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VELOCITY MEASUREMENTS AND GAS MIXING CHARACTERIZATION AT THE EXIT OF AN ISOTHERMAL MODEL OF A GAS TURBINE PREMIXER

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ABSTRACTS

Premixed flames have shown to provide sufficient low NO_x emission levels in gas turbine combustor. To achieve this goal several issues are to be addressed. Highly uniform fuel air ratio along with proper velocity profiles at the flame front has to be achieved. Vortex generators are commonly employed inside lean premixed combustor to generate a swirling flow that can assure the two aspects above. An experimental parametric study of the isothermal swirl flow of a non-confined prototype premixer is presented. Several different geometrical details have been considered for two different fuel air ratios. Velocity fields and mixing distribution between fuel and air at the premixer exit are described. Velocity and turbulence data can be related to formation of flashback and temporal homogeneity of the mixture respectively while the degree of spatial mixing, in terms of segregation factor, is connected with NO_x rate of formation. In both cases the vigorous and high responsive character of the vortex generated by the swirler plays a major role. The final objective is twofold: to define an optimum geometrical arrangement to be tested in subsequent combustion tests and to demonstrate the feasibility of a rapid assessment method of degree of mixing between fuel and air.

INTRODUCTION

The reduction of NO_x emissions from gas turbines has become a major environmental problem. There are different techniques that can give low NO_x concentration in the combustion process, but the most promising for gaseous fuel seems to be the lean premixing one. It is well known that the main part of the NO_x production is due to the so-called thermal NO_x (Zeldovich, 1972). This NO_x contribution increases exponentially with temperature and with the square root of oxygen concentration in the reactant gas. Thus, reducing both flame temperature and oxygen concentration constitutes a powerful mean for controlling NO_x formation. More exactly the flame temperature and its uniformity over the flame front are connected to the overall leanness and to the spatial-temporal distribution of the air fuel mixture respectively: the leaner the mixture and the higher the homogeneity the lesser the NO_x production (Lyons, 1981). In order to obtain the desired homogeneity, a series of premixer swirlers is commonly used. However, there are several drawbacks connected with the use of premixed flames, i.e. possibility of autoignition, flashback and flame instability (lean blowout and combustion oscillation).

The tests presented in this paper are part of a program aimed at the optimization of a premixed gas turbine combustor running on gaseous and liquid fuel (Burattini, 1998). The program comprises isothermal flow tests on a single premixer nozzle (Fig. 1) and combustion tests (presently under execution) on the entire combustor.

In this paper a preliminary characterization of the isothermal gas-mixing behavior at the premixer exit plane is reported. A first set of concentration measurements of the fuel-air mixing along with velocity distribution are presented. Usually, premixers produce either a single swirling flow or double counter-rotating flows. However, in this analysis, the premixer used presents a main swirling flow coupled with two no-swirled coaxial flows, which can be varied in dimension and characteristics by means of two annular by-passes. Several configurations are examined taking into account two fuel-air ratio and different sizes of the two by-pass channels. Indeed, it was shown that these channels can strongly influence the aerodynamic field of the swirling flow when the fuel it is not injected (Burattini, 1998). The purpose of this study is to achieve a thorough description of the cold flow arrangement and finally to establish a connection with the combustion results. Therefore, being the cold test faster and easier to be executed, the design process of a similar type of combustor could be accelerated.

In the following, after a brief description of the premixer nozzle, concentration data are presented followed by the velocity measurements. Then velocity and concentration data are compared.

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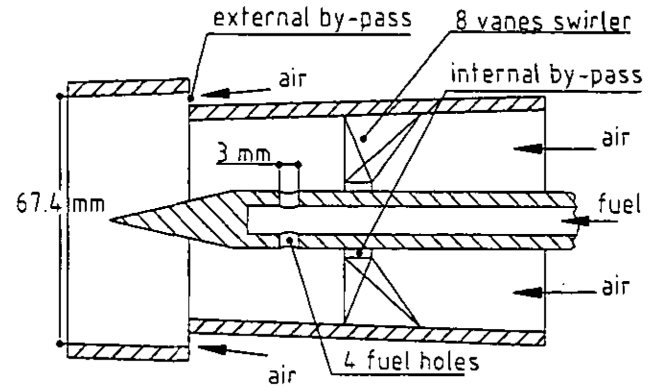


Fig. 1 Premixer swirler nozzle and fuel injector

Finally, preliminary results of an alternative technique for obtaining the fuel concentration data, based on images processing technique, are reported.

