0%	2	2	2
1.0%	2	4	5
0.5%	7	7	N/A

3.2.2 Normalized cross-sectional profile shape

To provide an independent assessment of flow development, axial velocity line profiles were extracted at a fixed transverse location for the first five unit cells, $n=1, \dots, 5$, as illustrated in Fig. 6. Each profile was normalized by the corresponding cross-sectional mean axial velocity at the same streamwise location. This normalization removes the magnitude difference among unit cells and flow cases, thereby enabling comparison of the profile shape alone.

For all three flow cases and for each of the three transverse channels visible within the field of view, the profile in the first unit cell was clearly distinguishable from those in the subsequent unit cells. In particular, the first-unit-cell profile exhibited a lower peak amplitude and a different normalized shape, indicating the persistence of inlet-induced flow development.

In contrast, the profiles from unit cells 2 to 5 showed nearly indistinguishable and recurrent shapes. The repeated agreement in the location of the velocity peak, the decay toward the wall region, and the overall normalized profile shape indicates that the cross-sectional flow distribution becomes periodic from the second unit cell onward. This result provides a shape-based confirmation that is independent of the tolerance value and the volume-averaging procedure used in Section 3.2.1.

3.2.3 Synthesis and conclusion

Taken together, the two complementary indicators examined in Sections 3.2.1 and 3.2.2 show that the flow development length in the Gyroid channel is governed primarily by the periodic unit-cell geometry rather than by the imposed flow rate. Under a practically relevant convergence criterion ($\epsilon=2\%$), a periodically developed state was reached after only two unit cells regardless of Reynolds number, and even under the stricter criteria the additional streamwise distance required to reach a highly converged periodic state remained limited to a few additional unit cells across the investigated Re range.

This near-invariance of the development length with Reynolds number is a significant advantage for the design of compact thermal-hydraulic components such as those required in SMR heat-removal systems, whose operating flow rate may vary with load condition. Because the entrance-adjustment region can be sized

primarily from the channel geometry rather than from a flow-rate-dependent estimate, the flow development length obtained in this study can serve as a practical, geometry-based design indicator for optimizing the Gyroid unit-cell shape and for minimizing the design margin otherwise required to accommodate flow-rate-dependent uncertainty in the developing-flow region.

3.3 Velocity profile analysis

3.3.1 General flow structure within the Gyroid channel

Fig. 7(a) and (b) present the axial and transverse velocity contours with superimposed streamlines on a cross-section perpendicular to the main flow direction, taken at the interface between the seventh and eighth unit cells (normalized streamwise position $z = 7/13$), where the flow was confirmed to be periodically fully developed. The streamlines reveal two distinct types of secondary-flow structures. The first is a vortex located near the center of the fluid domain, relatively distant from the solid walls, while the second is a vortex that develops along the curved Gyroid surface. These two vortex types rotate in opposite directions and are arranged in a checkerboard-like pattern across the cross-section. As shown in Fig. 7(a), the core-region vortices coincide with locally high axial velocity, since this

region experiences comparatively little interference from the solid boundary. In contrast, Fig. 7(b) shows that the transverse velocity is strongest within the wall-following vortices, indicating that the curvature of the Gyroid surface actively redirects the flow in the transverse direction and generates near-wall secondary motion.

This near-wall secondary motion is expected to play a key role in local heat-transfer enhancement. In a straight or mildly curved channel, the thermal boundary layer thickens continuously along the flow direction, progressively insulating the wall from the bulk fluid and reducing the local heat-transfer coefficient. In the Gyroid channel, however, the wall-following vortices repeatedly turn near-wall fluid toward the transverse direction and exchange it with fluid carried in from the core region at every unit cell. This happens at the same streamwise interval as the Gyroid unit cell, as shown by the spatially periodic secondary-flow structures identified in Fig. 8. As a result, the near-wall thermal boundary layer is repeatedly broken up before it can grow beyond a length scale set by the unit-cell size, rather than by the streamwise development length that governs a straight channel. This self-resetting, geometry-induced near-wall flow structure provides a physical basis for the elevated heat-transfer performance reported for Gyroid structures relative to conventional heat-exchanger geometries [9]. It also represents a structural mechanism by which the

