

Identification and characterization of a starting vortex from initiation within a confined tube

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ABSTRACT

Heat transfer in laminar flows is currently a limiting factor in many engineering applications, particularly at the micro-scale. Dominated by molecular diffusion, laminar flow is an inefficient mechanism for mass and hence energy transport. However, the introduction of large-scale coherent structures, specifically axially propagating toroidal vortices, can significantly enhance cross-stream transport. This study investigates the formation, propagation, and spatiotemporal evolution of a starting vortex generated by a pulsatile jet in both unconfined and confined environments. High-resolution Particle Image Velocimetry (PIV) was combined with a multi-criteria Combinatorial Vortex Detection (CVD) algorithm to objectively characterize the vortices and evaluate their topological development. Unconfined reference experiments demonstrate that the jet produces a highly symmetric toroidal vortex undergoing a distinct two-stage maturation process: an active ejection phase characterized by rapid core growth and circulation increase, followed by a passive viscous propagation phase where the vortex steadily advances to a downstream position of $x = 150$ mm. Conversely, experiments within a confined transparent tube reveal that wall proximity induces intense localized shear stresses. This interaction severely arrests downstream propagation, stagnating the surviving vortex core at approximately $x = 65$ mm, and can cause the coherent structure to undergo asymmetric fragmentation and breakdown. Ultimately, the CVD algorithm successfully isolated true rotational cores from adjacent wall-bounded shear layers, establishing a robust, validated framework for ongoing high-fidelity investigations into complex, wall-bounded flow dynamics.

1. Introduction

Heat transfer efficiency has become a critical limiting factor in modern engineering applications, where the inability to effectively dissipate thermal energy frequently dictates system performance, reliability, and cost. This thermal bottleneck is particularly acute in the electronics sector. For instance, the global thermal management technologies market was valued at approximately USD \$14 billion in 2023 and is projected to nearly double by 2030, reflecting the immense financial burden of cooling high-density devices (Research, 2024). Common examples include high-

performance computers, where thermal throttling limits processing speeds, and mobile devices such as cell phones, where form factor constraints prevent the use of bulky active cooling mechanisms (Garimella, Persoons, Weibel, & Gektin, 2016). In these confined geometries, the cooling fluid, whether air in a heatsink or liquid in a microchannel, typically operates within the laminar flow regime (Bergman, 2011). Under these conditions, heat transfer is dominated by molecular diffusion rather than convection, resulting in the development of thick thermal boundary layers that impede heat exchange between the wall and the fluid core (Shah, 1975). To overcome these diffusive limitations without incurring the high pressure-drop penalties of turbulent flow, methods for enhancing heat transfer are needed. One promising approach is the induction of large-scale flow motion (or chaotic advection) to disrupt the boundary layer and promote transverse mixing (Aldali, Elbaba, & Morad, 2015). In the analysis of engineering flows, the characterization of vortex structures relies on mathematical models that describe the tangential velocity distribution, $v_\theta(r)$, while resolving the singularity at the core typical of inviscid potential vortices. The Lamb-Oseen vortex (Lamb, 1932) describes the transient decay of a vortex under the influence of viscosity, where the core radius grows over time due to diffusion. Its tangential velocity profile is time-dependent and given by:

$$v_\theta(r, t) = \frac{\Gamma}{2\pi r} \left(1 - \exp\left(-\frac{r^2}{4\nu t}\right) \right),$$

where Γ is the circulation and ν is the kinematic viscosity. In contrast, the Burgers vortex (Burgers, 1948) represents a steady-state equilibrium often observed in turbulent flows, where the viscous diffusion of vorticity is exactly balanced by an intensifying extensional strain field. This balance prevents the vortex from decaying, maintaining a constant core size. Explicitly including the effects of the strain rate, a , and viscosity, ν , the Burgers velocity profile is defined as:

$$v_\theta(r) = \frac{\Gamma}{2\pi r} \left(1 - \exp\left(-\frac{ar^2}{4\nu}\right) \right).$$

Here, the characteristic core radius is determined by the fluid properties and flow conditions, specifically $r_c = \sqrt{\frac{4\nu}{a}}$. While these models are physically rigorous for specific regimes, they lack the flexibility to fit a wide range of experimental data. The Vatisstas vortex model (Vatisstas, Kozel, & Mih, 1991) addresses this by introducing a shape parameter, n , allowing for a generalized profile that interpolates between different vortex families:

$$v_\theta(r) = \frac{\Gamma}{2\pi r} \frac{r}{(r^{2n} + r_c^{2n})^{\frac{1}{n}}}.$$

In this formulation, $n = 2$ provides a close approximation to the Gaussian core of the Lamb-Oseen and Burgers models, while $n = 1$ recovers the algebraic decay of the Rankine-like vortex often observed in wing-tip vortices (Devenport, Rife, Liapis, & Follin, 1996).

These mathematical formulations were originally derived under strict assumptions that limit their direct applicability in complex engineering systems. All three models assume an unconfined, axisymmetric domain where the vortex is isolated, perfectly circular, and free from the influence of boundary layers or adjacent walls. This assumption of radial symmetry simplifies the Navier-Stokes equations but neglects the anisotropy inherent in many real-world flows. Consequently, when a vortex is subjected to external shear or strain, common in turbomachinery wakes or mixing tanks, these circular models fail to capture the resulting elliptical deformation. In such scenarios, the models must be altered, typically by replacing the scalar radius r with an elliptical coordinate system or by superimposing a straining flow field to account for core stretching and stripping mechanisms (Kida, 1981). The application of these models in confined flows, such as pipe flow or cyclone separators, presents significant challenges. While often used to initialize Computational Fluid Dynamics (CFD) simulations, the standard Lamb-Oseen and Vatistas models do not inherently account for the "no-slip" condition at the containment walls. In confined domains, the induced velocity field must vanish at the boundaries, a condition not satisfied by the algebraic tail of the Vatistas profile. To adapt these models for confinement, engineers typically employ the Method of Images, placing virtual vortices outside the domain to cancel the velocity at the walls, or employ empirical modifications that artificially truncate the vortex profile to prevent non-physical velocities near the boundaries (Saffman, 1992).

