

Assessment of In-Line Particle Image Velocimetry for Turbulence Measurements in Porous Media

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Keywords: In-Line PIV, Triply Periodic Minimal Surfaces (TPMS), Turbulent flow, Gyroid.

ABSTRACT

In-line particle image velocimetry (PIV) is implemented and assessed as a measurement technique for acquiring instantaneous velocity fields within porous structures traversed by turbulent flows. Focusing on triply periodic minimal surface samples, whose geometries are analytically defined, this study evaluates the potential of in-line PIV to maximize optical accessibility relative to conventional light-sheet PIV configurations, while maintaining acceptable particle-image quality despite the unavoidable presence of light-scattering solid surfaces. The primary objective is to assess the feasibility and limitations of in-line PIV when applied through a solid porous matrix, and to identify the methodological adaptations required to obtain reliable velocity fields. This methodological groundwork aims to establish in-line PIV as a robust diagnostic tool for future investigations of turbulent flows within porous media.

1. Introduction

Experimentally probing flow dynamics within porous materials remains a major challenge, particularly when aiming to resolve the spatial distribution of turbulent fluctuations at the pore scale and across multiple pores. Non-intrusive optical diagnostics such as particle image velocimetry (PIV) and laser Doppler velocimetry (LDV) are commonly used in free and wall-bounded flows. However, their application near solid walls is limited by optical obstruction and light-scattering. These effects can severely degrade velocity measurements, restrict spatial coverage, or prevent acquisition inside complex structures (R. Adrian & Westerweel, 2011).

In porous structures, classical PIV setups (using a laser light-sheet orthogonal to a camera axis) can result in large shadowed regions depending on the geometry. This is particularly illustrated in Figure 1 for the porous structure studied in the present work. Similarly, LDV beams are often blocked when probing complex porous matrices (Mure d'Alexis et al., 2025), or deviated when passing through transparent structures. Such limitations are well documented in studies of optical imaging in heterogeneous media, including index-matched flows and porous materials (Imuetinyan et al., 2024; Wildenschild & Sheppard, 2013).

To overcome these limitations, several strategies have been explored in the literature for optical measurements within porous structures. Zhang et al. (2023) and Khodsiani et al. (2024) used simplified pore geometries, such as ordered arrays of spheres or rods, which allow for easier optical access. Imuetinyan et al. (2024) employed transparent porous media with refractive-index matching (RIM) to facilitate internal visualization. Other studies, such as Seol et al. (2024), restricted measurements to near-wall regions or downstream of the porous material, where optical obstruction is reduced.

Despite promising results, these approaches remain restrictive. RIM experiments require careful tuning of refractive indices, which may vary with temperature or wavelength. Transparent porous materials are typically limited to polymers such as PMMA or hydrogels, which do not faithfully represent the optical, mechanical, or topological properties of real porous matrices. Most importantly, measurements inside porous materials often rely on oversized pores or highly idealized structures. Consequently, certain aspects of pore-scale turbulence, such as the conditions described by the Pore Scale Prevalence Hypothesis (PSPH) (Habib et al., 2020), cannot be thoroughly investigated.

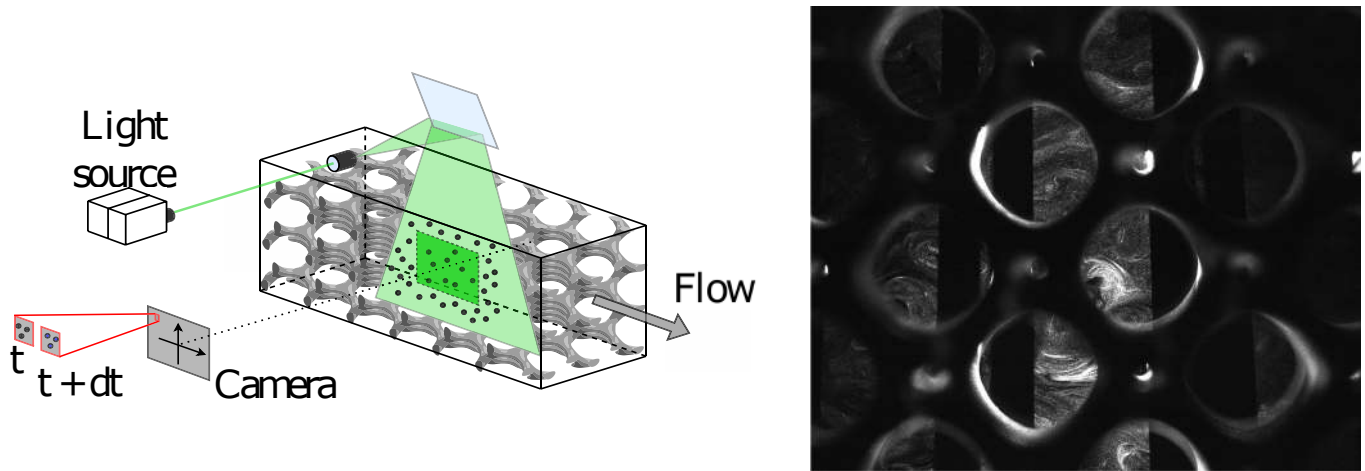


Figure 1. Schematic of a conventional PIV setup applied to the present porous gyroid structure (left), adapted from Raffel, Braukmann, et al. (2024), and an example image acquired using a standard PIV configuration (right), illustrating light-sheet obstruction.

This study aims to measure velocity fields within a representative complex porous geometry across multiple pore lengths at moderate to high Reynolds numbers, conditions that appear inaccessible via classical optical techniques. To address previous limitations, we investigate an in-line PIV configuration based on the work of Raffel, Braukmann, et al. (2024) and Raffel, Heintz, et al. (2024). Unlike standard PIV arrangements, the in-line configuration aligns the imaging axis with the light propagation direction, thereby minimizing shadowing and light-scattering effects within the porous matrix.

The physical principles underlying this configuration are closely related to those used in online

digital holography and darkfield microscopy, which have demonstrated superior penetration in scattering media (Katz & Sheng, 2010). The use of a single illumination axis minimises the areas where the laser beam cannot propagate through porous materials, allowing for a more comprehensive study of flow within complex structures. Furthermore, this single-axis alignment considerably simplifies the handling and positioning of different samples, thereby facilitating a wider range of experimental configurations. Finally, since the camera is positioned along the illumination axis, this setup requires lower light intensity (Mie scattering graph).

This approach is particularly well suited for investigating structures based on Triply Periodic Minimal Surfaces (TPMS), which can be readily fabricated using additive manufacturing. These geometries combine continuous curvature with high permeability, while still providing partial optical access to the internal flow. Recent work by Flores-Montoya et al. (2025) demonstrated the feasibility of optical measurements inside TPMS porous structures using a single-pore observation strategy. Building on this proof of concept, the present work extends the approach toward spatially resolved measurements across several interconnected pores, with the objective of capturing flow organization beyond a purely local description.

The objective of the present study is therefore twofold:

1. to **develop and adapt** an in-line PIV methodology tailored to the challenges of porous media, including scattering, shadowing, and geometric complexity;
2. to **validate** this approach through measurements conducted across multiple pores in a TPMS-based structure, thereby enabling future investigations of pore-scale turbulence mechanisms and the relevance of hypotheses such as the PSPH (Habib et al., 2020).

