PIV CHARACTERIZATION OF INDUSTRIAL FLAMES FOR NOx REDUCTION

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ABSTRACT

The evolution and variation of front flame configuration as function of the turbulence level and the non dimensional parameters is discussed in this work. For this research we focus our attention on a model of industrial annular hybrid burner, similar to an aeronautical one (in scale 1:2 and at room pressure and room temperature). The experimental data of the flame are acquired by means of the bidimensional PIV technique (2D2C), that gives the instantaneous map of the row vectors for every couple of Mie scattering images.

The application of digital post processing methods on gray levels images, gives us information about topological flame properties. Statistical and differential operators applied on instantaneous velocity distributions make it possible to compare front evolution to kinematics properties. The evaluation of the dimensionless parameters has been conducted by specific measurements to understand the interaction between the incoming structures and the flame front evolution.

Two pilot flames have to be lighted on the border of the hot jet to avoid the blow out of the flame at Re up to 7000. The two diffusive flames increase locally the Richardson number and consequently activate the process of destabilization of the jet by means of the buoyancy effect. Rising the air excess ratio, with the same fuel flow, we have modified the burner exit geometry to increase the vorticity and fix the base of the jet, causing a positive reduction of NOx concentration in the exhaust gas. The chemical analysis of burner emissions, with different air excess ratio, shows us the decreasing of NOx emission with the augmentation of the air flow, due to the progressive cooling of the flame and the corresponding reducing of thermal NOx.

INTRODUCTION

The reduction of pollutant emission and acoustical noise of industrial burners are the main goals of research in applied combustion. Our experiences for the realization of a low NOx

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burner and its experimental validation through PIV technique are described in this report.

The production of nitric oxide depends on three fundamentals factors (Lefebvre 1983): nitrogen concentration in the fuel, front flame intermediate reactions and temperature; as a matter of fact we have respectively the fuel, the prompt and the thermal NO_x emission.

If we use a fuel free from nitrogen (like the liquid propane gas -LPG-) we have only a NO_x emission due to the nitrogen presence in the premixing air. The prompt emission depends essentially on the intermediate species and high temperature gradient present in the reaction zone, its amount decreases with the air excess ratio. In air-propane mixtures the thermal emission (g/Kg propane) changes with the adiabatic flame temperature T (Kelvin) and the combustor residence time t (milliseconds) with the expression (Roffe and Venkataramani 1978):

$$\ln\left(\frac{NO_X}{t}\right) = -72{,}28 + 2{,}8\sqrt{T} - \left(\frac{T}{38}\right)$$

and is quite independent from pressure over the range 0.5 to 3 MPa.

On the basis of the above mentioned NO_x emission properties we design a model of an industrial burner that works with LPG fuel and with values of the air excess ratio (λ) greater then one. These two characteristics allow us firstly to avoid fuel NO_x emission, secondly to minimize thermal and prompt emission due to maximum flame temperature reduction. But larger λ correspond to less stable premixed flames. The basic aim of our work is to design a burner quarl that fixes the base of the flame at the exit of the burner, with high values of Reynolds number and premixing air flow.

Firstly we achieve the exit of the burner with a circular external wall (23 mm diameter) and a stabilizing inner cylindrical bluff body (7 mm diameter) fixed axially (150 mm long).

Then we increase maximum Reynolds using two pilot flames to preheat the edge of the jet, taking the air excess ratio about constant. PIV technique applied on these two configurations shows the kinematical properties of the flame in the considered range of non dimensional parameters. As a matter of fact fluctuations, which have a destabilising effect, are essentially due to the configuration of the exit section of the burner (fig. 1.a).

Finally the geometry of the exit section of the combustor has been optimized by inserting a conical bluff body on the pre-existing cylindrical one (fig. 1.b).

PIV SET-UP

The measurements have been performed by the PIV technique (2D2C), with the set-up components listed in the following:

1. Two pulsed Nd:Yag lasers (energy = 300 mJ, wave length = 532 nm);
2. Optical branch (with a plane/cylindrical lens);
3. Cylindrical test chamber (diameter = 0,4 m, height = 1,5 m), with a conical upper hood and a perforated base (porosity = 40%);
4. Annular burner
5. Air and fuel feeding systems (with an Al2O3 air seeder);
6. CCD camera (484 x 768 pixels);
7. Dantec PIV 2000 cross correlation and synchronization unit.

Dantec cross correlation unit is a main frame that evaluate the instantaneous row velocity field with the frequency of 2 Hz. Each instantaneous velocity map is obtained by crosscorrelating two Mie scattering images, that can be acquired with a time delay (in the range $100\ \mu s < \Delta t < 10000\ \mu s$) fixed by the researcher and depending on the velocity of the examined phenomenon.

BURNER SHAPE

The burner is 250 mm high and consists of three parts. The base is the in-letting zone, where the fresh air incomes with an opposite inlet configuration, through four holes (diameter=5 mm) situated in the vertical cylindrical walls (25 mm length); the fuel arrives from the base. The second region is a 25 mm length divergent that joint the premixing zone (diameter = 10 mm) to the burner top (diameter = 23 mm). The third part is the out-letting that is the principal object of our studies.

At the top of the burner we have, along the border, two nozzles (diameter = 0.2 mm) for the pilot flames, whose holes are 6 mm distant from the burner's external wall.