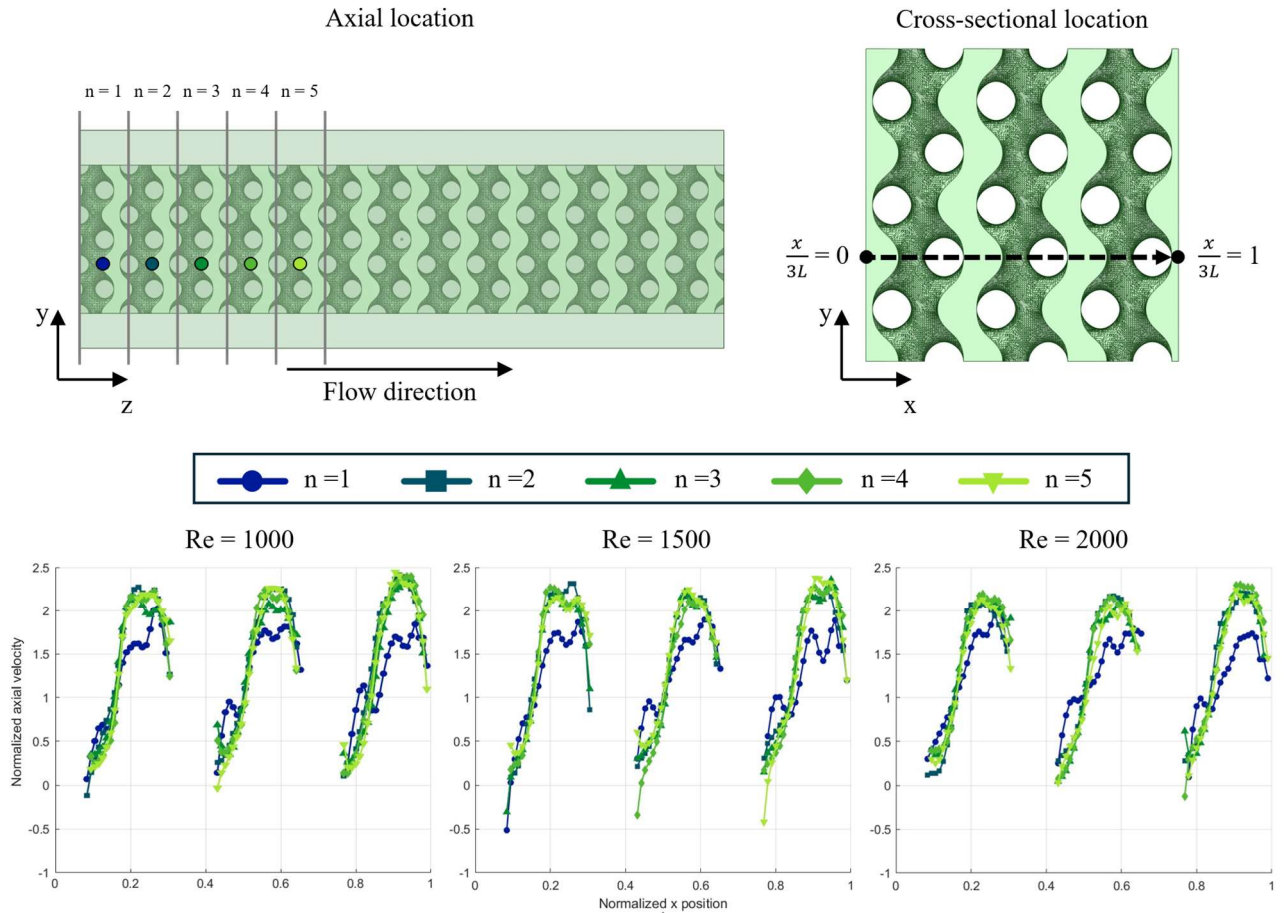


Fig. 6. Evolution of the normalized axial velocity profile over the first five Gyroid unit cells for $Re = 1000, 1500$, and 2000 .