2. Method

This section presents the methodology developed to investigate flow measurements inside a gyroid-based porous medium using an in-line PIV configuration. First, the geometry and fabrication parameters of the porous sample are described. The experimental setup is then detailed, including the optical arrangement, illumination strategy, and wind-tunnel facility. Finally, the depth of field associated with the in-line imaging configuration is characterized both theoretically and experimentally in order to estimate the effective measurement volume.

2.1. Porous Material

This study focuses on porous geometries based on TPMS, in particular the gyroid structure shown in Figure 2. This structure is chosen for its deterministic properties, geometric regularity, and

compatibility with advanced 3D printing techniques such as stereolithography (resin) printing. The material's solid part is defined by the following equation:

$$\cos(k_x x) \cdot \sin(k_y y) + \cos(k_y y) \cdot \sin(k_z z) + \cos(k_z z) \cdot \sin(k_x x) > \xi. \quad (1)$$

In the Gyroid topology, there are eight LoSDs (Light-of-Sight Directions) and their arrangement is sketched in Figure 2b. The four main LoSDs are in the xyz directions, offering the best optical access to the interior of the porous matrix, but were not used in this work. In the xy LoSD, optical access is more limited. This leaves us with the LoSDs along the axes where x is the flow direction and y is the chosen viewing direction. A detailed view of the y LoSD is shown in the 3D rendering in Figure 2b for a gyroid-based burner with a porosity of $\epsilon = 0.9$. Using this LoSD for imaging provides optical access to approximately 49% of the total volume. For this work, a gyroid-type porous sample measuring $20 \text{ cm} \times 11 \text{ cm} \times 11 \text{ cm}$ was fabricated, with a cell size of $11/7 \text{ cm}$, using the parameters $\xi = 1.2$ and $k_x = k_y = k_z = 2\pi \times 3/5 \times 10^2$. This cell size was chosen to allow an initial assessment of the feasibility of in-line PIV through such a porous structure, whilst retaining significant light scattering effects from the pore walls.

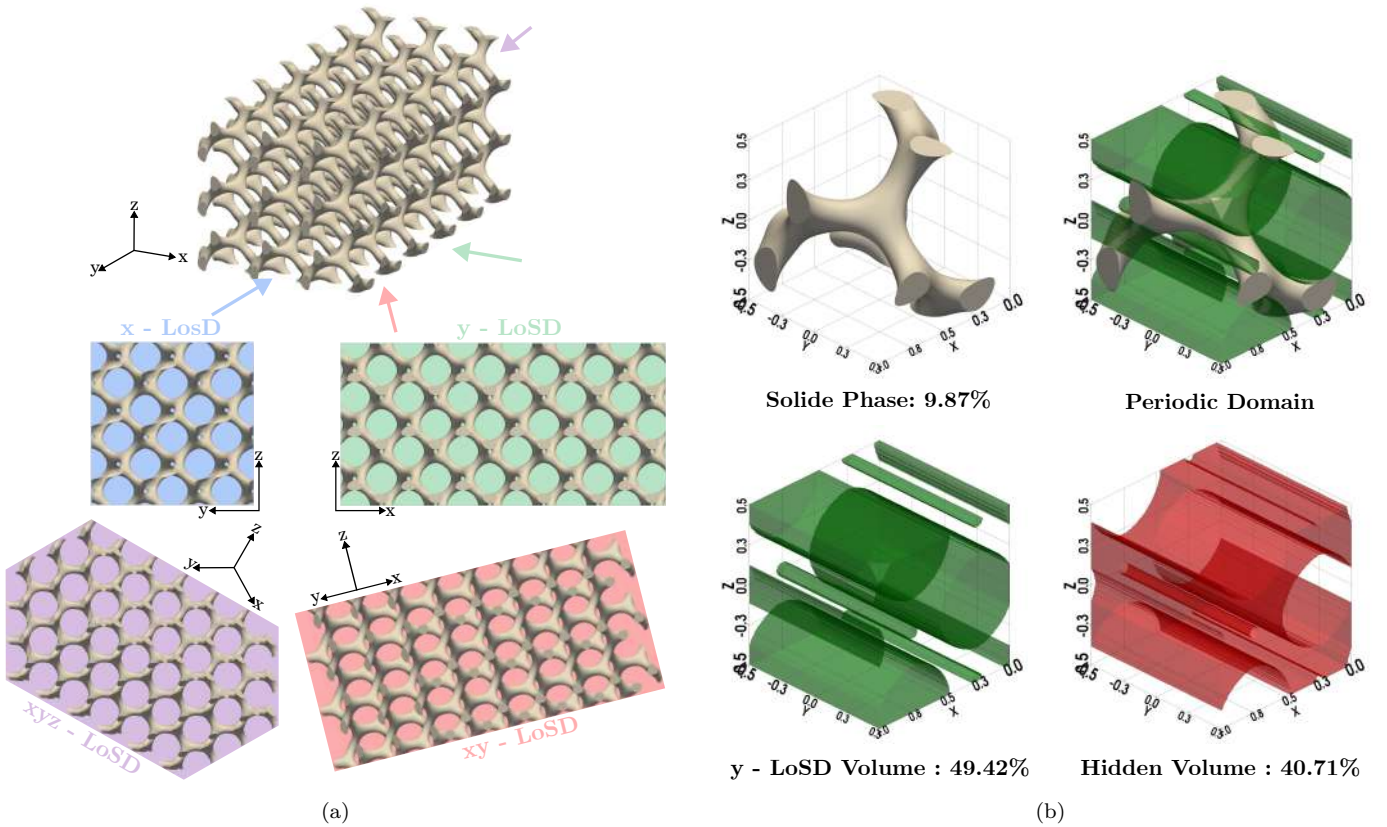


Figure 2. Inspired by Flores-Montoya (2024): (a) Arrangement of the LoSDs in a Gyroid-based topology. (b) 3D rendering of the different volume-partitions in an elementary volume.

2.2. Experimental setup

The present in-line PIV optical setup is designed with the light source and the camera aligned along the same axis, as shown in Figure 3a. Unlike conventional orthogonal PIV configurations, this arrangement relies on forward light scattering by the seeding particles, as illustrated in Figure 3b. Because Mie scattering is strongly anisotropic and peaked in the forward direction, an advantage of this configuration is that it requires lower illumination power than conventional PIV setups, which is favorable for high-speed acquisitions or the use of LED-based light sources. In the present study, pulsed-laser illumination is retained to ensure sufficiently short exposure time and because suitable pulsed LED equipment was not available.

The seeding is provided by a set of Laskin nozzles producing DEHS particles with a mean diameter of approximately $0.9\ \mu\text{m}$, following a Gaussian size distribution. Under the present experimental conditions, the associated Stokes number remains well below unity, indicating negligible particle inertia and therefore adequate tracer fidelity for the investigated flow scales. At the same time, the particles provide sufficient light scattering for robust identification against the residual bright background, as shown in Figure 6.