PREMIXER NOZZLE DESIGN

The premixer nozzle used in the cold test is shown in Fig. 1. The nozzle features an external by-pass (2% of the exit area). This by-pass, when opened, lets part of the air flow through, with no swirling motion, coaxially to the main flow. Inside the nozzle is located a swirler composed of eight curved vanes and a fuel injector with four equally spaced circular holes positioned downstream of the swirler. The vanes are twisted and have a cambered mean line, a tapered chord and constant thickness. Care was taken in order to avoid any separation of the flow. The orifices are put at right angle with respect the main flow. It can be noted that the aft part of the fuel injector has a streamlined end to limit the dimension of the wake. In Fig. 2 a schematic frontal view of the premixer with the position of the fuel injector points is given. Between the injector and the swirler there is an annular clearance whose dimension can be varied.

The size of this internal by-pass area can be a 2% or 1% or 0% (i.e. closed) of the main annular area. As the one mentioned above, this by-pass does not give a swirling motion to the flow inside it. Even if the dimensions of the two by-passes are very small, compared to the main exit area, they are potentially effective because swirling flows are known to be very sensitive to little changes affecting the boundary conditions.

The premixer model, which can be rotated to allow measurement at different azimuthal planes, is mounted at the end of a test-rig which has been designed and constructed for the purpose and described in detail in (Burattini, 1998). The setup is basically a carefully manufactured wind tunnel with a still chamber and a converging nozzles. The geometry of the convergent nozzle can be easily varied in order to mount at its end different types of premixers. To ensure a satisfactory axisymmetry of the stream, great care was devoted to a proper design of the air inlets. In particular, the air is conveyed through four radial ducts into the still chamber and then into the main duct through a fair inlet. Various screens and honeycombs are also present inside the duct. This ensured less than 0.5% deviations from axisymmetry in the mean and fluctuating flow quantities. The flow is produced at ambient temperature and pressure by means of a blower placed sufficiently upstream of the facility. The outlet velocity can be set with an accuracy of 0.1 ms^{-1} by means of a differential pressure measurements.

Probes are positioned in the flow by means of a high-precision, computer controlled, traversing mechanism allowing three translational and two rotational degree of freedom with an accuracy of 0.01 mm in translation and of 1/60° in rotation.

The tests are performed with an exit velocity of 30 ms^{-1} at a Reynolds number (based on the exit diameter and velocity) of $1.5x10^5$. At these conditions the turbulence level at the inlet of the premixer results to be around 1% while the swirl number varies between 0.35 and 0.43 depending on the different geometry conditions. Preliminary analysis showed that no particular periodic phenomena were present at the exit plane.

Tests have been done with different air fuel ratios (AFR). In this case, two condition (AFR=24 and AFR=40) which could be typically

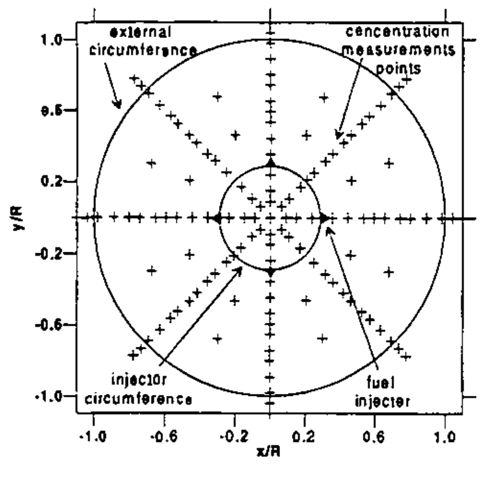


Fig. 2 Frontal view of premixer with point location of concentration measurements

