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# A swirling jet under the influence of a coaxial flow

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ABSTRACT

The recirculating flow field generated by a swirling jet and a coaxial annular stream entering a pipe is investigated with the use of 2D-DPIV. Parametric change of inlet flow rates (constant tangential injection with change of annular flow and vice versa) is being considered in order to study the mean and turbulent flow field. A recirculation bubble stabilized close to the swirler exit is the dominating feature of the interaction between the inner swirling jet and the annular stream. Results are discussed in terms of bubble topology and dynamics on the basis of a modified Rossby number that appears to describe the trends of the complex flow field.

## 1. Introduction

Swirl flows have been widely used in combustion systems as they enhance mixing between fuel and oxidant and flame stabilization. Introducing swirl in jet flows causes large-scale effects such as jet growth, entrainment and decay. Strongly swirling flows impose radial and axial pressure gradients generating an internal toroidal recirculation zone, which acts like an aerodynamic blockage similar to that of the well studied "bluff body" case. This phenomenon, known as "vortex breakdown", has been described by Leibovich [1] as a "disturbance characterized by the formation of an internal stagnation point on the vortex axis, followed by reversed flow in a region of limited extent". The complex structure of vortex breakdown has been a challenging issue for experimentalists over the past few decades. Several review-papers [2–5] and books [6,7] focusing on experimental, numerical and theoretical work regarding vortex breakdown have outlined the multitude of approaches pursuing our understanding of this complex phenomenon. Recently, Lucca-Negro and Doherty [8] presented an extensive guide to vortex breakdown literature.

Numerous efforts focusing on the visualization of the vortex breakdown flow field [9,10] have been reported providing qualitative data on the structure of vortex breakdown. Sarpkaya observed three basic modes of vortex breakdown by conducting visual experiments, namely: double helix, spiral and bubble type (axisymmetric). He also observed that for the bubble type vortex breakdown a toroidal vortex ring, whose axis gyrates at a regular frequency about the axis of the bubble, is formed at the downstream half of the bubble. Sarpkaya explained the fluid exchange that takes place between the recirculation bubble and the outer flow through the vortex ring as a simultaneous filling and emptying process that is possibly due to pressure instabilities in the wake of the bubble. Later measurements with the use of Laser Doppler Anemometry [11] and Particle Tracking Velocimetry [12] provided more detailed data about the mean properties of the recirculating flow field. Brücker and Althaus confirmed Sarpkaya's observation on the existence of an inclined vortex ring gyrating around the vortex axis, which plays a dominant role on the fluid exchange between the recirculation bubble and the ambient flow. They also provided information regarding the mean three-dimensional structure of the recirculating bubble. Turbulent properties of recirculating swirl flows have been studied by several experimentalists [13–18], focusing on the influence of the flow field topology on fluid transport and mixing and the characteristics of the precessing vortex core. Up to now, rather limited data has been presented, regarding the turbulent flow field created by coaxial jets with inner and/or outer swirl [19–22].

The development of numerical tools, over the last two decades, has provided important additional information on the structure of vortex breakdown and on the identification of the parameters affecting its occurrence and development [23–31]. However, relatively few studies have been reported, correlating numerical with experimental results [32–36].

Research on vortex breakdown phenomena has led to a parallel research on the critical parameters that could determine whether vortex breakdown will occur. The definition of non-dimensional parameters, mainly based on the correlation of axial and azimuthal

