Measurement of the 3D turbulent flow field of an annular jet and Proper Orthogonal Decomposition analysis.

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Abstract: - The annular jet is an example of complex shear flow situations. Two axisymmetric shear layers, originating at the jet exit, one at the nozzle lip and the other at the centre body, eventually meet downstream or interact with each other. The main aim of this study is to observe and analyze the 3D turbulent flow field on an annular jet with a great diameter ratio (r= 0.91). Measurements are conducted with a Reynolds number Re_{Do}=107800. This work will permit us essentially to have a better knowledge of annular jets which present the effect of asymmetries in the experimental jet exit velocities and to meet manufacturers' needs.

Key-Words: - Laser Doppler Anemometry 3D, Particle Image Velocimetry, Proper Orthogonal Decomposition, annular jet.

1 Introduction.

Annular jet is used in the industrial domain, in combustion (burners, bluff bodies…) or in industrial treatment processes. The geometry of the annular jet is determined by the ratio D_i/D_o, where D_i represents the internal diameter and Do the external diameter. The flow characteristics of the initial region of an annular jet discharging into stationary air have been investigated previously. Chigier [1], in 1964, studied them as a limiting case of coaxial jets. Because the configuration of the annular jet often adopted by authors was without after body or bullet at the nozzle exit, an internal recirculating region is formed downstream of the interface. This recirculation zone is the result of the lack of any air supply in the center and the entrainment of air from the main stream of the annular jet. The interests of the flow here are the interaction between the jet and the recirculation zone near the nozzle of the annular jet. Many authors, like Ko [2][3], work on small diameter ratio annular jets, with a ratio D_i/D_o smaller than 0.7. Only the fully-developed merging zone of a diameter ratio larger than 0.7 have been studied by Aly [4] in 1991.

The scientific interest in the study of turbulence has led to the development of a P.I.V. post-processing, which is able to bring out the inner driving mechanism of the flow [5]. In other words, the structure responsible for the development or the maintenance of flow instability has to be reached. So, in this context, Lumley [6] [7] has proposed a method for identifying coherent and instantaneous structures in turbulent flow. The method is the Proper Orthogonal Decomposition (P.O.D.). This method provides a base for the modal decomposition of a set of functions, such as data obtained in the course of the experiments. The most striking property of this decomposition is optimality: it provides the most efficient way of capturing the dominant components of an infinite-dimensional process with only a few functions [5]. That is why the P.O.D. process has been applied in different turbulent flows to analyze experimental P.I.V. data with a view to extracting dominant features and trends : coherent structures [6][7][8][9]. P.O.D. provides an optimal set of basis functions for an ensemble of data. The present study relies on an experimental investigation of the initial zone of a large diameter ratio annular air jet by the use of Particle Image Velocimetry (P.I.V). So it is useful to establish the link between the first P.O.D. eigen functions and the motion of the stagnation point at the end of the annular jet recirculation zone. The 3D evolution of the annular jet is very important to understand the evolution of the stagnation point wich will be explained by application of P.O.D. on P.I.V. measurements.

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2 Experimental set-up.

2.1 Annular jet

A diagram of annular jet is shown in fig 1. The annular jet is characterized by the outer diameter Do, equal to 53.88 mm, and the inner diameter D_i, equal to 48.75 mm. The thickness of the jet e is thus equal to 2.565 mm. In our set-up, D_i/D_o is equal to 0.91. The exit velocity U_o is equal to 30m/s which correspond to the value of the Reynolds number Re, based on the thickness e, of 7680. At a distance from the nozzle of 50 µm, the cross sectional profile of the longitudinal, measured with hot wire anemometry, shows a “top hat” distribution.

