SWIRL EFFECTS ON DYNAMICS CHARACTERISTICS OF A COAXIAL JET

by

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The reactants are generally injected into the industrial furnaces by jets. An effective method to act on combustion in such systems is to control the way injection jets. The present study concerns the control of an air-flow generated through a coaxial burner. The effects of passive control on a turbulent flow were investigated experimentally. The principal idea consists in adding small obstacles on the outlet side of the burner's annular jet with an aim of increasing the turbulence intensity in the vicinity close to the edge of injection and of having an act on the central flow. The objective of this study consists to study of a swirling flow in a circular pipe and conceiving of a control system significantly improving the mixture on a non-reactive flow in order to apply it to a reactive situation. The various profiles speed for various values of the air-flow injected into the annular tube will be presented in order to propose the effectiveness of our inspecting device in terms of improvement of the mixture between the two jets as well as the mixture with the ambient air. The particle image velocimetry technique has been used to characterize the dynamic field. Results show that the control by adding small obstacles has a considerable effect on the dynamic behavior.

Key words: *swirl coaxial burner, turbulent flow, passive control, particle image velocimetry*

Introduction

Coaxial jets are widely used in industrial applications as an effective way of mixing two different fluid streams, especially in chemical engineering systems and combustion devices. A coaxial jet is made when a fluid stream with velocity, U_e, issuing from an outer annulus of diameter, D_e, is added into a round jet flow with velocity, U_i, and (inner) nozzle diameter, D_i ($D_i < D_e$).

The existence of two (inner and outer) shear layer regions was evidenced by Mergheni *et al.* [1], Ko and Kwan [2], and Ko and Au [3] in coaxial jets.

Swirling flow burners are not only used in gas turbines, but also in industrial furnaces because of their significant beneficial influences on flame stability, local mixing and pollutant emissions as the NO_x [4-6]

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The perpendicular arrangement of tube actuators at the periphery of a main jet can confer a helical movement on the flow. This kind of swirl actuators has very significant effects on the flow. Faivre [7] indicated that radial fluid injection into the main jet enhances mixing with the surrounding air. Boushaki *at al.* [8]show that the addition of swirl significantly changes the aerodynamic pattern and can be opens interesting possibilities in NO_x reduction and modularity of flame properties such as the lift-off height and the flame length.

According to the burner geometry, the flame falls apart of the injection edge in some devices. This behavior is called *Lift-off*. Also, some instability appear for which the installations are not always initially designed, and this in an increasing need to produce more or to pollute less. These instabilities are the noise, the vibrations and the destruction partial or total of the burner.

All these phenomena are naturally undesirable on an industrial system, also it is important to be able to remove or control instabilities of combustion. The control of combustion becomes then a priority, not only to avoid the appearance of combustion instabilities but also to improve reactants mixture, to ensure the stabilization of the flame and to reduce the polluting emissions [9-11].

However, in many applications, the physical characteristics of the flow (composition, capacity PCI) can strongly vary. It thus becomes delicate to keep the stable mode of operation and this is why it is necessary to seek a solution on the side of the instabilities control [7].

According to the industrial application, we can control a jet to improve the mixture at exit of an injector, also to direct it, decrease the pollution emission or even sound pollution.

In general, there are two main roads in the flow control: passive or active control. Passive control consists in changing the geometry of the burner or the furnace which affects the dynamics of the flow. Active control consists of an external contribution of energy through actuators while keeping the same device geometry [8, 12].

Nevertheless, the study of the aerodynamic behavior of coaxial jets is of great interest from both a scientific and a practical point of view. Indeed, the characterization and, possibly, the control of the mixing between the streams of coaxial jet configuration is a primary design feature in many industrial applications, as, for instance, in the design of new generation industrial burners. Therefore, research activities aimed at an increased understanding of the relative influence of the various parameters on the near-field development are in any case highly needed.

This study has as an aim the dynamics of the flows generated by coaxial jets. In order to obtain a better definition and, possibly a deeper physical understanding of the flow control of a coaxial jet configuration, we put on the outlet side of the annular tube small obstacles which will create axial vorticity and thus will improve the mixture. This work consists in making a control device on a non-reactive flow in order to apply it to a reactive situation. We will study an air-flow in a coaxial burner.