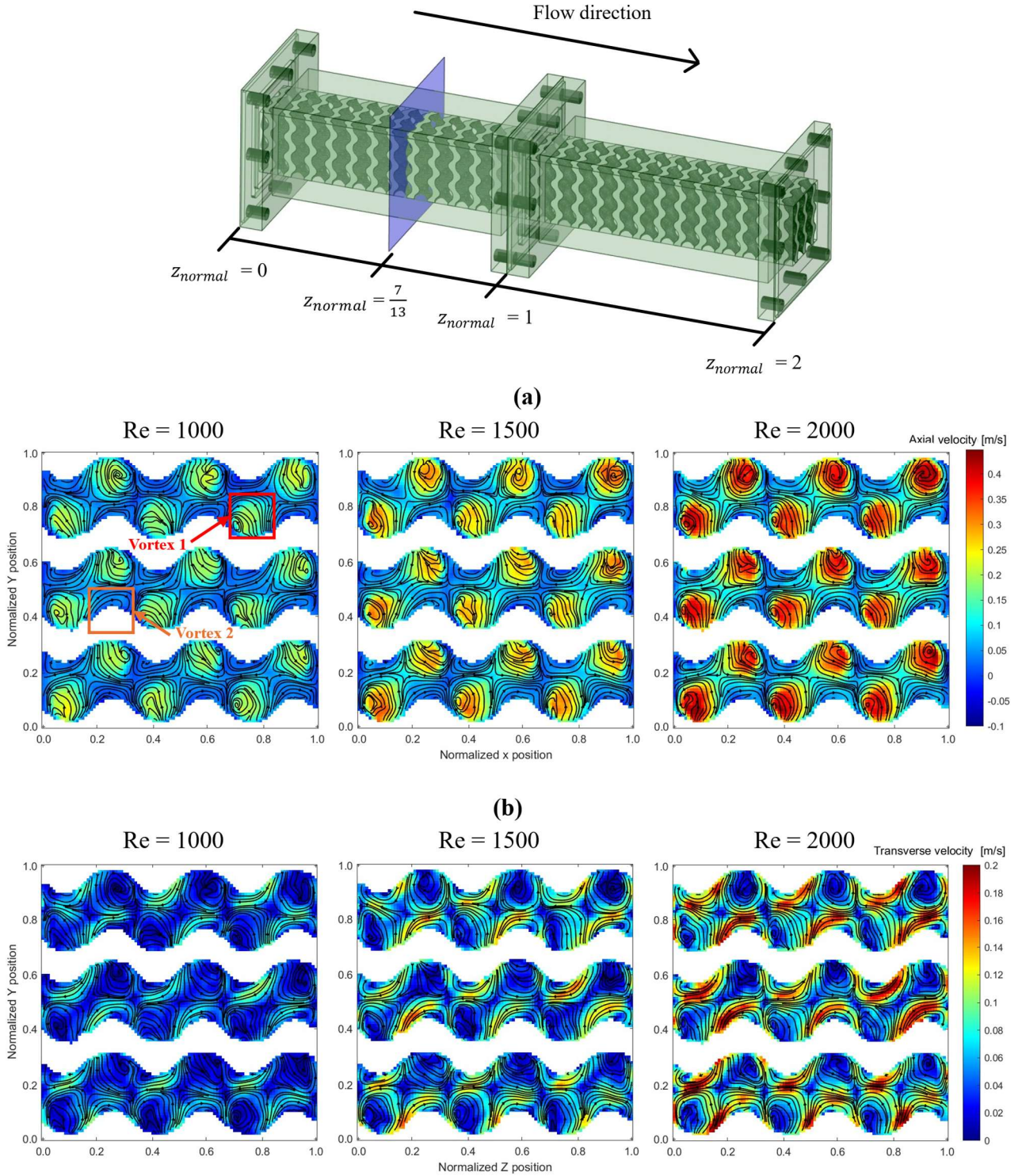


Fig. 7. Contours of (a) axial velocity and (b) transverse velocity with streamlines on a cross-section perpendicular to the main flow direction (normalized z position = $7/13$), for $Re = 1000, 1500$, and 2000 .

Gyroid geometry can meet the high heat-transfer efficiency and volumetric compactness simultaneously required by SMR thermal-hydraulic design, without relying on external flow-disturbing devices or additional pressure-drop penalty beyond that inherent to the geometry itself.

