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In this paper, we report on the structure and dynamics of double helix vortex breakdown in a turbulent annular swirling jet. Double helix breakdown has been reported previously for the laminar flow regime, but this structure has rarely been observed in turbulent flow. The flow field is investigated experimentally by means of time-resolved tomographic particle image velocimetry. Notwithstanding the axisymmetric nature of the time-averaged flow, analysis of the instantaneous three-dimensional (3D) vortical structures shows the existence of a vortex core along the central axis which breaks up into a double helix downstream. The winding sense of this double helix is opposite to the swirl direction ($m = -2$) and it is wrapped around a central vortex breakdown bubble. This structure is quite different from double helix breakdown found in laminar flows where the helix is formed in the wake of the bubble and not upstream. The double helix precesses around the central axis of the jet with a precessing frequency corresponding to a Strouhal number of 0.27.

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I. INTRODUCTION

Vortex breakdown, implying the abrupt change of state of a vortex core, is a well-known phenomenon which has been studied already for more than five decades. A comprehensive overview of the different experimental, numerical, and theoretical investigations can by found in the review paper by Lucca-Negro and O'Doherty [1]. Despite the abundance of experimental and numerical research, there is still no general theory capable of explaining all of the observed features and which would therefore find general acceptation in the scientific community. An interesting flow topology to study vortex breakdown is an axisymmetric pipe flow. Numerous theoretical and numerical studies, both on viscous and inviscous flows, have led to much insight in the phenomenon [2–8]. These studies have contributed to the basic understanding of the mechanisms involved in the transition to vortex breakdown and the sensitivity to changing boundary conditions or the dynamics in pre- and postbreakdown states. Vortex breakdown manifests itself in different types, which makes the analysis very complex as no fewer than seven types have been identified. The two most commonly observed, called bubble and spiral breakdown, were first reported by Lambourne and Bryer [9]. In

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bubble breakdown, a straight vortex core breaks up into an axisymmetric bubble near the central axis of rotation, while in spiral breakdown, the core breaks up into a helix, which precesses around the central axis. Bubble and spiral breakdown have been observed in different experiments with similar settings and even transitions between them within the same experiment (without changing the inflow conditions) have been reported [10]. This has led to disagreement on the origin of breakdown (see, for instance, the recent review papers, Refs. [1,11]). For laminar flow, recent studies have showed that spiral breakdown occurs in the wake of an axisymmetric breakdown as a global instability mode of the flow [12–16]. Two modes of spiral breakdown have been observed: the single helix ($|m| = 1$) and the double helix ($|m| = 2$), where m is the azimuthal wave number. In experimental studies, the observation of the double helical mode is very rare [17–20] as this type of breakdown is highly sensitive to disturbances. It is mostly observed in pipe flow; however, recently Calderon et al. [21] reported it also to occur on delta wings. A recent study of Meliga et al. [15] showed that both single and double helix breakdowns are a bifurcation from axisymmetric breakdown and that mode selection depends on the swirl number.

In the case of highly turbulent flow, the structure of vortex breakdown is quite different from the laminar case. Studies for highly turbulent jets ($50\,000 \leqslant \mathrm{Re} \leqslant 300\,000$) [22,23] have shown that vortex breakdown is associated by the appearance of a kink along the vortex axis, followed by a high-frequency rotating spiral that breaks in turbulence, while the upstream core flow expands axisymmetrically around the centerline zone. Other studies showed the appearance of a central recirculation zone (one could consider this to be bubble breakdown) is accompanied by a precessing structure, called the "precessing vortex core" (PVC). An extensive review of the PVC is given by Syred [24]. Numerous studies have reported on the structure of the PVC and most of them found that it is a single spiral which is wrapped along the shear layer between the central vortex breakdown bubble and the jet [24,25]. A few studies report on a possible double helical motion in turbulent flow [26]. However, only indirect suggestion is provided, as the three-dimensional structure of the vortex core was not revealed.

A special topology of jet flow is annular jet flow, i.e., a round jet with a cylindrical inner body. These annular jets are widely used as bluff-body combustors in many industrial applications, as they demonstrate several favorable characteristics. Because of flow separation, a region of subatmospheric pressure is created in the immediate wake behind the bluff body, causing the flow to recirculate. This central recirculation zone (CRZ) promotes flue-gas recirculation and flame stabilization [27,28]. Often swirl is added to the flow to produce the same effects. The coherent structures in the flow for swirl levels above the critical swirl number, like bubble and spiral breakdown, are the same as the ones observed in round jet flow [29–34]. Like for round jets, the PVC is reported as a single helix which is wrapped around the breakdown bubble.