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## Nomenclature

| | |
|---|---|
| $a$ | mean statistical divergence |
| $D_{\mathrm{CRZ}}$ | vertical distance between recirculation zones centres (m) |
| $D_i$ | swirl orifice diameter, $R_i = D_i/2$ (m) |
| $D_0$ | pipe diameter, $R_0 = D_0/2$ (m) |
| d$t$ | time between laser pulses (s) |
| $D_{\mathrm{VR}}$ | transverse bubble length (vortex ring diameter) (m) |
| $F_{U_x}$ | flatness value of longitudinal velocity, $F_{U_x} = \frac{\overline{u_x'^4}}{\sqrt{\overline{u_x'^2}}^4}$ (–) |
| $L_{\mathrm{B}}$ | bubble longitudinal length (m) |
| $L_{\mathrm{IA}}$ | length of interrogation area (m) |
| $M_{\mathrm{a}}$ | annular mass flow rate (kg/s) |
| $M_{\mathrm{t}}$ | tangential mass flow rate (kg/s) |
| $m$ | mass flow ratio $m = M_{\mathrm{a}}/M_{\mathrm{t}}$ (–) |
| $m^*$ | recirculating mass flow ratio, $m^* = \int_0^{\mathrm{r}^*} U_x r\,\mathrm{d}r / \int_{\mathrm{r}^*}^{R_0} U_x r\,\mathrm{d}r$ (–) |
| $Q$ | volumetric flow rate ($\mathrm{m}^3/\mathrm{s}$) |
| $r^*$ | distance of zero $U_x$ contour line from vortex axis (m) |
| $R$ | ratio of the radial to the tangential velocity, $R = U_\theta/U_x$ (–) |
| $Re_{x,i}$ | Reynolds number based on $U_{x,i}$, $Re_{x,i} = U_{x,i}D_i/\nu$ (–) |
| $Re_{x,0}$ | Reynolds number based on $U_{x,0}$, $Re_{x,0} = U_{x,0}(D_0 - D_i)/\nu$ (–) |
| $Re_{\omega,i}$ | Reynolds number based on $U_{\theta,i}$, $Re_{\omega,i} = U_{\theta,i}\, D_i/\nu$ (–) |
| $Ro$ | Rossby number: $Ro = \frac{U_{x,0}(x_0) - U_{x,i}(x_0)}{U_{\theta,i}(x_0)}$ (–) |
| $S$ | swirl number (–) (see definition in Table 1) |
| $S^*$ | swirl ratio: $S_* = \frac{2U_{\theta,i}(x_0)}{U_{x,i}(x_0)}$ (–) |
| $S_{\mathrm{Ux}}$ | skewness value of longitudinal velocity, $S_{U_x} = \frac{\overline{u_x'^3}}{\sqrt{\overline{u_x'^2}}^3}$ (–) |
| TI | turbulence intensity, $\mathrm{TI} = \frac{\sqrt{\overline{u_x'^2} + \overline{u_r'^2}}}{\sqrt{U_x^2 + U_r^2}}$ (–) |
| $U$, $V$, $W$ | Cartesian velocity components |
| $U_{\mathrm{r}}$ | mean radial velocity (m/s) |
| $\sqrt{\overline{u_r'^2}}$ | RMS value of radial velocity (m/s) |
| $U_x$ | mean longitudinal velocity (m/s) |
| $U_{x,i}$ | swirling jet spatially mean longitudinal velocity, $U_{x,i} = 4Q_i/\pi D_i^2$ (m/s) |
| $U_{x,0}$ | annular flow spatially mean longitudinal velocity, $U_{x,0} = 4Q_0/\pi(D_0^2 - D_i^2)$ (m/s) |
| $\sqrt{\overline{u_x'^2}}$ | RMS value of longitudinal velocity (m/s) |
| $\overline{u_x' u_r'}$ | Reynolds stress component ($\mathrm{m}^2/\mathrm{s}^2$) |
| $U_\theta$ | mean tangential velocity (m/s) |
| $U_{\theta,i}$ | swirling jet spatially mean tangential velocity, $U_{\theta,i} = 2\int_0^{R_i} U_\theta r\,\mathrm{d}r/R_i^2$ (m/s) |
| $x$, $y$, z | Cartesian coordinates |
| $x$, $r$, $\theta$ | polar coordinates |
| $x_{\mathrm{CRZ}}$ | longitudinal distance of the recirculation zone centre from the jet's exit mouth (m) |
| $\overline{x_{\mathrm{CRZ}}}$ | longitudinal distance of the vortex ring axis from jet's exit mouth, $\overline{x_{\mathrm{CRZ}}} = (x_{\mathrm{CRZ}(1)} + x_{\mathrm{CRZ}(2)})/2$ (m) |
| $x_0$ | longitudinal distance from jet's exit mouth, where inlet conditions are set, $x_0 = 0.25D_i$ (m) |
| $y_{\mathrm{c}}$ | vertical position of longitudinal axis (m) |

*Greek letters*

| | |
|---|---|
| $\delta$ | laser sheet thickness (m) |
| $\zeta$ | velocity ratio, $\zeta = U_{x,0}/U_{x,i}$ (–) |
| $\Phi$ | mean value of $i$ samples |
| $\Omega$ | circulation number (–) |
| $\Omega_x$ | mean axial vorticity (1/s) |
| $\Omega_\theta$ | mean azimuthal vorticity (1/s) |
| $\sqrt{\overline{\omega_\theta'^2}}$ | RMS value of azimuthal vorticity (1/s) |

velocities or momenta, has been an issue of scientific interest that has often led to different approaches and criteria for vortex breakdown prediction.