The two scheme reported in figure 1 represent the burner quarl with the cylindrical bluff body (left side) and with the divergent inner body (right side).

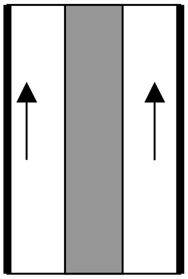

Fig. 1.a: Cylindrical bluff body shape

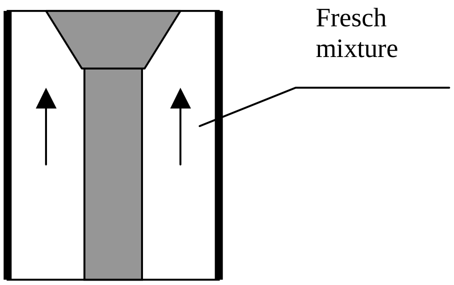

Fig. 1.b: Conical bluff body shape

NON DIMENSIONAL PARAMETERS

There are three different groups of dimensionless parameters that we consider for the description and comprehension of flame evolution and properties.

COLD JET PARAMETERS

Upstream the flame front, for the fresh mixture we have:

Reynolds number $Re=(Uj\ D)/\nu$ (Uj is the mean velocity at the base of the jet, D is the inner maximum diameter and ν is the kinetic viscosity $\nu=\mu/\rho$) represents the ratio between inertial and viscous forces and governs the evolution of the structures inside the jet and the effect of the shear at the border of it.

Aspect ratio $l = L/D$ (L is the length of the burner exiting duct) influences the turbulence level of the jet.

Gap ratio $\gamma = gap/D$ ($gap = D-d$) governs the formation properties (frequency and amplitude) of the annular structures beginning at the top hat of the burner.

Air excess ratio $\lambda=(O/F)/(O/F)_{STEC}$ (O is the air flow and F is the LPG flow for the burning mixture and the stoichiometric mixture), is useful to know the amount of the premixing air (fixed from us) and to forecast the pollutant gas emitted from the flame.

HOT GASSES

Grashof number $Gr = [(T_J-T_o)\ g\ D^3]/(T_o\ \nu^2)$ (Tj and To are the flame adiabatic temperature and the room temperature, g is the gravity acceleration) shows the intensity of the thermal forces.

Richardson number $Ri=Gr/Re^2$ is the ratio between buoyancy and inertia. If $Ri \ll 1$ we can consider the flame fundamentally governed by inertial forces and the effect of combustion is located only in the flame front, while the post flame regions appear laminarized. For $Ri \gg 1$ we have a jet evolution strongly dependent on buoyancy. In the intermediate cases the evolution of the reactive jet is governed by both of these forces.

TURBULENCE - COMBUSTION INTERACTION

Length scale ratio $\pi_1=l/\delta_F$ allows to compare the integral scale of the burner with the thermal thickness of the flame.

Velocity ratio $\pi_2=U'/S_L$ is the ratio between velocity fluctuation (RMS) and laminar front flame velocity. Higher turbulence levels produce larger values of flame thickness, due to the effect of the structures that penetrate through the preheating zone, with an increasing of thermal exchange and mixing. To evaluate statistical flame properties we compare a set of 100 instantaneous samples to obtain mean velocity and local fluctuations.

The knowledge of these two parameters allows us: to know the combustion properties through the Damkohler diagram and to obtain other dependent parameters like Damkohler number $(Da = \frac{\pi_1}{\pi_2})$, turbulent Reynolds ($\mathrm{Re}_T = \frac{u' L_T}{\nu}$) and Karlovitz ($Ka = \sqrt{C}\pi_1^{\frac{-1}{2}}\pi_2^{\frac{3}{2}}$).

PIV RESULTS

The experimental results are acquired in two different configurations: firstly we study the flame behavior correspondingly to the cylindrical bluff body configuration (with and without pilot flames); secondly we apply the same technique to a conical bluff body configuration. With these two different quarl configurations we put in evidence outletting vortices dependency from exiting duct geometry. All flame measurements have been made at maximum stability regime, with the same fuel flow (0.14 m^3/h) and three different air flows. Using cylindrical bluff body we have an air flow of 7 m^3/h without pilot flames and of 9 m^3/h with two diffusive flame burning. The conical bluff body geometry reaches the maximum air flow of 15 m^3/h without pilot flames. The instantaneous experimental results that are presented are acquired through the PIV set-up described above and consist of Mie scattering images and the corresponding velocity fields. Post processing methods based on statistical calculations are fundamental for the evaluation of quantities such as turbulence level, mean velocity, vorticity, divergence of velocity and other kinematical properties of the reactive fluid. Digital processing of grey levels images (Giordano et al 2000) is necessary to obtain binarized image and front flame contour (represented by black dotted line in the following vector maps). To verify the efficiency of front line extraction method the dotted contour line is superimposed on the dilatation of velocity field of the same flame. When the points with maximum divergence of velocity fit this contour we can consider this line like a good flame front representation (Stella et al. 2000).

Results of the different configurations examined are reported above.

