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# Passive control of annular jet instabilities studied by Proper Orthogonal Decomposition.

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**Abstract:** - Shear flows are complex turbulent flows which are widely used in the industrial domain. An annular jet is an example of these particular flows (used in burners, cooling processes, inlet valve in a combustion chamber, processing glass fibers...): an obstacle for the flow, placed in the center of a round nozzle creates two axisymmetric shear layers at the jet exit. These shear layers are significant for the organization and the evolution of the flow. This study talks about coherent structures developed in shear layers and their effects on three-dimensional instabilities of the annular jet flow. A method to detect and identify coherent structures, called Proper Orthogonal Decomposition (P.O.D.) is applied on velocity fields recorded by Particle Image Velocimetry (P.I.V.) measurement to understand how a modification of the nozzle geometry could change the flow morphology. The P.O.D. post-processing is used to compare different central obstacle geometries (a conical, cylindrical or ellipsoidal shape). The Reynolds number based on the outer diameter  $D_o$  is equal to 107 800 (for a velocity  $U_0$  at the exit of the nozzle equal to  $30\text{m}\cdot\text{s}^{-1}$ ). Instabilities of annular jets are a real handicap for industrial processes. Studying the influence of a passive control could improve understanding of shear flows mechanisms and then determining a new way to reduce or suppress annular jets instabilities in order to meet manufacturer's needs.

**Key-Words:** - Annular jet, Particle Image Velocimetry, Proper Orthogonal Decomposition, passive control.

## 1 Introduction

Annular jet is an axisymmetric jet defined by many parameters as the diameter ratio  $r=D_i/D_o$ , where  $D_o$  represents the outer diameter (diameter of the round nozzle) and  $D_i$  is its internal diameter (diameter of the central obstacle). At the outlet of the nozzle, the jet is in the shape of an annular flow and, downstream of the obstacle, the lack of any air supply and the entrainment of air from the main stream generate a recirculation zone. The majority of industrial processes use annular jets of large diameter ratios (burners, bluff-bodies....). But, in contrary to all expectations, there are only few studies on large diameter ratio annular jets.

In 1964, Chigier et al.[1] studied annular jets as a limited case of coaxial jets (the central jet has no velocity). Ko et al.[2]described then an annular jet flow for small diameter ratios (smaller than 0.7). This flow may be divided in three different zones: the zone of established flow, where the flow behaves as a round axisymmetric jet, the transition zone and the initial zone which extends from the nozzle exit to the end of the potential core in the case of small diameter ratio jets. On the other hand, the study performed by Aly et al.[3], in 1971 shows that in this configuration, the initial zone extends to the end of the recirculation zone (the potential core is then

smaller than the recirculation zone as it can be shown on figure Fig. 1).

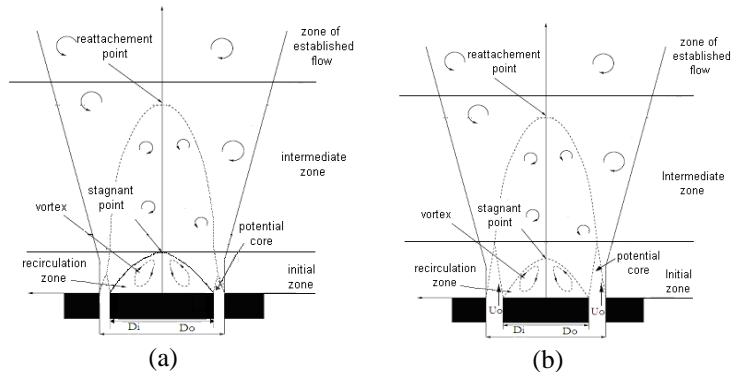


Fig.1: Diagram of an annular jet flow for (a) a large diameter ratio ( $r>0.7$ ) and (b) a small diameter ratio ( $r<0.7$ ).

A turbulent flow consists in a random part of vortex structures which make the flow unpredictable but there are also many organized structures called coherent structures. These large-scale structures play a significant role in the flow dynamics because of their effects on friction, vibration phenomena, mixing process or noise generation. To find a way to control annular jet flows and to bring instabilities in industrial processes under control, it is essential to know how coherent structures

appears, develop and interact in annular jets. There is no exact definition to present coherent structures but many authors suggest different criteria to detect and analyze these fundamental structures.