The inventory of the swirling structures is first of all carried out with assistance of visualizations by particles image velocity (PIV). Then, the profiles speeds are raised more close possible of the tail pipe of the jets. The results obtained are compared and discussed. The taking into account of profiles speeds directly resulting from the experiments as basic solution for later calculations of stability constitutes the objective of this approach.

Experimental set-up

Burner and experimental description

The experimental device consists in generating two coaxial jets in the ambient air. A schematic of the coaxial-jet burner apparatus is shown in fig. 1. The burner is composed of an internal tube of diameter D_i = 6 mm with exit velocity, U_i, and of an annular tube of

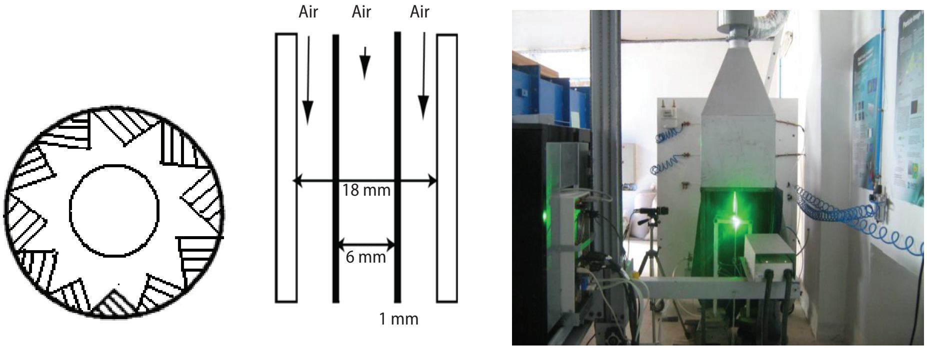


Figure 1. Schematic of burner apparatus and the top sight of the burner

external diameter D_e = 18 mm with exit velocity, U_e, bringing of both of them the air. The internal tube is chamfered on its external part. The air oxygen comes from the network with pressure of 8 bars. The flow of the annular jet is controlled $m = U_i/U_e$, (tab. 1). The coaxial jet is directed vertically down ward, the vertical jet flow discharges in still ambient air. The stream wise direction is the x-axis and the radial direction is the r-axis. The Reynolds number is defined as: $\text{Re}_i = \rho U_i D_i/\mu$, where ρ = 1.14 kg/m^3 is the air density, $\mu = 1.86 \cdot 10^{-5}$ Ns/m^2 is the dynamic viscosity

Table. 1. Central and annular air-flow characteristics, included exit velocity, Reynolds number and velocity ratio

	U_i [ms^{-1}]	U_e [ms^{-1}]	Re_e	$m = U_i/U_e$
Flow (I)	35	7.77	5714	4,5
Flow (II)	35	14	10296	2,5
Flow (III)	35	25	18387	1,4

This control consists in modifying the geometry of the injector in order to improve the performances of the burner used and to reduce instabilities of the flow. It seemed to us interesting to study the configuration of an angular injector. With this intention, we added small obstacles of triangular form on the outlet side of the annular tube. We will study thereafter the effect of these modifications on our flow. The experimental tests consist in fixing the velocity of the central jet and to vary each time the velocity of the annular jet and to characterize the effect of control on the flow for various air-flows injected into the annular tube.

The swirl number is a dimensionless quantity characterizing the rotating flow. It is defined as [4]: $S = G_\phi/RS_x$ where G_ϕ is the axial flux of the tangential momentum, S_x – the axial flux of axial momentum, and R – the exit radius of the burner nozzle.

The geometrical swirl number related to this configuration is defined as [7]:

$$S = \frac{1}{1-\omega}\left(\frac{1}{2}\right)\frac{1-\left(\frac{R_h}{R}\right)^4}{1-R_h^2}\tan\alpha$$

where Ψ is the blockage factor, R_h – the swirl external radius, R – the swirl external radius, and α – the angle. Values of these geometric parameters are summarized in tab. 2.