FRONT FLAME IN THE CYLINDRICAL BLUFF BODY SHAPE

The dependency of the front fluctuations on the structures evolving in the hot jet are examined in the experiments described in this section. To emphasize this behavior we exam we acquire instantaneous images at the maximum Reynolds obtained with this configuration (with a fuel flow of 0.14 m^3/h). The described above presents a front topology characterized by a V shape. Consequently we have an inner hot zone, about one diameter over the burner exit, due to the exhaust gas outcoming from the inner (V shape) reactive zone. In this region there is a strong acceleration of burned gas, with a maximum velocity ratio Vx / Vexit that is about 1.8 - 2. This increase in velocity is correlated to the density variation due to an abrupt augmentation of the gas temperature. In our experiences we have a temperature of the fresh mixture (T_{exit}) of the order of 300 °K and a maximum temperature (T_{max}) of the order of 1200 °K in the reactive zone (values measured through thermocouples). So the theoretical maximum velocity ratio due to temperature variation can be evaluated by giving (Rolls-Royce 1966): Vmax / Vexit = (Tmax / Texit)^0.5 = 2 which is in good agreement with the presented PIV results.

The instantaneous vector map (reported in figure 3) and the corresponding Mie scattering image (i.e. fig. 2) give the evidence of the typical evolution of vortices, that are located in the annular region above the external walls of the burner. The destabilization takes place alternatively on the right side and/or the left side of the base of the jet. This behaviour has been confirmed by a number of PIV images not showed for brevity.

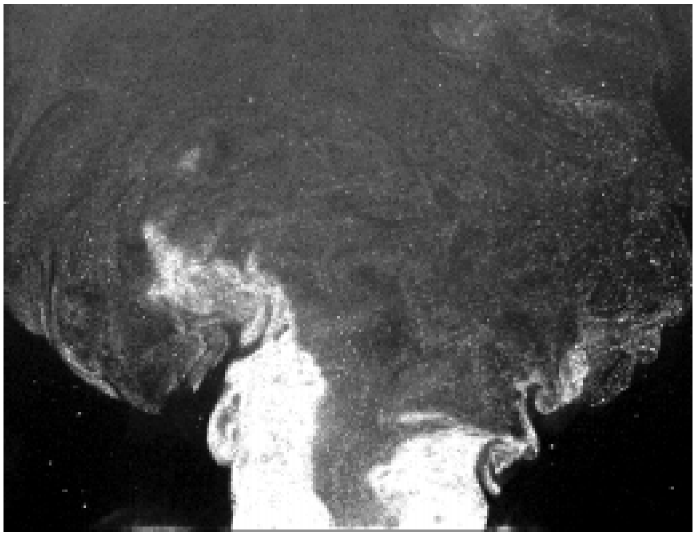

Fig. 2: Mie scattering image of the flame with a ring vortex forming on the right side of the jet base, while on the other side a structure already formed goes away.

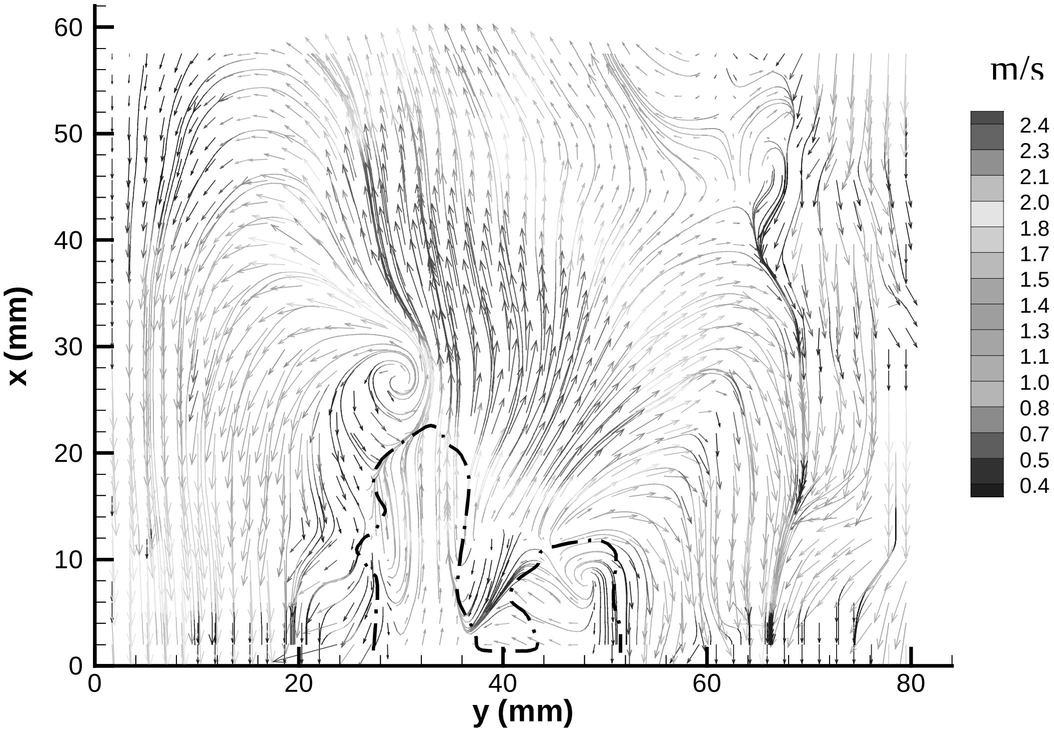

Figure 3: PIV result with Re=7500, λ=1.43, Ri=0.08 (the dotted line represents the contour of the front).

