A swirling jet under the influence of a coaxial flow

A. Giannadakis, K. Perrakis, Th. Panidis *

University of Patras, Department of Mechanical Engineering and Aeronautics, Laboratory of Applied Thermodynamics, Greece

A R T I C L E   I N F O

Article history:
Received 16 October 2007
Received in revised form 30 March 2008
Accepted 28 April 2008

Keywords:
Swirling jets
Coaxial flow
Vortex breakdown
DPIV

A B S T R A C T

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
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: $Re_h \approx \Omega^{-2}R^{-1}$; where $Re_h$ 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 $Re > 250$ 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

<table>
<thead>
<tr>
<th>Formula</th>
<th>Description</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S = \frac{\int_0^\pi \rho U_r U_t \sqrt{r^2 - h^2} dr}{\int_0^\pi \rho U_r U_t \sqrt{r^2 - h^2} dr}$</td>
<td>Mattingly et al. [20]</td>
<td></td>
</tr>
<tr>
<td>$S = \frac{\int_0^\pi \rho U_r U_t \sqrt{r^2 - h^2} dr}{\int_0^\pi \rho U_r U_t \sqrt{r^2 - h^2} dr}$</td>
<td>Ivanic [45]</td>
<td></td>
</tr>
<tr>
<td>$S = \frac{\int_0^\pi \rho U_r U_t \sqrt{r^2 - h^2} dr}{\int_0^\pi \rho U_r U_t \sqrt{r^2 - h^2} dr}$</td>
<td>Ribeiro [41], Champagne [21]</td>
<td></td>
</tr>
<tr>
<td>$S = \frac{1}{1 - \frac{1}{\tan(\phi)}}$</td>
<td>Gupta [6], Heitor [11]</td>
<td></td>
</tr>
</tbody>
</table>

**Greek letters**

- $\delta$ laser sheet thickness (m)
- $\zeta$ velocity ratio, $\zeta = U_{ax}/U_{ax} (-)$
- $\Phi$ mean value of $i$ samples
- $\Omega$ circulation number (-)
- $\Omega_s$ mean axial vorticity (1/s)
- $\Omega_{az}$ mean azimuthal vorticity (1/s)
- $\Omega_{ax}$ RMS value of azimuthal vorticity (1/s)

**Fig. 1.** Validity confirmation of swirl ratio calculation according to Fitzgerald [37].
for the initiation of vortex breakdown which is independent of the velocity profiles as it is defined by the ratio of the mass flow averaged azimuthal velocity to the averaged axial velocity. The definition of this swirl ratio is similar to that proposed by Marliani et al. [16]. Its critical value is in the range of $S^*_{c} = 1.2–1.3$ with

$$S_c = \frac{2U_{h,i}(x_0)}{U_{x,i}(x_0)}$$

where $U_{h,i}$ is the swirling jet spatially mean tangential velocity and $U_{x,i}$ is the swirling jet spatially mean longitudinal velocity.

The authors confirmed the validity of this swirl ratio (Fig. 1) for the case of coaxial jets with outer swirl [39,21] and inner swirl [40]. The swirl ratio proposed by Fitzgerald et al. is in average 2.6 times higher than that calculated by Champagne and Kromat due to the different approaches in swirl number definition.

Still, predicting vortex breakdown is not by itself adequate to characterize the mean and turbulent features of the recirculating flow field. Moreover, in the case of coaxial jets, with or without swirl, previous studies [41–43,21,44] have shown that the flow field created is strongly affected not only by the velocity or mass flow ratio of the jets but also by the absolute values of the jets’ velocities or the velocity jump ($\Delta U = U_{x,0} - U_{x,i}$) between the two streams. For the case of coaxial swirling jets it is apparent that the interaction between the shear layers (mainly azimuthal and
axial) is the key to understand the features of such a complex flow field [22].

In this work mean and turbulent characteristics of the recirculating flowfield generated by a swirling jet under the influence of a coaxial stream are discussed, laying emphasis on the structure of the recirculation bubble and its effect on the interaction and mixing of the two streams. Analysis of the experimental results is based on a modified Rossby number, defined as the ratio of the jets’ velocity jump – or velocity deficit – to the mass flow averaged swirl velocity, which appears to describe the trends and characteristic features of the recirculating flow field.

\[
Ro = \frac{U_{0}(x_{0}) - U_{an}(x_{0})}{U_{an}(x_{0})}
\]  

(2)

where \(U_{an}\) is the annular flow spatially mean longitudinal velocity.