Fig. 8(a) and (b) show the corresponding axial and transverse velocity fields on a section parallel to the main

flow direction, taken at a normalized y position of 0.42 , allowing the streamwise evolution of these structures to be examined. The same two flow features identified in the cross-sectional view are also observed here: a streamline that penetrates continuously through the core of the Gyroid channel, and a streamline that wraps around the Gyroid solid surface. Notably, both the high axial-velocity streak in Fig. 8(a) and the high transverse-

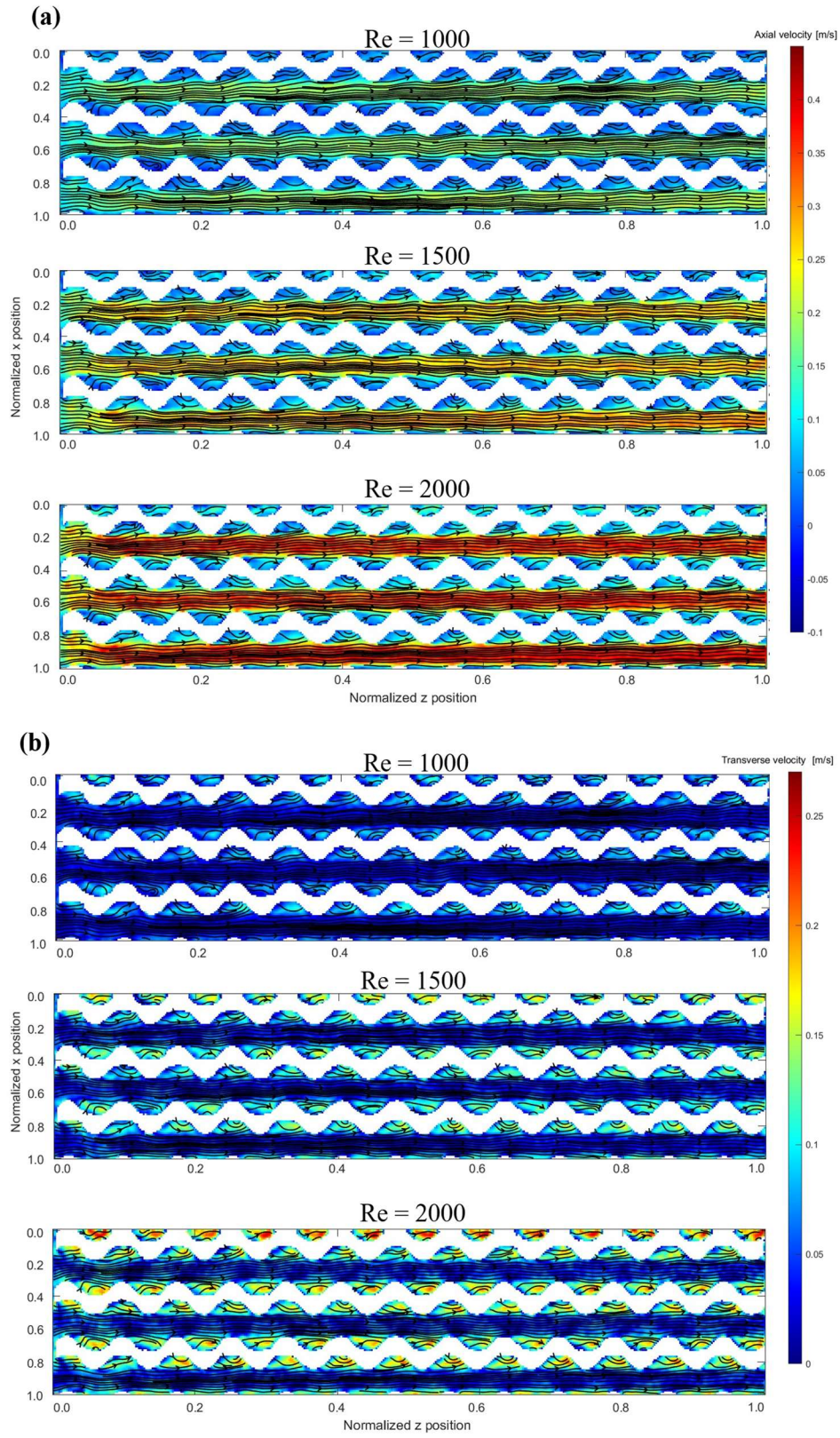


Fig. 8. Contours of (a) axial velocity and (b) transverse velocity with streamlines on a section parallel to the main flow direction (normalized y position = 0.42), for Re = 1000, 1500, and 2000.