Various algorithms have been developed for vortex detection in fluid flows, ranging from local criteria based on velocity gradients to global geometric methods. Common techniques include the Q-criterion (Hunt, Wray, & Moin, 1988), which identifies vortices as regions where the magnitude of the rotation rate dominates the strain rate, and the λ_2 -criterion (Jeong & Hussain, 1995), which detects pressure minima associated with vortical motion by analyzing the eigenvalues of the symmetric and antisymmetric parts of the velocity gradient tensor. Other methods include the Δ -criterion, swirling strength (λ_{ci}), and geometric approaches such as the winding angle method (Portela, 1998). While widely used, the Q-criterion and λ_2 -criterion have significant limitations, particularly when applied to experimental data such as Particle Image Velocimetry (PIV). Both rely on spatial derivatives of the velocity field, making them highly susceptible to measurement noise. They also require the selection of subjective, arbitrary thresholds to define vortex boundaries, an incorrect threshold can lead to the fragmentation of a single vortex or the false identification of shear layers as vortices. These methods also struggle to provide a clear, objective definition of the vortex size and often fail to distinguish between individual structures in complex, interacting flows. To address these limitations, a Combinatorial Vortex Detection (CVD) algorithm was developed by Bussi re et al. (2024) (Bussi re, Bessa, Koch, & Nobes, 2024) specifically to characterize the wake of

an oscillating wing. This approach was developed for detecting vortices in PIV data from experimental free vortex flows, such as wakes, as it avoids arbitrary thresholds and provides a robust, objective determination of vortex parameters. The complete CVD integrates three distinct techniques sequentially:

1. Maximum Vorticity (MV): This step scans the flow field to identify local maxima in the vorticity magnitude, providing initial candidate locations for vortex cores.
2. Cross-Sectional Lines (CSL): This method verifies the candidate cores by analyzing velocity profiles along lines passing through the center, ensuring the flow exhibits the expected rotational symmetry and structure.
3. Winding Angle (WA): This geometric verification tracks streamlines seeded around the candidate core. A vortex is confirmed if the streamlines complete a full rotation (winding angle $\alpha \geq 2\pi$) around the center.

A key feature of the CVD algorithm is that the size of the vortex is physically determined by the last closed streamline surrounding the core, rather than an arbitrary contour of vorticity or Q-value. This allows for the precise calculation of physically meaningful parameters. The vortex size (R) is defined as the equivalent radius of the area (A) enclosed by this last closed streamline:

$$R = \sqrt{\frac{A}{\pi}}$$

The circulation (Γ) is calculated by integrating the velocity field along this bounding streamline (the last closed streamline C), providing a robust measure of the vortex strength:

$$\Gamma = \oint_C \mathbf{u} \cdot d\mathbf{l}$$

By using the last closed streamline, the CVD approach ensures that the calculated circulation and size encompass the entire rotational region of the free vortex, offering a significant improvement in accuracy for characterizing experimental wake flows.

The primary objective of this work is to investigate the spatiotemporal evolution of a toroidal vortex translating within a confined round tube. To achieve this, the study first characterizes a starting vortex generated by an unconfined (free) pulsatile jet to establish baseline flow behavior and validate the multi-criteria Combinatorial Vortex Detection (CVD) algorithm. Building upon this robust baseline, the validated methodology is subsequently applied to the confined tube geometry. The confined-flow findings highlight the complex interactions between the vortex and the solid boundary, capturing critical phenomena such as the severe arrest of downstream propagation and the asymmetric breakdown of the coherent vortex structure. Ultimately, the baseline behaviors and interaction mechanisms documented in this work establish a highly reliable

experimental framework for future comprehensive parametric studies on wall-bounded flow dynamics.

2. Experiment Setup

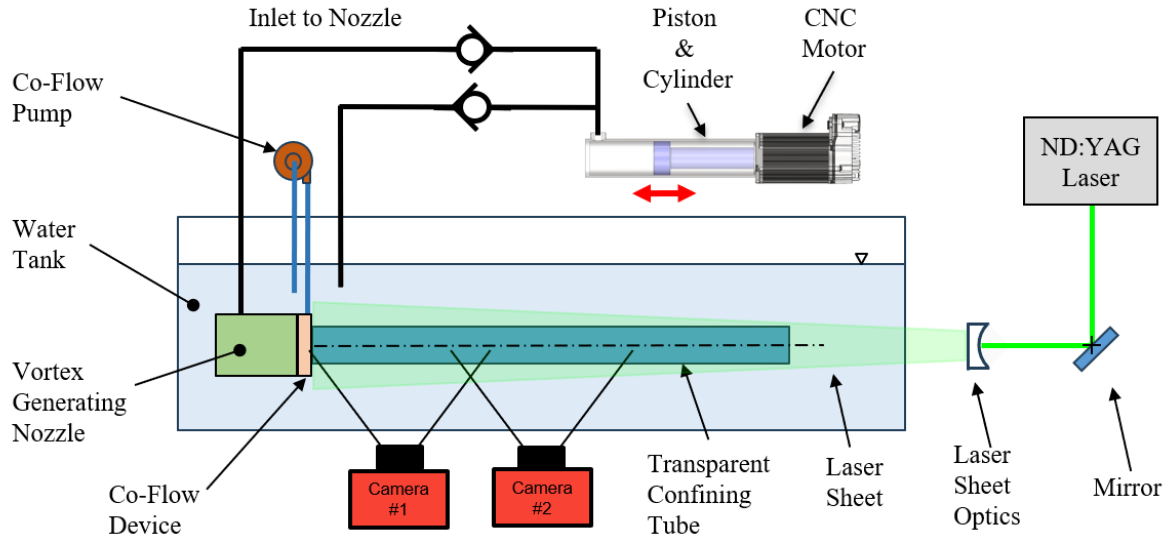


Figure 1 Schematic of the experimental setup for the vortex investigation, depicting a pulsatile jet issuing from a nozzle submerged in a water tank. For the unconfined (free jet) reference cases, the transparent confined tube was removed.