In this study, a P.I.V. pos-processing has been applied to annular jets to bring out the inner driven mechanism of the flow [4]. Proper Orthogonal is a method suggested by Lumley et al.[5] [6] which provides an optimal base for the modal decomposition of a set of functions (data obtained with experiments). Only few modes allow to capture the dominant components of an infinite-dimensional process then P.O.D. is an efficient tool for analyzing of experimental P.I.D. data in turbulent flows [7].

The present work investigates instabilities of annular jets and more especially, instabilities of the stagnant point in the initial zone which is responsible of many difficulties in industrial processes. P.O.D. technique is applied on P.I.V. velocity fields to know the influence of a passive control on the behavior of the flow with a modification of the central obstacle geometry using three different configurations: a conical, a cylindrical or ellipsoidal shape. A first step of this study shows that the information contain in the first P.O.D. eigenmodes translate the stagnant point instabilities. Next all configurations are submitted to the same treatment to notice the evolution of the flow in each studied case.

## 2 Experimental set-up

### 2.1 Annular jets

Nozzles used for experiments are presented on figures Fig.2 and Fig.3. In all these configurations, the outer diameter of the jet is  $D_o=53.88\text{mm}$  and the internal diameter of obstacles is  $D_i=48.75\text{mm}$ . The diameter ratio of our study is then  $r=0.91$ . The exit velocity of the air jet is fixed at  $30\text{m}\cdot\text{s}^{-1}$  (so the Reynolds number  $Re_{D_o}$  is 107 800). The nozzle is made in order to have a “top hat” distribution of velocity at the outlet of the nozzle.

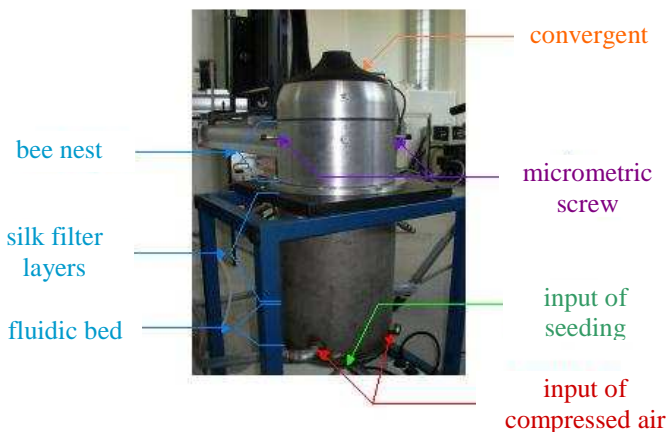


Fig.2: Structure of the nozzle used for the study

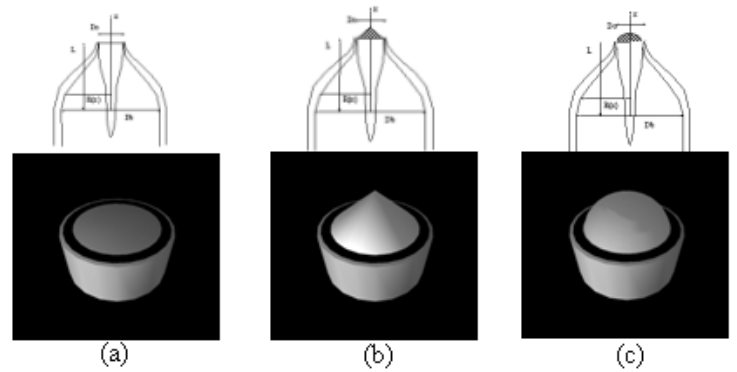


Fig.3: Diagram of annular jet nozzles with central obstacle made of (a) a cylindrical shape (b) a conical shape and (c) an ellipsoidal shape.

The recirculation zone created downstream the obstacle extends from the obstacle to the stagnant point (where velocity is equal to zero in the longitudinal direction). This particular point of the flow is situated at  $D_o/2$  from the obstacle on the jet axis. Its position is independent of the velocity of the air flow. The conical and the ellipsoidal obstacles have both a length equal to  $D_o/2$  (the recirculation zone length), in order to modify or even suppress the recirculation zone, which is probably responsible for the stagnant point instabilities.