velocity regions in Fig. 8(b) recur regularly at each unit cell along the streamwise direction, without noticeable distortion or decay across the field of view. This spatial periodicity indicates that the two secondary-flow structures identified from the cross-sectional analysis are not localized or transient features specific to a single measurement plane, but rather a stable, geometry-induced flow pattern that is intrinsically repeated at every unit cell of the Gyroid channel. This regular recurrence is consistent across $Re=1000-2000$, suggesting that the checkerboard-type secondary-flow structure is a robust characteristic of the Gyroid geometry over the Reynolds number range investigated.

3.3.2 Reynolds number sensitivity of axial velocity

Fig. 9(a) compares the normalized axial velocity profiles measured at a normalized streamwise position of $z = 0.5$ within the Gyroid channel for the three flow conditions. The axial velocity was normalized by the bulk velocity, to remove the trivial increase in dimensional velocity with flow rate and to focus on changes in the internal velocity distribution.

The normalized axial velocity profiles show broadly similar spatial distributions for all three cases. In each profile segment, a peak value of approximately $v_z/U_b=2.0-2.4$ is observed near the center of the Gyroid flow passage, followed by a decrease toward the wall region. The similar locations of the high-velocity and low-velocity regions indicate that the preferential axial flow paths are primarily determined by the continuous Gyroid geometry rather than by the imposed flow rate.

The profiles are not perfectly identical. In the third profile segment, $Re=1500$ and $Re=1000$ exhibit slightly higher local peak values than $Re=2000$. This difference suggests a modest redistribution of axial momentum within the preferential flow passages.

3.3.3. Reynolds number sensitivity of transverse velocity

Fig. 9(b) shows the normalized transverse velocity profiles at the same streamwise location ($z = 0.5$) as those used for the axial velocity comparison. In contrast to the axial velocity profiles, the transverse velocity profiles exhibit more pronounced case-to-case variations. Although the locations of the major peaks are generally preserved, the peak magnitudes and the distributions of low-transverse-velocity regions vary among the three cases.

This result indicates that local transverse momentum redistribution is more sensitive to the flow condition than the primary axial channeling pattern. The continuous curved surface of the Gyroid geometry enforces repeated changes in flow direction. Therefore, the locations of the transverse-velocity peaks are broadly shared among the cases, particularly near wall-adjacent regions and geometrical turning sections. However, the transverse velocity magnitude is more sensitive to the imposed flow condition because it is influenced by local curvature, contraction and expansion, channel reconnection, and