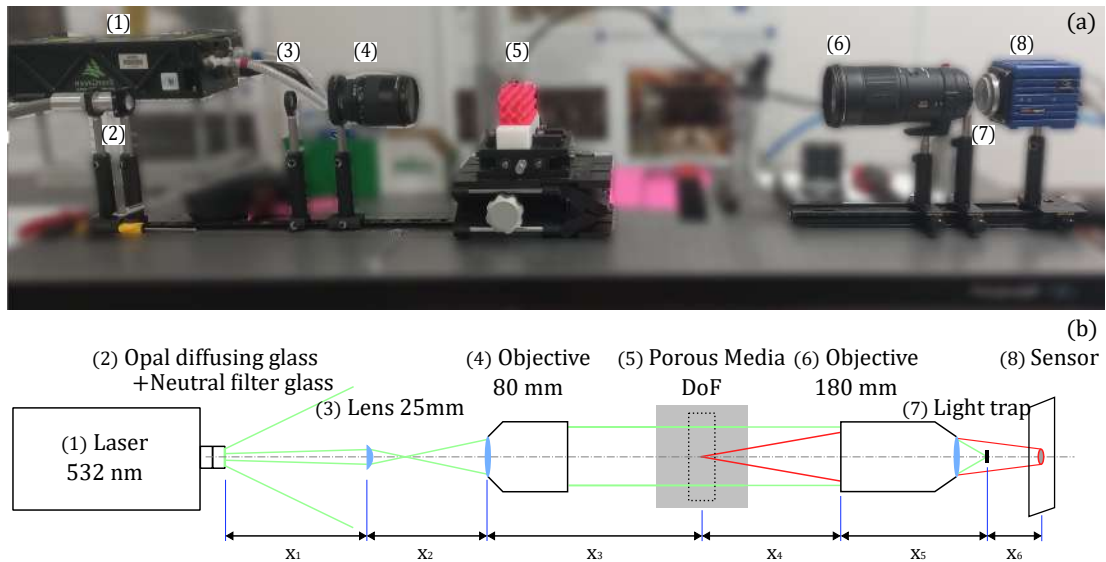


Figure 3. Photograph (top) and schematic (bottom) of the in-line PIV setup used for measurements through the porous medium.

To avoid sensor saturation, the laser intensity was reduced. However, at low power, the beam becomes unstable due to fluctuations in the laser source (Label ① in Figure 3, double-pulse Nd:YAG Evergreen laser, Quantel, 532 nm). A neutral-density filter (label ②) with 5% transmission was therefore used to attenuate the light power in a controlled manner. In addition, a diffusing opal glass window (label ②) with 40% transmission and 10° divergence angle was employed to improve illumination uniformity, at the expense of a slight increase in beam divergence, which in

turn slightly degrades subsequent focusing.

To compensate for the divergence introduced by the diffuser, a plano-convex aspheric lens (label ③, Effective Focal Length 50 mm, AR coating 350–700 nm) is placed at an appropriate distance to select a portion of quasi-parallel rays. These rays are then focused upstream of a 100 mm lens (label ④, Milvus Zf.2, Zeiss) to provide collimated light through the porous sample (label ⑤). The light is then focused by a 180 mm lens (label ⑥, Sigma, $f/2.8$) and partially blocked by a small 3D-printed light trap (label ⑦, 4 mm diameter, 2 mm thickness, black matte) positioned at its focal plane. This trap intercepts only the direct, unscattered light from the source, effectively acting as a high-pass filter in the Fourier domain, before reaching the camera sensor (label ⑧, LaVision, sCMOS). The camera acquires images in a double-frame mode at 15 Hz, with a 15 μ s interval between the two laser pulses for each PIV measurement.

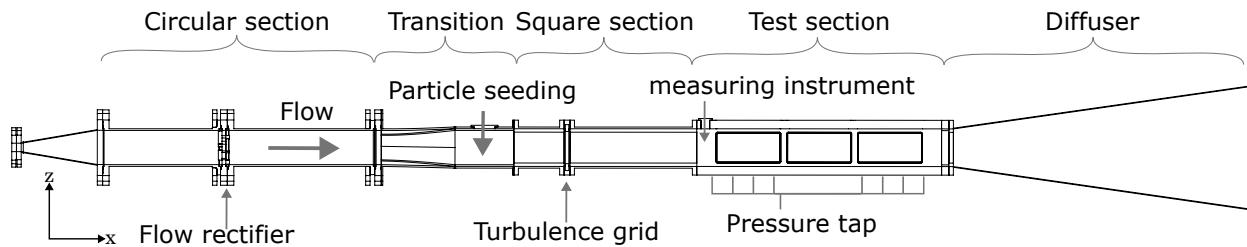


Figure 4. Overview of the experimental wind tunnel developed for turbulence investigation in porous media.
IMP-FACT : Imaging Measurement in Pores and Flow Analysis for Control of Turbulence

The setup shown in Figure 3 was installed on the Imp-Fact wind tunnel; a simplified diagram is shown in Figure 4. This wind tunnel is connected to ONERA's 80-bar network and is subsequently reduced to 15 bar, a control valve and a coriolis flow meter are used to adjust the flow velocity. The velocity range can therefore vary from 0.5 m/s to 17 m/s. The measurement section has a cross-section of 11×11 cm and is 80 cm long; the maximum size of the porous materials is $11 \times 11 \times 20$ cm, and these are placed in the centre of the measurement section. Upstream of the measurement zone, a turbulence grid can be placed to control the size of the turbulent structures upstream of the materials.

2.3. Depth of Field

With this in-line configuration, the illumination spans a three-dimensional volume rather than a thin laser sheet as in classical PIV setup. Consequently, the thickness of the region in which particles are in focus and thus detectable is governed by the depth of field (DoF) of the imaging optics. A precise estimation of the DoF is therefore essential to determine the effective measurement volume.

The theoretical DoF of an optical system combined with a digital image sensor can be expressed with the following formulation (Ishiwata et al., 2022), which accounts for the effect of the sensor pixel size:

$$\text{DoF} \approx K \frac{n\lambda}{2\text{NA}}, \quad (2)$$

where NA is the numerical aperture of the objective, n is the refractive index of the medium between the objective and the object, λ is the illumination wavelength. The coefficient K accounts for the influence of the pixel size relative to the optical system and is calculated as:

$$K \approx \frac{1}{2} \left(A + B \frac{f_N}{f_C} \right). \quad (3)$$

In these equations A and B are empirical coefficients, f_C is the cut-off frequency of the optical system, $f_N = 1/(2c)$ is the Nyquist frequency of the sensor, and c is the pixel size of the digital sensor.

Using typical experimental parameters for our setup, this formulation leads to a theoretical DoF of approximately 1.5 mm. This estimation takes into account the finite size of the sensor pixels, which modifies the classical Rayleigh criterion.

To provide a more accurate value, an experimental estimate was obtained using a high-contrast resolution target placed at the focal plane of the imaging optics and translated along the optical axis in steps of 0.1. For each position, image sharpness was quantified using the spatial standard deviation of the intensity distribution, which provides a robust measure of local contrast. Given an image $I(x, y)$, the sharpness metric is defined as

$$\sigma_I = \sqrt{\frac{1}{N} \sum_{x,y} (I(x, y) - \mu_I)^2}, \quad \mu_I = \frac{1}{N} \sum_{x,y} I(x, y). \quad (4)$$

where μ_I is the mean image intensity and N the number of pixels. A high value of σ_I corresponds to a well-resolved pattern (in focus), whereas a decrease of σ_I indicates the progressive loss of fine spatial details as the target moves out of the focal plane.