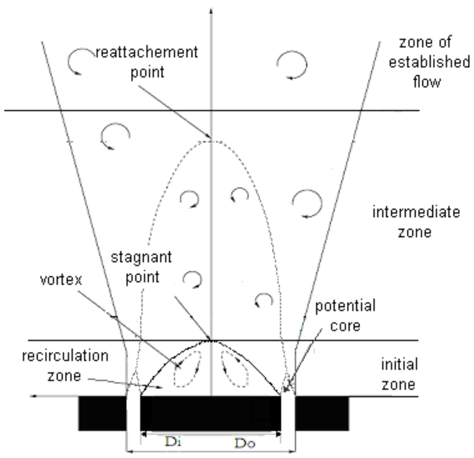

Fig 1: Shape of the flow of a basic annular jet with a large diameter ratio

2.2 Cross correlation PIV set-up

The experimental set-up of the P.I.V. measurements is presented in fig 2. A double pulsed Nd-Yag laser is used to set up the light sheet. The output energy is nearly 30 mJ for each laser pulse. The wavelength is 532 nm. The laser beams are focused onto a sheet across the median plane of the annular jet by one cylindrical lens (f=-0.02 m) and one spherical lens (f=0.5 m). The time delay between the two pulses, which depends on the exit velocity U_o, is 10 µs. The observation field is 2.8*2.5 cm².

In this study, the video images are recorded by a LAVISION Flow Master 3S camera. The frame grabber, using a pixel clock, digitizes the analogue video signal to an accuracy of 12 bits. In the frame grabber, each field is digitized in 1280*1024 pixels with grey levels. The acquisition frequency is 4 Hz.

Interrogation of the recorded images is performed by two-dimensional digital cross correlation analysis using “Davis 6.2.2.”

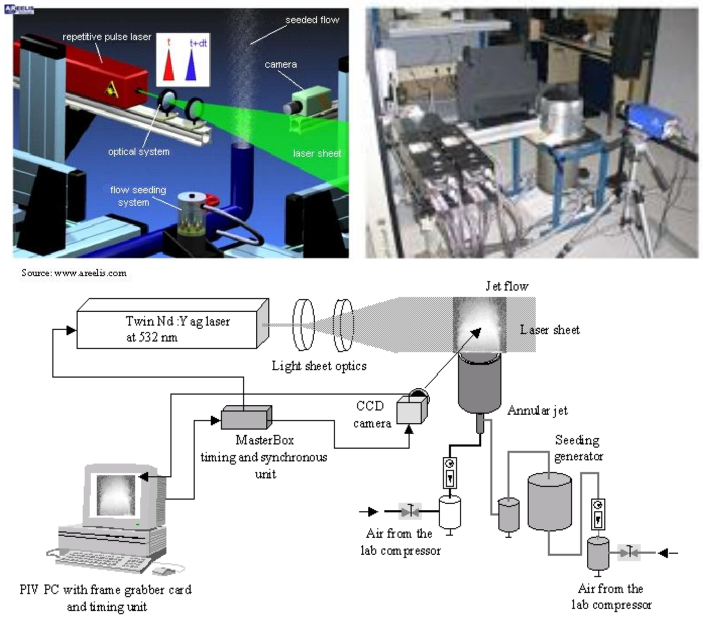

Fig 2: experimental PIV set-up

For all velocity fields, the sampling window has a size of 16 by 16 pixels (0.377 by 0.377 mm) and there is a 50 % overlap with the next window. 400 P.I.V. images have been recorded. We observed less than 1 % of false vectors calculated in the flow.

2.3 Laser Doppler Velocimetry 3D.

Laser Doppler Anemometry (LDA), also known as Laser Doppler Velocimetry (LDV), is an optical technique ideal for non-intrusive 1D, 2D and 3D point measurement of velocity and turbulence distribution in both free flows and internal flows. For this study a 3D Laser Doppler Anemometer is used which consists of two Dantec Dynamics probes, one being an Ar-Ion laser (COHERENT Innova 300) driven 2D FiberFlow probe and the other 1D Fiber Flow (fig 3).

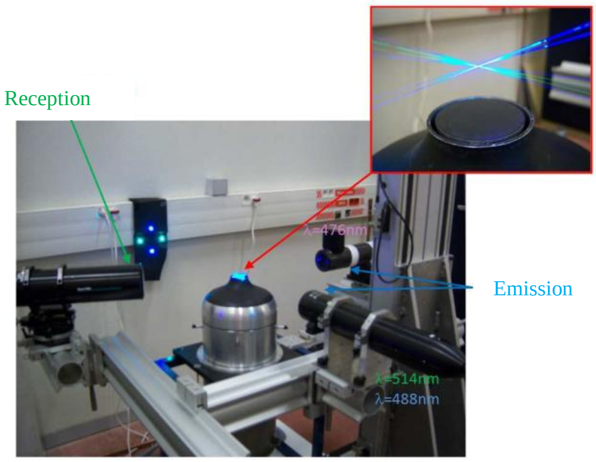

Fig 3: experimental LDV 3D set-up Laser

The measures of A.D.L. 3D are realized for the heights H1, H2, H4 and H5 corresponding to various axial positions of the initial and intermediate zones of the flows. For each of these heights, 8 profiles of speeds are drawn. Each of these profiles passes by the center of the jet. The meshing of every profile is based on a set of 33 points spaced out of 3mm. Points are spaced out of 0.5mm between r* = 0.43 and r* = 0.50 (fig 4).

