

Biased Sweeping Cross-flow in Helical Cruciform Metallic Fuel Subchannels Measured by Magnetic Resonance Velocimetry

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1. Introduction

Small modular reactors (SMRs) are increasingly viewed as a way to complement variable renewables with firm, low-carbon generation, and several current designs pursue high-assay low-enriched uranium (HALEU) metallic fuel to extend cycle length and enable more compact, power-dense cores. The helical cruciform fuel (HCF) concept, developed from earlier twisted four-petal fuel elements used in Russian icebreaker reactors and later proposed for the PIK research reactor, arranges four-petal cruciform metallic rods on a square-pitch lattice and twists each rod about its own axis [1]. The resulting helical vane promotes coolant self-mixing without discrete spacer grids, increases the heated surface area relative to a conventional cylindrical rod, and has been projected to allow a meaningful power uprate in both boiling and pressurized-water reactor cores [2]. Figure 1 shows the cross-sectional geometry of a single HCF rod, including the concave “valley” region between adjacent petals, which coincides with the location of minimum cladding thickness and is explicitly designated as the swelling accommodation zone in the fuel design.

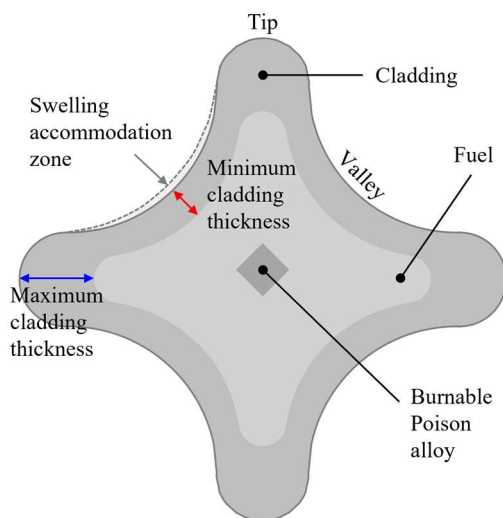


Fig. 1. Cross-sectional schematic of the HCF rod, reproduced from [1], showing the valley region (minimum cladding thickness) and the swelling accommodation zone.

Despite these projected benefits, the true thermal margin of twisted cruciform bundles remains uncertain because no critical-heat-flux (CHF) correlation yet captures the combined effects of rod twist, swirl, and azimuthally varying heat flux. Closing this gap requires subchannel or CFD-level predictions that are themselves validated against resolved velocity data, yet the experimental record for HCF bundles remains comparatively thin: Conboy et al. measured the pressure drop of a 4×4 HCF assembly and found it essentially independent of twist pitch for long pitches [3], while a companion CFD benchmark by Shirvan and Kazimi showed that Reynolds-averaged Navier–Stokes (RANS) turbulence closures could not accurately reproduce the measured pressure drop [4]. Zhang et al. used a wire-mesh sensor (WMS) to quantify transverse mixing in a 5×5 HCF bundle [5], and Kinsky et al. more recently reported friction-factor correlations and flow-regime transition data for a 9×9 HCF bundle [6]. None of these studies, however, resolved the full three-dimensional, three-component (3D-3C) velocity field within the subchannels themselves.

To close this gap, the authors previously employed magnetic resonance velocimetry (MRV) – a non-intrusive technique that encodes fluid velocity into the phase of a magnetic-resonance signal and is well suited to complex, opaque internal flows [7], and has previously been applied to resolve secondary flows in wire-wrapped rod bundles relevant to reactor subchannels [8] – to acquire the time-averaged 3D-3C velocity field in a 3×3 HCF subchannel bundle (twist pitch $\lambda = 17.1$ cm) at $Re \approx 1 \times 10^4$ [1]. That study established that the bulk flow reaches a pitch-wise periodic state after approximately one twist pitch, that the subchannel flow-split factor follows a stable ordering of corner < edge ≈ 1 < interior with an overall range of 0.830–1.221, and that the secondary-flow intensity (SFI) averaged over each subchannel ranges from about 3.66% to 4.87% of the bulk axial velocity. Most notably, unlike the fully symmetric flow field that an idealized CFD simulation with symmetric geometry and boundary conditions would be expected to produce, the measured inner-core vortex was found to migrate systematically away from the geometric subchannel center, tracing an eccentric, helical trajectory downstream that was interpreted using an image-vortex model of wall-induced drift.