Comparing the instantaneous results we observe, in the reaction zone (2 diameters lenght), alternate structures with a quite constant distance (wave length = 20 mm) and a velocity similar to local fluid speed. The direct consequence of this structures is the fluctuation of the flame front and the eventual quenching in regions where the structures interact with the flame front. The frequency of these structures, obtained by the ratio between vortex speed and vortex wave length (fig. 4) are plotted as function of edge velocity (figure 5) giving a fundamental frequency of 110 –120 Hz. The frequencies at about 300 Hz (fig 5) are probably due to alternate formation of vortices at the base of the jet. The sound pressure level measurements of the same flame (fig. 6) seem to confirm the result obtained PIV technique (fig. 5).

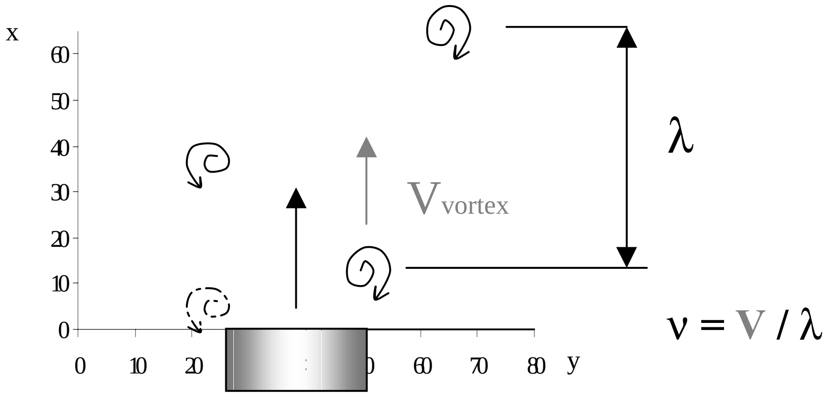

Fig. 4: Conventions used for the evaluation of vortex frequency, wave length and velocity

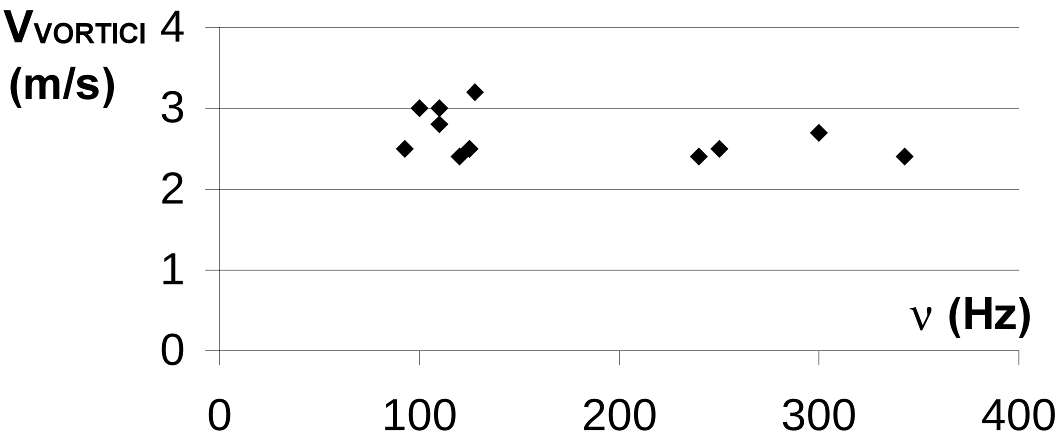

Fig. 5: Main frequency of outcoming vortexes of 100-110 Hz.

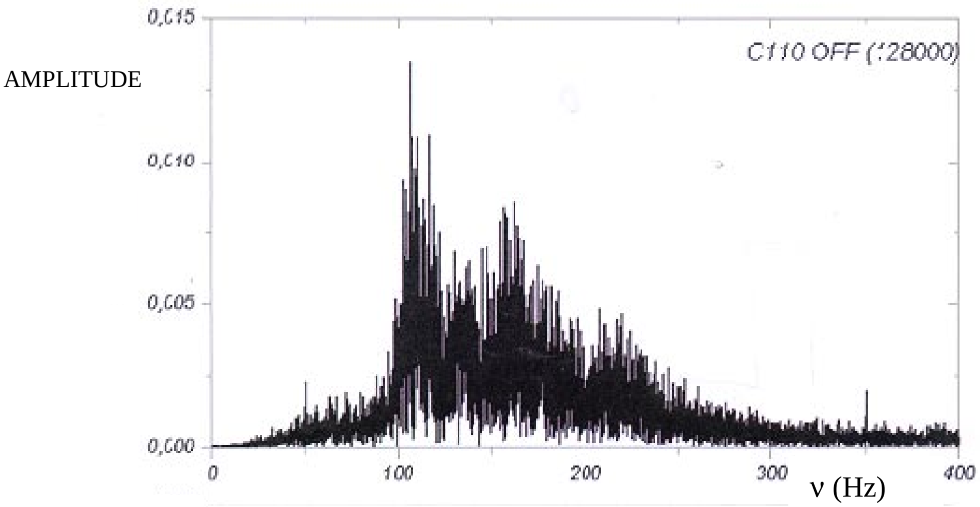

Fig. 6: Sound pressure level measured for the same flame

EFFECT OF PILOT FLAMES

The destabilization showed before is the reason of the stability limit with an air flow of 7 m^3/h. In the second part of the work we succeed in increase the air flow to 9 m^3/h (with the same fuel flow of 0,14 m^3/h), with the introduction of a set of nozzles at the top of the burner, close to the external wall (fig. 7).