Measurement techniques

The experimental device for the PIV measurement requires the basic elements used in laser tomography: a laser sheet which clarifies the

Table 2. Geometric data of the swirl generator

	R [mm]	R_h [mm]	α	Ψ
S = 0.73	8	3,8	45	0.17

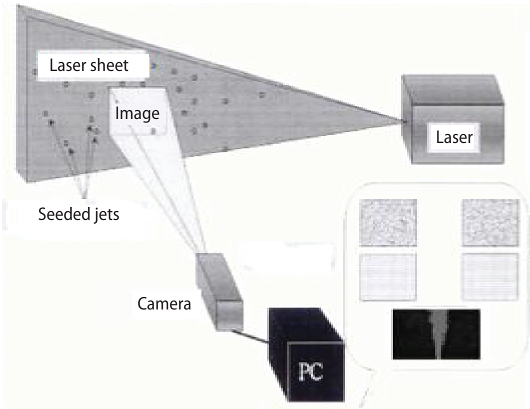


Figure 2. Schematic of experimental model

zone of studied flow, a CCD camera, and a personal computer (PC) of acquisition and control of equipment, fig. 2.

The laser used is Nd-YAG Dual Power of 532 nm wavelength and 15 Hz frequency. The laser sheet is formed by a first divergent cylinder lens, which spreads out the beam then by second convergent spherical lens, which refines the sheet. The signal of Mie scattering emitted by particles is collected by a camera, having a dynamics of 10 and 8 bits and a resolution of 1600 × 1200 pixels. It is associated to an objective of Nikkor mark, focal distance 60 mm, and opening 2.8. The images are stored in real-time on a PC. The synchronization of both pulsate laser and the opening of the camera are carried out by the software FLOW MANAGER. Time between pulsate is of 5 μs.

For the seeding of jets, we used olive oil particles of 3 to 4 μm of size for cold measurements. These particles are easy to produce, and have the property not to agglomerate too much, to settle on the walls of the burner and can be well mixed in the flow because of their small size. The production of the particles is ensured by two fluid atomizers of tracer fluid. Visualizations were carried out in the longitudinal plan parallel with the plan of the jets. A classical image processing was used to determine the dynamic fields of the flow. The calculation of image cross-correlation is carried out by the FLOW MANAGER. It is necessary to carry out a post processing to detect and correct the aberrant vectors appeared in the cross-correlation calculation.

Results and discussion

Characterization of the uncontrolled flow

The study of the uncontrolled flow, for which the geometry of the coaxial burner is simple, is an indispensable prerequisite for the analysis of the effects of control. Indeed, from the experimental point of view, this configuration is a priori the only way a comparison with results from the literature. And to characterize the effect of the control device to the flow, it is obviously necessary to characterize the latter when the control is disabled.

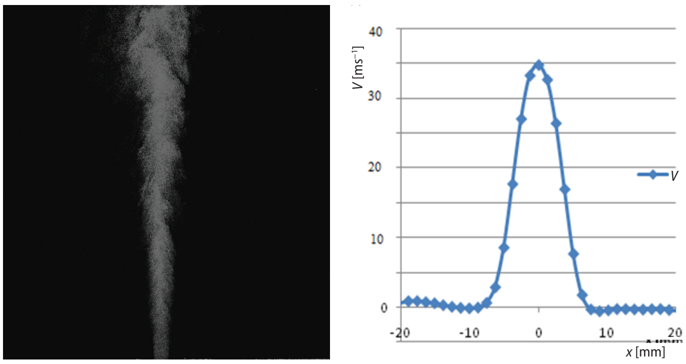


Figure 3. Scheme of the PIV set-up

The experimental study of a free jet is a database in light of a comparison with the experimental results of the coaxial configuration as that in which the flow is controlled, fig. 3.

The two preceding figures, respectively, show the photograph of the flow through a free jet obtained by PIV and the axial velocity profile for a height above the burner outlet $y = 5$ mm that is to say in the close proximity of the injection zone.

In this section, the flow is studied in a jet powered by a 6 mm diameter tube, with a mass flow of 1.23 g/s an average speed of about 35 m/s the Reynolds number for this flow, based on the diameter of the tube is about 11290.