Figure 1 shows the experimental setup used to interrogate the formation and evolution of vortex rings. A pulsatile jet was generated using a programmable CNC-motorized piston-cylinder assembly. The working fluid was ejected through a square-edged nozzle characterized by a sudden contraction, with an inlet diameter of $D_{in} = 60.2$ mm and an outlet diameter of $D_{out} = 20$ mm. This specific nozzle geometry ensured the generation of repeatable and well-controlled toroidal vortices. The nozzle was positioned at one end of a transparent acrylic confinement tube with an inner diameter of 47 mm and an outer diameter of 50 mm. Although a secondary pump-driven system was integrated into the rig to facilitate potential co-flow features, superimposed co-flow was not investigated in the current work. The entire apparatus was submerged in a water tank to provide a reservoir of seeded fluid and to ensure unobstructed optical access, thereby minimizing optical distortion across the measurement plane. Regarding the flow kinematics, the piston assembly features an inner diameter of 40 mm and accommodates a maximum stroke of 260 mm. The current experimental protocol utilized a stroke length of 26 mm executed over a duration of 1 s. During this ejection phase, the piston velocity was approximated as constant. The total actuation cycle was set to 8 s, comprising this 1 s quick ejection phase followed by a 7 s slow withdrawal

phase, with strictly identical total forward and backward stroke lengths. This configuration yielded a nominal outlet Reynolds number (Re) of approximately 2100, firmly placing the fluid motion within the laminar flow regime.

The resulting flow field was interrogated using a high-resolution, double-shutter, two-dimensional, two-component (2D-2C) Particle Image Velocimetry (PIV) system. The working fluid was homogeneously seeded with micron-scale tracer particles and illuminated by a double-pulsed Nd:YAG laser, with laser-sheet optics expanding the beam into a thin planar light sheet aligned with the jet centreline. To capture the extended downstream evolution of the vortex, two high-resolution ImagerPro X 4M cameras (2048×2048 pixels) were positioned side-by-side, parallel to the jet axis. This dual-camera configuration defined two individual Fields of View (FOVs) of approximately $98 \text{ mm} \times 98 \text{ mm}$. A central overlap region of $21 \text{ mm} \times 98 \text{ mm}$ was utilized to seamlessly stitch the two FOVs into a single, extended measurement domain. To ensure precise temporal resolution and phase-locked data acquisition, a synchronized pulse generator provided triggering signals to the dual-pulsed laser and both cameras at specific phase delays relative to the initiation of the ejection stroke. A laser pulse separation time ($d\hat{t}$) of 2 ms was employed for all velocity measurements. Concurrently, the motor trajectory dictating piston speed and direction was independently regulated by a separate function generator. Finally, geometric calibration was performed *in situ* using a standard double-sided, two-level dot-grid target. This procedure effectively corrected for perspective distortions arising from the camera arrangement and compensated for minor optical aberrations induced by the refractive index mismatch at the tank walls. A third-order polynomial mapping function was computed within the DaVis software to accurately map image plane coordinates to physical object space, resolving radial and tangential lens distortions and perfectly aligning the spatially stitched fields of view.

3. Results and Discussion

To facilitate a consistent analysis of the vortex evolution throughout the ejection phase, a dimensionless time scale t_p , is defined to normalize the stroke duration:

$$t_p = \frac{t}{T_{stroke}}$$

where t denotes the instantaneous time relative to the start of the ejection and T_{stroke} represents the total duration of the piston stroke (1 s).

The following results are presented in two distinct subsections. The first subsection details the fundamental flow characteristics derived from the PIV measurements, focusing on the formation and topological evolution of the starting vortex. The flow fields of both the unconfined (free jet)

and confined tube configurations are investigated based on the measured velocity and vorticity distributions.

The second subsection evaluates the application of the Combinatorial Vortex Detection (CVD) algorithm to this experimental dataset, assessing its performance and suitability for automated vortex characterization. As near-wall optical distortions currently limit the resolution of the confined-tube measurements, the CVD analysis is primarily conducted using the unconfined free jet reference cases. Further refinement of the experimental technique for the confined geometry is ongoing to yield high quality data required for future algorithmic analysis.

3.1 Experimental Results of PIV

The raw PIV images were processed using a multi-pass cross-correlation scheme with a decreasing interrogation window size, ending with a final window of 24×24 pixels to ensure solution convergence and adequate spatial resolution. To isolate the coherent flow structures and mitigate the influence of random fluctuations, the instantaneous velocity fields were ensemble-averaged over 20 independent realizations at each specific t_p .

Figure 2 illustrates the spatiotemporal evolution of the ensemble-averaged flow field across a dimensionless time interval from $t_p = 0.3$ to 2.5, visualizing the vorticity contours superimposed with velocity vectors and streamlines. To facilitate a highly detailed examination of the flow topology, the data is split across the horizontal centerline ($y = 0$); the lower-half plane ($y < 0$) is presented in Figure 2 (a), while the upper-half plane ($y > 0$) is depicted in Figure 2 (b). A direct comparison of these opposing half-planes confirms an exceptionally high degree of bilateral symmetry in both the vortex trajectory and circulation strength throughout the entire ejection process, thereby validating the stability, alignment, and repeatability of the pulsatile jet generation mechanism. At the early stages of development, the overall flow topology reveals a highly coherent toroidal structure characterized by two counter-rotating primary vortex cores accompanied by a distinct trailing shear layer. Immediately downstream of the nozzle exit, a prominent *vena contracta* effect is observed, where local fluid acceleration yields a region of peak velocity along the central axis ($y = 0$). The smooth, consistent distribution of this velocity profile further serves to validate the spatial accuracy of the stitched PIV velocity fields.

