Magnetic Resonance Velocimetry Study of Secondary Flow and Vortex Migration in a Helical Cruciform Fuel Bundle

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1. Introduction

Helical cruciform fuel (HCF) has attracted attention as a high-mixing fuel concept for compact light-water reactor cores. The twisted four-petal geometry induces intrinsic swirl and transverse motion without relying on spacer grids, potentially enhancing heat transfer and inter-subchannel exchange while limiting additional hydraulic components. Understanding the underlying flow physics inside HCF subchannels is therefore essential for evaluating its thermal-hydraulic behavior.

The HCF geometry continuously rotates along the axial direction. This rotation generates geometry-driven secondary flows and coherent vortical structures within each subchannel. The interaction between these vortices, the channel-box wall, and neighboring subchannels produces non-uniform flow partitioning and cross-gap transport. In particular, the position and stability of the inner-core vortex are expected to influence transverse momentum exchange and overall mixing intensity.

Although prior studies have reported global pressure-drop characteristics and concentration-based mixing trends [1,2], volumetric velocity-field measurements resolving the three-dimensional structure of secondary flow in HCF remain limited. Direct measurement of the full three-component velocity field is necessary to clarify vortex topology, migration behavior, and the resulting subchannel transport mechanisms.

Magnetic resonance velocimetry (MRV) enables non-intrusive measurement of three-dimensional velocity fields based on phase-encoded magnetic resonance principles [3]. In the present study, MRV is employed to obtain three-dimensional, three-component, time-averaged velocity fields in a 3×3 HCF assembly under fully turbulent conditions. The measured data are analyzed to quantify flow partitioning, secondary-flow intensity, vortex migration, and inter-subchannel crossflow. The objective is to provide a physics-based interpretation of the flow structures inherent to twisted cruciform geometry and to establish an experimental reference for future thermal-hydraulic assessments. MRV has previously been applied to complex rod-bundle configurations, demonstrating its suitability for resolving coherent secondary structures in nuclear thermal-hydraulic systems [4].

2. Methodology

2.1 Test Section and Geometry

The experiments were conducted in a closed-loop water flow facility designed to operate inside an MRI environment. A schematic of the overall loop is presented in Fig. 1. The system consists of a reservoir, pump, flowmeter, and a flow-conditioning section installed upstream of the measurement region. The test section was positioned inside the MRI bore, while auxiliary components were located outside the magnet room to avoid magnetic interference.

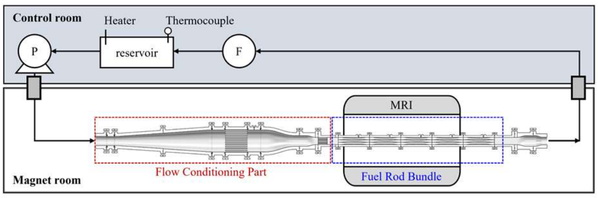


Fig. 1. Schematic of the experimental flow loop and MRV measurement configuration.

A photograph of the assembled test section is shown in Fig. 2. The upstream flow development section includes honeycomb structures to suppress large-scale inlet non-uniformities. Downstream of the conditioning region, the 3×3 helical cruciform fuel bundle was installed as the measurement domain.

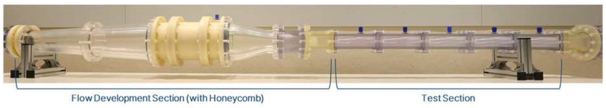


Fig. 2. Photograph of the flow development section and test section installed for MRV measurement.

Each fuel rod consists of a four-petal cruciform cross-section (Fig. 3) and follows a constant axial twist. The axial development of the twisted configuration is illustrated in Fig. 4. Five consecutive twist pitches (λ = 17.1 cm) were connected to form the full measurement length. The hydraulic diameter of the subchannel was 7.68 mm, and the inter-rod gap was 0.1 mm.

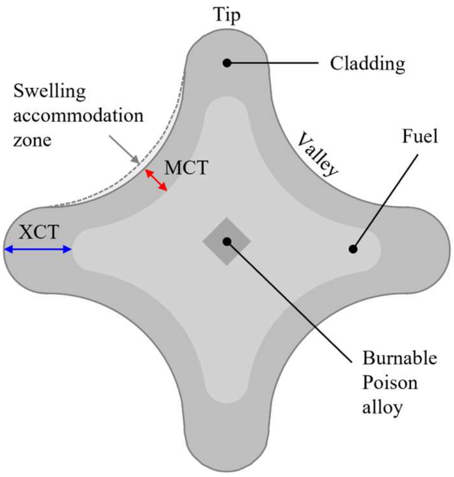


Fig 3. Cross-sectional geometry of the cruciform fuel rod.