Note that in the close vicinity of the injection edge, the flow is well organized and opens slightly and when increasing more and more the height along the axis of flow, the latter has small vortices in the mixing region with the ambient air. This aspect of the flow can be justified by the dissipation of kinetic energy of the structures that constitute the flow to the ambient air.

Characterization of the flow without control

Figure 4 presents instantaneous images of laser tomography for the flow fractions $m = U_i/U_e$ in non-reactive flow. The structure evolution of the flow when the ratio velocities of injection of the principal flow by the annular one, *m*, vary, shows that according to the value of this parameter, the structure of the flow is completely modified:

– for high values of *m* ($m > 4$), we note that the jet remains strongly organized with a weak opening,
– for values of *m* ranging between 4 and 2, the jet opens gradually, as *m* increases. The zone of mixture significantly increased, and
– for low values of *m* ($m < 1.5$) the flow becomes strongly disorganized. The swirling structures surrounding the injection zone appear which support the mixture of the fluids injected.

In order to characterize quantitatively the turbulent intensity when the annular flow injected increase, fig. 5 presents the superposition of the profiles of axial velocity. It is noted

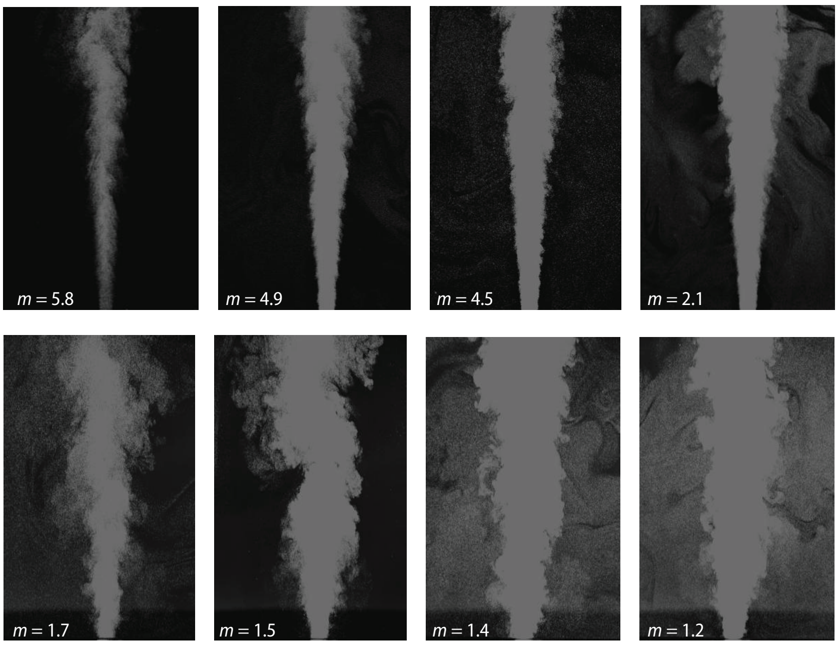


Figure 4. Evolution of the jets opening according to the parameter *m*; visualization by PIV

that the layer of mixture widens in the zone of transition. This means that the annular layer is closed again around the potential cone as we move away from the exit of the burner.

The first observation is that the rates of the flow are more important in the vicinity close to the edge of injection, and then they start to decrease along the flow according to the height of iso-surface, *x*. This decrease of the velocity maximum of the central jet is justified by