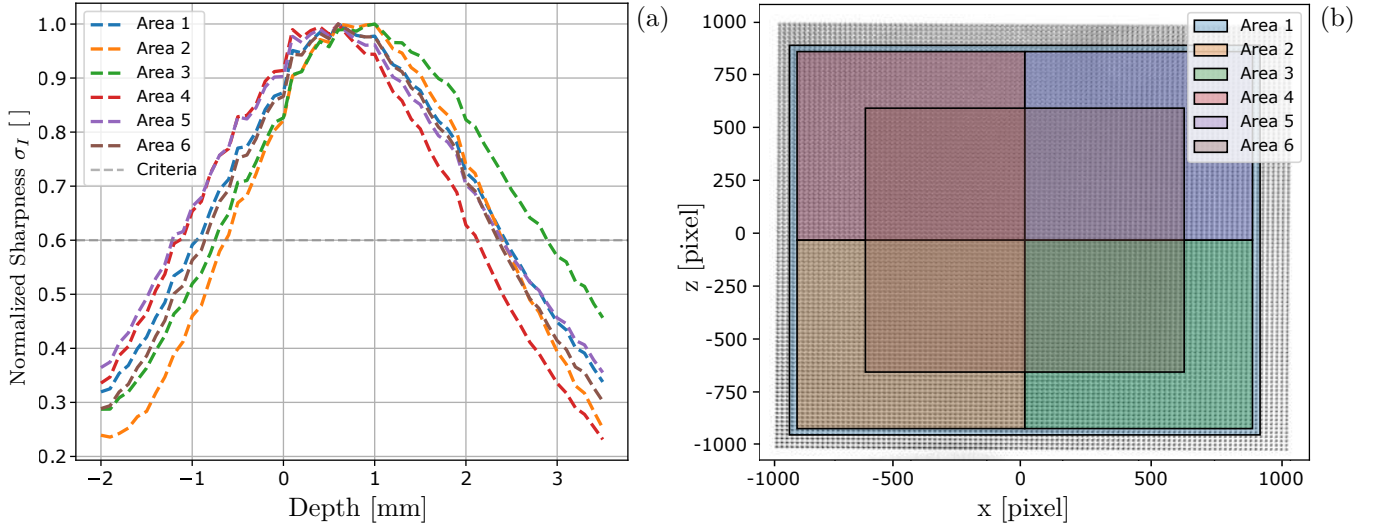


Figure 5. Determination of the DoF using a focus chart: (a) sharpness curves obtained for each region of interest; (b) regions of interest in the image plane.

The DoF is determined as the axial range over which the *normalized sharpness* remains above a chosen threshold relative to its maximum value. Using a criterion of 60% of the peak normalized sharpness, the experimentally measured DoF is found to be approximately 3 mm.

3. Image preprocessing

Before performing any correlation to estimate velocity fields, the raw images are preprocessed to enhance particle detection and remove artefacts that could compromise PIV analysis. As shown in Figure 6, the raw images exhibit several challenges: the contrast between seeding particles and the background is relatively low due to residual illumination (Raffel, Braukmann, et al., 2024), and additional parasitic scattering occurs on the pore walls. To overcome these limitations, a sequence of preprocessing steps is applied to isolate particle images, suppress background variations, and enhance signal-to-noise ratio. These steps form the basis for the following subsections.

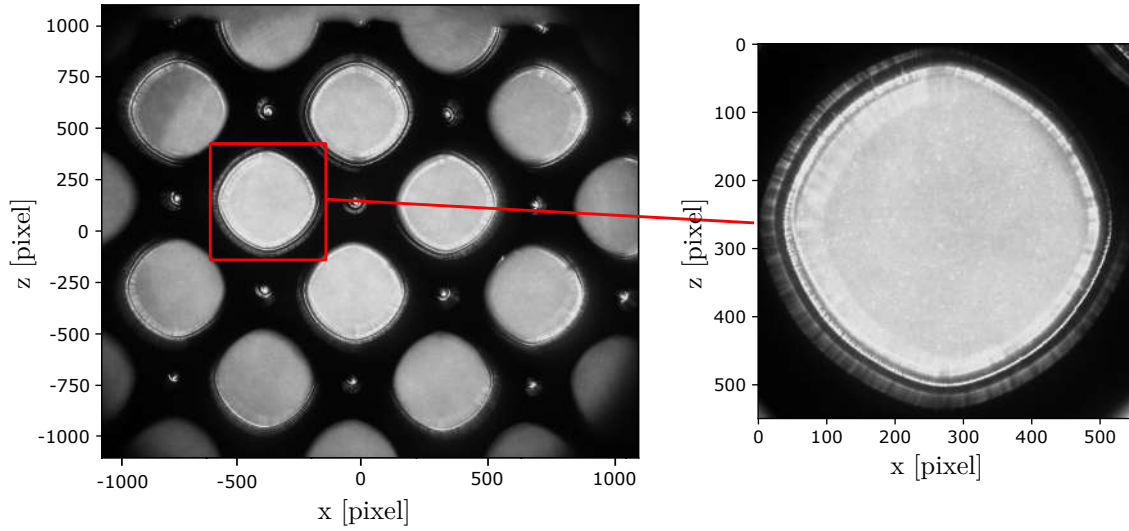


Figure 6. Left: example of raw in-line PIV image acquired with the setup shown in Figure 3. Right: zoom on a single porous cell used for detailed analysis.

3.1. Butterworth filter

To reduce illumination drift and low-frequency fluctuations while preserving the high-frequency intensity variations generated by convected particles, a temporal Butterworth high-pass filter is applied to each pixel of the image sequence (Sciacchitano & Scarano, 2014). The filtered intensity field is defined as:

$$I_{\text{filt}}(x, y, t) = \mathcal{F}^{-1} [H(\omega) \mathcal{F}(I(x, y, t))], \quad (5)$$

where $I(x, y, t)$ is the raw image, $\mathcal{F}$ and $\mathcal{F}^{-1}$ denote direct and inverse Fourier transforms, and $H(\omega)$ is the transfer function of an p -th order Butterworth high-pass filter:

$$H(\omega) = \frac{1}{\sqrt{1 + \left(\frac{\omega_c}{\omega}\right)^{2p}}}. \quad (6)$$

with $\omega_c = 2\pi f_c$ the cut-off pulsation. This formulation removes slowly varying background illumination and low-frequency artefacts, thereby enhancing the temporal contrast of particle images inside the porous medium. Figure 7(b) shows an example of the filtered image.

3.2. Temporal occurrence filtering

To further isolate relevant particle images and remove transient noise, a temporal occurrence filter is applied. For each pixel, the filter counts the number of frames in which its intensity exceeds a

threshold $I_{\min}$. Pixels that do not exceed the threshold in at least $N_{\min}$ frames are removed:

$$\text{mask}(x, y) = \sum_i [I(x, y, t_i) > I_{\min}] > N_{\min} . \quad (7)$$

This method preserves pixels corresponding to persistent particle traces while eliminating spurious bright spots caused by reflections or detector noise (Sciacchitano & Scarano, 2014). The resulting mask is applied to the images, setting all other pixels to zero (Figure 7(c)).