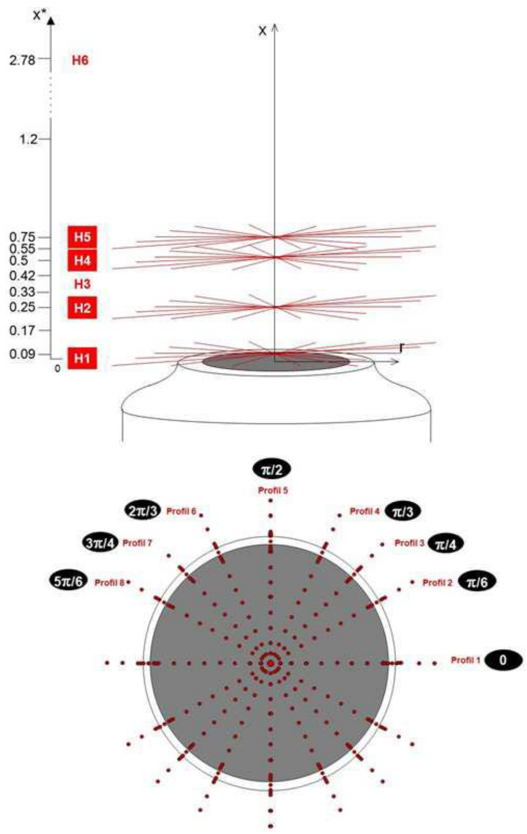

Fig 4: various axial positions and meshing

2.4 Flow seeding

Flow seeding is one of the most important aspects of P.I.V. measurements. The intake air is seeded with 2-3 µm diameter olive oil droplets. These were generated in an atomizer by passing air through a bath of olive oil. The air pressure varied from 1.5 to 2.5 bars (fig 2). The particle seeding density was controlled by the flow rate of air through the atomizer.

3 Proper Orthogonal Decomposition.

Coherent structures are present in turbulent flow and P.I.V. is able to highlight those on the largest scale at any given moment. The scientific interest in the study of turbulence has led to the development of P.I.V. post-processing, which is able to bring out the inner driving mechanism of the flow [5].

Lumley [6] [7] has proposed a method for identifying coherent and instantaneous structures in turbulent flow. The method is Proper Orthogonal Decomposition (P.O.D.). P.O.D. provides an optimal set of basis functions for a set of data, Delville [12], Graftieux [13], Sirovish [14], Patte-Rouland [15]. It is optimal in the sense that it is the most efficient way of extracting the most energetic components of an infinite dimensional process with only a few modes. The proper orthogonal decomposition is a linear procedure, which decomposes a set of signals in modal base. The P.O.D. analysis is introduced in this context by the use of physical functions with finite kinetic energy equivalent to the square integrable function. Coherent structures should be the structures that have the largest mean square projection on the velocity field. If it represents the candidate structure, then:

$$\frac{\left\langle (U.\Phi)^2 \right\rangle}{\left\langle (U.U)^2 \right\rangle} = \underset{\Psi}{Max} \frac{\left\langle (U.\Psi)^2 \right\rangle}{\left\langle (U.U)^2 \right\rangle} \qquad (1)$$

Where $\langle\ \rangle$ represents an ensemble average. That is, the field that maximises the inner product with the velocity field is found. Maximising this inner product leads to the solution of the following eigenvalue problem:

$$\iint_D \left\langle U(x)U^*(x') \right\rangle \Phi(x')dx' = \lambda .\Phi(x) \qquad (2)$$

Or in another way,

$$\iint_D R_{ij}(x,x').\Phi_j^{(n)}(x')dx' = \lambda^{(n)}\Phi_i^{(n)}(x) \qquad (3)$$

D represents the two dimensional domain of the velocity fields. R is the averaged two-point correlation tensor defined by:

$$R_{ij}(x,x') = \left\langle U_i(x).U_j(x') \right\rangle \qquad (4)$$

The solutions of (3) represent a set Φ_k of base functions where each velocity field U_i is:

$$U_i = \sum_{k=0}^{N-1} a_{k,i}\Phi_k \qquad (5)$$

Then the eigenfunctions Φ can be of the following form:

$$\Phi = \sum_{k=0}^{M-1} A_k U^{(k)} \qquad (6)$$

We will order the eigenvalue by $\lambda_i > \lambda_{i+1}$ and since R is non negative we can be sure that $\lambda_i > 0$ ($\forall$ i $\in$ N).