In this study, we provide evidence of the presence of a double helix breakdown in turbulent annular swirling flow. The three-dimensional structure and dynamics are analyzed by the use of time-resolved tomographic particle image velocimetry measurements. The structure of the double helix is quite different from that in the laminar flow regime and the insights provided by this experimental data can help in further understanding the complex phenomenon of vortex breakdown.

II. EXPERIMENTAL SETUP

The experiments were conducted in a water tank facility at the Aerodynamic Laboratories of Delft University of Technology. An annular jet orifice with an inner diameter $D_i = 18$ mm and an outer diameter $D_o = 27$ mm was installed at the bottom wall of an octagonal water tank (600 mm in diameter and 800 mm high), which is made of Plexiglass to enable full optical access for illumination and tomographic imaging (Fig. 1). The symmetry axis of the jet is aligned with the y axis in the measurement coordinate system with the origin located at the end of the inner tube. The velocity components in the x, y, and z directions are labeled u, v, and w, respectively. The experiments were performed at a Reynolds number of 8 300 based on the hydraulic diameter of the annular jet ($D_h = 9$ mm) and the mean outlet velocity, $U_m = 0.92$ m/s. The flow in the system was driven by a pump that was submerged in a reservoir containing water mixed with seeding particles. The swirl generator

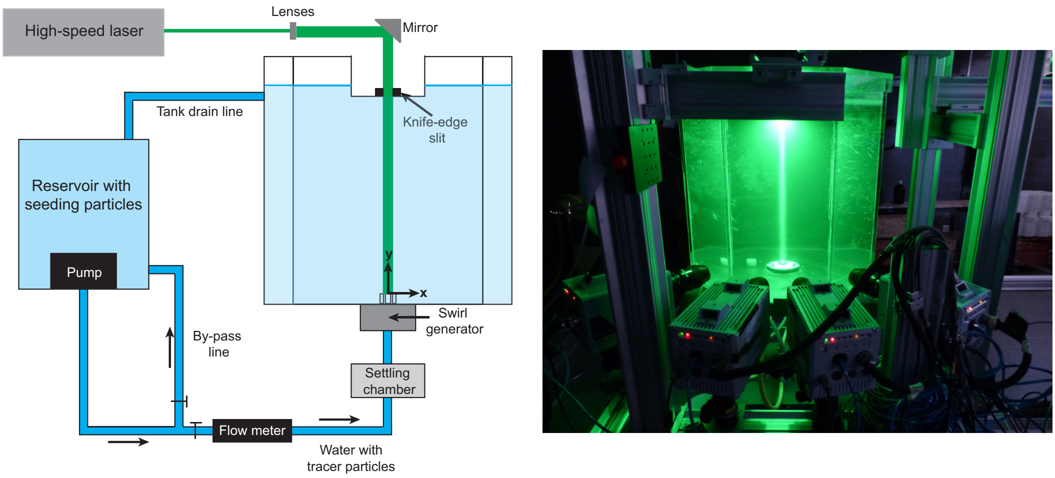

FIG. 1. Overview of the experimental setup and tomographic PIV system. (a) Schematic view of the experimental setup, (b) photograph of the experimental setup.

consists of 12 guide vanes that can be adjusted to change the swirl strength. In this study, the swirl number based on the ratio of tangential and axial momentum times outer radius is 0.36. Neutrally buoyant polyamide spherical particles 56 μm in mean diameter were employed as tracer particles at a concentration of 0.65 particles per mm^3. The flow was illuminated by a double-pulse Nd:YLF laser (Quantronix Darwin Duo, 2×25 mJ/pulse at 1 kHz) at a wavelength of 527 nm. The light scattered by the particles was recorded by a tomographic system composed of four LaVision HighSpeedStar 6 CMOS cameras (1024×1024 pixels, 5400 frames/s, pixel pitch of 20 μm). Each camera was equipped with a Nikon 105 mm focal objective with a numerical aperture $f\# = 32$ to allow focused imaging of the illuminated particles. The measurements were performed in a cylindrical volume with a diameter of $3.6D_h$ and a height of $5.3D_h$ at a digital resolution of 21.6 pixels/mm. The choice of a cylindrical measurement volume eliminated the need for a lens-tilt mechanism to comply with the Scheimpflug condition. Moreover, the cylindrical volume provides a more favorable condition for the accurate volumetric reconstruction since the particle image density does not vary with the viewing angle along the azimuth and decreases when moving toward the periphery of the jet. The average particle image density is approximately 0.045 particles per pixel (ppp). The images were captured in a single-frame mode at a recording frequency of 2.5 kHz (which is about two orders of magnitude larger than the precession frequency) to enable the visualization of the time-series phenomena. A total of 5456 samples are taken to obtain sufficiently converged phase-averaged results. Image preprocessing, volume calibration, self-calibration, reconstruction, and three-dimensional cross-correlation-based interrogation were performed in LaVision DaVis 8.1.6. The measurement volume was calibrated by scanning a calibration target through the measurement volume. The initial calibration was refined by means of the volume self-calibration technique, resulting in a misalignment of less than 0.05 pixels. The raw images were preprocessed with background intensity removal and particle intensity normalization. The particle images were then interrogated using windows of final size $48 \times 48 \times 48$ voxels with an overlap factor of 75%, resulting in a vector spacing of 0.56 mm in each measurement direction.