3.3. Connectivity-based masking

After temporal filtering, a connectivity-based mask is applied to eliminate spurious features, using the following steps:

1. Binarization: pixels below a threshold intensity are identified.
2. Labeling: connected regions are labeled using an 8-connectivity scheme.
3. Filtering: regions with an area below a minimum surface threshold or with abnormal mean intensity are removed.
4. Mask application: all rejected pixels are set to zero in the image.

This approach efficiently removes isolated bright spots or extended background structures that are not related to particle motion, as illustrated in Figure 7 (e).

3.4. Summary of preprocessing steps

The combined effect of the Butterworth temporal filter, temporal minimum subtraction, and connectivity-based masking produces clean images suitable for velocity estimation using in-line PIV. Figure 7 provides a visual summary of the different preprocessing steps applied to a representative frame:

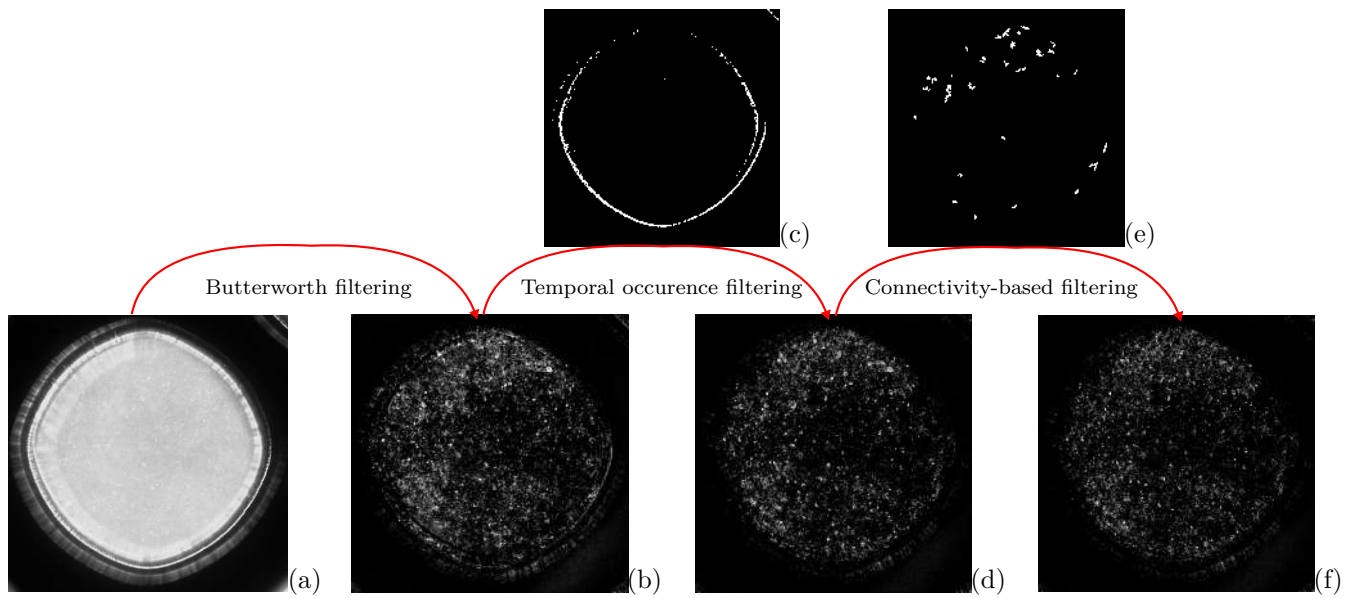


Figure 7. Example of preprocessing treatment

A final mask can be applied manually to remove light scattering emitted by the porous structure in regions far from the edges of the pores, such as the bottom-right area shown in Figure 7(f).

3.5. Correlation quality

In PIV, the velocity field is obtained by determining the most probable particle displacement through the cross-correlation of interrogation windows extracted from two consecutive particle images R. J. Adrian (1991). Figure 8 presents representative correlation maps resulting from the processing of two PIV image pairs. The correlation coefficient ranges from 0 (no correlation) to 1 (perfect correlation).

As shown in Figure 8(a), processing the raw images leads to strong spatial heterogeneity, with localized peaks of high correlation caused by intense light scattering from the solid walls of the porous material. Because these stationary bright structures remain nearly unchanged between successive frames, they generate spurious correlation peaks that bias the displacement estimation toward artificially low velocity values in near-wall regions.

After applying the full preprocessing workflow, the correlation field becomes significantly more homogeneous within the observed pores. The preprocessing does not increase the maximum correlation values; instead, it suppresses spurious peaks associated with material-induced light scattering and homogenizes the correlation levels throughout the measurement region.

As a result, the measured correlation coefficients remain lower than those typically achieved in conventional planar PIV, with values ranging between 50% and 70%. Nevertheless, the result-

ing correlation field is sufficiently homogeneous to provide robust and spatially coherent velocity estimates throughout the optically accessible regions of the porous structure.

After applying the full preprocessing workflow, the correlation field becomes significantly more homogeneous in the observed pores. The preprocessing does not increase the maximum correlation values; instead, it suppresses spurious correlation peaks related to material-induced light scattering and equalizes correlation levels throughout the measurement region.

As a result, the measured correlation coefficients remain lower than those typically achieved in classical PIV, with values ranging between 50% and 70%. However, they are sufficiently uniform to enable robust and coherent velocity-field estimation throughout the optically accessible regions of the porous structure.

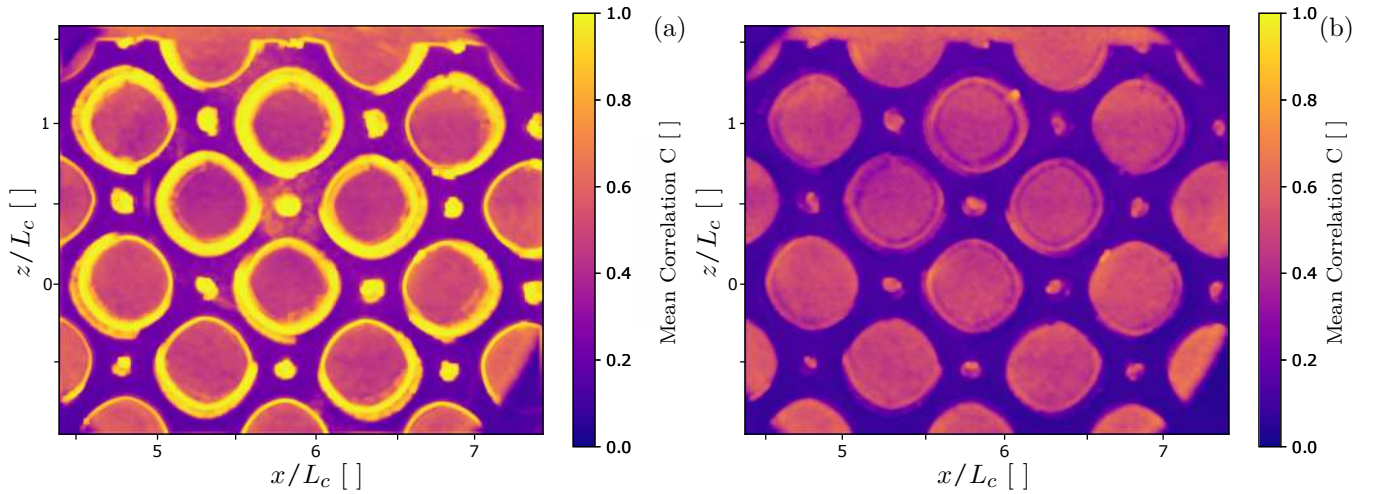


Figure 8. Correlation maps over the full camera field obtained by processing (a) raw PIV images, showing low and uneven correlation in obstructed regions, and (b) preprocessed PIV images, displaying more uniform correlation in flow regions.