Each velocity fields can be decomposed as a linear combination of proper mode ϕ such that:

$$u_i(x,y) = \sum_{k=0}^{N-1} a_{i,k}\phi_k(x,y) \text{ and } \delta_{kk'}\lambda_k = \left\langle a_k a_{k'}^* \right\rangle \qquad (7)$$

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Where λ_k is the energy contained in the mode k. The computation has been done with 400 velocity fields. This number is sufficient for a good representation of the flow.

4 Velocity characteristics of annular jet.

4.1 Aerodynamic characteristics of the initial zone of annular jet.

For the annular jet, it appears that the stagnation point is put through important radial fluctuations and, axially, the maximal fluctuations are localized on the external-mixing layer. This was also observed by Ko and Chan [3], but they used a hot wire and this cannot measure null velocity. Therefore, for a spatial quantification, the P.I.V. technique has been used [9].

Figure 5 shows an example of the mean velocity field with the corresponding Reynolds decomposition fluctuation fields. The initial merging zone extends from the jet exit to the tip of the potential core. This zone contains a recirculation zone. The stagnation point which marks the end of the recirculating region is located at x/Do=0.5.

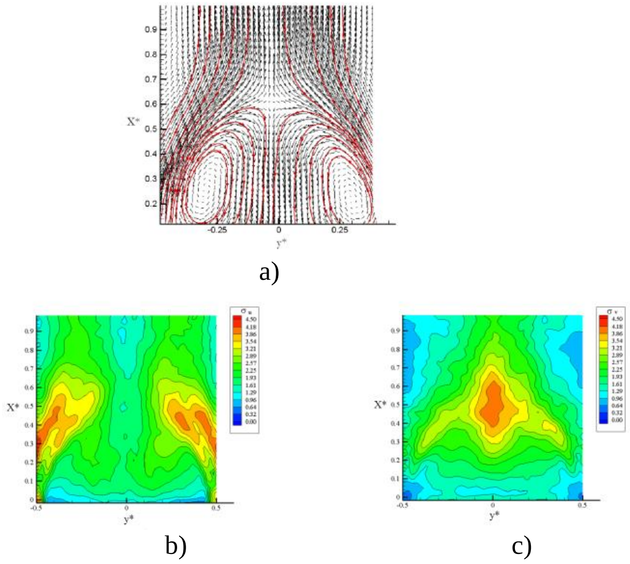

Fig 5: Aerodynamic characteristics of the annular jet: Re_e = 7680. a) Average velocity field calculated with 400 P.I.V. fields. b) Reynolds decomposition radial velocities c) Reynolds decomposition axial velocities.

4.2 Results of Proper Orthogonal Decomposition application

In this study the P.O.D. is applied on P.I.V. velocity fields of the recirculation zone of this annular jet. Reynolds decomposition velocity fluctuations show two effects: the importance of oscillations for the stagnation point and the air entrainment in the annular jet.

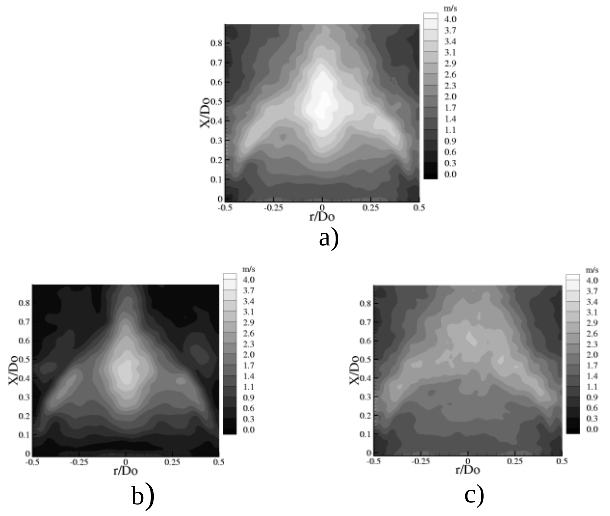

Fig 6: Influence of mode 1 on Reynolds decomposition radial velocity fluctuations: a) Radial velocity fluctuations b) Radial velocity fluctuations reconstructed with mode 0 and 1. c) Radial velocity fluctuations reconstructed without mode 1.