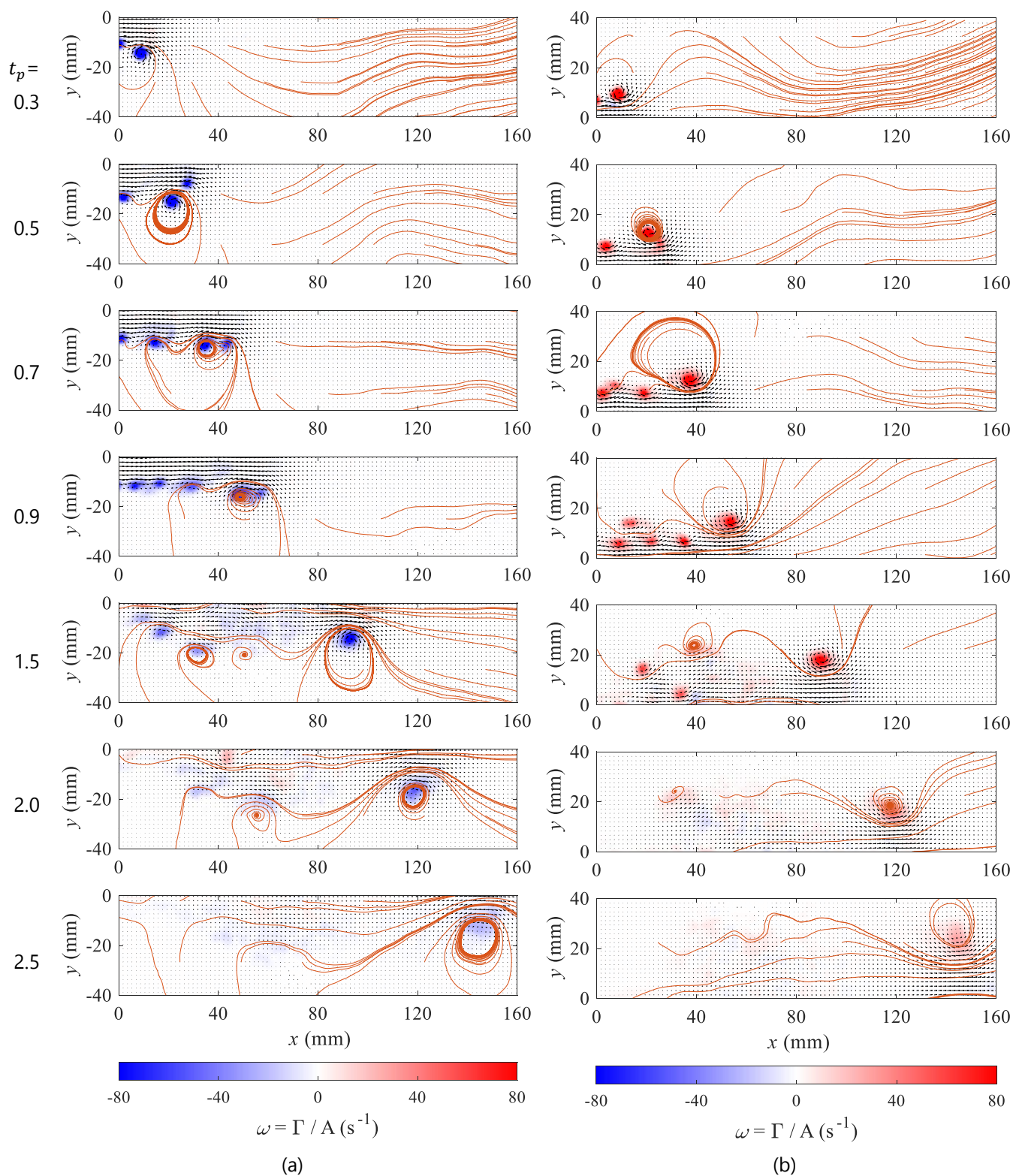


Figure 2 Results of the non-tube free jet cases, (a) Lower-half ($y < 0$), and (b) Upper-half ($y > 0$), of the vorticity field with velocity vector and streamlines, showing original vortex formation and evolution with t_p varied from 0.3, 0.5, 0.7, 0.9, 1.5, 2.0, and 2.5.

Visual inspection of the topological development over time reveals distinct stages of starting vortex maturation. Specifically, the primary vortex ring is fully formed and coherent by $t_p = 0.3$, indicating that the initial roll-up of the detached shear sheet occurs rapidly at the immediate onset of the piston stroke. As the ejection phase progresses, the flow structure evolves to include secondary instabilities, with the formation of a distinct trailing vortex becoming visually apparent at $t_p = 0.5$. Throughout all investigated phases, a concentrated region of high vorticity is consistently observed in close proximity to the primary vortex core, located radially inward toward the centerline. This zone characterizes an intense shear layer resulting from the sharp velocity gradient between the accelerated core jet and the ambient fluid. Notably, the vorticity distribution within this high-shear region exhibits magnitudes and spatial footprints highly similar to those of the adjacent primary and trailing vortex cores. This topological similarity poses a significant challenge for automated vortex detection schemes, demonstrating that isolating independent vortex structures based exclusively on thresholding the raw vorticity field is insufficient. Crucially, the time-resolved sequence demonstrates that the leading vortex ring continues its forward downstream propagation through the final captured frame at $t_p = 2.5$, by which stage the primary vortex core has advanced to a downstream position of approximately $x = 150$ mm. As the vortex translates further away from the nozzle exit and interacts with the surrounding fluid, a clear decay and spatial dissipation in the peak vorticity intensity are observed, capturing the gradual diffusion of momentum and the structural relaxation of the vortex ring before its eventual breakdown.