III. RESULTS AND DISCUSSION

A. Instantaneous flow structures

The instantaneous flow structures are illustrated in Fig. 2. The vortical core is visualized by the Q criterion, where $Q = \frac{1}{2}(\|\Omega\|^2 - \|S\|^2)$, with Ω being the antisymmetric and S being the

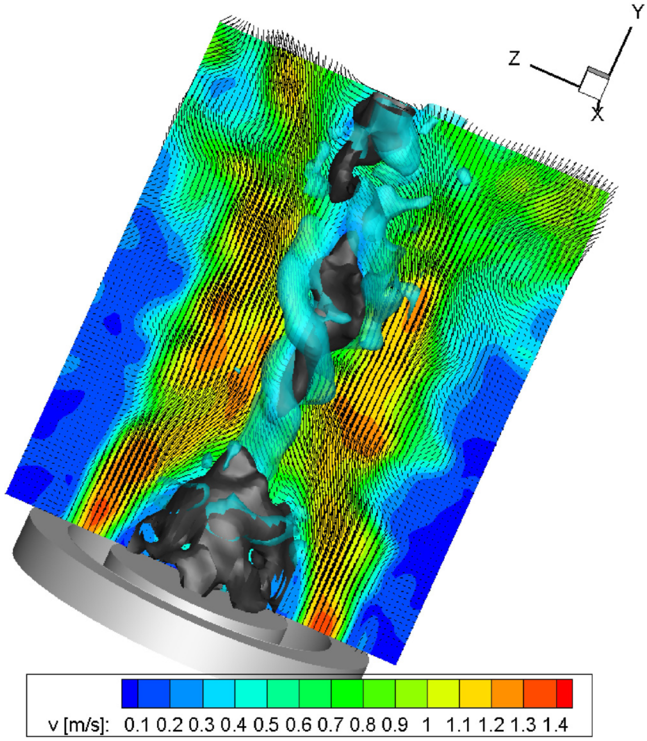

FIG. 2. Instantaneous flow structures in the jet. The blue isosurface corresponds to the isocontour $Q = 0.07 \times 10^6 1/s^2$ and the black contours are isosurfaces of $v = 0$.

symmetric parts of the velocity gradient tensor. The blue isosurface corresponds to the isocontour $Q = 0.07 \times 10^6\ 1/\mathrm{s}^2$ and the black contours are isosurfaces of $v = 0$, hence denoting recirculation zones. Two large recirculation zones exist in the flow. The first one is the central recirculation zone (CRZ) immediately behind the bluff body of the jet. This CRZ originates from separation of the jet from the inner body and is not related to vortex breakdown. This CRZ is very favorable for combustion as it promotes flue gas recirculation, flame stabilization, and increased mixing. The second recirculation zone more downstream is the vortex breakdown bubble. Isocontours of Q show a central vortex core along the central axis of the geometry, which breaks up into a double helix downstream at the beginning of the vortex breakdown bubble. Since the double helix is formed already upstream of the bubble, one could say that the breakdown mode in this case corresponds to a double helix vortex breakdown. Analysis of the temporal behavior shows a precession around the central axis. As such, the double helix possesses the features of the well-known precessing vortex core (PVC) found in swirling flows; i.e., it is situated in the region between the vortex breakdown bubble and the jet flow, it precesses around the central axis, and its winding is opposite to the swirl direction. Although most studies report a single spiral, this study shows that in the case of annular jet flow, the PVC is a double helix. Temporal analysis of the w velocity component along the central axis, Fig. 3, shows a distinct frequency peak at a Strouhal number of 0.27 at the axial location where the vortex core breaks up into the double helix. This peak corresponds to the precession frequency.