### 2.2 Flow seeding

The intake air of the annular jet nozzle is seeded with 2-3 $\mu\text{m}$  diameter olive oil droplets. An atomizer by passing air through a bath of olive oil generates these droplets. The air pressure varied from 1.5 to 2.5 bars. A “trap vat” is placed downstream the olive oil bath in order to obtain droplets with an almost identical diameter (the biggest droplets stay in the “trap vat”).

### 2.2 P.I.V. set-up

The experiments of P.I.V. measurements are conducted with a double pulsed Nd-Yag LASER to set up a light sheet of the flow (figure Fig.4). The output energy is nearly 75mJ for each laser pulse in 5ns. The wavelength is 532nm. One cylindrical lens and one spherical lens create a sheet across the median plane.

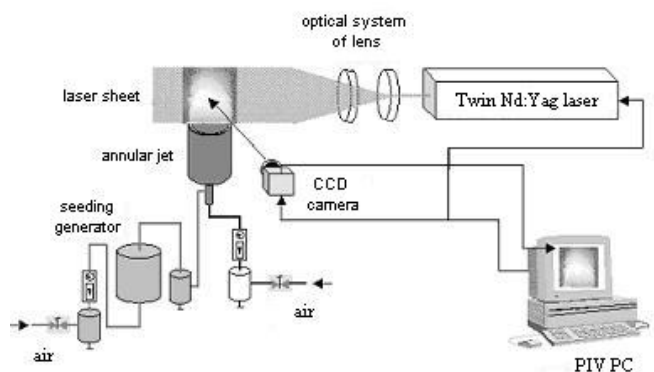


Fig.4: Diagram of the experimental P.I.V. set-up

The two pulses are separated by a time delay equal to 10  $\mu$ s. These pulses are synchronized with the opening of the camera. The CCD camera used is a 12bits LaVision FlowMaster 3S with a resolution equal to (1280x1024) pixels<sup>2</sup> (the physical size of pixels is (6.7x6.7) $\mu$ m<sup>2</sup>). The images recorded show the initial zone and a part of the intermediate zone (2Do from the outlet of the nozzle). The acquisition frequency is 8Hz.

Each recorded image is divided into small interrogation windows of (32x32) pixels<sup>2</sup>. Calculation of velocity vectors is performed by two-dimensional digital cross-correlation analysis using "Davis 6.2." (Data Acquisition and Visualization Software) with a 50% overlap with the next window. 1000 P.I.V. images have been recorded for each annular jet configuration.

### 3 Proper Orthogonal Decomposition

P.I.V. is a technique able to highlight coherent structures present in the flow on the largest scale, at any given moment. Proper Orthogonal Decomposition (P.O.D.) is an efficient technique to detect these structures and to analyze flow mechanisms, as Lumley et al. suggested [5] [6]. This P.I.V. post-processing is widely used because it can provide an optimal set of basis functions for a set of data [8][9]. The most energetic components of an infinite dimensional process can be extracted with only few modes. P.O.D. is a linear procedure which in this context uses physical functions with finite kinetic energy equivalent to the square integrable function. As coherent structures should be the structures that have the largest mean square projection, the method implies to find the functions  $\Phi$  the most "similar" to the set of fields of velocity  $U$ . It boils down to find the field that maximizes the inner product with the velocity field ( $\langle \cdot \rangle$  represents an ensemble average):

$$\frac{\langle (U \cdot \Phi)^2 \rangle}{\langle (U \cdot U)^2 \rangle} = \text{Max}_{\Psi} \frac{\langle (U \cdot \Psi)^2 \rangle}{\langle (U \cdot U)^2 \rangle} \quad (1)$$

Maximising this inner product leads to the solution of the following eigenvalue problem:

$$\iint_D \langle U(x)U^*(x') \rangle \Phi(x') dx' = \lambda \cdot \Phi(x) \quad (2)$$

Or, in another way :

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

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

$$R_{ij}(x, x') = \langle U_i(x) \cdot U_j(x') \rangle \quad (4)$$

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

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

Then the eigenfunctions  $\Phi$  can be of the following form:

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

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 field can be decomposed as a linear combination of proper mode  $\phi$  such that:

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

Where  $\lambda_k$  is the energy contained in the mode k. As we have used 1000 velocity fields to compute P.O.D., results are valid to give a good representation of the flow thanks to the sufficient number of chosen fields.

## 4 Description of a basic annular jet flow

### 4.1 Aerodynamic characteristics of the initial zone of a basic annular jet

The annular jet configuration most used in industrial processes presents a cylindrical shape for the central obstacle. This type of annular jet is called basic annular jet.

