Vortex Breakdown in a Swirling Jet with Axial Forcing

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Abstract :

A swirling jet has been generated in water by passing the fluid through a rotating honeycomb and discharging it into a water tank. Experiments were conducted at $3000 \leq Re_D \leq 7000$ *and* $1.15 \leq S \leq 1.5$*. In addition, axial periodic perturbations were applied in order to excite the shear layer by an axisymmetric mode* $m = 0$*. The amplitudes of the forcing were in the range* $4\% \leq A \leq 44\%$*. Quantitative measurements were carried out by using STEREO-PIV. Experiments show that at higher Reynolds numbers the vortex breakdown does not occur abruptly as often mentioned in the literature. Instead, all mean quantities which characterize the vortex breakdown show a continuous change with increasing swirl. The high turbulence level may explain the differences to former studies. Velocity contours of the cross-sectional view indicate azimuthal modes that decrease from* $m = 4$ *close to the nozzle to* $m = 2$ *near the vortex breakdown. Phase-locked data show that the location of vortex breakdown alternates with the forcing frequency without a significant mean displacement, whereas for a certain combination of frequency and amplitude it sheds downstream while losing its intensity.*

Key-words :

Vortex Breakdown ; Periodic Perturbations ; STEREO-PIV

1 Introduction

The vortex breakdown is a very unique feature which may occur in swirling flows. It occurs when the ratio of axial to azimuthal velocity exceeds a certain threshold. Both quantities have to be in the same order of magnitude. Billant *et al.* (1998), who did flow visualizations in water at low Reynolds numbers describe the breakdown as an abrupt widening of the vortex core into a new stable coherent structure. It can be observed in geophysical flows such as tornadoes or in man-made flows such as tip vortices produced over delta wings. In the latter case vortex breakdown usually occurs at very high angle of attack and it is believed to lead to a sudden drop in lift. In most premixed combustors the vortex breakdown is used to stabilize the flame in order to decrease noise generated by resonance effects. The onset of vortex breakdown is dominated by complex three-dimensional mechanisms, that are not fully understood. In addition, the occurrence of pressure gradients in axial and radial direction and their interaction with the flow field yield to fundamental scientific questions. Thus, numerous studies of vortex breakdown have been conducted in the last three decades.
According to experiments carried out at high Reynolds numbers by Panda *et al.* (1993),

the introduction of swirl complicates the flow tremendously. The overall growth of all modes of instability is small relative to the non swirling jet, in particular the generation of subharmonics through vortex pairing is completely suppressed. Furthermore, Panda *et al.* (1993) found it difficult to excite any natural modes and observed that the growth of large coherent structures is very low.

Khalali *et al.* (2006) succeeded in moving the location of vortex breakdown downstream by sinusoidal pulsing in axial direction. The experiments, conducted at low Reynolds numbers show, that the maximum displacement can be achieved by forcing the flow at its natural shedding frequency. The displacement of the vortex breakdown could first be determined by flow visualizations at amplitudes of 5% and a saturation of displacement was reached at 40% of the mean mass flow.

Another important feature of swirling jets is the occurrence of azimuthal modes that are believed to contribute to the onset of vortex breakdown. Only a few experimental studies about the governing instabilities have been done. Loiseleux *et al.* (2003) investigated the modes in a swirling laminar jet for swirl numbers in a pre-breakdown range. For swirl numbers $1 \leq S \leq 1.3$ they observed that axisymmetric and helical modes exist. For low swirl numbers various azimuthal modes occur. With increasing swirl the $m = 1$ mode gets more dominant then the $m = 0$ mode. Furthermore, for higher Reynolds numbers a trend to higher modes could be observed.

2 Scientific Contents

The goal of the conducted experiment was to investigate the flow field of a turbulent swirling jet at higher Reynolds numbers undergoing vortex breakdown, by means of quantitative measurement. Natural and axially forced swirling jets at swirl numbers below and beyond the onset of vortex breakdown were under consideration. STEREO-PIV was used to determine the development of integral values as the axial flux of axial and tangential momentum and the static pressure due to centrifugal forces. By phase-locking the data-acquisition with the forcing frequency, the evolution of the coherent structures in the shear layer could be investigated and the dynamical response of the coherent structures for various forcing frequencies and amplitudes could be investigated. To get access to the development of the azimuthal modes the cross-sectional view of the swirling jet was investigated for various locations downstream the nozzle.