The present work extends that study along three lines. First, the measured sweeping cross-flow is directly benchmarked against the symmetric sweeping-flow results reported in the CFD and WMS-based HCF literature, to test whether the common assumption of a symmetric, near-zero net cross-flow is representative of an as-built bundle. Second, a quantitative vortex-identification criterion (the Γ_1 criterion) is applied to the MRV velocity field to characterize the vortex-core eccentricity and its helical appearance-dissipation cycle.

2. Cross-flow Classification and Subchannel-code Closure

2.1. Classification of subchannel cross-flow

Following Todreas and Kazimi [9], lateral exchange between adjacent subchannels is classified along two independent axes – forced vs. natural, and directional (net mass flow $\neq 0$) vs. non-directional (net mass flow = 0) – yielding the four mechanisms summarized in Table 1. Diversion cross-flow is a natural, directional pressure-driven flow arising from differences in subchannel hydraulic resistance; turbulent interchange is a natural, non-directional pulsating exchange that transports momentum and energy while its net mass exchange averages to zero; flow sweeping is a forced, directional mixing driven by an inserted structure – a spacer, a wire wrap, or, in HCF, the twisted vane itself – that pushes coolant in a preferred direction; and flow scattering is the corresponding forced but non-directional turbulence generated by the same structures.

In an HCF bundle, the gap s_{ij} between neighboring subchannels i and j is not fixed but varies periodically as each rod twists along its axis, cycling between a maximum opening and full closure. Fig. 2 shows both states. In Fig. 2(a), with the gap open, cross-flow splits into a sweeping flow region near the rod surfaces, where net cross-flow peaks along the twist direction ($w_{ij} \neq 0$, $s_{ij} = s_{ij,max}$), and a shear-dominated region at the gap, where net cross-flow vanishes ($w_{ij} \rightarrow 0$) despite a persistent turbulent interchange ($w'_{ij} \neq 0$). In Fig. 2(b), once the gap closes ($s_{ij} = 0$), cross-flow through it is blocked and the momentum is redirected into an induced vortex within subchannels. This periodic gap closure, driven by the rod's helical twist, is what produces the forced, directional flow-sweeping mode of mixing characteristic of HCF bundles.

Table 1. Subchannel cross-flow classification, after Todreas and Kazimi [9].

	Natural	Forced
Directional (<i>net</i> $\neq 0$)	Diversion cross-flow	Flow sweeping
Non-directional (<i>net</i> = 0)	Turbulent interchange	Flow scattering

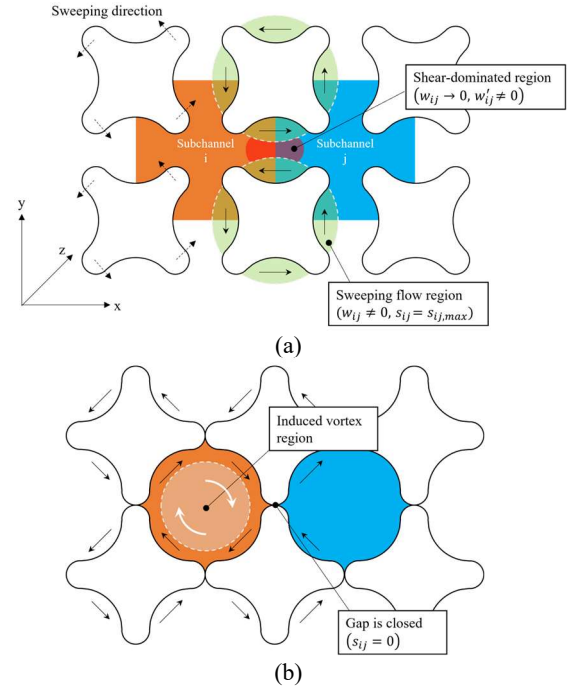


Fig 2. Local cross-flow regions in the gap between subchannels i and j over one helical sweeping cycle of the helical cruciform fuel rods: (a) crossing phase, (b) contacting phase