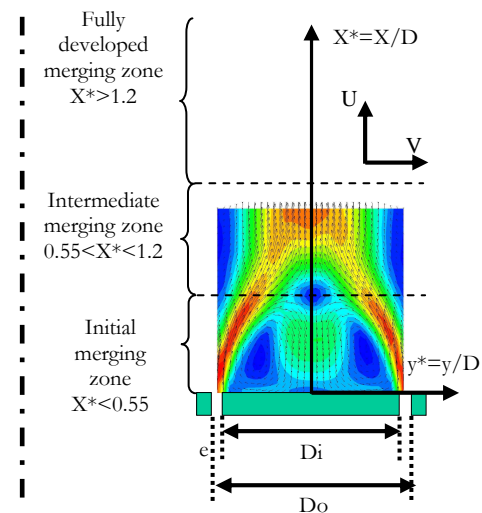


Fig.4: Diagram of the studied zone of annular jets.

The stagnant point is a point situated at the boundary at the recirculation zone. This point is put through important radial fluctuations and, axially the maximal fluctuations are localized on the external mixing layers. This was observed by Ko and Chan [2] with using a hot wire anemometer. But, this technique is not appropriate for stagnant point fluctuations measurement because of the null radial component velocity of the stagnant point.

Therefore, for a spatial quantification, the P.I.V. technique has been used. The figure Fig.5 presents the mean velocity field with the corresponding Reynolds decomposition fluctuation fields for a basic annular jet.

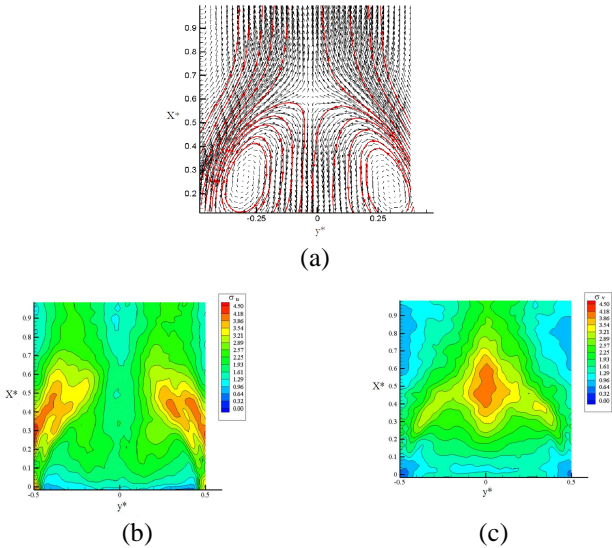


Fig.5: Aerodynamic characteristics of the annular jet:  $Re_{D_0} = 107\ 800$ . (a) Average velocity field, (b) Reynolds decomposition radial velocities, (c) Reynolds decomposition axial velocities.

Fig.5 (a) shows the place of the stagnant point (on the jet axis at  $x^*=0.5$ ) which is represented on the Fig.5(c) by 30% of transversal fluctuations. These fluctuations are important and provide an asymmetric movement of the flow around the jet axis. The aim of this study is to reduce these radial fluctuations by testing different obstacle geometries in order to modify the aerodynamic characteristics of the initial zone, and more especially the characteristics of the recirculation zone.

**4.2 P.O.D. results on the initial zone of a basic annular jet**

P.O.D. analysis has been applied on a basic annular jet in order to put the stress on the significance of the stagnant point [9]. Results have been discussed and the first modes are presented on figure Fig.6. Each instantaneous velocity fields is then reconstructed, after P.O.D. calculation. The reconstruction can be made by all modes or only selected modes. Next the Reynolds decomposition radial fluctuations are estimated in order to evaluate the influence of each mode on an instantaneous field. As it is shown on the figure Fig.6, the mode 0 is the most energetic mode (it represents about 70% of the total kinetic energy of the flow) and is similar to the average field. By combining modes with their associated weight in the flow (their projection value of the instantaneous field), we can extract the mode responsible for stagnant point radial fluctuations.