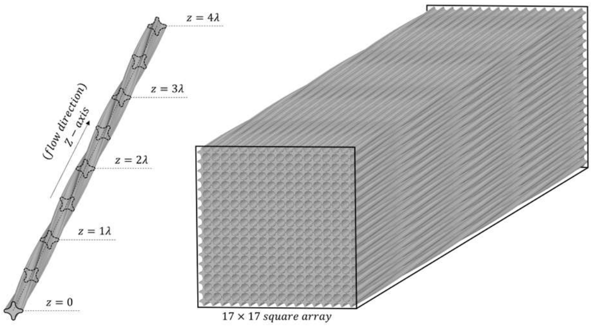


Fig. 4. Helical configuration of cruciform rods along the axial direction.

The Reynolds number was maintained at approximately 1.0×10^4, defined as $Re = \frac{\rho U_b D_h}{\mu}$, where D_h is the hydraulic diameter of the subchannel and U_b is the bulk axial velocity. This condition corresponds to a fully turbulent regime.

2.2 Magnetic Resonance Velocimetry

Three-dimensional velocity measurements were obtained using magnetic resonance velocimetry (MRV) at a 3.0 T MRI system. The technique encodes fluid velocity into the phase of the magnetic resonance signal by applying controlled magnetic field gradients. Independent encoding along three orthogonal directions enables reconstruction of the full three-component velocity vector field.

Four axial fields of view (FOVs) were sequentially measured to cover the entrance and periodically developed regions of the bundle. Each FOV had a spatial resolution of 0.30 mm with isotropic voxels. The velocity encoding parameters were selected to capture both dominant axial motion and weaker transverse components while avoiding phase wrapping.

To eliminate background phase errors, pump on/off reference scans were performed and subtracted from the flow measurements. The resulting velocity fields were masked to isolate the fluid region and registered into the bundle-aligned coordinate system.

2.3 Flow Analysis Procedure

The measured velocity fields were used to evaluate bulk flow characteristics and subchannel-scale transport phenomena. Subchannels were categorized as corner, edge, and interior regions according to their geometric location.

The subchannel-averaged axial velocity was calculated to determine the flow split factor, defined as the ratio of local average velocity to the bulk velocity. Secondary-flow intensity was quantified as the magnitude of transverse velocity components relative to the axial component.

Inter-subchannel exchange was evaluated by integrating the velocity component normal to each subchannel interface. This procedure allowed identification of net diversion flow and the spatial variation of crossflow along one twist pitch.

All analyses were performed on time-averaged velocity fields, focusing on mean flow structures and coherent vortex behavior.

3. Results

3.1 Flow Development and Periodicity

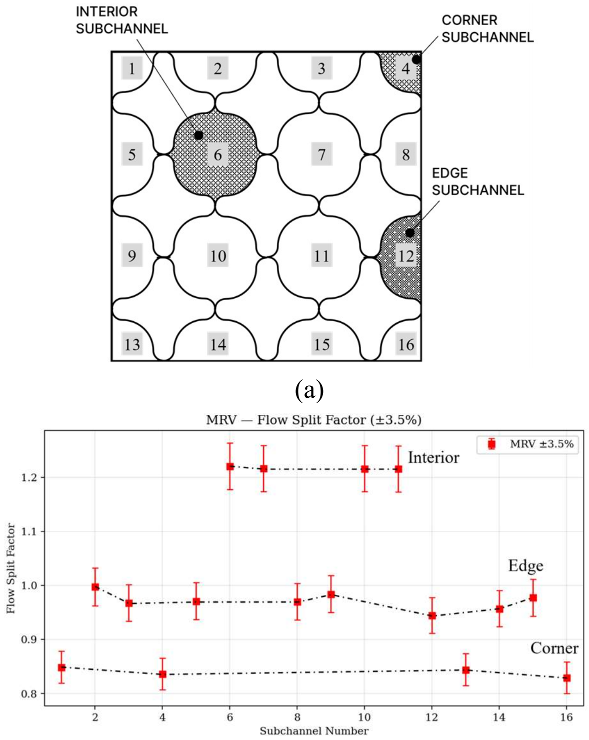
Axial correlation analysis of the subchannel-averaged axial velocity indicates that the bulk flow reaches a pitch-wise repeating state after approximately one twist pitch. However, inspection of local velocity distributions shows that near-wall regions require a longer distance to fully stabilize. The detailed profiles suggest that spatial development is essentially completed after about two pitches.