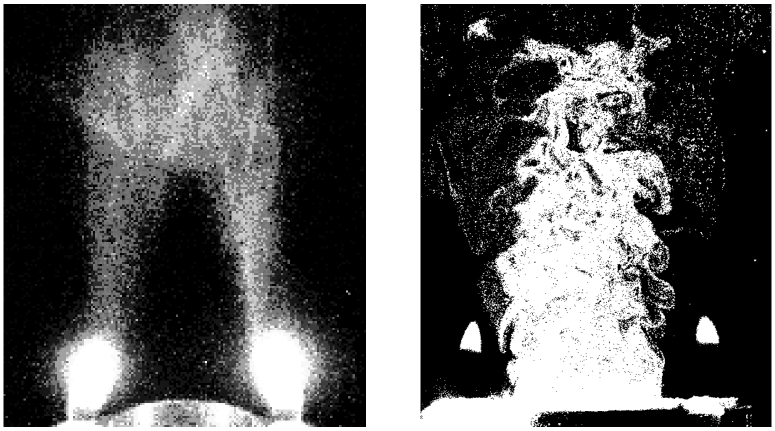

Fig. 7: Photograph and Mie scattering image of the reactive get with pilot flames

Two pilot flames are positioned borderly the jet, to anchor the flame front to the exit of the burner. The front flame becomes conical for the lower value of Richardson number along the axis. The local temperature augmentation facilitates the preheating of the fresh mixture and, contemporary, increases the buoyancy forces acting directly on the shedding structures, that develop with a higher frequency along the border of the jet as it is possible to see in the instantaneous velocity field of figure 8.

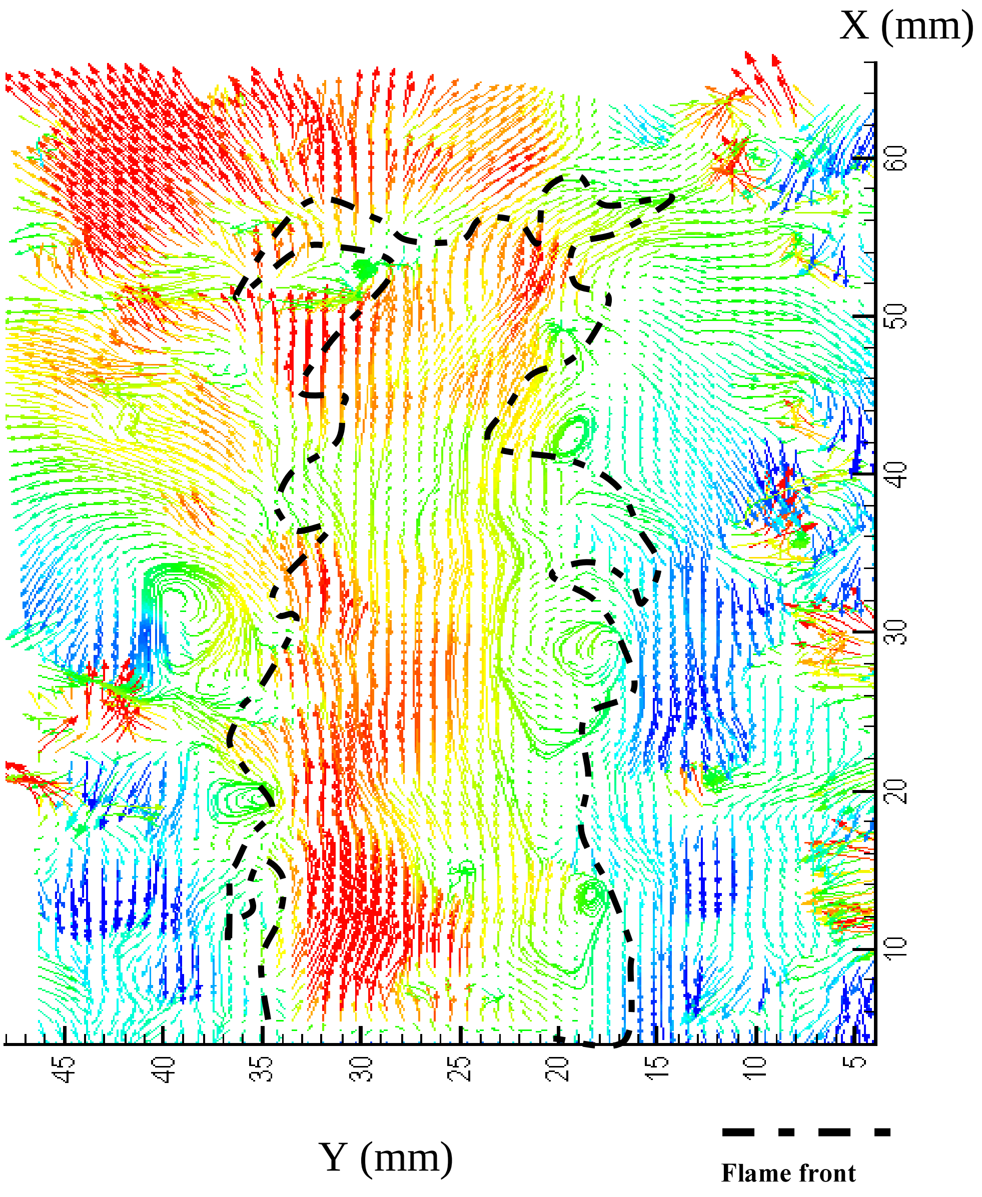

Fig. 8: Fluctuating velocity field of the hot jet with pilot flames, situated sidely the base of the premixed jet (Re = 8700, Ri = 0.06, λ=1.6, π_1 =18, π_2 = 2).