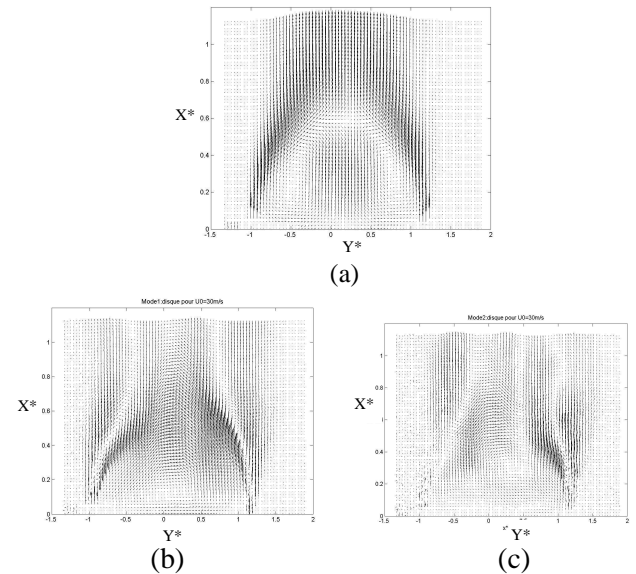


Fig.6: First modes of the P.O.D. analysis of velocity fields of a basic annular jet. (a) Mode 0, (b) Mode 1, (c) Mode 3.

On the figure Fig.7 the mode 1 is underlined as the major actor for these particular instabilities.

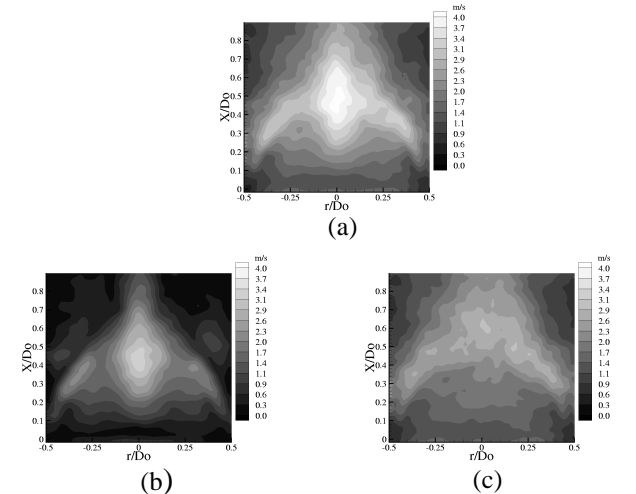


Fig.7: Influence of mode 1 on Reynolds decomposition radial velocity fluctuations: (a) Radial velocity fluctuations (b) Radial velocity fluctuations reconstructed with mode 0 and 1. (c) Radial velocity fluctuations reconstructed without mode 1.

As we want to study essentially the modification of coherent structures of the initial zone of the flow, this study focuses on the first five modes.

**5 Effects of a passive control**

**5.1 Ellipsoidal annular jet**

The ellipsoidal jet seems to narrow a little more towards the central axis than in the case of a basic annular jet (Fig.8). When we observe the field of average velocities (Fig.8 (a)), we notice that the recirculation zone completely disappears in the initial zone. The jet fits the

obstacle wall as far as the separation point. The area where the jet velocity is high (red zone on the outline of the obstacle) goes on more downstream from the flow. The length of the potential core, for a basic annular jet, is equal to  $l_{cp}=3.5e$  ( $e$  is the thickness of the flow at the outlet of the nozzle) but for an ellipsoidal annular jet, this length is equal to  $l_{cp}=6e$ . We can see that the transversal fluctuations are no more situated in the stagnant point but rather in the separation point (Fig.8(c)). A new area of transversal fluctuations appears on the rims of the jet, which is not present for a basic annular jet. The standard deviation of longitudinal velocities (Fig.8 (b)) shows that there is only one zone of shear in the case of ellipsoidal obstacle. The flow of the ellipsoidal annular jet is then totally different from the basic annular jet.

The figure Fig.9 shows the results of the P.O.D. computation on an ellipsoidal annular jet. Mode 0 represents the mean velocity field of the flow. The transversal fluctuations of velocities situated in the separation zone (downstream the ellipsoid) seem to be reflected on mode 1 while the transversal fluctuations part dedicated to the shear flow on the rims of the jet seem to be represented by the mode 2. And then the mode 3 looks like the longitudinal fluctuations manager.