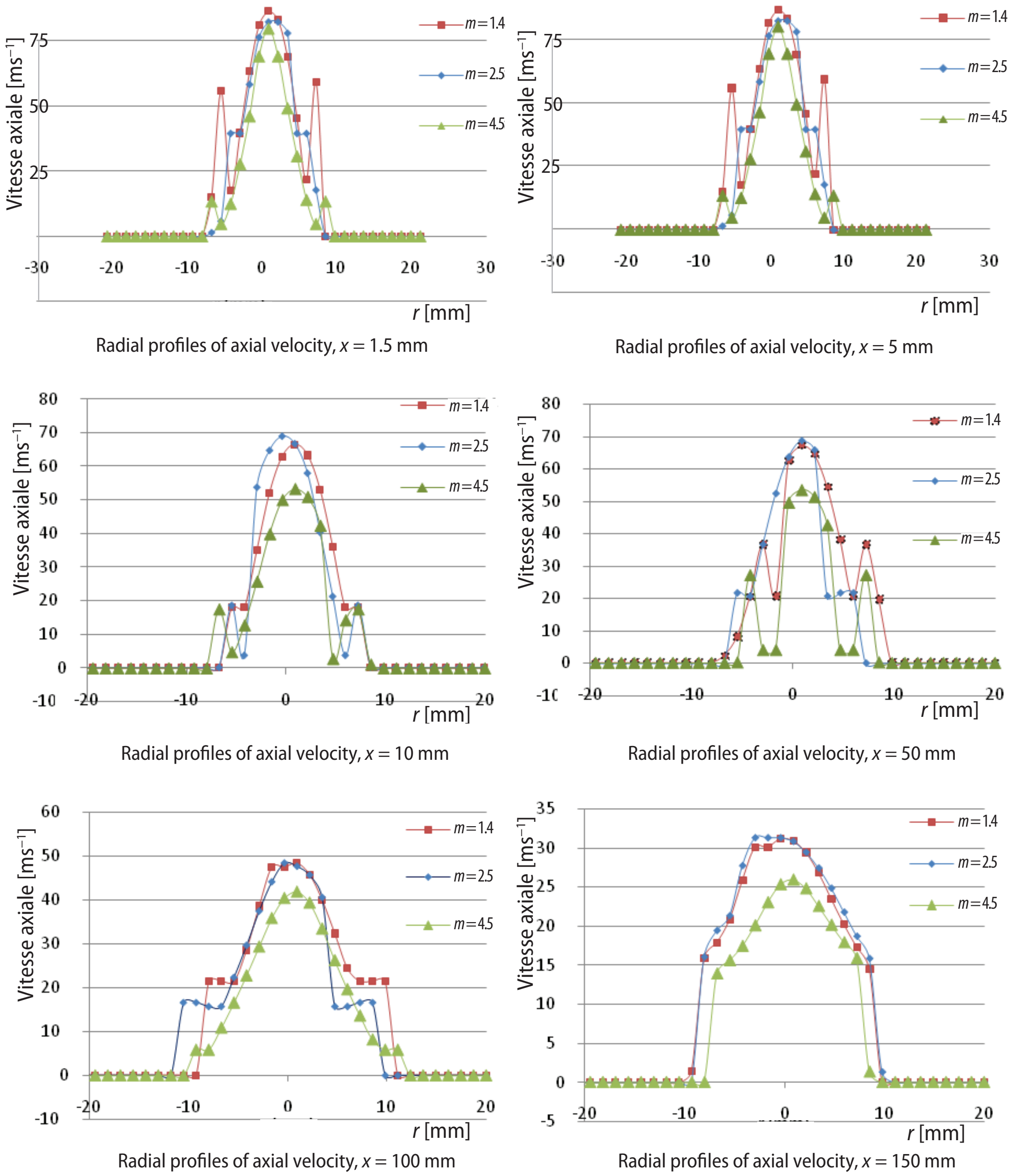


Figure 5. Characterization of the non-controlled flow

the dissipation of the kinetic energy of the structures which constitute the central flow towards those of the annular jet. Indeed, by viscosity effect, the particles of the central jet with high kinetic energy lose part of this energy towards the particles of the annular jet at low velocity, which in their turn lose their energy towards the particles of the ambient air. This explains well the decrease of the flow rate.

Characterization of the controlled flow

This part consists in studying the influence of the control on the behavior of the airflow through a coaxial burner. The results obtained by PIV visualization for the two configurations without (CS) and with (SW) control of the flow are represented in the fig. 6.

Figure 6 shows the influence of various modes of control on the flow (m = 4.5, m = 2.5, and m = 1.4) for the two studied configurations. It is noted that the controlled flow (with swirl) presents an opening more important than with a simple coaxial flow. This pace remains the same one for all the values of m. We also note that the aperture of the flow is more important when the jet is controlled. This is due to the effect of rotation generated by the obstacles added to the second configuration.