3 Experimental Approach and Results

3.1 Governing Variables

Two dimensionless variables characterize the flow. The Reynolds number, defined as $Re = \frac{D\overline{u}}{\nu}$, is based on the nozzle diameter D and the average axial velocity $\overline{u}$ which is extracted from the mean mass flow rate. The swirl number, defined as $S = \frac{2w(r=R/2)}{u(r=0)}$, provides a measure for the ratio between the maximum azimuthal velocity w to axial velocity u. Another swirl number S_{int}, which is commonly used in the literature of swirling flows, is defined as the ratio between the axial flux of angular momentum $\dot{G}_\theta$ and the axial flux of axial momentum $\dot{G}_x$, thus

$$S_{int} = \frac{\dot{G}_\theta}{R\dot{G}_x} = \frac{2\pi \int_0^\infty \rho u w r^2 dr}{R 2\pi \int_0^\infty (\rho u^2 + P) r dr}. \tag{1}$$

For a pulsating swirling jet two additional parameters appear. The Strouhal number, defined as $St = \frac{Df}{\bar{u}}$, is necessary to nondimensionalize the frequency of the axial pulsing and $A = \frac{\dot{m}_{max} - \bar{\dot{m}}}{\bar{\dot{m}}}$ characterizes the relative amplitude during a forcing cycle.

3.2 Setup

The experimental setup consists of a horizontal swirling jet discharging into a large water tank that is $127cm$ long, $102cm$ wide and $102cm$ high. A $57.64cm$ long plexiglass cylinder with an inner diameter of $26.2cm$ serves as an settling chamber and houses the apparatus that generates the swirl. Similar to the method used by Billant *et al.* (1998), the swirl was generated by passing the water through a rotating cylinder, placed in the interior of the settling chamber. The jet axial velocity was generated by a pump. The flow was set into a state of solid body rotation by inserting two honeycombs, $20cm$ long, into the inner rotating cylinder. The swirling jet was then guided through a converging nozzle attached to the outer cylinder and mounted to the tank. The flow was tripped by a serrated ring that was glued to the interior surface of the contraction to improve the symmetry of the flow. The nozzle diameter is $D = 5.24cm$. The relatively large size of the test tank minimizes the effect of confinement and the measured recirculation currents were found to be negligible. Axial pulsations were conducted by a piston connected to the water circuit of the facility. A shaker provided sinusoidal motions and could be run from $0.2Hz$ to $3Hz$. A stereoscopic particle image velocimetry (STEREO-PIV) was used to measure the flow field. It consists in the velocity measurement of particles going through a laser sheet generated by a double pulsed Nd:Yag laser at $532nm$ and and $400mJ$ in $5ns$ burst. Two X-STREAM VISION CCD cameras with a resolution of 1.3 million pixels were used. Both cameras were positioned outside the water tank facing the walls of the tank at $45°$. In order to avoid reflexions and distortions, two prisms made of plexiglass and filled with water, were built and mounted on the outer tank walls. Cameras, the laser and the piston were triggered in time in order to obtain phase-locked data.

3.3 THE EXPERIMENTAL PROCESS

In order to transform the captured displacement of the particles in the flow into velocities a calibration procedure was mandatory. Therefore the cameras had to be focused on a target, aligned to the laser sheet, that was mounted in the water tank. Using the PIV software a grid of points was mapped onto the pictures of the target manually to define the physical length scale of the images. The pump was running continuously to provide a constant temperature in the entire tank. Furthermore, the tank was covered in order to avoid a temperature gradient due to surface evaporation. 20 minutes before acquiring data the tank was mixed to obtain a homogeneous seeding. Phase locked data and randomly averaged data was taken from each parameter set and location. The previous was averaged over 125 events and the latter over 400.