2. Experimental setup

2.1. Experimental facility

The experimental facility (Fig. 2) consists of a slightly diverging conical swirler (3%) with \(D_{i} = 28\) mm exit diameter and a coaxial annular duct from which parallel flow is introduced into the chamber. The test chamber consists of a 400 mm long Plexiglas tube of \(D_{0} = 100\) mm inner diameter. At the inlet of the test chamber an annular gap between the swirling nozzle and the annular duct exists, due to the wall thickness of the swirling nozzle (1.5 mm). Swirl is produced through tangential injection of air into the swirling nozzle. Four tangential injectors of 4 mm inner diameter are located five nozzle diameters upstream (140 mm) from the jet exit. A centrifugal blower supplies the tangential flow, while a centrifugal fan feeds the annular flow. Homogenization of the annular flow is achieved with the use of circular screens.

2.2. Measurement technique

2.2.1. General description of the DPIV system and experimental setup

2D Digital Particle Image Velocimetry is used to monitor the flow field. The measurement equipment consisted of a Flowsense 2M CCD Camera (1600 × 1200, 15 Hz acquisition rate) and two Quantel pulsed lasers (30 mJ). Both the CCD Camera and the laser were mounted on a 3D traversing mechanism (0.1 mm step accuracy), aligned to the test rig. Longitudinal and transverse planar cuts along and normal to the swirl axis are used for flow field monitoring.

2.2.2. Time control and illumination setup

Regulation of the time interval between laser pulses (\(dt\)) is based on the bulk velocity of the flow field and the length of the interrogation area that is being monitored (\(L_{qa}\)). As swirling flows

<table>
<thead>
<tr>
<th>Table 2</th>
<th>Mean PIV divergence error evaluation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pairs of images</td>
<td>(U_{i} (%))</td>
</tr>
<tr>
<td>500–1000</td>
<td>2.83</td>
</tr>
<tr>
<td>1000–1500</td>
<td>2.48</td>
</tr>
<tr>
<td>1500–2000</td>
<td>1.25</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 3</th>
<th>Inlet conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test case</td>
<td>(M_{i} (kg/s))</td>
</tr>
<tr>
<td>a</td>
<td>1.35E–03</td>
</tr>
<tr>
<td>b</td>
<td>1.19E–03</td>
</tr>
<tr>
<td>c</td>
<td>9.76E–04</td>
</tr>
<tr>
<td>d</td>
<td>1.35E–03</td>
</tr>
<tr>
<td>e</td>
<td>1.19E–03</td>
</tr>
<tr>
<td>f</td>
<td>9.76E–04</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 4</th>
<th>Recirculation bubble length scales</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test case</td>
<td>(D_{crz} (%))</td>
</tr>
<tr>
<td>(a)</td>
<td>0.51</td>
</tr>
<tr>
<td>(b)</td>
<td>0.54</td>
</tr>
<tr>
<td>(c)</td>
<td>0.58</td>
</tr>
<tr>
<td>(d)</td>
<td>0.59</td>
</tr>
<tr>
<td>(e)</td>
<td>0.63</td>
</tr>
<tr>
<td>(f)</td>
<td>0.64</td>
</tr>
<tr>
<td>0.61 ± 5%</td>
<td>0.79 ± 4%</td>
</tr>
</tbody>
</table>
are three dimensional the light sheet thickness (\(d\)) has to be regulated accordingly. Taking into consideration the Nyquist criterion, the following conditions have to be satisfied for the measurement control volume for longitudinal measurements:

\[
\begin{align*}
    dt &\leq 0.25 \frac{L_{IA}}{U} \\
    \delta &\geq 4W dt 
\end{align*}
\]

where U and W are the reference velocity components on the laser sheet plane and normal to it, respectively.

In the case of cross sectional measurements the criteria are reversed as far as the velocities are concerned. Satisfying both of the criteria is a task that, for the case of high swirl flows, results into the weakening of the laser sheet illumination strength and thus introduces errors in image capturing. For the present experiments such errors are dealt with in a satisfying manner for the longitudinal measurements.