Indeed, the controlled flow generates small swirling structures surrounding the annular jet, which increases the turbulence intensity of the flow and thus improves the mixture rate. This phenomenon is developed for low values of m.

This pace is justified by the average profiles rates of the flow at the exit of the burner. We present thereafter the profiles carried out to various values of m, and by modifying each time the height along the flow axis.

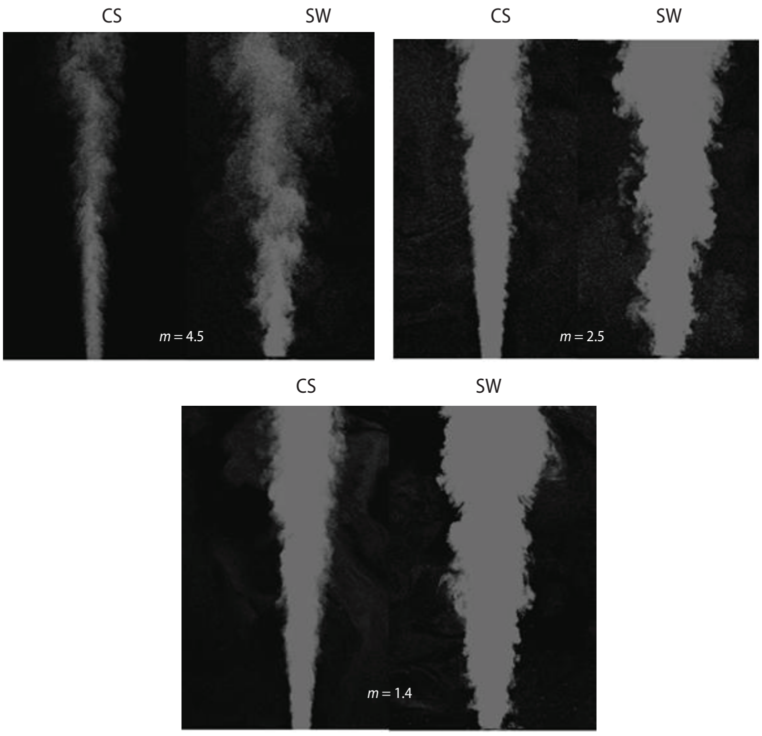
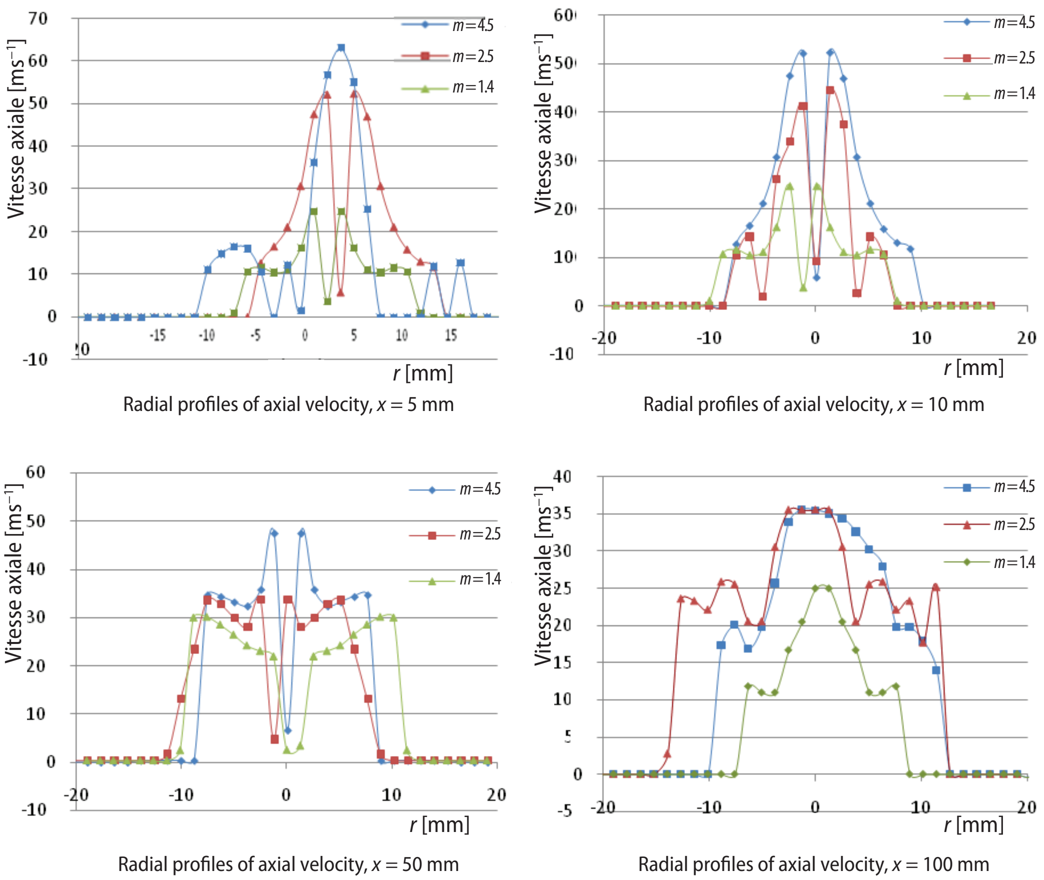