Figure 3 illustrates the spatiotemporal evolution of the starting vortex within the transparent acrylic confinement tube, with the early-stage development $t_p = 0.1$ to 0.9 presented in Figure 3 (a), and the late-stage translation and breakdown $t_p = 1.5$ to 3.5 captured in Figure 3 (b). In contrast to the unconfined reference case, the presence of the solid tube boundary introduces profound changes to the vortex trajectory, core topology, and propagation dynamics. During the early stages of the ejection phase $t_p \leq 0.5$, the primary vortex cores roll up in a manner similar to the free jet case. However, as the structure translates downstream, an asymmetric proximity to the tube wall becomes apparent. Due to a minor alignment tolerance within the experimental assembly, the jet centerline was slightly offset toward the bottom of the tube, causing the lower vortex core to experience wall proximity effects much sooner than its upper counterpart. By $t_p = 0.9$, strong interaction with the solid boundaries induces a rapid deceleration of the toroidal structure, severely arresting its downstream translation speed. It is worth noting that because the motorized piston stroke terminates at exactly 1 s, no further fluid mass or momentum is injected into the domain during the subsequent phases. Consequently, any forward propagation past this threshold is driven entirely by the self-induced velocity of the vortex ring and its remaining inertial momentum.

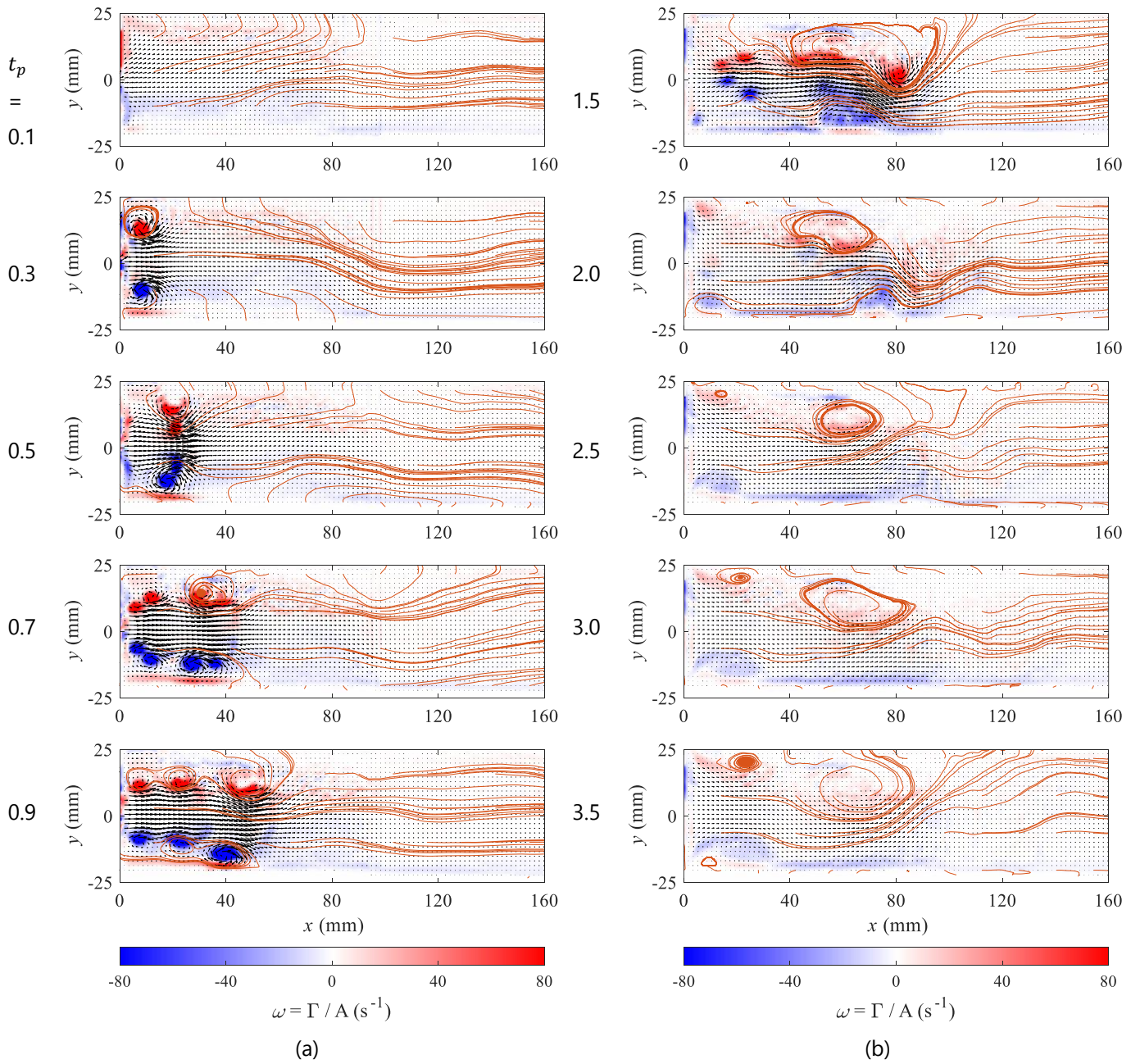


Figure 3 Results of the confined tube cases, vorticity field with velocity vector and streamlines, t_p varied from (a) 0.1, 0.3, 0.5, 0.7, and 0.9; (b) 1.5, 2.0, 2.5, 3.0, and 3.5.