4 Results

Investigations of the velocity fluctuations in the shear layer indicating a fully turbulent flow, can be seen in the thesis of Oberleithner (2006). The axial flux of axial and angular momentum is independent of x. Thus, the integral swirl number S_{int} is constant with x (figure (c)).

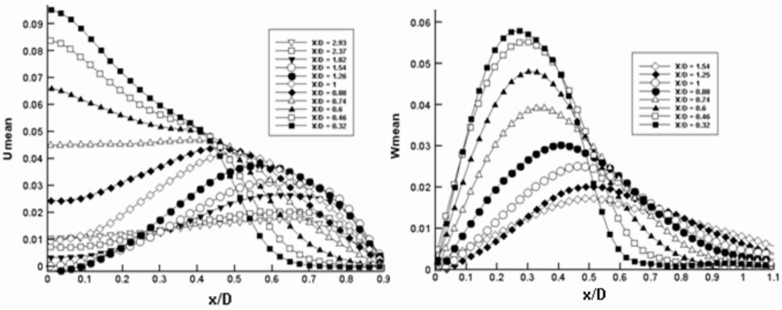
In figure (a) profiles of the axial and azimuthal velocity components for $S = 1.3$ are shown. The transition of the axial velocity from a jet-like profile to a wake-like profile is responsible for the change in sign of the azimuthal vorticity component. The hump of the axial velocity profile at the jet center could be explained by an inviscid analysis performed by Batchelor (1967). He explained the change in u by considering vortex lines going through a contraction zone. The diminishing axial velocity on the jet axis at $x/D = 1.2$ indicates the vortex breakdown. The swirl number $S = 1.3$ is derived from the velocity profiles at $x/D = 0.3$. The maximum of the azimuthal velocity at $r/D = 0.25$ at $x/D = 0.3$ and the appearence of a stagnation point for $S = 1.3$ compare favorable to the results of Billant *et al.* (1998). Considering the flow as a Rankine vortex with a superimposed axial velocity, the linear part of the azimuthal velocity can be identified as the vortex core.

Due to centrifugal forces, the swirl generates a pressure gradient in the vortex core. In order to nondimensionalize the pressure loss, the Bernoulli equation and the equation representing the balance between pressure and centrifugal forces were introduced into the definition of c_p, becoming $c_p = \frac{\int_0^\infty \frac{w_0^2}{r} dr - \int_0^\infty \frac{w^2}{r} dr}{\frac{1}{2} u_0^2}$.

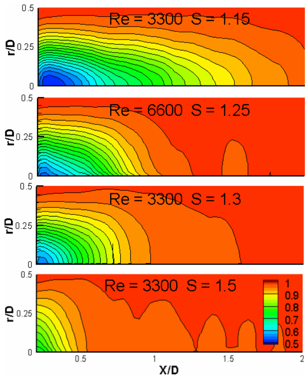
Figure (b) indicates the pressure decay which leads to the deceleration of the fluid at the jet center. The gradient changes continuously with the swirl. The Reynolds number dependence disappeares by using c_p.

Velocity contours indicating azimuthal modes are displayed in Figure (d). The global mode number decreases downstream from $m = 4$ to $m = 2$. The helical modes are perfectly steady, otherwise the averaging process would have evened out any azimuthal deformation. These results are in agreement with Loiseleux *et al.* (2003).

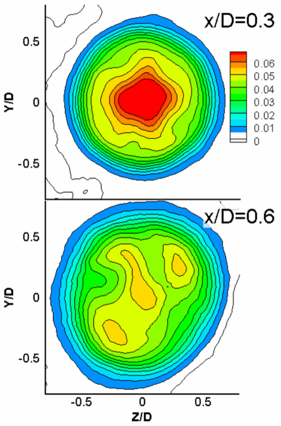
By introducing sinusoidal perturbations to the flow the location of vortex breakdown alternates synchronously to the forcing, without any significant mean displacement for most of the investigated parameters. Figure (e) shows the c_p distribution during one forcing cycle. For this particular parameter set, the region of the pressure decay associated with the vortex breakdown moves downstream while decreasing the intensity. The phase-velocities and wavelength presented in figure (f) confirm that the shedding could lock onto the forcing frequency for $St = 0.78$ in a better way than for $St = 0.3$, in agreement with Khalali *et al.* (2006).