Swirl number (S) is a parameter often used to describe the behavior of swirling jets. The definition of swirl number varies in the literature as it depends strongly on the means of swirl generation (rotating nozzles, guide vanes, tangential injectors, etc.). Calculation of swirl number (or ratio) is based either on the comparison of the axial flux of swirl momentum to that of the axial momentum or on the ratio of characteristic velocity scales of the flow field such as a tangential velocity to an axial velocity (geometric swirl number). A commonly used critical value for vortex breakdown initiation is $S = 0.57$. For the case of tangentially injected swirl flows, the tangential to the total momentum flux ratio has been employed as a similarity parameter [14,27] as it is not possible to control the axial momentum flux independently. In Table 1, several approaches of swirl number definition are presented.

Escudier and Zehnder [4] proposed a simple criterion for the occurrence of vortex breakdown at a fixed location in a tube: $Re_{\mathrm{B}} \sim \Omega^{-3}R^{-1}$; where $Re_{\mathrm{B}}$ is the pipe Reynolds number at which vortex breakdown occurs, $\Omega$ is the circulation number and $R$ the ratio of the radial to tangential velocities in the inflow region. The correlation is good over a wide range of $Re$ ($5 \times 10^2$–$10^5$) although "departures are evident for very high circulation numbers". In the case of more complex flow fields, such as wing tip or leading edge vortices, a correlation between Reynolds and Rossby number has been proposed as more appropriate to explain flow attributes, such as vortex breakdown initiation [23,5]. A critical Rossby number value for $Re \geqslant 250$ is $Ro \approx 0.65$.

However, all approaches are highly dependent on the inlet velocity profile. Fitzgerald et al. [37], following the work done by Billant et al. [38], proposed the calculation of a swirl ratio critical

**Table 1**
Swirl number calculation approaches

| | |
|---|---|
| $S = \frac{\int_0^{R_i} \rho(U_x U_\theta + \overline{u_x' u_\theta'}) r^2\,\mathrm{d}r}{R_i \int_0^{R} (\rho U_x^2 + \rho\overline{u_x'^2} + (p - p_\infty)) r\,\mathrm{d}r}$ | Mattingly et al. [20] |
| $S = \frac{\int_0^{R_i} U_x U_\theta r^2\,\mathrm{d}r}{R_i \int_0^{R} U_x^2 r\,\mathrm{d}r}$ | Ivanic [45] |
| $S = \frac{\int_0^{\infty} U_x U_\theta r^2\,\mathrm{d}r}{R_i \int_0^{\infty} (U_x^2 - \frac{1}{2}U_\theta^2) r\,\mathrm{d}r}$ | Ribeiro [41], Champagne [21] |
| $S = \frac{2}{3}\frac{1 - \left(\frac{D_i}{D_0}\right)^3}{1 - \left(\frac{D_i}{D_0}\right)^2}\tan(a)$ | Gupta [6], Heitor [13] |

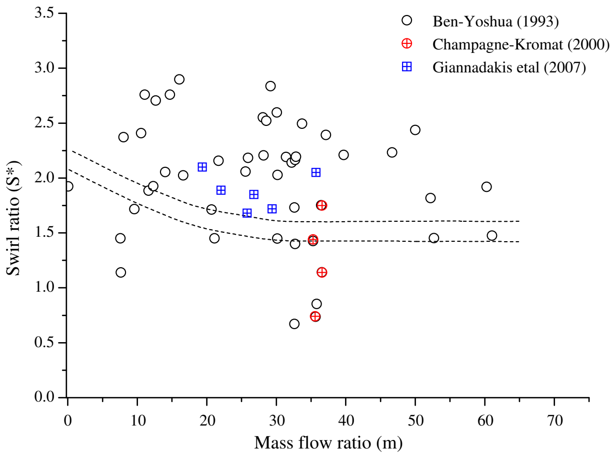

**Fig. 1.** Validity confirmation of swirl ratio calculation according to Fitzgerald [37].