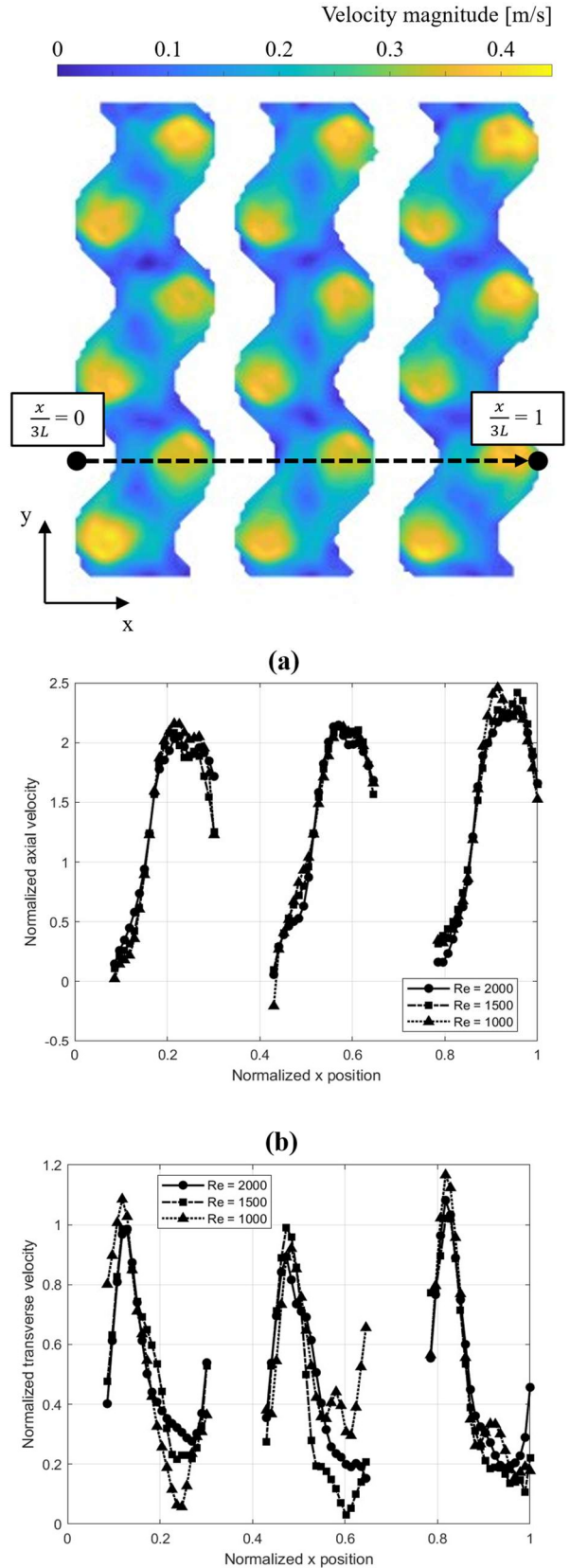


Fig. 9. Normalized axial and transverse velocity profiles at representative locations within the Gyroid channel for $Re = 1000, 1500$, and 2000 : (a) axial velocity and (b) transverse velocity.

secondary motion induced by the three-dimensional flow path.

A local difference in transverse velocity may result either from an increase in the overall magnitude of transverse motion or from a redistribution of transverse velocity within the Gyroid passages while the global secondary-flow magnitude remains unchanged. Therefore, the transverse velocity variation is further examined at the macroscopic level in Section 3.3.3.

3.3.4 Secondary flow intensity

Fig. 10 presents the streamwise variation of secondary-flow intensity (SFI), defined as [10]

$$SFI(z) = \frac{\langle \sqrt{u^2 + v^2} \rangle_A}{\bar{w}} \quad (8)$$

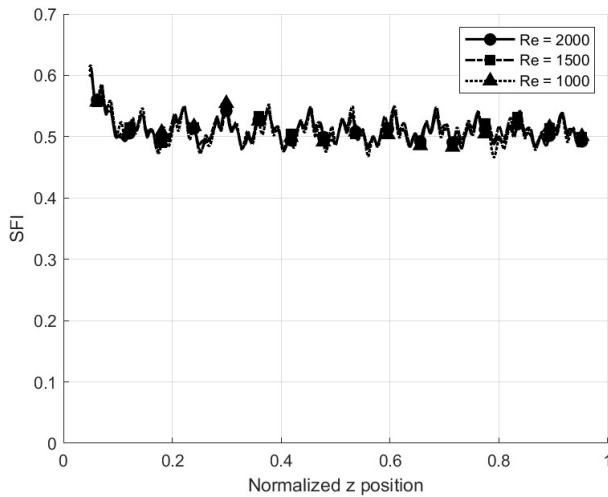


Fig. 10. Streamwise variation of secondary flow intensity (SFI) for Re = 1000, 1500, and 2000.

Although local differences are observed in the transverse velocity profiles, the secondary-flow intensity shows relatively elevated values near the channel inlet before converging to approximately 0.47–0.55 over most of the interior measurement region for all three cases. The considerable overlap among the cases indicates that the domain-integrated contribution of secondary motion remains nearly unchanged over the investigated flow range. This result demonstrates that the local variation in transverse velocity does not lead to a systematic increase in the global secondary-flow strength. Instead, the increasing flow rate modifies the local location and magnitude of transverse motion while preserving the overall relative contribution of secondary flow to the three-dimensional velocity field.