CONICAL BLUFF BODY

A combustor with the same aspect ratio (L/D=5,6), a conical bluff body (fig. 1.b) and a lower gap ratio (new γ=0.39, old γ=0.69), is designed to reduce the lack of stability connected to the periodical formation of shedding vortices at the base of the jet. The picture and the Mie scattering image (fig. 9) represent the flame at Re=11000 and λ=1.8.

The extension of the front flame is around one diameter and the evolution of the exhaust gas seems to resemble the flow field of a cold jet with Re=11000 (Giordano, Giammartini, Manfredi 2000). In figure 10 we see the velocity distribution, where the front has a V shape and the acceleration of the reactive fluid takes place along the lateral region occupied from the fresh mixture. The effect of laminarization of the flow field throughout the flame front is evident in the same figure.

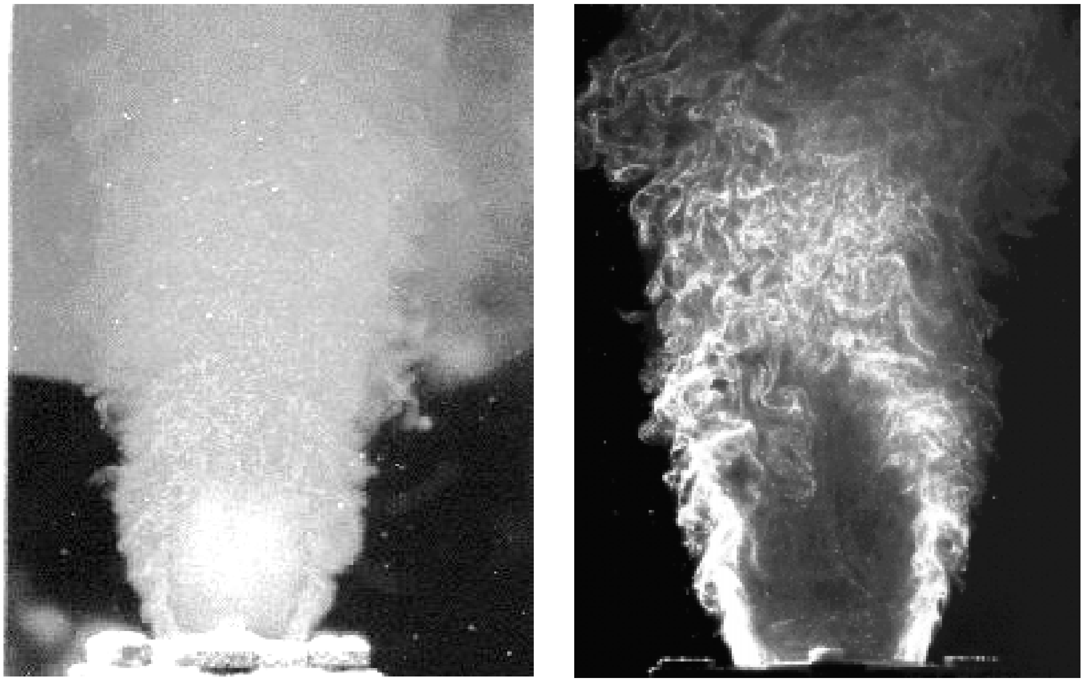

Fig. 9: Photograph and Mie scattering image of the flame downstream the conical bluff body.

The stream lines distribution (fig. 11), evaluated on the base of the instantaneous vector map (fig. 10), are a powerful instrument for the detection of two kinds of structures (contemporary evolving in the flame) that are here listed:

1. The shedding structures that outcome with a forecastable evolution and generate a noise with the 100 Hz frequency found before.

2. The internal ring likes structures (which in the 2D section appear as a couple of counter rotating vortices) recirculate downstream the bluff body reducing the time necessary to preheat the mixture exiting from the feeding annular duct. These vortices generate a central zone where the exhaust gasses stay for few seconds.

The stable working of the burner with a very lean premixed flame is the direct consequence of this axial hot zone, that undoes the effects of the external structures and fixes the evolution of the flame front.