Fig. 5. Contours of mean longitudinal velocity \(U_x\) (m/s).
and transverse measurements, since \( U \) and \( W \) are of the same order of magnitude.

In order to diminish reflection effects, the swirl orifice and half the test chamber are smoothly colored black.

2.2.3. Seeding particles

Droplets of 4 \( \mu \text{m} \) mean diameter are used as seeding particles, generated by an OMRON nebulizer, with adjustable air-flow and nebulization rate. Homogeneity of particle concentration is achieved by seeding both the annular and the tangential inlets.

2.2.4. Image post processing and evaluation of results

Post-processing of the images is accomplished by subtracting a static image (with no seeding particles) from the seeded images in order to remove white noise produced by reflections. Additionally, low-pass filters are applied on the subtracted images.

Raw vector data of the flow field is produced with the use of adaptive correlation processing. Each frame is divided into interrogation windows, fixed at 32 \( \times \) 32 pixels with 25\% overlap. Mean and turbulent statistics from raw vector data are calculated with the use of a home developed code.

Two thousand pairs of images for each test case are acquired in order to evaluate the mean and turbulent flow field. The criterion for the amount of images needed was the convergence of the evaluation output for every additional five hundred pairs of images. In Table 2 a typical result of the mean statistical divergence resulting from the increase in image pair samples by 500 is shown \((a = ||\Phi_{t=500}|| - ||\Phi_{t=100}||)\). Results show good convergence of \( U_t \) due to the fact that it takes relatively large percentage error.

DPIV measurements at the inlet of the test rig, supplying only the annular flow, showed a symmetric flow field with no secondary flows, ensuring that coaxiality and homogenization of the annular flow is achieved at a satisfying level. Hot wire measurements of this flow field with an X probe further validated the symmetry of the annular flow which presented a turbulence intensity of 1.5 \% [41] at the inlet of the test chamber. Measured velocities at all test cases satisfy continuity with a maximum divergence error of 10\%.

For further evaluation of the experimental results, axisymmetry is checked for both measurement planes by comparing the axisymmetric terms of the vorticity components calculated using the measured velocity distributions in polar coordinates with the directly measured vorticity:

\[
\omega_a = \frac{1}{r} \frac{\partial (rU_r)}{\partial r}, \quad \omega_z = -\frac{\partial U_z}{\partial r}, \quad \text{axisymmetric vorticity terms}
\]

\[
\omega_x = \frac{\partial W}{\partial y} - \frac{\partial V}{\partial z}, \quad \omega_y = \frac{\partial V}{\partial x} - \frac{\partial U}{\partial y}, \quad \text{measured vorticity terms}
\]

Comparison (Fig. 3) between the calculated axisymmetric terms and the measured vorticity components shows that the mean flow field is almost axisymmetric and that the location of the vortex axis center is correctly estimated.

3. Experimental results

In Table 3 the experimental conditions corresponding to the six test cases considered using three tangential and two annular mass flow rates are presented. Inlet conditions are calculated from the experimental data according to Ivanic [45] and Fitzgerald et al. [37], at a distance \( x_0 = x/D \), = 0.25.

3.1. Basic topology description of the recirculation bubble

In Fig. 4, the characteristic length scales of the recirculation bubble are defined, based on the measured streak line plot of test case \( f \), depicting the main features of the flow field. The internal structure of bubble vortex breakdown is characterized by the formation of two counter-rotating recirculation zones and the existence of a stagnation zone \((U_t = 0)\). The stagnation zone passes through the centers of the recirculation zones and defines the limits of the bubble on the vortex axis (bubble nose and aft). The recirculation zones constitute a planar cut of a vortex ring which gyrates around an axis almost parallel to the longitudinal axis of the flow and an azimuthal defined by the vortex ring core. Small asymmetries are observable in all test cases, despite the efforts to eliminate them. Since these asymmetries are not consistent (e.g. the longitudinal distance in the x-direction between the upper and the lower center of the recirculation zones is at times positive or negative) they should not be attributed to secondary effects due to misalignment but rather to secondary effects due to inlet conditions.