2.2. Subchannel-code mixing closure

COBRA-family subchannel codes quantify turbulent interchange through a single empirical mixing coefficient β via $w'_{ij} = \beta \cdot S_{ij} \cdot G$, where G is the axial mass flux and S_{ij} is the gap width. When forced-mixing mechanisms such as spacer grids, wire wraps, or the HCF vane are lumped into the same effective coefficient, this generalizes to $\beta_{eff} = \beta_{turb} + \beta_{diversion} + \beta_{sweep}$. Because MRV, like other time-averaged measurement techniques, records the mean velocity field rather than the instantaneous flow through a gap, the corresponding measured exchange rate captures only the diversion and sweep contributions, since the turbulent-interchange contribution converges to zero once time-averaged:

$$\bar{w}_{ij} = \bar{w}_{ij,diversion} + \bar{w}_{ij,sweep} + \bar{w}_{ij,turb}(\rightarrow 0). \quad (1)$$

Only $\beta_{diversion}$ and β_{sweep} can therefore be extracted from the present dataset; β_{turb} requires fluctuation data – e.g., from PIV or from transient, turbulence-resolving CFD – that lie outside the scope of a mean-flow MRV measurement.

2.3 HCF-specific complication

Standard β correlations implicitly assume a gap width s that is constant along the axial direction, as is the case for straight rod bundles fitted with discrete spacer grids or a constant-lead wire wrap. In HCF, by contrast, the cross-section itself rotates continuously about the bundle axis, so the gap between adjacent rods is intrinsically a function of axial position, $s(z) = s_0 - \Delta s \cdot f(\theta(z))$ with

$\theta(z) = 2\pi z/H_{\text{twist}}$, cycling between a minimum at the “contacting phase” (where the vanes nearly touch) and a maximum at the “crossing phase” ($\theta = 90^\circ$, halfway through a twist pitch). Conboy’s experimental data [3] showed that the effective mixing coefficient β_{eff} for HCF bundles depends strongly on the reference gap $s(0)$: shorter mixing lengths – i.e., shorter twist pitches, as in the present $\lambda = 17.1$ cm test section – cause the gap to narrow and widen more rapidly with axial position, producing a correspondingly larger effective cross-flow. This axial dependence, and its coupling to a forced, directional sweeping mechanism, is precisely what the present study seeks to resolve experimentally rather than assume.

2.4 Prior HCF Cross-flow

To date, published cross-flow analyses of HCF bundles have relied either on CFD or on wire-mesh sensors, and none has reported a fully resolved 3D-3C experimental velocity field. Jiang et al. [10] performed RANS simulations of a helical cruciform rod bundle and reported the axial development of the positive and negative gap mass-flow-rate components (W^+ , W^-) together with their net value (W_{net}) at two Reynolds numbers and two gap locations; in every case W^+ and W^- developed as near mirror images of each other and W_{net} remained close to zero throughout the twist pitch (Fig. 3(a)). Xiao et al. [11], using a CFD-informed sweeping-mixing model, likewise reported a crossflow rate (n) that stayed near zero across the full range of twist angle while the positive and negative components (w^+ , w^-) varied symmetrically and in phase opposition (Fig. 3(b)). Both results are consistent with what a RANS solver would be expected to produce for a bundle with perfectly symmetric geometry and boundary conditions: because ensemble-averaged RANS closures smooth out the small stochastic asymmetries that would otherwise bias the flow toward one side, the sweeping flow computed in the gap is essentially mirror-symmetric and its net component is negligible. Whether this assumption holds for an as-built, experimentally realized HCF bundle – where geometric imperfections, fabrication tolerances, and upstream flow conditioning are inevitably imperfect – had not previously been tested against a direct 3D-3C measurement.