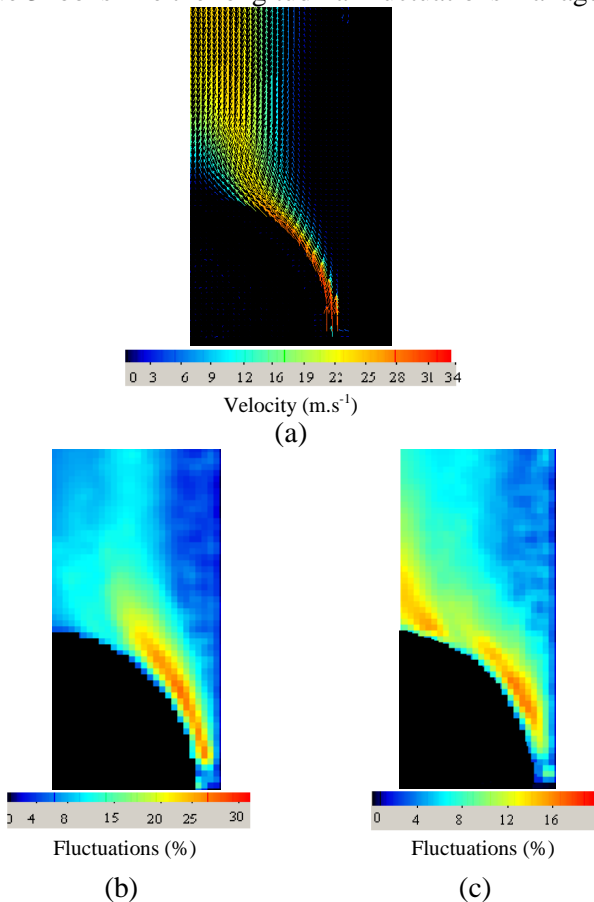


Fig.8: P.I.V. measurements of an ellipsoidal annular jet. (a) mean velocity field, (b) longitudinal fluctuations, (c) transversal fluctuations.

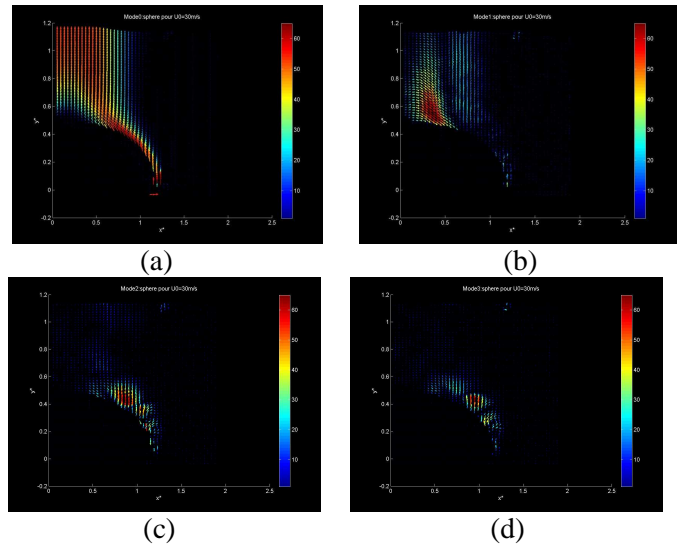


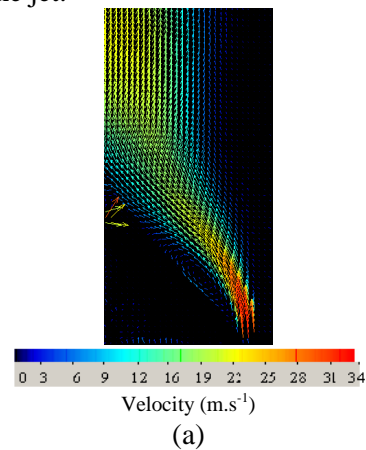
Fig. 9: P.O.D. analysis of an ellipsoidal annular jet. (a) Mode 0, (b) Mode 1, (c) Mode 2, (d) Mode 3.

### 5.2 Conical annular jet

The flow of a conical jet seems to be more spread than in the case of an ellipsoidal annular jet (Fig.10). The jet seems to not narrow so much towards the central axis.

The field of average velocities (Fig.10(a)) shows a recirculation zone very reduced at the nozzle exit. As in the basic case, the zone of higher velocities, at the nozzle exit, on the rim of the jet seems to extend less far downstream from than in the ellipsoidal annular jet. The length of the potential core in this flow is  $l_{cp}=3.4e$ .