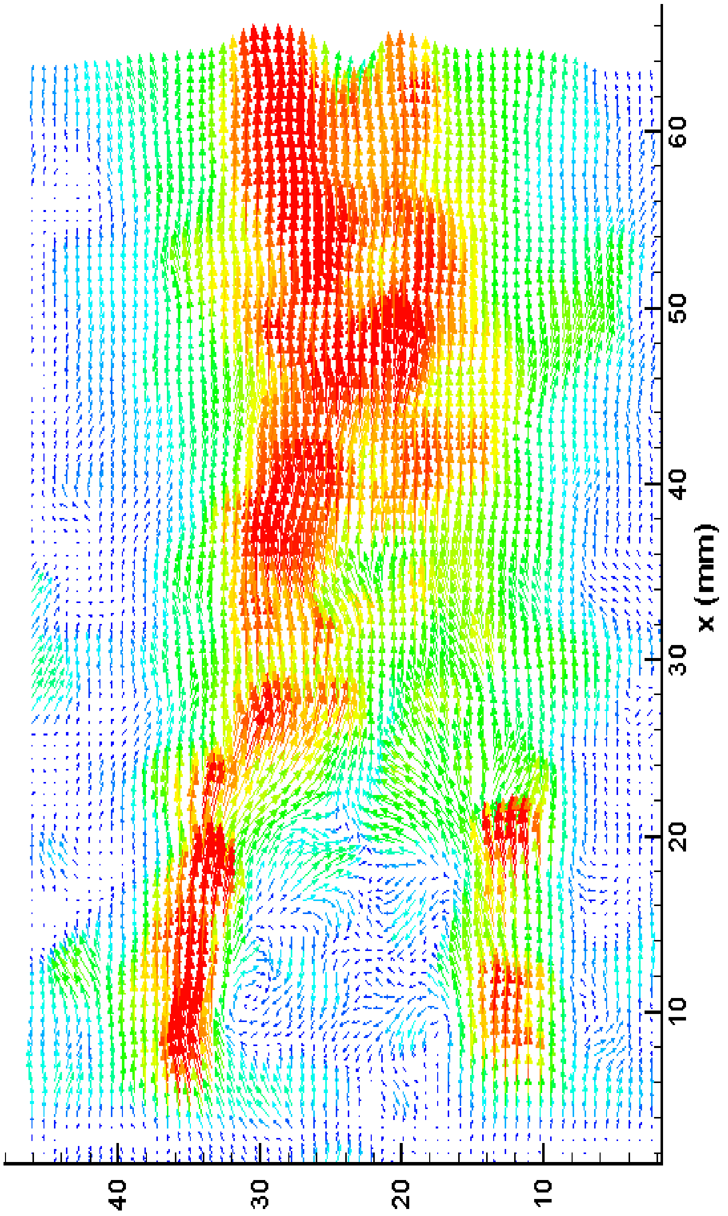

Fig. 10: Instantaneous velocity field at Re = 11000

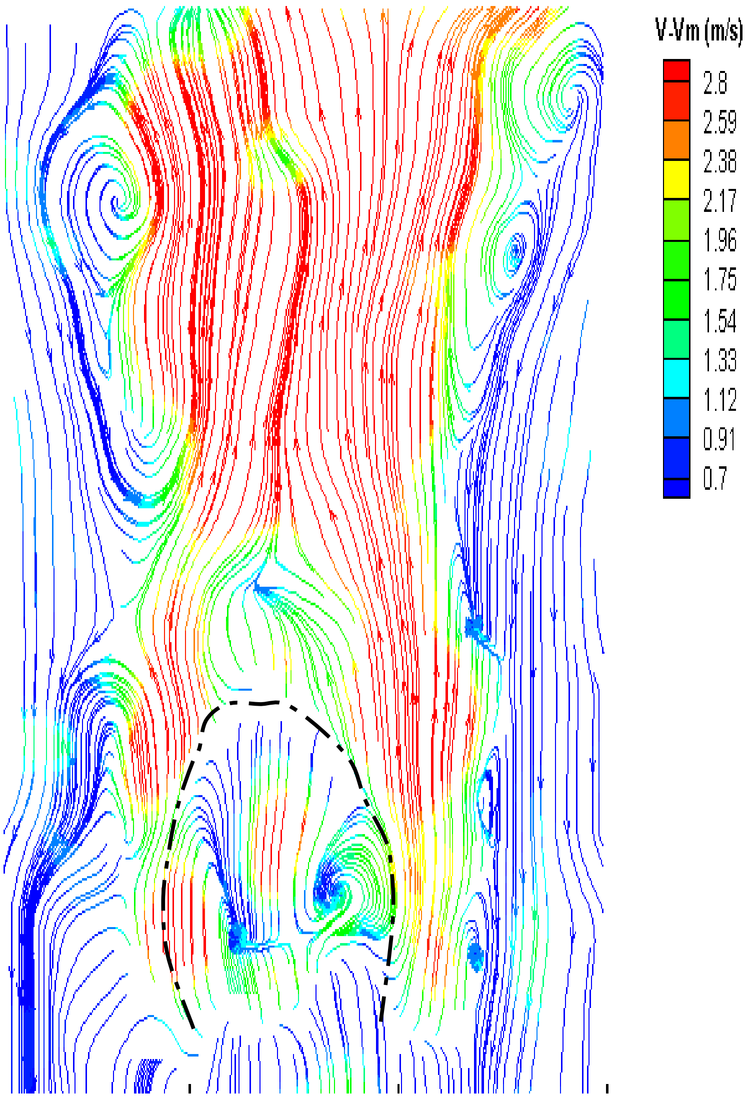

Fig. 11: Mie scattering and stream lines of the flame (Re=11000, λ= 1.8)

The increased value of the air flow (17 m^3/h) gives an air excess ratio of 1.8, with a high reduction of the flame temperature that reaches the maximum value of 1100°K. This behavior allows the emission of thermal NOx to be reduced, in agreement with the aims of the design of premixed burner requirements.

CONCLUSIONS

PIV technique is a very useful instrument that allows us to make an on-line investigation about: the cinematic properties (velocity fields, vorticity, turbulence levels, front thickness), the topology of the reactive fluids and the dependency of hot (and cold) jet evolution from burner shape. All the results here reported have been obtained with the same fuel flow and a variable air flow.