This distinction between bulk periodicity and local convergence highlights the importance of volumetric measurements when assessing twisted geometries.

3.2 Subchannel Flow Partitioning

Subchannels were classified as interior, edge, and corner regions according to their geometric location, as illustrated in Fig. 5(a). The axial velocity distribution is not proportional to geometric area. Instead, interior subchannels exhibit the highest normalized axial velocity, whereas corner regions show reduced values due to wall confinement effects.

The corresponding flow split factors derived from MRV measurements are shown in Fig. 5(b). The values span approximately 0.86 to 1.19 across the bundle. This persistent ordering (corner < edge < interior) reflects the influence of rotationally induced pressure redistribution and secondary motion on axial flow allocation.



(a)

(b)

Fig. 5. (a) Subchannel classification in the 3×3 HCF bundle. (b) Flow split factor obtained from MRV measurements (error bars indicate ±3.5%).

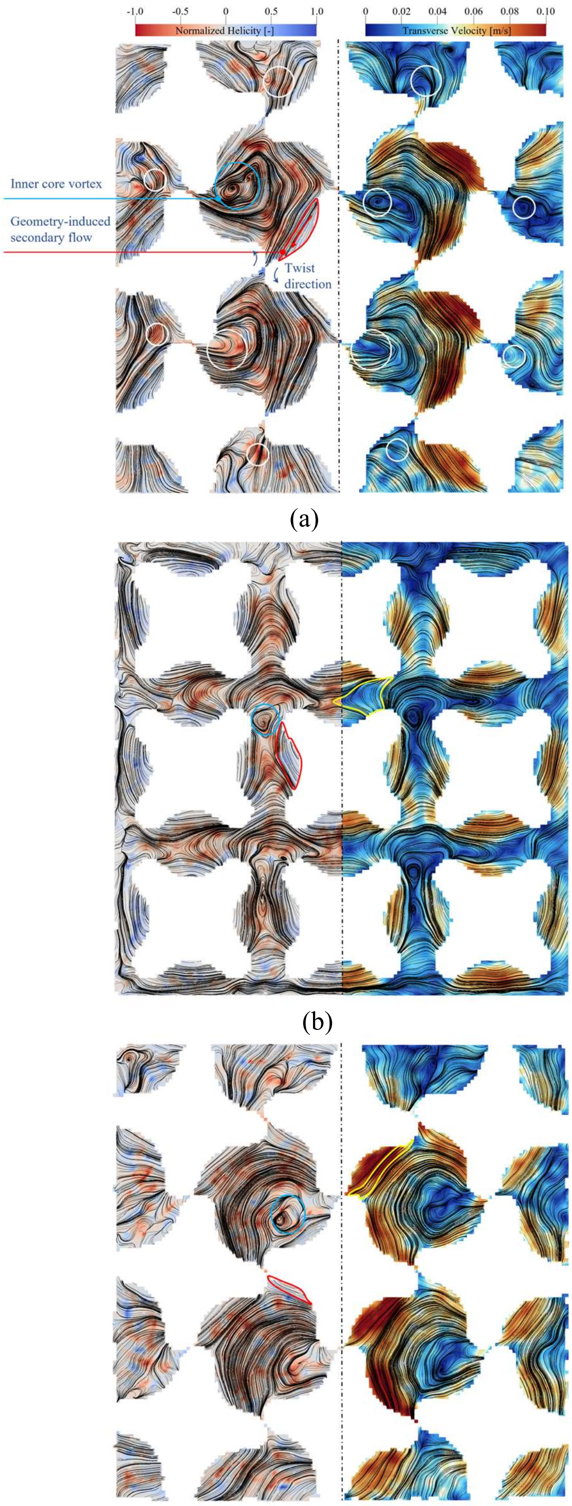
3.3 Secondary Flow and Vortex Behavior

Transverse motion is clearly observed throughout the measurement domain. The secondary-flow intensity ranges between approximately 4–6% of the bulk axial velocity. A local minimum appears near half of the twist pitch, suggesting partial cancellation between interacting vortical structures as the rods rotate.