With the conical obstacle, there is no more stagnant point transversal fluctuation. On the other hand, this annular jet induces as well transversal fluctuations on the rims of the jet. The standard deviation of longitudinal velocities shows the presence of the external and the internal zones of shear, as in the case of a basic annular jet. The conical annular jet is able to establish a control located on the stagnant point but destabilizing a zone on the rims of the jet.



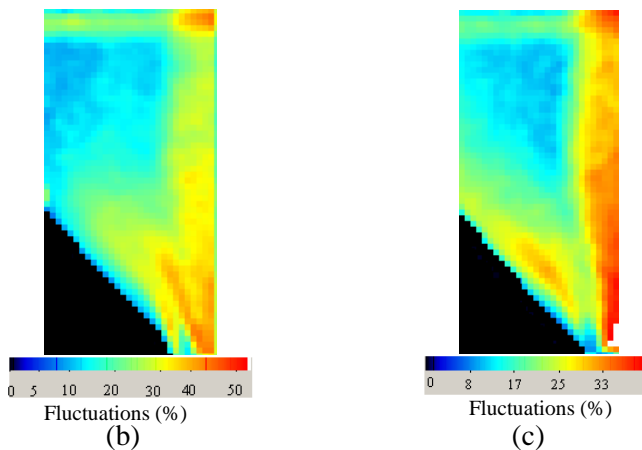


Fig. 10: P.I.V. measurements of a conical annular jet. (a) mean velocity field, (b) longitudinal fluctuations, (c) transversal fluctuations.

The mode 0 shows on the figure Fig.11 the appearance of the mean velocity field. There is no real special characteristic drawn on the mode 2. Modes 1 and 3 seem to represent structures responsible for instabilities on the rims of the jet that we can see on the longitudinal (modes 1 and 3) as much as the transversal (mode 1) fluctuations of velocities.

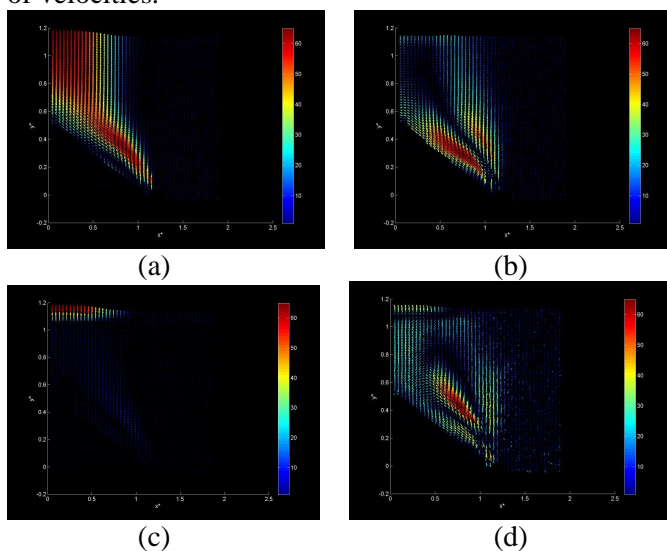


Fig. 11: P.O.D. analysis of an ellipsoidal annular jet. (a) Mode 0, (b) Mode 1, (c) Mode 2, (d) Mode 3.

## 6 Conclusion

The aim of the present study is to detect and analyze coherent structures in annular jet flows in order to find an efficient technique to reduce or even suppress instabilities of the initial zone of a basic annular jet. Three obstacles have been investigated: a cylindrical, a conical and an ellipsoidal obstacle. P.O.D. technique applied on velocity field provided by P.I.V. measurements permit to isolate different instabilities and

to localize them in the flow (on the area of the stagnant point or on the rims of the nozzle).

Each obstacle modifies different characteristics of the flow. Instabilities disappear in the stagnant point in the case of a conical annular jet but a new area of transversal fluctuations appears on the rims of the jet. The ellipsoidal annular jet suppresses the recirculation zone but there is always a lot of fluctuations in the flow, at the separation point or on the rims of the jet. This particular annular jet contains much more coherent structures than in the other configurations and then it has more energy represented in the first ten modes.

This study shows that a partial control of the stagnant point fluctuations can result from a modification of the central obstacle but this obstacle has other effects on the rest of the flow. All effects have to be taken into account in order to determine the efficiency of the passive control.

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