The recirculation bubble geometry is strongly influenced by inlet conditions. Comparison of length scales (Table 4) shows that increase of tangential flow rate (comparing cases a–b–c and d–e–f) results in a positive shift of the bubble aft position \((x_B)\) and an elongation of the bubble shape \((W_B)\) symbols are defined in Fig. 4 and in the nomenclature). On the other hand, increase in the annular flow rate (comparing cases a–d, b–e and c–f) leads to negative shift of the bubble aft position and widening of the recirculation bubble. Vortex ring length scales follow the same trends as the recirculation bubble (see \( L_B \) and \( D_B \)). Comparing all test cases from a to f it is seen that an increase in the proposed Rossby number results in the widening of the recirculation bubble and an upstream shift of its aft. This observation along with that of Escudier and Zehnder [4] who noted that increase of swirl causes breakdown to occur upstream, provide evidence that in the case of coaxial flows the swirl parameter is not by itself adequate to describe the recirculating flow regime. This is more clearly shown in the following section, where the influence of the proposed Rossby number on the recirculating trend of the flow is discussed.

3.2. Mean flow field

As seen in Fig. 5, depicting the mean longitudinal velocity contours \((U_x)\), only for test case d a closed bubble shape is formed. The bubble interior is in all test cases characterized by negative velocities. “Zero” longitudinal and radial velocity values \( (U_x = 0 \) and
$U_{rc} = 0$) are observed at the centers of the recirculation zone (vortex ring core center). This observation is in agreement with the static nature of the vortex ring [6]. While keeping $U_{x,0}$ constant (case a–b–c and d–e–f), the flow field’s tendency to recirculate increases with the velocity jump ($\Delta U = U_{x,0} - U_{x,i}$). This relates to previous work on coaxial jets without swirl [44], where it was found that for velocity ratio higher than a specific limit ($\zeta > 8$) the outer jet begins to penetrate upstream on the inner jet axis imposing a pressure deficit which leads to recirculation. In general swirl is expected to intensify the recirculation trend of a jet. However, in the present experiments the rotation of the internal stream and the associated centrifugal forces seem to inhibit the penetration of the outer flow towards the inner jet axis leading to decreased recirculation. The swirler’s exit mouth sets the reference location for the stabilization of the recirculation bubble. The proposed Rossby number takes into account these effects, related to the

![Fig. 7. Contours of mean radial velocity $U_r$ (m/s).](image-url)
interaction of a longitudinal and an azimuthal shear layer and appears to describe the observed trends. The recirculation mass flow ratio \( \left( \frac{m}{C_3} = \frac{R_r}{C_3 U_{r d}} \right) \) depicted in Fig. 6 shows explicitly this agreement as it increases with Rossby number. Maximum values of \( m^* \) occur at the vortex ring core plane and scale almost linearly with the Rossby number.

Contours of the mean radial velocity \( (U_r) \) component (Fig. 7) show how the flow travels around the recirculation bubble. Bubble interior is characterized by low radial velocities. Within the bubble, fore and aft the vortex ring core, relatively high radial velocities indicate the recirculation pattern. In the downstream boundary of the bubble, the combined effect of the expanding flow around the bubble and the flow entering the bubble results to high radial velocities.

Mean azimuthal vorticity \( (\Omega_\theta) \) contours (Fig. 8) show the interaction of the shear layer, created by the swirling jet and the
annular flow, with the rotating vortex ring. Maximum values of $\Omega_0$ increase with the Rossby number and are observed in two regions:

(i) The first and stronger one is located at the jet exit, where the shear layer between the two flows is formed.

(ii) The second is located at the position of the vortex ring core due to the rotation of the vortex ring.

The interior of the recirculation bubble is characterized by low azimuthal vorticity values in the upstream region, close to the swirling nozzle and higher ones in the region between the vortex ring core and the bubble’s aft, due to fluid exchange between the recirculation bubble and the outer flow. Increase of Rossby number results into the widening of the latter region.

The increase in azimuthal vorticity values has also been correlated by Althaus et al. [7] with the upstream displacement of the...
recirculation bubble, as it has been discussed earlier in the bubble topology section, illustrating the ability of the proposed Rossby number to describe the flow field’s trends.