As the flow transitions into the late-stage regime shown in Figure 3 (b), the severe hydrodynamic consequences of this wall confinement become starkly evident. At $t_p = 1.5$, intense viscous interactions and strong shear layer formations along the tube boundaries cause massive deformation of both vortex structures. The upper vortex core undergoes an axial stretching and structural elongation process; while it manages to survive this initial wall shear, its forward translation is almost entirely stalled. Beyond $t_p = 2.5$, the upper vortex remains virtually stationary, persisting through to the final captured frame at $t_p = 3.5$ as a stagnant structure characterized by a severely decayed vorticity magnitude. Conversely, the lower vortex core suffers a catastrophic

structural collapse due to its rapid, premature compression against the lower wall. The intense localized shear stresses destroy the coherence of the lower core, causing it to rapidly fragment and dissolve after $t_p = 1.5$, until it completely disappears from the measured vorticity field by $t_p = 2.5$. When directly contrasted with the unconfined free jet reference case, where the coherent toroidal vortex propagated unimpeded to a downstream position of $x \approx 150$ mm by $t_p = 2.5$, the confined tube configuration demonstrates that wall interactions introduce severe momentum penalties. Hitting or translating too close to the confining wall not only forces a dramatic reduction in spatial propagation speed but can induce highly asymmetric structural breakdown, ultimately leading to the complete annihilation of localized vorticity clusters.

3.1 Algorithmic Vortex Characterization via CVD

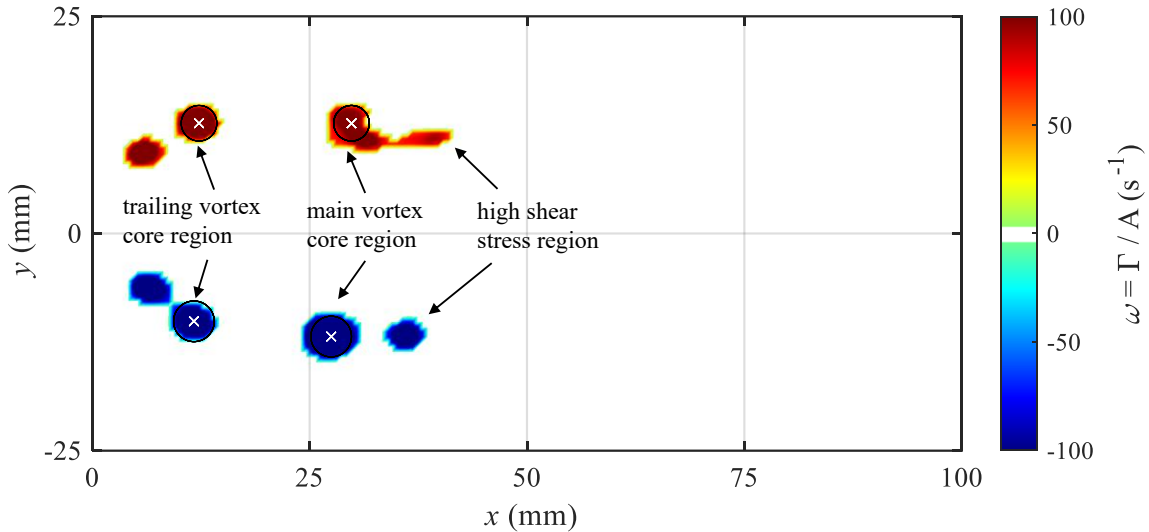


Figure 4 CVD-based vortex detection of constrained tube case when $t_p = 0.7$, with illustration of typical high vorticity regions.

Figure 4 illustrates the application of the Combinatorial Vortex Detection (CVD) algorithm to the experimentally derived flow field within the confined tube geometry at a dimensionless time of $t_p = 0.7$. The detection scheme employs a rigorous, multi-criteria approach that integrates Maximum Vorticity (MV), Cross-Sectional Lines (CSL) identification, and Winding Angle (WA) analysis. Within this framework, a fluid region is only classified as a genuine vortex structure if it simultaneously satisfies all three independent geometric and kinematic conditions. As demonstrated in Figure 4, this multi-layered verification allows the algorithm to successfully segment the complex, confined flow topology into distinct, physically meaningful features, precisely categorizing the primary vortex core, the trailing vortex region, and the surrounding zones of high shear stress. The algorithm explicitly highlights the calculated vortex centers and delineates the core boundaries, enabling the core radius (R_c) to be quantitatively defined by the radial distance from the center to

the location of maximum tangential velocity.

A critical capability of this combinatorial approach is its capacity to distinguish coherent vortex cores from the adjacent regions of intense shear stress. While both of these flow features exhibit comparable peak vorticity magnitudes, they differ fundamentally in their underlying streamline topologies; true vortex cores possess closed, re-circulating rotational streamlines, whereas stress regions are characterized by open shear lines. To eliminate the high risk of mis-detection inherent to simple, single-threshold vorticity thresholding, the algorithm is fine-tuned using a normalized Threshold Intensity Vector (TIV):

$$TIV = [0.35, 0.48, 0.72] \times \max(|\omega|).$$

This specific parameter set effectively isolates the true rotational cores from the non-vortical, high-shear layers.

Figure 5 presents the chronological evolution of the vortex structures identified by the CVD algorithm within the lower-half plane ($y < 0$) across the dimensionless time phases $t_p = 0.3$ to 2.5 of the unconfined cases. The detection results demonstrate the algorithm's capability to consistently track the trajectory and growth of the coherent structures throughout the ejection stroke. The main vortex is successfully identified at all time steps, moving downstream with a coherent core structure. As the flow develops, the algorithm successfully captures the emergence and evolution of the trailing vortex, distinguishing it from the primary core despite the increasing complexity of the wake region. This temporal tracking validates the robustness of the combinatorial approach in automated feature extraction for unsteady jet flows.

A specific challenge persists when interrogating the high shear stress regions due to the influence of convective velocity. In a fixed frame of reference, strong shear layers in a traveling wave can exhibit streamline curvature that mimics closed loops, potentially leading to false detections if the local drift velocity is not subtracted. In the current application, the CVD algorithm operates on the time-averaged vector fields without localized drift correction. While the multi-criteria approach largely mitigates these false positives, the inability to account for drift velocity represents a limitation, suggesting that future iterations of the CVD should incorporate adaptive frame-of-reference adjustments to better isolate true rotational cores from translating shear layers.