4. Results

The following results are obtained from the processed in-line PIV dataset after application of the full preprocessing and validation procedure described in the previous section. These steps provide sufficiently robust and spatially coherent velocity fields for the investigation of pore-scale flow behavior within the TPMS porous structure.

The operating conditions of the flow together with the main geometric characteristics of the porous material are summarized in the following Table 1, and serve as the reference basis for all subsequent analyses.

Table 1. Operating Conditions and Material Characteristics.

Flow condition	Porous materials
$U_{\infty} = 10 \text{ m/s}$	Gyroid
$Re \approx 7.3 \times 10^4$	$(200 \times 110 \times 100) \text{ mm}$
$T = 21.3^{\circ}\text{C}$	$\phi = 0.90$
$Re_c \approx 9.51 \times 10^3$	$L_c = 18.3 \text{ mm}$
	$d_p = 9.8 \text{ mm}$

4.1. GYROID Channelling

In this section, we focus on the macroscopic behavior of the flow within the porous material in order to identify the dominant transport mechanisms induced by the gyroid architecture. In particular, the velocity fields are analyzed at different locations inside the unit cell to highlight the role of geometrical confinement on the flow distribution.

Figure 9 compares the flow structure in the central region of the cell (a) and near the cell boundary (b). A clear channelling effect can be observed, where the flow preferentially organizes into high-velocity pathways aligned with the porous structure. This effect is more pronounced near the boundaries of the unit cell, where the geometric constraints guide and accelerate the flow along preferential directions, leading to locally increased velocities compared to the bulk region.

This macroscopic flow organization highlights the strong influence of the gyroid topology on momentum redistribution and confirms that the porous structure does not behave as a homogeneous medium, but rather induces spatially heterogeneous flow paths governed by channelling mechanisms. Importantly, these observations are in good agreement with the numerical simulations performed by Rusnak et al. (2025), which predict a similar preferential flow organization and confirm the robustness of the observed channelling behavior across both experimental and numerical approaches.

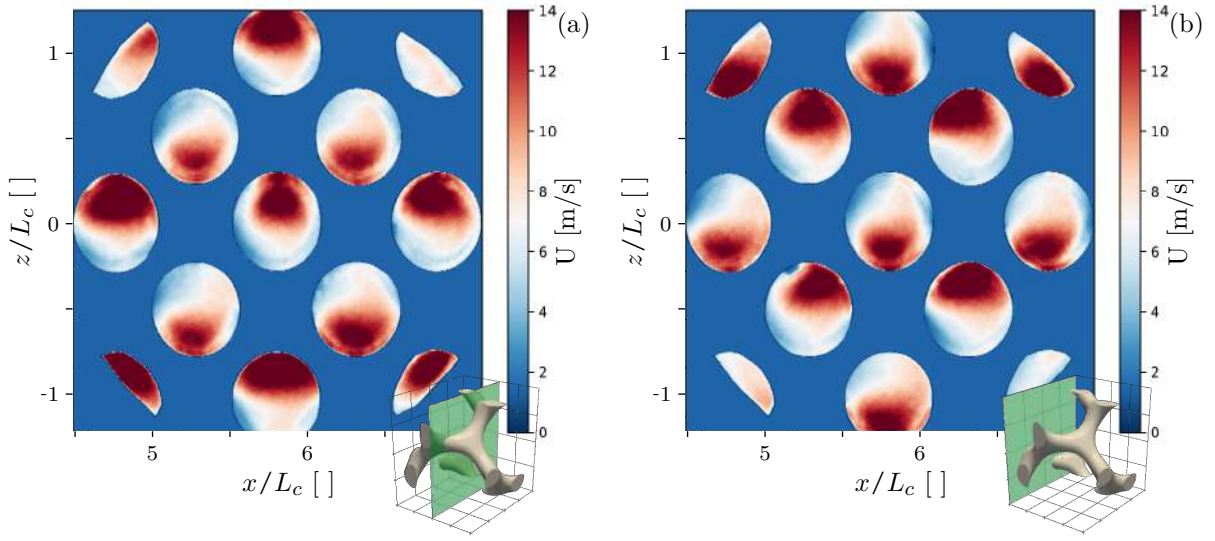


Figure 9. (a) Velocity norm in the central region of the gyroid unit cell. (b) Velocity norm near the cell boundary, highlighting flow channeling effects.

4.2. Turbulence scale adaptation

In turbulent flows through porous media, the characterization of turbulence scales is particularly important because the porous structure modifies the energy cascade and introduces additional dissipation mechanisms at the pore scale. Beyond mean velocity fields, turbulence intensity and integral length scales provide essential information regarding the spatial organization of turbulent structures and their interaction with the porous matrix. The integral length scale represents the characteristic size of the largest energy-containing eddies in the flow and therefore constitutes a key parameter for describing momentum transport inside the porous structure.

From the experimental low-frame-rate PIV measurements, the spatial autocorrelation function is computed directly from the velocity fields using ensembles of velocity fluctuation samples extracted over multiple time steps. Because the flow is strongly influenced by the porous geometry and exhibits significant spatial inhomogeneity, the correlation analysis is performed locally within each pore region. The resulting integral length scales therefore characterize the spatial extent of coherent turbulent motions within the porous medium and should not be interpreted as being equivalent to integral scales derived from Taylor's frozen turbulence hypothesis. The longitudinal autocorrelation function is defined as:

$$R_{ii}(\chi_k) = \frac{\overline{u'_i(x)u'_i(x + \chi_k)}}{\overline{u'^2_i(x)}}, \quad (8)$$

where the overbar denotes ensemble averaging. In practice, the discrete form of R_{ii} is obtained

directly from the PIV velocity fields by evaluating correlations between velocity fluctuations separated by a spatial shift χ_k .

The measured correlation curves generally exhibit an approximately exponential decay in the near-field region. A characteristic correlation length can therefore be estimated using the classical $1/e$ criterion, corresponding to the spatial separation at which the autocorrelation decreases to $1/e$ of its initial value. This criterion provides a robust estimation in experimental conditions where noise, finite field of view, and spatial filtering may affect the convergence of the full integral scale estimation (Tennekes & Lumley, 1972; Pope, 2000).

These turbulence quantities are used to provide a first characterization of the evolution of turbulent structures inside the porous medium and provide reference data for the validation of numerical turbulence models. In the present study, the analysis is restricted to the integral length scales based on the streamwise velocity fluctuations, namely the longitudinal and transverse integral length scales $(L_{11,1})$ and $(L_{11,2})$, respectively. In this context, particular attention is given to the PSPH (*Pore-Scale Prevalence Hypothesis*), which assumes that the macroscopic hydrodynamic behavior of the flow is predominantly governed by pore-scale phenomena. The validation of this hypothesis is therefore essential to determine whether averaged numerical approaches can accurately reproduce the flow characteristics without explicitly resolving the entire pore geometry. Establishing the validity of the PSPH framework also provides a consistent basis for future extensions toward coupled heat transfer and combustion studies in porous media.