Cross-sectional visualization reveals two dominant features:

1. A wall-attached swirling layer following the helical contour of the fuel petals
2. A coherent inner-core vortex located within the central subchannel region

The inner vortex does not remain centered. Instead, it migrates circumferentially as the flow advances downstream, tracing a helical trajectory. The off-axis displacement is consistent with asymmetric wall proximity and geometry-induced pressure gradients. This eccentric vortex motion governs much of the transverse momentum redistribution inside the bundle.



(a)

(b)

(c)

Fig. 6. Axial evolution of secondary flow structures over one twist pitch. (a) Normalized helicity with in-plane streamlines. (b) Transverse velocity magnitude. (c) Demonstrating circumferential vortex-core displacement within the central subchannel.

3.4 Inter-Subchannel Exchange

Integration of the velocity component normal to subchannel interfaces shows systematic cross-gap transport aligned with the rotational direction of the fuel twist. The strongest exchange occurs across interfaces aligned with the dominant tangential motion induced by the rotating vortex core.

Normalized net exchange velocities remain below approximately 0.02 relative to the bulk velocity, while the total mixing magnitude (excluding cancellation effects) reaches values of order 0.03–0.05. These results confirm that vortex-driven transverse motion, rather than purely geometric area differences, controls subchannel interaction.

4. Discussion

The present measurements clarify how the twisted cruciform geometry organizes the internal flow field. Unlike straight rod bundles where secondary motion is primarily turbulence-driven, the HCF configuration generates persistent geometry-induced swirl. This deterministic rotational forcing establishes a stable inner-core vortex that coexists with wall-following shear layers.

The observed circumferential migration of the vortex core suggests that the equilibrium position of the structure is continuously redefined by the local pressure field and wall proximity. This behavior can be interpreted in the framework of classical vortex dynamics, where asymmetric image-vortex interaction near a boundary induces lateral drift [5]. As the rods rotate, asymmetric confinement produces differential induction, leading to a systematic off-axis displacement. This behavior explains the spatial variation of transverse velocity intensity along one twist pitch.

The flow partitioning trend further indicates that axial momentum redistribution is not governed solely by geometric area. Instead, the interaction between induced swirl and pressure gradients directs higher axial flux toward interior regions while suppressing motion near corners. Consequently, subchannel transport in HCF assemblies is strongly vortex-mediated.

The measured crossflow magnitudes confirm that coherent structures, rather than random turbulent exchange alone, dominate inter-subchannel interaction. This implies that mixing in twisted geometries is structurally organized and potentially predictable based on vortex dynamics.

5. Conclusions

Three-dimensional MRV measurements were performed in a 3×3 helical cruciform fuel bundle at turbulent flow conditions to clarify the intrinsic flow structures generated by the twisted geometry. The results show that bulk periodicity is achieved after roughly one twist pitch, whereas full local stabilization requires a longer axial development length.

Axial flow partitioning is consistently ordered as corner < edge < interior, demonstrating that rotationally induced pressure redistribution modifies the subchannel velocity distribution beyond simple geometric scaling.

Secondary flow remains significant throughout the bundle, with transverse intensity on the order of several percent of the bulk velocity. A coherent inner-core vortex is identified within the subchannel, and its circumferential migration along the axial direction forms a helical trajectory. This off-axis vortex motion governs transverse momentum exchange and drives inter-subchannel transport.

The measurements provide direct experimental evidence of vortex-controlled mixing mechanisms in twisted cruciform geometry and establish a physics-based reference for evaluating thermal-hydraulic performance of HCF assemblies.

These findings demonstrate that vortex-controlled transport is a defining characteristic of twisted cruciform geometry. Future studies will aim to quantify vortex-core migration and relate its trajectory to subchannel mixing and numerical predictability.

Acknowledgement

REFERENCES

[1] T. M. Conboy et al., Nuclear Technology, 2013.
[2] Q. Zhang et al., Annals of Nuclear Energy, 2021.
[3] C. J. Elkins and M. T. Alley, Experiments in Fluids, 2007.
[4] C. Im et al., Physics of Fluids, 2024.
[5] P. G. Saffman, Vortex Dynamics, Cambridge University Press, 1992.