3. Experimental and Analysis Methods

3.1 Test section and MRV measurement

The measurements analyzed here were acquired on the same 3×3 HCF subchannel bundle described in detail in [1]; key parameters are summarized in Table 2. Briefly, four-petal cruciform rods with a twist pitch $\lambda = 17.1$ cm were arranged on a 13.1 mm square pitch and fabricated by stereolithographic 3D printing; the assembled test section spanned five twist pitches (85.5 cm total length) and was operated at $Re \approx 1.0 \times 10^4$ using a 20 mM CuSO_4

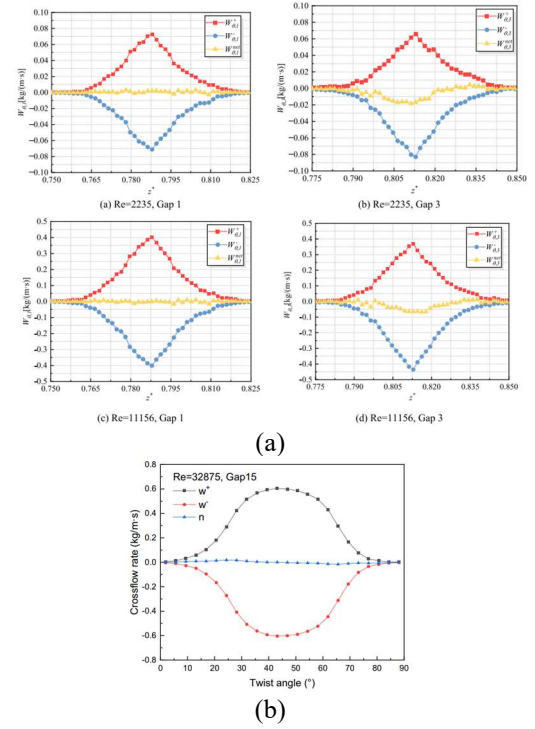


Fig. 3. Symmetric sweeping cross-flow computed by prior CFD-based studies: (a) Jiang et al. [10], gap mass-flow-rate decomposition into positive (W^+), negative (W^-), and net (W_{net}) components at two Reynolds numbers; (b) Xiao et al. [11], crossflow rate (w^+ , w^- , n) vs. twist angle at an interior gap.

aqueous solution. Time-averaged 3D-3C velocity fields were acquired with a 3 T phase-contrast MRV sequence at an isotropic voxel size of 0.3 mm across four overlapping fields of view (FOV1 to FOV4) spanning the entrance to the fully developed region, and the reconstructed volumetric flow rate agreed with the flowmeter reading to within $\pm 3.5\%$. Full fabrication, acquisition, and uncertainty-quantification details are given in [1] and are not repeated here.

Table 2. Key geometric and operating parameters of the test section [1].

Parameter	Value	Parameter	Value
Gap [mm]	0.1	Twist pitch [cm]	17.1
Rod pitch [mm]	13.1	No. of sections	5
Dh [mm]	7.68	Total length [cm]	85.5
Flow area [mm ²]	931.99	Reynolds number	10,000
Array	3×3	Voxel size [mm]	0.3

3.2 Cross-flow decomposition

Following the coolant-centered subchannel framework of [1], the transverse mass-exchange rate between adjacent subchannels i and j is defined as

$$w_{ij}(z) = \left(\frac{1}{\Delta z}\right) \iint_A \rho v n dA \quad (2)$$

This quantity was evaluated at four interior gaps arranged sequentially around the HCF twist (SC6-SC7, SC6-SC10, SC7-SC11, SC10-SC11) and decomposed at each axial position into a net component (the signed

value of w_{ij} , isolating the directional/sweeping contribution) and an exchange component ($|w_{ij}|$ with the net contribution removed, retaining only the symmetric bidirectional mixing).

3.3 Vortex-core identification

To quantify the spatial migration of the inner-core vortex reported qualitatively in [1], the Γ_1 vortex-identification criterion of Graftieaux et al. [12], widely used for PIV/POD-based vortex detection in unsteady swirling flows, was applied to the MRV data:

$$\Gamma_1(P) = \left(\frac{1}{N}\right) \frac{\sum M[(\mathbf{PM} \times \mathbf{U}_M) \cdot \hat{\mathbf{z}}]}{|\mathbf{PM}| |\mathbf{U}_M|} \quad (3)$$

where P denotes the candidate point in the measurement plane being tested as a possible vortex-core location, and M denotes any point within a fixed local interrogation window of N points centered on P . $\mathbf{PM}$ is the position vector from P to M , and $\mathbf{U}_M$ is the local velocity vector at M .