4. Conclusions

MRV measurements of the three-dimensional velocity field in a Gyroid TPMS channel at Re = 1000–2000 agreed with reference flowmeter data within $\pm 4.55\%$

and showed that the flow becomes periodically developed after approximately two unit cells under a practical convergence criterion, though this development length increases with Reynolds number under stricter criteria. Because this development length was found to be governed primarily by the periodic unit-cell geometry rather than by the imposed flow rate, it can serve as a practical, geometry-based design indicator for sizing the entrance region and minimizing design margins in Gyroid-based thermal-hydraulic components. The internal flow was characterized by a stable, geometry-induced checkerboard pattern of counter-rotating secondary vortices that recurred at every unit cell, with axial velocity profiles remaining largely Reynolds-number-independent while transverse velocity distributions showed greater local sensitivity to flow rate. The wall-following vortices were found to repeatedly turn near-wall fluid toward the transverse direction at every unit cell, a self-resetting mechanism that is expected to disrupt the growth of the near-wall thermal boundary layer and thereby enhance local heat transfer, providing a physical basis for the elevated heat-transfer performance previously reported for Gyroid structures. Despite this local variability, the domain-averaged secondary-flow intensity remained nearly constant (approximately 0.47–0.55, after an initial elevated region near the inlet) across all cases, indicating that increasing flow rate redistributes secondary motion locally without altering its overall contribution. Together, these results indicate that the Gyroid geometry can provide high heat-transfer efficiency and volumetric compactness simultaneously, without relying on external flow-disturbing devices, and provide a validated experimental dataset for future CFD studies of Gyroid-based thermal-hydraulic components for SMR applications.

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REFERENCES

- [1] S. Samson, P. Tran, P. Marzocca, Design and modelling of porous gyroid heatsinks: Influences of cell size, porosity and material variation, *Appl. Therm. Eng.* 235 (2023) 121296, <https://doi.org/10.1016/j.applthermaleng.2023.121296>.
- [2] Idaho National Laboratory. (2025, December 1). Futuristic nuclear fuel shape mimics nature to dramatically improve performance. <https://inl.gov/feature-story/futuristic-nuclear-fuel-shape-mimics-nature-to-dramatically-improve-performance>

- [3] Li, W., Li, W., & Yu, Z. (2022). Heat transfer enhancement of water-cooled triply periodic minimal surface heat exchangers. *Applied Thermal Engineering*, 217, 119198.
- [4] H. Dong, G. Yi, C. Kang, S. Ki, J.-H. Cho, J. Park, S. Song, Magnetic resonance velocimetry-based diagnosis-modification-validation framework for flow and acoustic improvement in heat pump tumble dryer machine room, *Int. Commun. Heat Mass Transf.* 178 (2026) 111743.
- [5] H. Dong, S. Kang, C. Kang, Y. Son, S. Ki, S. Song, Non-intrusive flow and pressure field analysis in compressor mufflers using magnetic resonance velocimetry and integrated pressure estimation, *Int. Commun. Heat Mass Transf.* 170 (2026) 109984.
- [6] Yan, K., Deng, H., Xiao, Y., Wang, J., & Luo, Y. (2024). Thermo-hydraulic performance evaluation through experiment and simulation of additive manufactured Gyroid-structured heat exchanger. *Applied Thermal Engineering*, 241, 122402.
- [7] Elkins, C. J., & Alley, M. T. (2007). Magnetic resonance velocimetry: applications of magnetic resonance imaging in the measurement of fluid motion. *Experiments in Fluids*, 43(6), 823-858.
- [8] S. V. Patankar, C. H. Liu, and E. M. Sparrow, "Fully Developed Flow and Heat Transfer in Ducts Having Streamwise-Periodic Variations of Cross-Sectional Area," *J. Heat Transfer* 99, 180–186 (1977).mann, S., 2016a. New insights into the flow inside CANDU fuel bundles using magnetic resonance velocimetry. OECD/NEA IAEA Workshop on Computational Fluid Dynamics for Nuclear Reactor Safety.
- [9] Li, W., Yu, G., & Yu, Z. (2020). Bioinspired heat exchangers based on triply periodic minimal surfaces for supercritical CO₂ cycles. *Applied Thermal Engineering*, 179, 115686.
- [10] Moon, H., Dong, H., Oh, S., Song, M., & Song, S. (2026). In-depth flow investigation in subchannels of helical cruciform fuel using magnetic resonance velocimetry. *Physics of Fluids*, 38(8).