Turbulence in TPMS Porous Media with DNS run on JAGUAR code

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1 Context

Porous media play a crucial role in various industries such as energy, chemical processing, and environmental engineering due to their ability to enhance heat and mass transfer, improve fluid mixing, and optimize flow dynamics. In particular, their potential in turbulent combustion systems can lead to ultra-low emission technologies through enhanced mixing and flame stabilization (Figure 1). However, the complex flow dynamics in porous structures, particularly at high Reynolds numbers (Re), present significant numerical and experimental challenges. Of particular interest the class of Triple Periodic Minimal Surface (**TPMS**) porous media, which are structures known for their superior thermal, structural, and diffusive properties. These materials are easy to fabricate and parametrize, making them ideal candidates for applications requiring fine control of flow and mixing properties.

2 Objectives and Motivations

This thesis presents work undertaken during my six-month internship at ONERA (Toulouse, France) with the primary aim of analyzing turbulent behavior in TPMS materials using **Direct Numerical Simulations (DNSs)**. This research is part of the 2023 ERC-funded POROLEAF project, led by my supervisor, R. Roncen. My role focused on developing post-processing analysis and strategies for data obtained from DNSs conducted by my supervisor on GENCI (the French National High-Performance Computing Facility).

A preliminary goal is to validate the use of Pressure Gradient Scaling (**PGS**) method to increase the efficiency of simulations by enabling larger time steps, which is crucial for reducing computational costs while maintaining accuracy. This study also aims to compare turbulence characteristics between **TPMS structures of varying porosities** to understand their effect on turbulence intensity, energy dissipation, and length scales.

3 Numerical Approach

This study uses the **JAGUAR** code, which employs the Spectral Difference Method (**SDM**) along with Immersed Boundary Conditions (**IBC**) and the **PGS** technique to simulate the turbulence in TPMS materials. The Synthetic Random Fourier Method (**SRFM**) was applied to inject a controlled turbulence spectrum, providing a more realistic approximation of flow conditions. The simulation approach includes fine mesh discretization and high-resolution turbulence modeling, ensuring that both large and small-scale eddies are captured. The order of magnitude of the degrees of freedom of a simulation is around 1 billion. Calculations were run at the GENCI, for an estimation of 2 million h CPU per simulation.

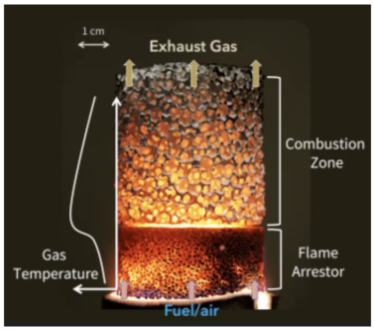

Figure 1: Example of application: Heterogeneous combustion.

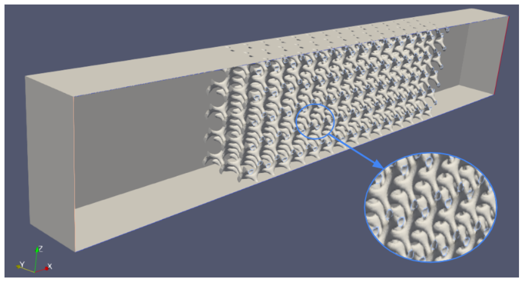

Figure 2: 3D view of the computational setup

4 Results

4.1 Post-Treatment Techniques

Handling the large datasets generated by DNS was one of the key challenges. To manage this, we developed a post-treatment strategy using the *Antares Library* and *mpi4py* for efficient extraction and processing of the simulation data. In particular we extracted highly time-resolved in probes at specific locations and we developed a parallelized code for the extraction of highly space-resolved sub-volumes, such as sections and volumes. The latter data extraction code significantly reduced the computational and storage capacity overhead, allowing us to process the simulation results without loosing in fidelity.

4.2 PGS Validation

The **PGS** method was validated using coarser and lower-resolution simulations, where the mean error in velocity mag-

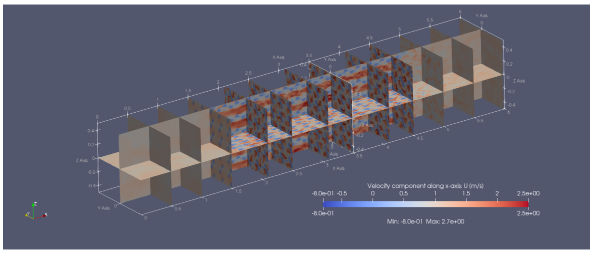

Figure 3: 3D view of the post-treated data through the extraction of sub-volumes (in this case plane sections) from the computational setup.

nitude and turbulent kinetic energy (TKE) remained below 4% and 5%, respectively. This method allowed for larger time steps, improving the efficiency of the DNS simulations without sacrificing accuracy.