Table 3. Sensitivity of the peak Γ_1 value to the interrogation window radius R .

R [voxel]	Γ +peak	Γ -peak
4	0.865	-0.892
6	0.761	-0.849
8	0.710	-0.858
9	0.693	-0.843
10	0.647	-0.841
12	0.613	-0.813
14	0.607	-0.790

To exclude the influence of axial shear, Γ_1 was evaluated independently at each axial cross-section using only the in-plane (cross-flow) velocity components projected onto that 2-D plane, rather than a fully 3-D criterion. Because Γ_1 depends on an interrogation window of radius R around each candidate point P , R was first estimated analytically from the HCF channel geometry: at the contacting phase the largest resolvable vortex is bounded by the inscribed circle of diameter $D_1 = \sqrt{2} \cdot D_{\text{rope}} + D_{\text{elbow}}$, while at the crossing phase it is bounded by the diagonal of the open square channel, $D_2 = P(\sqrt{2}-1) = 5.43$ mm, giving $R_{\text{voxel}} = (D_2/2)/\Delta s_{\text{voxel}} \approx 9$ voxels for the 0.3 mm voxel size used here. A sensitivity study over $R = 4$ –14 voxels (Table 3) confirmed that the location of the peak Γ_1 value converges as R approaches this analytically estimated value, supporting the use of $R = 9$ voxels for the vortex-core tracking presented in Section 4.3.

4. Results and Discussion

4.1 MRV-measured directional bias in sweeping flow

The MRV-measured tangential velocity distribution at FOV4 (Fig. 4) does not preserve the left-right symmetry assumed in the literature results of Fig. 3; instead, the sweeping flow maintains a clear directional bias that

repeats with the twist pitch λ . The ensemble-averaged net w_{ij} across the four interior gaps (Fig. 5(a)) varies with axial position from roughly $+0.20$ kg/(m $\cdot$ s) to -0.10 kg/(m $\cdot$ s) and does not converge to zero, reaching a magnitude equal to roughly half of the exchange-component peak at the same location (≈ 0.39 kg/(m $\cdot$ s), Fig. 5(b)) – a net contribution too large to be dismissed as measurement noise. Consistent with the geometric reasoning of Section 2.3, the net crossflow grows rapidly where the gap begins to widen and reverses sign as the shear layer, most active near the crossing phase, is carried downstream.

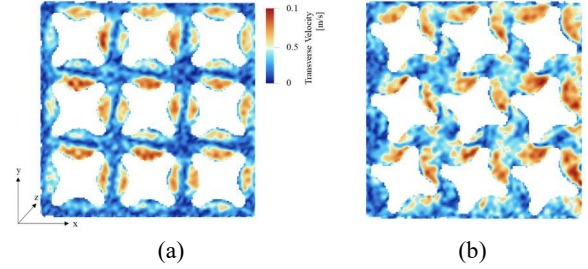


Fig. 4. MRV-measured transverse velocity magnitude at FOV4 ($z = 0.5\lambda, 0.75\lambda$; z aligned with both the flow and helical twist directions), showing sweeping flow that does not preserve bundle symmetry.

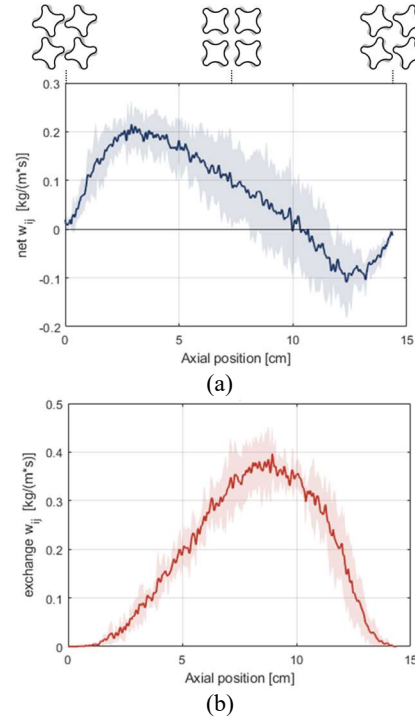


Fig. 5. Ensemble average over the four interior gaps: (a) net cross-flow and (b) exchange cross-flow along the axial direction.