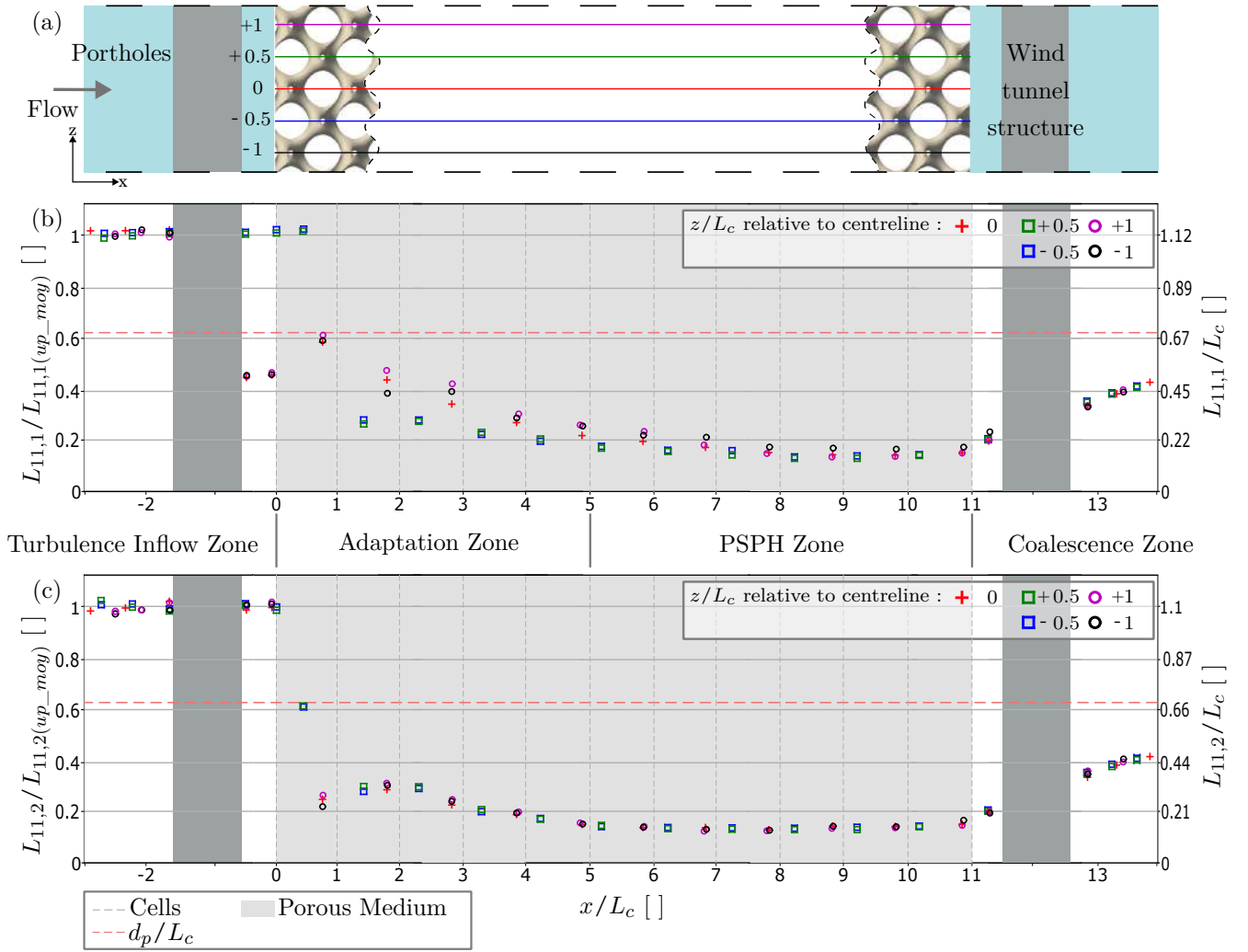


Figure 10. Schematic representation of the principle of measurement zones (a). Streamwise evolution of the longitudinal (b) and transverse (c) integral length scales associated with the velocity component in the $\vec{x}$ direction within the porous material.

Figure 10 presents the evolution of the longitudinal (b) and transverse (c) integral length scales based on axial velocity fluctuations ($L_{11,1}$ and $L_{11,2}$ respectively) through the porous material, normalized by the corresponding mean upstream turbulence length scale. These measurements were obtained along the centreline of the flow in the $\vec{y}$ -direction, at different positions in $\vec{z}$. The red curve (0) corresponds to the centre of the wind tunnel test section. The green and blue curves are located at intermediate positions between two adjacent cells, while the magenta and black curves correspond respectively to the upper and lower cell centres relative to the central cell. For clarity, the curves are separated into two groups: the *cell centre* group (red, black, and magenta curves) and the *cell edge* group (blue and green curves).

In addition, the secondary vertical axis on the left side of the graphs represents the integral length scales normalized by the characteristic cell length L_c , allowing direct comparison between the

longitudinal and transverse scales. The red horizontal line indicates the maximum integral scale directly observable within the porous structure and is defined by the projected pore diameter d_p normalized by the cell length L_c .

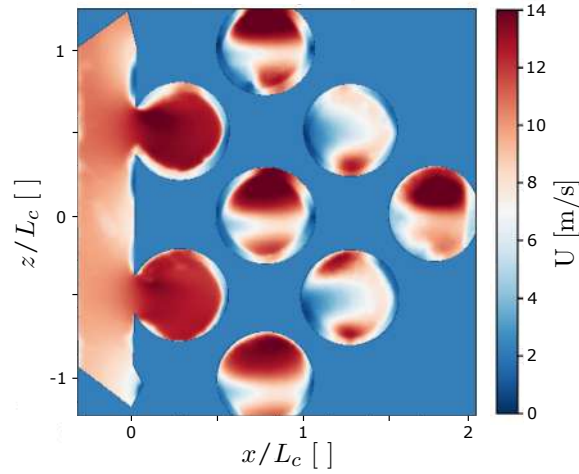


Figure 11. Velocity norm upstream of the gyroid

Four distinct regions of turbulence structure evolution can be identified. The first corresponds to the upstream region, where the incoming turbulent structures develop before interacting with the porous material. As shown in both graphs (b) and (c), the longitudinal and transverse integral length scales exhibit similar magnitudes upstream of the porous structure when normalized by L_c , indicating an approximately homogeneous and fully developed turbulent flow.

In graph (b), the integral length scales associated with the *cell centre* curves exhibit a sharp decrease as the flow approaches the porous material.. This apparent reduction is mainly caused by the restricted size of the measurable region near the porous interface. This limitation is illustrated schematically at the top of Figure 10 (a), where the combined obstruction generated by the wind-tunnel structure and the solid part of the porous medium significantly reduces the accessible measurement domain. As a result, the largest turbulent structures cannot be fully captured, which biases the estimation of the integral length scales toward lower values.