The burner with cylindrical bluff body generates annular structures that develop (at the maximum air flow reachable for the stability of the flame – Re=7500, λ =1.4 -) alternatively at the base of the hot jet with a mean fundamental frequency of 100-120 Hz. The same burner with two pilot flames situated borderly the jet, can work up to Re=8700 with an increased value of the air excess ratio of 1,6. This result is already sufficient to reduce NOx emissions, but shows a reduced margin of stability.

The burner with the conical bluff body generates at the maximum regime (Re=11000 and λ =1.8) two kind of structures: the annular vortices developing along the wall of the jet and recirculating zone downstream the bluff body, these structures are schematically reported in figure 12:

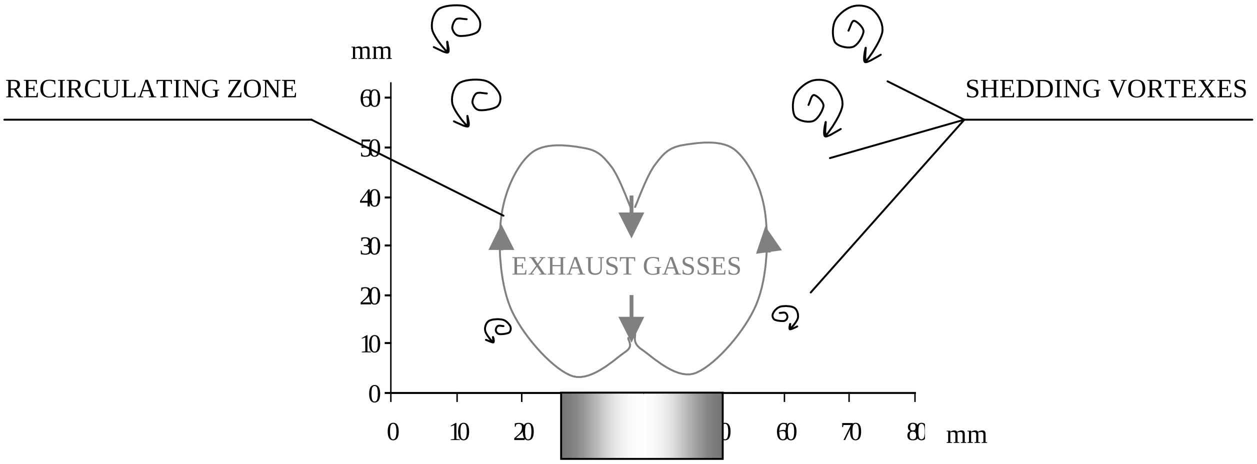

Fig. 12: Scheme of the structures developing downstream the bluff body burner

These counter rotating movements involve the residence of exhaust gas closed to the inlet zone of the fresh mixture with a consequent increase of the preheating effect and the reduction of front flame extension. This last phenomenon is quite independent from the presence of an increasing in buoyancy due to the effects of the pilot flames.

By means of this conical geometry it is possible to reach a large operative range of the burner (Remax=11000) with a high value of the maximum air excess ratio (λ=1.8). A larger dilution corresponds to a lower NOx emission as confirmed by the measurements reported in figure 13, obtained by means of an Emicont Analyzer. This instrument evaluate the composition of the gas (incoming from its prob) with the comparing of the hot air conductivity (examined in its internal cells) respect to the cold one measured before as a reference.

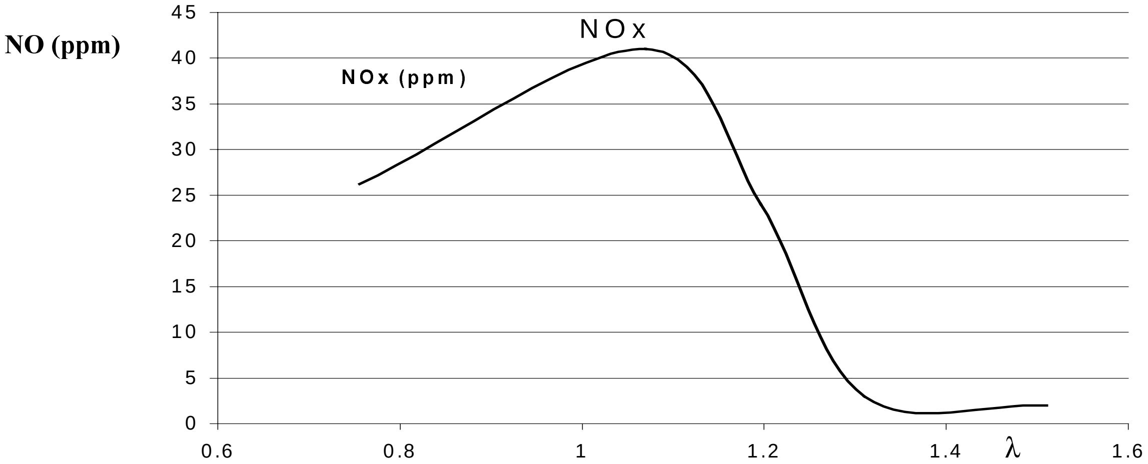

Fig. 13: NOx emission v/s air excess ratio measured by means of the Emicont analyzer

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