B. Phase-averaged flow structures

The most widely used method to separate large-scale periodic motions in a flow field from more irregular dynamic processes, for instance, turbulence, is phase averaging. In this method, time is transformed into a phase angle α as $\alpha = \omega t$, where ω is the precession frequency and samples

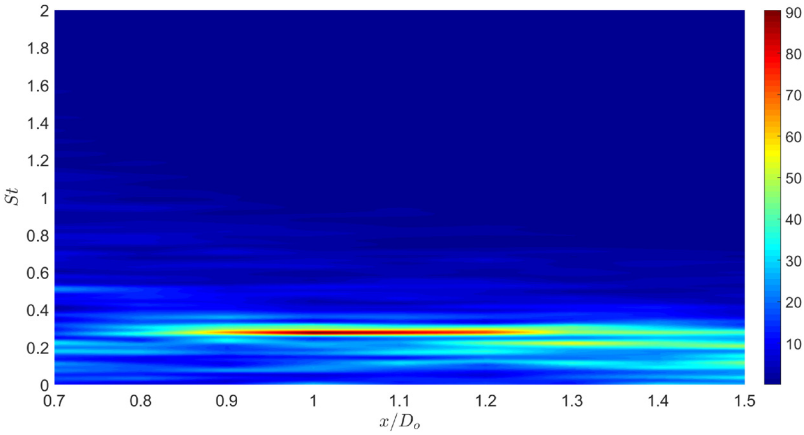

FIG. 3. Normalized frequency spectra of the w velocity component along the central axis.

within a small phase interval are ensemble averaged [35]. The phase-averaged flow structures are shown in Fig. 4, which reproduces the same essential features as observed in the instantaneous flow realization of Fig. 2. The blue isosurface corresponds to the isocontour $Q = 0.07 \times 10^6\ 1/\mathrm{s}^2$ and the black contours are isosurfaces of $v = 0$, hence denoting recirculation zones. Phase averaging clearly reveals the structure of the vortex breakdown. As the central vortex core near the nozzle breaks up into a double helix, a small vortex breakdown bubble is formed downstream. This vortex breakdown bubble is axisymmetric and the double helix is wrapped around it. This observed structure

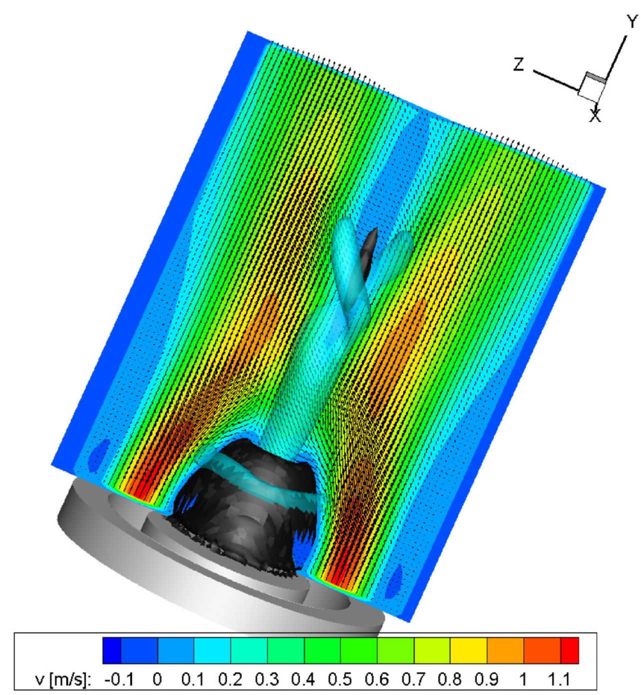

FIG. 4. Phase averaged flow structures in the jet. The blue isosurface corresponds to the isocontour $Q = 0.07 \times 10^6 1/s^2$ and the black contours are isosurfaces of $v = 0$.

is interesting for two main reasons. First of all, the double helix mode of vortex breakdown is very rare and not many authors have observed it in their experiments. Moreover, it has mainly been reported for laminar flow and this study reports it for turbulent flows. Second, in most studies that reveal a double helix mode, the double helix is positioned in the wake of the axisymmetric bubble; see, for instance, the studies of Liang and Maxworthy [12], Ruith et al. [13], Gallaire et al. [14], Meliga et al. [15], and Qadri et al. [16]. In the present study, the double helix is already formed upstream of the breakdown bubble as it is wrapped around it.

IV. CONCLUSIONS

In this study, the flow structures of an annular swirling jet flow have been studied using time-resolved tomographic PIV measurements. For turbulent swirling jet flow, 3D visualization of the vortical structures in the flow field has revealed a central vortex core along the central axis, which breaks up into a double helix. This double helix is wrapped around a central vortex breakdown bubble and precesses with a Strouhal number of 0.27. Combined with the fact that its winding is opposite to the swirl direction, the observed structure has all the features of the well-known PVC found in swirling flows. This study proves evidence that the PVC is a double helical structure, a type of breakdown which is very rarely observed in experiments and mainly reported for laminar flow.

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