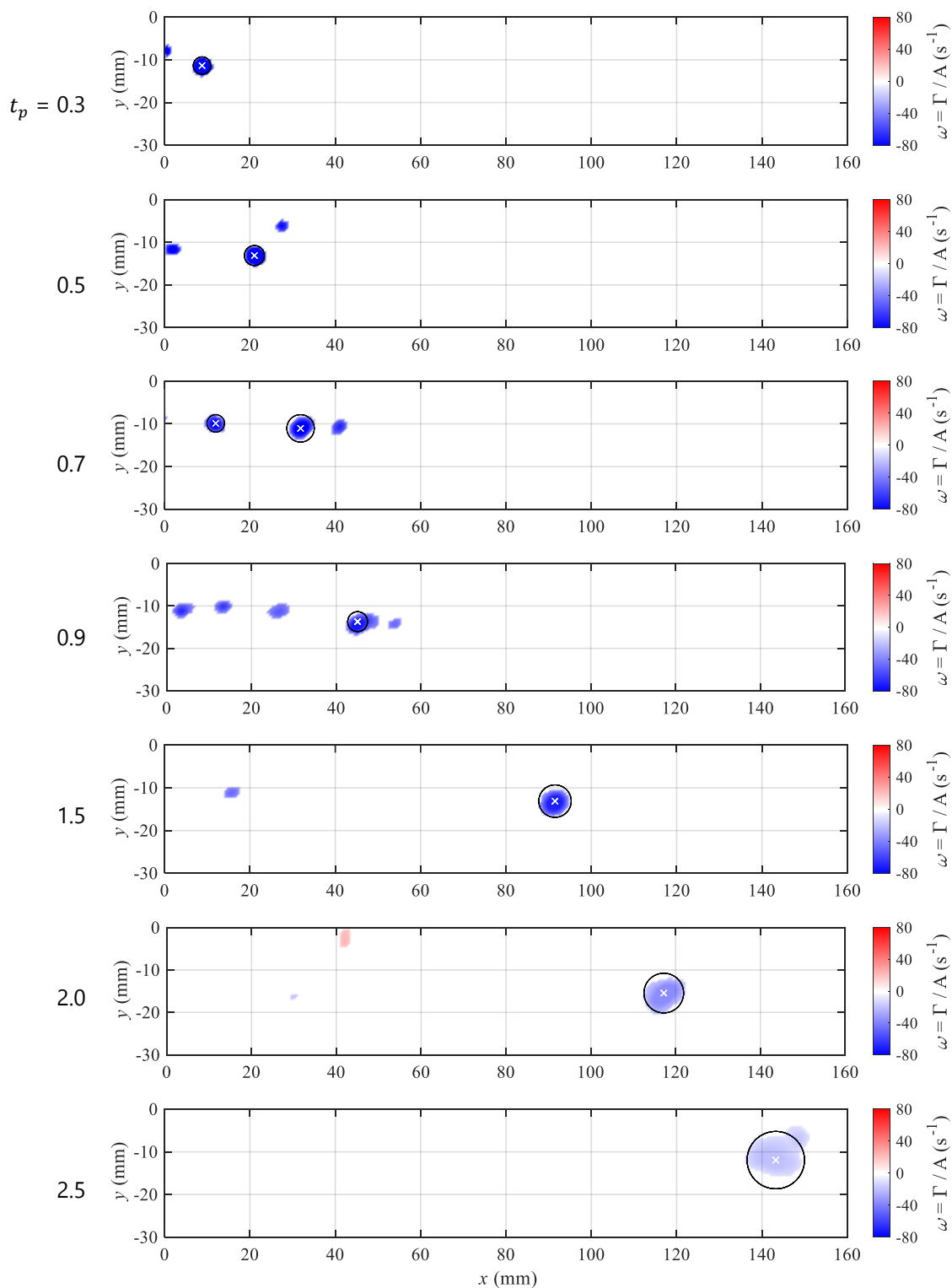


Figure 5 Lower-half ($y < 0$) of the vorticity field of the non-tube cases, showing vortex detection results using CVD method with $t_p = 0.3, 0.5, 0.7, 0.9, 1.5, 2.0$, and 2.5 .

In addition, the sensitivity of the detection scheme to experimental background noise warrants discussion. The verification criteria rely on the consistency of the vorticity sign; specifically, the

vorticity at the calculated geometric center must share the same polarity as the surrounding circulation region. In raw PIV data, high-frequency noise can occasionally cause local sign inversions near the core center, leading the algorithm to reject a valid vortex candidate due to apparent inconsistency. To mitigate this, a Gaussian smoothing filter was applied to the vorticity field prior to detection. However, the smoothing parameters introduce a trade-off. While necessary to suppress noise, aggressive smoothing attenuates the peak vorticity magnitude and diffuses the core boundaries. Consequently, improper smoothing settings can significantly alter the detected core radius and circulation strength, or in extreme cases, reduce the peak intensity below the threshold vector, resulting in misdetection. Therefore, careful selection of the Gaussian kernel size is critical to balancing noise reduction with the preservation of peak flow gradients in the application of the CVD method.