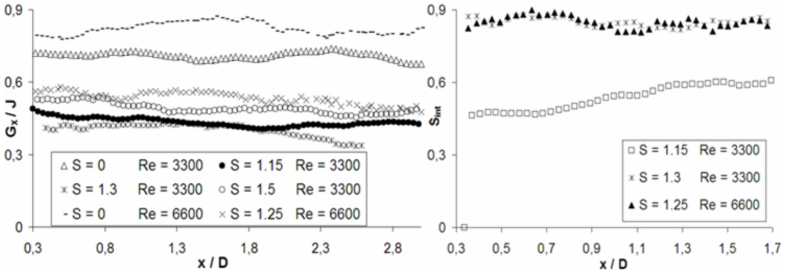


(a) velocity profiles [m/s] for $Re = 3300$ $S = 1.3$ $S_{int} = 0.8$



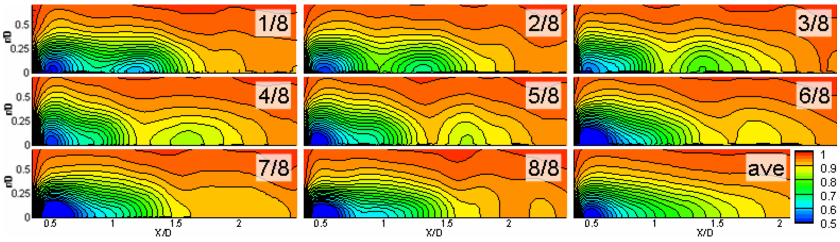
(b) distribution of c_p representing the loss of pressure





(c) development of axial flux of axial and angular momentum

(d) axial velocity [m/s] $S = 1.3$ $S_{int} = 0.8$ $Re = 3300$



Re	S	St	λ/D	$c_{ph}/\overline{u}$
3300	0	0.3	2.4	0.75
3300	0	0.78	0.75	0.53
3300	1.15	0.3	1.1	0.26
3300	1.15	0.78	0.7	0.51
3300	1.3	0.3	1.1	0.33
3300	1.3	0.78	0.7	0.5
6600	0	0.3	2.4	0.6
6600	0	0.78	0.7	0.53
6600	1.25	0.3	1.2	0.3
6600	1.25	0.78	0.65	0.44

(e) c_p distribution of pulsed swirling jet $Re = 3300$ $S = 1.3$ $S_{int} = 0.8$ $St = 0.78$ $A = 22\%$

(f) wavelength, phase-velocity

5 Conclusions

Vortex breakdown of a fully turbulent jet was under investigation using STEREO-PIV. An abrupt onset of vortex breakdown cannot be confirmed. The high turbulence level in the shear layer is believed to be responsible for the continuous change of the static pressure field with increasing swirl number. The momentum flux is conserved along the jet axis, which brings credibility to the measured data. Furthermore, the use of c_p as a non dimensional variable to characterize the loss of static pressure by applying the Bernoulli equation along the jet axis appears promising. Applying axial forcing at high amplitudes, the location of vortex breakdown was set into alternating motion. Phase-velocity and wavelength of the dominant coherent structures indicate the existence of favored parameter sets, where the flow locks on the forcing frequency, resulting in a significant displacement of the location of vortex breakdown. Cross-sectional contour plots of the axial velocity components indicate azimuthal modes. As the azimuthal modes remain perfectly steady the mode number can be determined from averaged data as $m \leq 4$. Further investigations will focus on the mechanisms of the azimuthal instabilities, since they are believed to be responsible for the onset of vortex breakdown. A pattern recognition software will be developed to post-process the PIV-Data in order to expose phase-velocity and wavelength of the azimuthal modes more precisely.

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