This behavior is not observed for the *cell-edge* curves because these measurement lines remain connected to open pore regions and are therefore not directly interrupted by solid ligaments. As a consequence, the incoming turbulent structures can propagate through the pore with limited interaction with the porous geometry, allowing them to retain a larger degree of spatial coherence. In contrast to regions where the flow encounters solid obstacles, the turbulence remains closer to its upstream state, which results in larger estimated integral length scales. Moreover, because the flow is less strongly affected by geometric discontinuities in these open-pore regions, the assumption of local homogeneity underlying the spatial correlation analysis is more likely to be satisfied,

making the estimated length scales more representative of the incoming turbulent structures.

A second region "Adaptation Zone" corresponds to the progressive adaptation of the turbulent structures within cells 1 to 5 of the porous medium. In both configurations, the integral length scales evolve toward similar values when normalized by L_c . More specifically, the *cell centre* curves in graph (b) and the *cell edge* curves in graph (c) reach a value equal to the projected pore size ratio d_p/L_c in the first cell. At this stage, the projected pore opening limits the measurable extent of the autocorrelation function, indicating that the incoming turbulent structures remain larger than the accessible pore dimension.

Considering now the longitudinal integral length scales, an overall reduction in turbulent structure size is observed throughout the entrance region of the porous medium. However, the *cell edge* curves exhibit a more rapid decrease than the *cell centre* curves. Referring to Figure 11, this behavior can be directly related to the onset of flow channelling induced by the gyroid geometry. The *cell centre* measurement lines are located within preferential flow pathways, where the absence of obstacles along the flow direction promotes the maintenance of large-scale spatial coherence. As a consequence, the main turbulent structure preserve coherence over a larger axial extent. In contrast, the *cell edge* curves correspond to regions where the flow interacts more strongly with the porous structure, leading to a more rapid loss of spatial coherence and consequently smaller turbulent length scales.

As the channelling mechanism progressively develops through the porous structure, both the *cell centre* and *cell edge* curves continue to decrease and eventually converge toward a nearly constant value corresponding to approximately 20% of the cell size.

Focusing now on the cross-sectional (transverse) analysis, a more pronounced reduction in turbulent structure size is observed within the first and second pores of the porous medium. As shown in Figure 11, this behavior is associated with a strong local acceleration of the flow along the *cell centre* measurement lines. This acceleration leads to an effective contraction of the turbulent structures in the transverse direction, as the flow is progressively reorganized by the pore geometry. Following this initial acceleration phase, a partial re-expansion of the turbulent structures is observed, which is attributed to a local stabilisation of the flow within the pore. However, this effect is temporary, and the transverse integral length scales decrease again as the flow continues through the porous matrix. Ultimately, as in the longitudinal case, both *cell centre* and *cell edge* curves converge toward a characteristic transverse length scale of approximately 20% of the cell size.

A potential PSPH validation region is then identified between cells 6 and 11, where the turbu-

lent structures exhibit a clear stabilisation in size. In both longitudinal and transverse analyses, the stabilised value reached within this region corresponds to approximately 20% of the cell size, indicating that the flow dynamics are predominantly governed by the pore-scale geometry. This behaviour suggests that the porous medium imposes a characteristic length scale on the turbulence, beyond which the turbulent structures become constrained by the geometry of the porous network.

Finally, downstream of the porous structure, a coalescence region is observed, where the turbulent structures progressively grow again. In this region, the flow gradually relaxes from the geometric constraints imposed by the porous medium, and the structures tend to recover sizes comparable to those observed in the upstream region before the porous material.

In summary, the turbulence analysis reveals a progressive adaptation of the turbulent structures to the gyroid porous architecture. The observed evolution of the integral length scales highlights the strong coupling between flow channelling and turbulence redistribution within the porous matrix. After an initial adjustment region, the stabilization of the turbulent structure size inside the material suggests that the pore geometry governs the dominant flow dynamics, supporting the validity of the PSPH framework in the central region of the porous medium. These results confirm that pore-scale mechanisms play a leading role in the macroscopic hydrodynamic behavior.

5. Conclusions

In this study, an in-line PIV methodology was successfully implemented to investigate turbulent flows through a gyroid porous structure under realistic flow conditions. The combination of a dedicated optical configuration and a tailored preprocessing workflow made it possible to obtain exploitable velocity fields despite the strong light scattering and geometric obstruction induced by the porous matrix. The preprocessing strategy significantly improved the spatial homogeneity of the correlation fields and enabled reliable turbulence statistics within the optically accessible regions of the material.

The measurements revealed a pronounced channelling effect imposed by the gyroid topology, demonstrating that the porous structure strongly redistributes momentum and generates preferential high-velocity pathways. The evolution of the integral length scales further showed that energy-containing, large-scale turbulent structures progressively adapt to the porous geometry. Several characteristic regions were identified, including an upstream influence zone, a turbulence adjustment region associated with the establishment of flow channelling, a stabilization region inside the porous medium, and a downstream coalescence region.

The stabilization of turbulent structure sizes observed between cells 6 and 11 suggests that the turbulence dynamics become predominantly governed by the pore-scale geometry. These observations provide encouraging evidence supporting the relevance of the PSPH framework within the core region of the porous medium, where the turbulence appears to reach a statistically stabilized state controlled primarily by local pore-scale mechanisms. In contrast, the upstream adjustment region and downstream recovery zone exhibit significant spatial evolution of the turbulent structures, indicating that the assumptions underlying the PSPH framework may not be uniformly applicable throughout the entire flow domain.

Overall, this work demonstrates the feasibility and potential of in-line PIV for turbulence investigations in complex porous architectures. Beyond the present gyroid configuration, the methodology developed here opens the way for systematic studies of turbulence–porous media interactions in TPMS structures with varying porosity, pore size, and orientation. These future investigations will contribute to a deeper understanding of turbulence modulation, transport phenomena, and coupled thermo-fluid processes in architected porous media.

Acknowledgements

Co-funded by the European Union (ERC, POROLEAF, 101103502). The views and opinions expressed are, however, those of the authors alone and do not necessarily reflect those of the European Union or the European Research Council Executive Agency. The authors thank Philippe Cornic for his help in designing the pre-processing image filters.

Nomenclature

PIV	Particle Image Velocimetry
DoF	Depth of Field
NA	Numerical aperture of the lens
ξ	TPMS structure parameter
ϕ	Porosity of the TPMS
L_c	Cell length [mm]
d_p	Pore diameter by projection [mm]
λ	Wavelength of the illumination
n	Refractive index of the medium between the objective and the object
K	DoF coefficient accounting for the pixel size effect
A, B	Empirical coefficients (e.g., $A \approx 1.0$, $B \approx 1.1$)
f_C	Cut-off frequency of the optical system
f_N	Nyquist frequency of the sensor, given by $f_N = 1/(2c)$
c	Pixel size of the digital sensor
μ_I	Mean image intensity
N	Number of pixels in the image
σ_I	Sharpness metric
$I(x, y, t)$	Raw image intensity at pixel (x, y) and time t
$I_{\text{filt}}(x, y, t)$	Temporally filtered image intensity
$\mathcal{F}$	Direct Fourier transform operator
$\mathcal{F}^{-1}$	Inverse Fourier transform operator
$H(\omega)$	Transfer function of the Butterworth high-pass filter
ω_c	Cut-off pulsation of the high-pass filter
p	Order of the Butterworth high-pass filter

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