Figure 6. Influence of the control on the jet structur; visualizations by PIV

According to fig. 7, in the close exit of the burner and for high values of *m*, it is noted that the effect of the control is negligible which contributes to increase the rate of the annular flow, in the mean-time the central flow keeps the same values of velocity. When the speeds ratio, *m*, decreases, the mean velocities profiles widened and the device starts to be efficient. We can also notice another important component related to the decrease of axial velocity. Indeed, for $m = 4.5$, speed in the center is about 60 m/s. However, for $m = 1.5$, it became 25 m/s. Control accelerates the decrease of axial velocity, in accordance with swirl flows.

When the height, *x*, following the flow axis increases, speed on the flow axis strongly decreases as ratio speeds, *m*, increases. That can be justified by the improvement of the turbulence effect around the axis. Thus, the intensity of the axial velocity fluctuations increases from where the increase of the turbulence intensity. The mixture layer widens considerably: the objective of the control system is achieved and we support the mixture of the fluids from the two burner jets as well as the mixture with the ambient air. If we move away from the output area of the burner, *i. e.* for an important value of *x*, $x = 10$ cm the values of axial velocity increase. This behavior is similar to that obtained without control. The effect of the control decreases then for important heights along the axis. The rotation influence is then observed in the zone close to the edge of injection, the profile is increasingly broad, and average axial velocity takes low values.



Radial profiles of axial velocity, $x = 5$ mm

Radial profiles of axial velocity, $x = 10$ mm

Radial profiles of axial velocity, $x = 50$ mm

Radial profiles of axial velocity, $x = 100$ mm

Figure 7. Characterization of the controlled flow

When the controlled flow, *i. e.* the flow of the annular jet becomes important, it becomes difficult to regard the flow as a jet. The radial profiles of average axial velocity in the close exit show not easily interpretable behaviors, strongly disturbed by the presence of the obstacles. Downstream, the profiles with $x = 10$ cm show that the profiles rate of the flow are considerably flattened for low values m. Thus, with $m = 1.4$, velocity in the center represents only 50% of that in the center of the not controlled flow and the profile are broader.

Conclusions

This paper presents a study on non-premixed flame generated by a burner constituted with a central air jet surrounded by an annular controlled air jet. These controlled jets burner generates a turbulent flow developing in ambient air. The work consisted in mainly characterizing experimentally the influence of the control on the behavior of the flow. The addition of the obstacles in the annular jet presents double advantages: a better mixture of the fluids from the two burner jets carried out thanks to the increase of the intensity of turbulence and the decrease of axial velocity which contributes to the reduction of the lift-off height and the stabilization of the flame in the reactive case.

This work made it possible to propose the effectiveness of our inspecting device in terms of improvement of the mixture between the two jets as well as the mixture with the ambient air. An important component to add is that this effect is flexible: more we increase the annular flow injected more we act on the mixture.

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