Thus, to evaluate the importance and the influence of each mode on an instantaneous velocity field, each instantaneous field reconstructed by choosing P.O.D. modes, and then the Reynolds decomposition radial fluctuations are calculated. A reconstruction with the first mode and the k^{th} mode, using the projection value of the instantaneous field on the modes, automatically shows what instability is represented by this k^{th} mode.

Fig 6 shows the reconstruction of all the instantaneous fields with the first two modes and without mode 1. So, it is clear that with modes 0+1 the position and the intensity of the Reynolds decomposition radial fluctuations are the same as those calculated for all modes, contrary to the reconstruction without mode 1. So mode 1 is responsible for the radial fluctuations of the stagnation point.

5 Third component.

In this present work, the experiments were performed using the three-dimensional LDA technique and transversal planes of velocity fields measured at different heights in the flow are plotted in Fig 7. The first height of the jet studied, x* = 0.09, corresponds to a zone close to the exit of the jet. Velocity vectors leave the center of the flow and go to the outside. This plane of the flow is situated in fact in the lowest part of the recirculation zone. The flow returns towards the wall of the central obstacle and goes through the surface of this obstacle towards the exit of the jet. The outside crown which begins in r* = 0.5 does not seem to pull a lot of surrounding air, in spite of an outside seeding. The middle of the zone of recirculation is displayed for x*=0.25.

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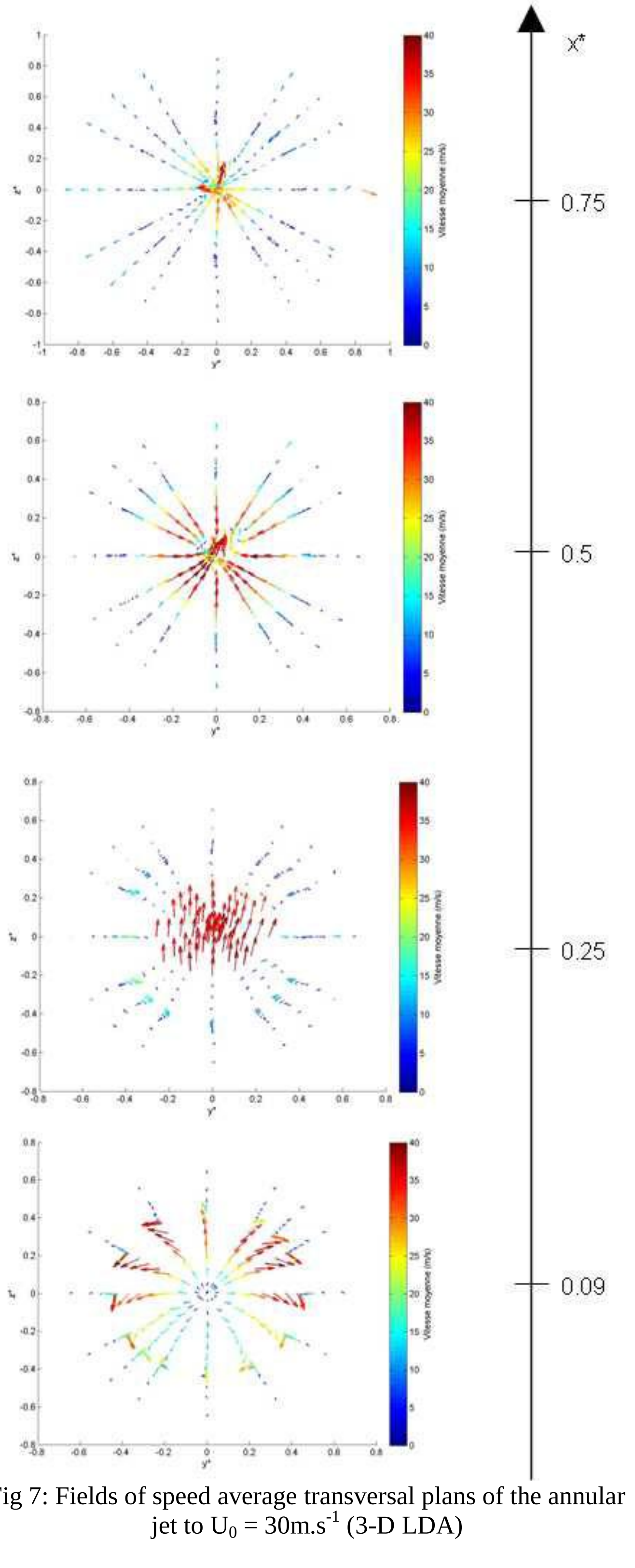