4.3 Gyroid (Struct = 1.20, Porosity = 0.90)

For the high-porosity TPMS configuration with a structural factor of 1.20 (porosity $\phi = 90\%$), the injected turbulence length-scales were quickly reduced to the pore scale as the flow passed through the structure. This demonstrated that the TPMS acts as a scale reducer, decreasing both the length and time scales of turbulence, which begin to increase again downstream (Figure 5). The length-scales were computed using a zero-crossing peak integration method (Z-PIM), developed in this work. The turbulent kinetic energy (TKE) increased by about 4% per pore, following an initial 600% surge upon entering the porous medium. Additionally, power spectral density (PSD) analysis confirmed that the TPMS promotes isotropy in the flow, similar to the behavior of turbulent grids (Figure 4).

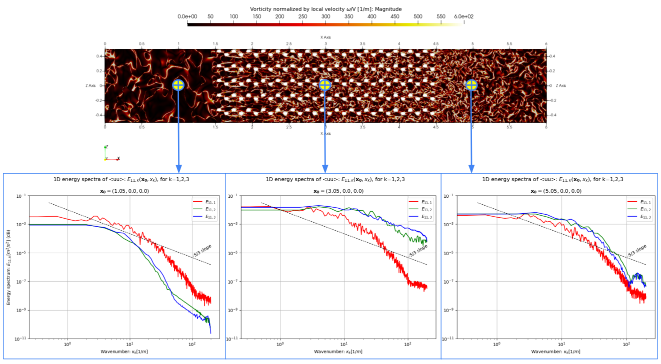

Figure 4: Gyroid with struct = 1.20: Spectral analysis comparing energy spectra at different positions in the domain.

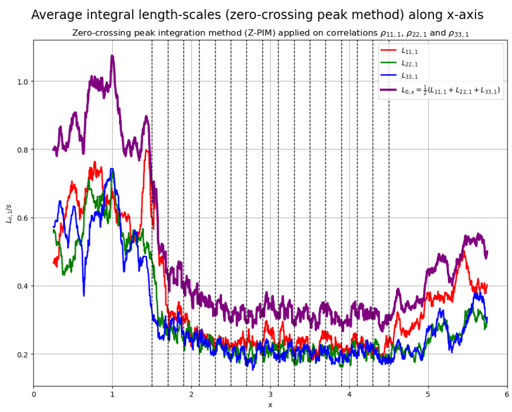

Figure 5: Gyroid structure with struct = 1.20: length scales $L_{ii,x}$ computed with the Z-PIM method averaged along x-axis.

4.4 Gyroid Comparison Based on Structural Factor

A comparative study was conducted between two Gyroid TPMS configurations: one with a structural factor of 1.20 (porosity $\phi = 0.90$) and another with a structural factor of 0.75 (porosity $\phi = 0.72$). Reducing the porosity increased TKE by 65%, with a tenfold increase in dissipation rates (Figure 6). The characteristic turbulent length scales adapted to the pore size much more quickly in the lower-porosity configuration (within one pore), while the higher-porosity configuration required about three pores for full adjustment. This supports the **Pore-Scale Prevalence Hypothesis (PSPH)**.

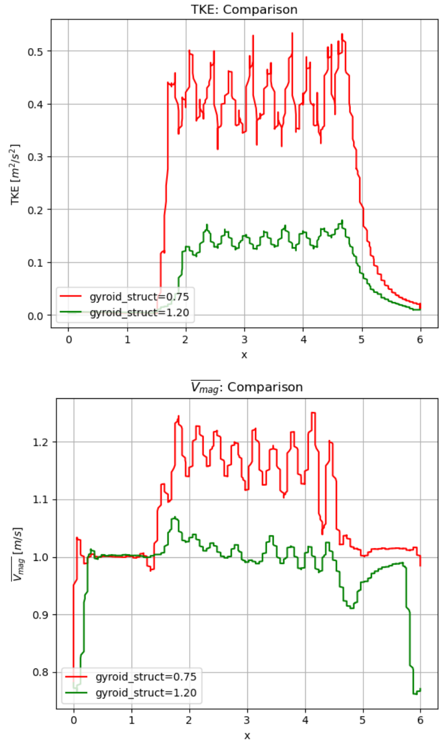

Figure 6: TKE and velocity magnitude comparison between two Gyroid structures.

5 Conclusions

The findings from this research demonstrate that TPMS materials, particularly Gyroids, effectively control turbulence intensity, length-scales and energy dissipation. The validated PGS method improves simulation efficiency, enabling larger time steps without significant accuracy loss, making it an invaluable tool for future high-resolution DNS studies, when the Mach number is very low. The results also highlight how TPMS geometries act as scale reducers and TKE enhancers, influencing turbulence dynamics and potentially optimizing processes like heat exchange and combustion.

6 Future Perspectives

Future research should explore various TPMS topologies, investigate the role of porosity, and refine turbulence injection parameters. Expanding to multiscale TPMS and multiphase flows could uncover new flow regimes, while PIV and wind-tunnel experiments, along with alternative solvers like LBM, will ensure more robust validation. Additionally, incorporating chemical reactions is crucial for advancing combustion-related applications.