3.3. Turbulent flow field

Contours of longitudinal and radial RMS velocities ($\sqrt{u_x^2}$ and $\sqrt{u_r^2}$), presented in Figs. 9 and 10, show the effect of the recirculation bubble on the turbulent dynamics of the coaxial flow field. Intense values of $\sqrt{u_x^2}$ and $\sqrt{u_r^2}$ occur in the shear layer between the outer flow and the recirculation bubble, while maxima are located at the vortex ring core plane (bubble–annular flow interaction) and the bubble aft (wake flow region), respectively. Furthermore, their intensity is increased with the Rossby number. As expected, the interior of the recirculating bubble is characterized by lower values of turbulent kinetic energy [10]. Contours of
$\sqrt{u'^2}$ form a low value 'tail' at the recirculation bubble aft depicting the effect of the aft stagnation zone on fluid flowing inside and outside the bubble. High turbulence intensity ($TI = \sqrt{u'^2 + \bar{u}^2}$) is observed at the periphery of the recirculation bubble (Fig. 11). In the central region of the bubble an elliptic zone of low turbulence intensity is formed. This zone corresponds to the high recirculating velocities zone observed in the longitudinal mean velocities contour (Fig. 4). The area occupied by this zone increases with the Rossby number. Azimuthal vorticity fluctuations ($\sqrt{\omega_z^2}$) maxima (Fig. 12) show the strong interaction of the vortex ring with the outer flow. An interesting feature of vorticity fluctuations is the fact that its maxima are located between the first and the second region of maximum mean vorticity, depicting the strong effect of the vortex ring on flow turbulence dynamics and a diffusion-like
process from the shear layer to the vortex ring. Topology of $\sqrt{w'^2}$ is quite similar to that of $\sqrt{u'^2}$. Intense turbulence mixing via the $u'u''$ Reynolds stresses component (Fig. 13) between the swirling jet and the annular flow is initiated in the shear layer close to the vortex ring core plane occupying a broader area in the aft shear layer where fluid exchange between the outer flow and the bubble takes place. Inside the bubble, local maxima are located in the vortex ring core due to fluid recirculation. Shear stresses increase with Rossby number.

Longitudinal velocity skewness ($S_{U_L}$) contours (Fig. 14) depict values close to zero (indicating a symmetric probability density function, pdf) within the area of the bubble. Zero value contour moves towards the bubble fore with the Rossby number. A similar trend is observed in the longitudinal velocity flatness ($F_{U_L}$).
contours (Fig. 15) within the bubble. The area surrounded by the value 3.0 contour level (typical value for normal pdf) is getting larger and moves towards the bubble fore with the Rossby number. The shear layer developing at the bubble boundaries is characterized by skewness and flatness values of 0 and 3, respectively, along with high $\sqrt{\bar{u}_x^2}$ values. Intermittent presence of fluid parcels penetrating from the high velocity outer stream to the lower velocity inner stream result to positive skewness values on the low velocity side of the shear layer whereas the inverse mechanism results to negative values on the high velocity side. These effects also lead to increased flatness values on both sides of the shear layer.

4. Conclusions

The near flow field of a recirculating swirling jet interacting with an annular flow was studied with the use of 2D DPIV. A
A modified Rossby number has been proposed which appears to describe the flow trends adequately. Length scale characteristics of the recirculating bubble scale with the Rossby number. Increase of Ro results to the widening of the bubble and an upstream shift of its aft. Results of the mean and turbulent flow field demonstrate the important role of the recirculation bubble on flow dynamics and the mixing process between the swirling jet and the annular flow. High recirculating velocities are observed at the central area of the bubble, the amplitude of which increases with the Rossby number. The bubble interior is characterized by low turbulent dynamics. Vorticity diffusion from the shear layer to the vortex ring results to the creation of a second region of high $\Omega_z$ and high values of $\sqrt{\alpha^2}$ at the vortex ring core plane. Skewness and flatness contour diagrams indicate a normal velocity pdf distribution in the bubble interior. Change of sign in skewness values and
high flatness values depict the intense momentum transfer between the two streams in the shear layer. Characteristics of mean and turbulent flow field depict two zones in the flow field. The first one is dominated by the recirculation bubble and the vortex ring dynamics while the second one is located downstream the aft of the bubble acquiring wake flow characteristics. The modified Rossby number, relating the azimuthal with the axial shear layer influence on the flow field, appears to describe the flow field's trends and recirculation bubble topology in a satisfying manner.

Acknowledgements

The support of the European Social Fund (ESF), Operational Program for Educational and Vocational Training II (EPEAEK II), and particularly the Program HERAKLITOS, is gratefully acknowledged.