Fig 7: Fields of speed average transversal plans of the annular jet to $U_0 = 30m.s^{-1}$ (3-D LDA)

On this plane, the center of the jet shows strong velocities in the center of the jet. At the end of the recirculation zone, in the stagnation point plane, all velocity vectors converge on the center of the jet, in the temporal mean location of the stagnation point. These transverse velocity fields so allow showing that the orientation of velocity vectors towards the central axis of the jet is essentially driven by the longitudinal component U of the speed. The preferred directions can be envisaged as a characteristic behavior of the jet. Velocity vectors of the outside crown bounded by r* > 0.4, are oriented towards the surrounding air, outside of the jet. These vectors indicate the external shear layer where the structures of Kelvin-Helmohltz develop.

The fourth transversal plane of the annular jet is chosen in the intermediate zone. The outside crown of the jet drawing the limit between the zone of internal and external shear layers, is reduced when x* increase. The effect of asymmetries in the experimental jet exit velocities is advanced.

In 2004, Del Taglia uses for the first time a three-dimensional simulation to study annular jets of diameter ratio included between 0.55 and 0.99.

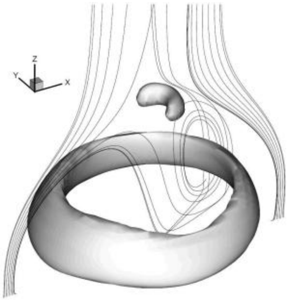

Fig 8: Three-dimensional lines of current of an annular jet RANS (Del Taglia)

Del Taglia & al [16] presented 3-D numerical simulations and 3-D LDA measurements of an annular jet with a blockage ratio of 0.89 and Reynolds number 4400. At these flow conditions, the flow inside of the recirculation zone is asymmetric, with a preferential direction. A comparison of the means velocities presented significant difference between simulated and measured values which proved that there is an effect of asymmetry in the experimental values of jet exit velocities as it has been presented here.

6 Conclusion.

The study describes the recirculation zone of an annular jet by Particle Image Velocimetry. The Proper Orthogonal Decomposition has been applied to find the relationship of these radial fluctuations to the inner structures of the instantaneous P.I.V. fields. This statistical method can help to find the overall behavior of the flow and to link fluctuations with typical modes. The P.O.D. analysis has shown that the flow could be decomposed into four main modes (90% of the total

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kinetic energy). Each one is responsible for a characteristic motion of the recirculation zone. The mode 0 represents the carrier flow, which is the most energetic. The space fluctuation of the stagnation point is principally due to the mode 1. Indeed, when the instantaneous fields are reconstructed with the modes without the first eigenfunction, the statistical analysis of these fields does not show local fluctuations.

The main aim of this study is to observe and analyze the 3-D turbulent flow field on an annular jet with a great diameter ratio (r= 0.91). Measurements are conducted with a Reynolds number Re_{Do}=107800. This work presents the real effect of asymmetries in the experimental jet exit velocities. The center of the jet shows strong velocities in the center of the jet. At the end of the zone of recirculation, in the plane of the stagnation point, all velocity vectors converge on the center axis of the jet. Velocity measurements show an average asymetry of the annular jet flow but also preferred directions that are well identified. These results highlight that studying a three-dimensional annular jet submitted to shear layers and global fluctuations around the central axis implies to develop new methods of analyzing data. Average and fluctuations are not sufficient to have an access of the flow dynamics. Proper Orthogonal Decomposition applied on 2D velocity measurements is a first step to obtain new results to clarify this singularities but this particular flow needs a 3D POD analysis to capture all the dynamics of this jet.

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