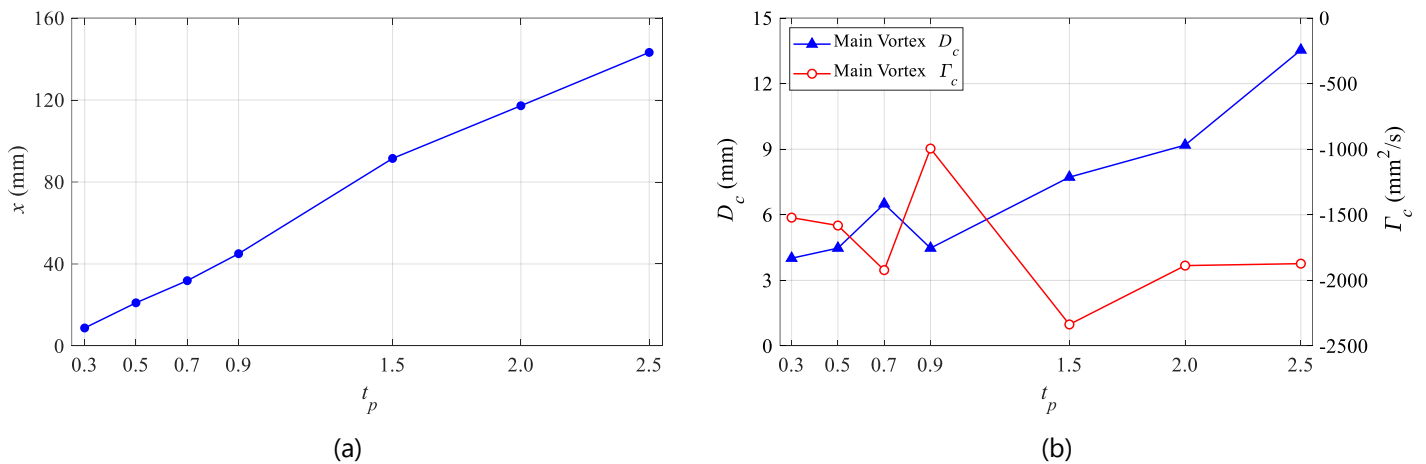


Figure 6 Vortex features of the non-tube unconfined cases using CVD method, (a) main vortex x -position change over t_p ; (b) main vortex diameter D_c and circulation Γ_c change over t_p .

Figure 6 presents the quantitative evolution of the vortex parameters for the lower-half plane of the unconfined cases, specifically tracking the core x -position, core diameter ($D_c = 2R_c$), and core circulation strength (Γ_c) for the unconfined case. Throughout the observation window, the main vortex exhibits a highly linear downstream trajectory, advancing steadily along the flow direction. To accurately quantify the vortex strength, the core circulation was calculated in a discretized manner by summing the product of the local vorticity magnitude and the area of the corresponding pixels strictly within the algorithmically identified core boundary. During the active ejection phase $t_p \leq 1$, both D_c and Γ_c increase sharply as the core actively entrains high speed fluid from the nozzle shear layer. Specifically, the core diameter expands rapidly from roughly 5 mm to 11 mm, while the circulation climbs to a peak of approximately 1900 mm^2/s . Once the piston stroke terminates $t_p > 1$, the absence of further mass injection causes the core growth rate to slow into a passive viscous diffusion regime, expanding to 13 mm by the end of the window. Concurrently, the circulation

enters a distinct plateau with a slight downward trend, reflecting the cessation of vorticity feeding and the onset of gradual energy dissipation. This clear transition between active growth and passive propagation quantitatively validates the expected physical evolution of the starting vortex ring and demonstrates the accuracy of the CVD algorithm in isolating the true rotational core from the surrounding shear layers.

In summary, the CVD algorithm successfully identified and tracked the complex topological evolution of the starting vortex in the unconfined pulsatile jet experiment, yielding physically reasonable and highly accurate results. While the algorithm requires careful parameter fine-tuning and has room for improvement regarding drift velocity effects, it proved highly effective for the current dataset. Consequently, with future improvements in experimental data quality, this method will be utilized to investigate the more complex flow dynamics and vortex-wall interactions within the confined tube configurations

4. Conclusion

This study experimentally investigated the formation, propagation, and topological evolution of a starting vortex generated by a pulsatile jet, comparing its behavior in an unconfined free jet environment against a confined transparent tube geometry. High-resolution 2D-2C Particle Image Velocimetry (PIV) was employed to capture the flow field, and a Combinatorial Vortex Detection (CVD) algorithm was applied to objectively extract key physical parameters. Based on the spatial and temporal analysis of the flow structures, the following key conclusions are drawn:

- a) Unconfined vortex evolution: In the free jet reference case, the pulsatile jet reliably produced a highly symmetric and coherent toroidal vortex. The primary vortex core demonstrated a linear downstream trajectory, reaching approximately $x = 150$ mm at $t_p = 2.5$. Quantitative extraction via the CVD algorithm revealed a distinct two-stage maturation process: an active ejection phase $t_p \leq 1$ characterized by rapid vortex growth, followed by a passive propagation phase $t_p > 1$ dominated by viscous diffusion and energy dissipation.
- b) Confinement and wall interactions: The presence of the rigid tube wall drastically altered the vortex dynamics. Wall proximity induced intense localized shear stresses, resulting in severe momentum penalties and the arrest of the vortex's downstream propagation. Specifically, the surviving upper vortex core stagnated at a downstream position of approximately $x = 65$ mm after $t_p = 2.5$. Furthermore, minor misalignments in the jet trajectory relative to the tube centerline led to asymmetric breakdown of the lower core, highlighting the extreme sensitivity of coherent structures to boundary interactions.
- c) Performance of the CVD algorithm: The multi-criteria CVD algorithm proved highly effective

in processing experimental PIV data. By utilizing Maximum Vorticity, Cross-Sectional Lines, and Winding Angle criteria, the algorithm successfully isolated true rotational cores from adjacent, high-magnitude shear layers without relying on arbitrary thresholding.

Ultimately, while the CVD algorithm requires careful parameter tuning and further development to account for local drift velocities, it provides a robust framework for objective flow feature extraction. The baseline behaviors and interaction mechanisms documented in this work lay the critical groundwork for future, high-fidelity investigations into complex, confined flow dynamics tailored for heat and mass transfer enhancement.

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