4.2 Vortex-core eccentricity and helical dissipation trajectory

Applying the Γ_1 filter with $R = 9$ voxels (Fig. 6) confirms that the inner-core vortex is detected at a position clearly offset from the geometric channel center, consistent with the wall-induced-drift (image-vortex) mechanism proposed in [1]. Tracking the vortex core

along the flow direction (Fig. 7) shows that it is first detectable near the contacting phase, migrates along a helical path, and dissipates just upstream of the crossing phase (0.5λ) at $z = (n + 0.379)\lambda$. This appearance–migration–dissipation cycle, repeating once per twist pitch, is the structural counterpart of the directional net cross-flow reported in Section 4.1: a vortex that is systematically displaced to one side of the channel, rather than randomly wandering about the center, necessarily biases the local sweeping flow in the same direction on every twist-pitch cycle.

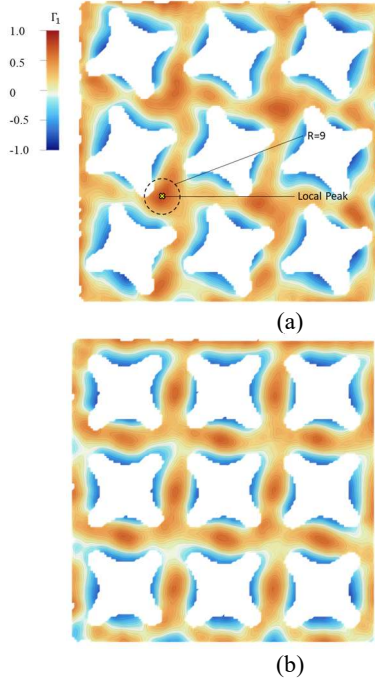


Fig. 6 Eccentric vortex-core position identified with the Γ_1 criterion ($R = 9$ voxels).

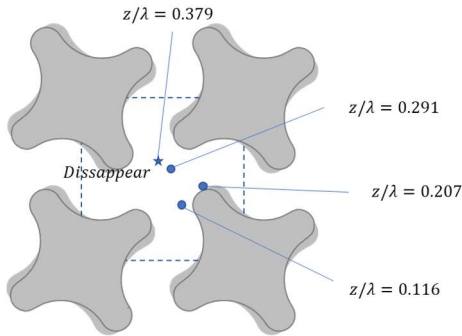


Fig. 7 Vortex-core migration and dissipation trajectory within the 3×3 HCF inner subchannel over one twist pitch.

4.3 Limitations

This study has several limitations. The measurements were obtained at a single, relatively low Reynolds number, and no direct heat-transfer data were acquired. In addition, the 3×3 test bundle is a wall-dominated assembly with a comparatively high fraction of near-wall subchannels, and it remains an open question how the observed vortex-core eccentricity would evolve in a

larger assembly where the wall-adjacent fraction is substantially smaller.

5. Conclusion

3D-3C MRV measurements in a 3×3 HCF subchannel bundle show that, contrary to the near-zero net cross-flow computed in prior CFD and WMS-based studies that assume fully symmetric geometry and boundary conditions, the net sweeping cross-flow in an as-built HCF bundle is not negligible.

The sweeping flow is biased periodically with the twist pitch, and Γ_1 -based vortex tracking shows that the inner-core vortex follows an eccentric helical trajectory that dissipates just upstream of the crossing phase on every cycle. RANS-based CFD, whose ensemble-averaged closures smooth out the small asymmetries responsible for this behavior, has an inherent limitation in resolving it.

Future work will quantify the impact of the biased sweeping flow on heat-transfer performance and re-scope the ongoing validation study from full CFD validation to a comparison-level assessment against the present MRV benchmark.

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