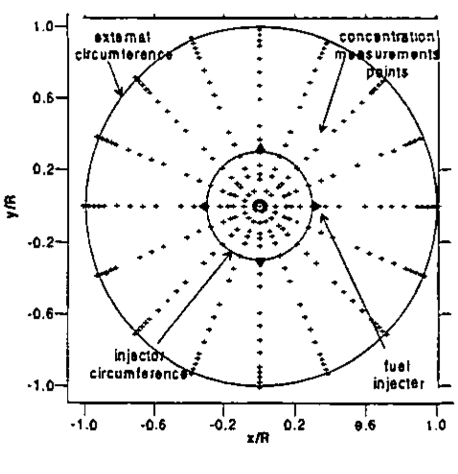


Fig. 3 Frontal view of premixer with point location of velocity measurements

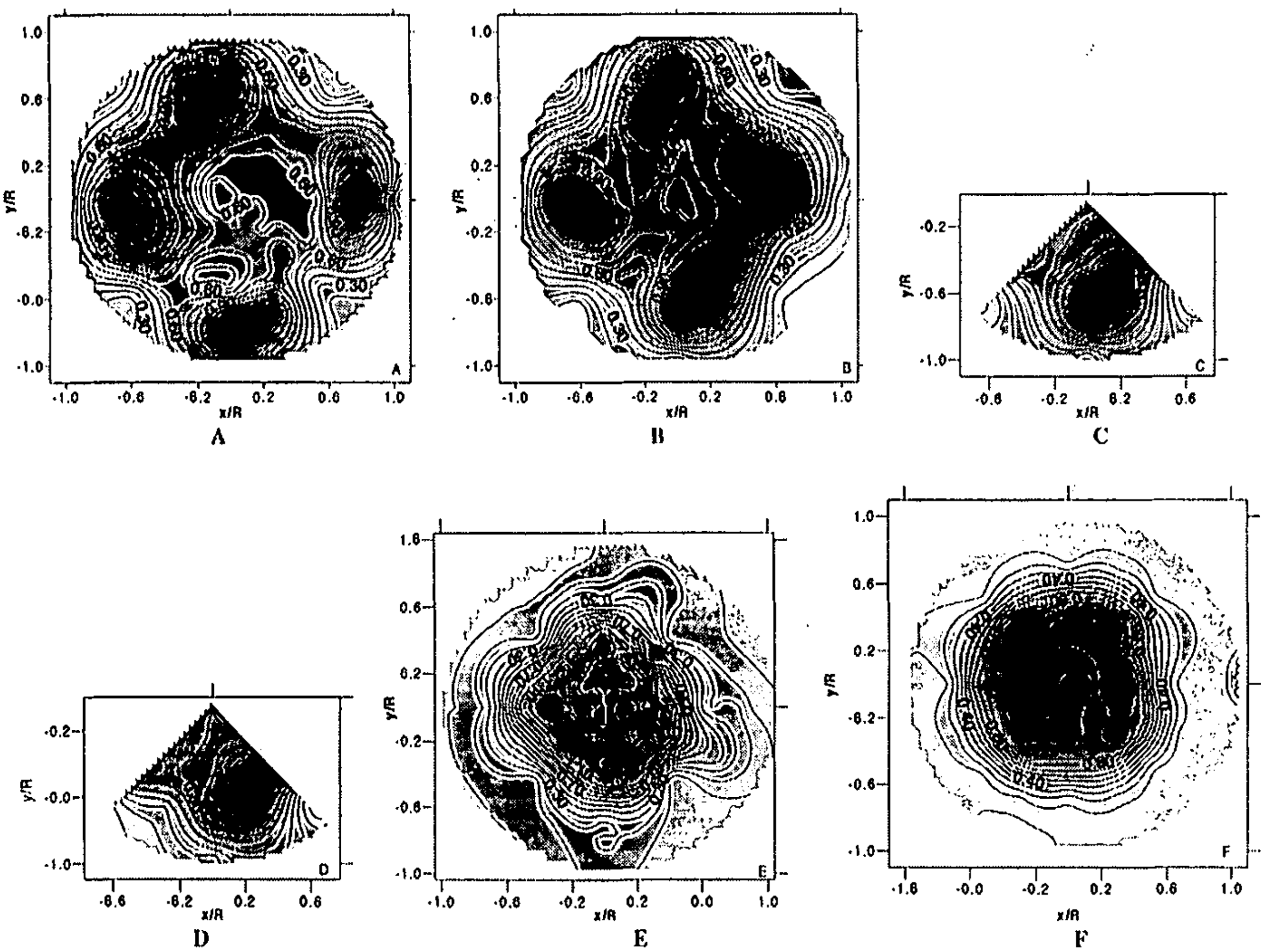


Fig. 4 Gas mixing at the exit plane: equivalence ratio distribution (nozzle A through F)

encountered during operation in lean combustion, are examined (Table 1). All of the measurements are taken at the exit plane where the influence of the geometrical details and of the AFR is more evident and also where the effect of the non-confinement is less strong.

In the final arrangement the premixer, examined in this paper, will be installed in a combustor which is currently in use. In the combustion section it will be one element of eight arranged on a circumference around a central diffusion pilot flame. In operation, while starting up, only a fraction of all the premixers are used. It must be pointed out that all of them (i.e. pilot and premixer) are designed to run either on gas (viz., methane) or liquid fuel.

CONCENTRATION MEASUREMENTS

The fuel, flowing inside the injector, is simulated with a surrogate composed of air traced with nitrogen oxide at a known concentration. The error in terms of diffusivity is acceptable given the little difference existing between the Schmidt number of the couples air-methane and air-air. Moreover, in this kind of premixer, mixing is essentially controlled by turbulence rather than by molecular diffusivity (Dugué, 1994).

The tracer distribution is measured by means of a sampling probe connected to a NO_x analyzer (Lear Siegler ML 8841) following the grid shown in Fig. 2. The NO_x analyzer works on the principle of the chemiluminescence process produced by the NO/O_3 reaction and uses

Nozzle name	internal by-pass	External by-pass	AFR	ϕ
A	closed	open	24	0.73
B	open (1%)	open	24	0.73
C	open (2%)	open	24	0.73
D	closed	closed	24	0.73
E	closed	open	40	0.44
F	open (1%)	open	40	0.44

Table 1 Configurations and AFR tested in gas mixing and velocity measurements

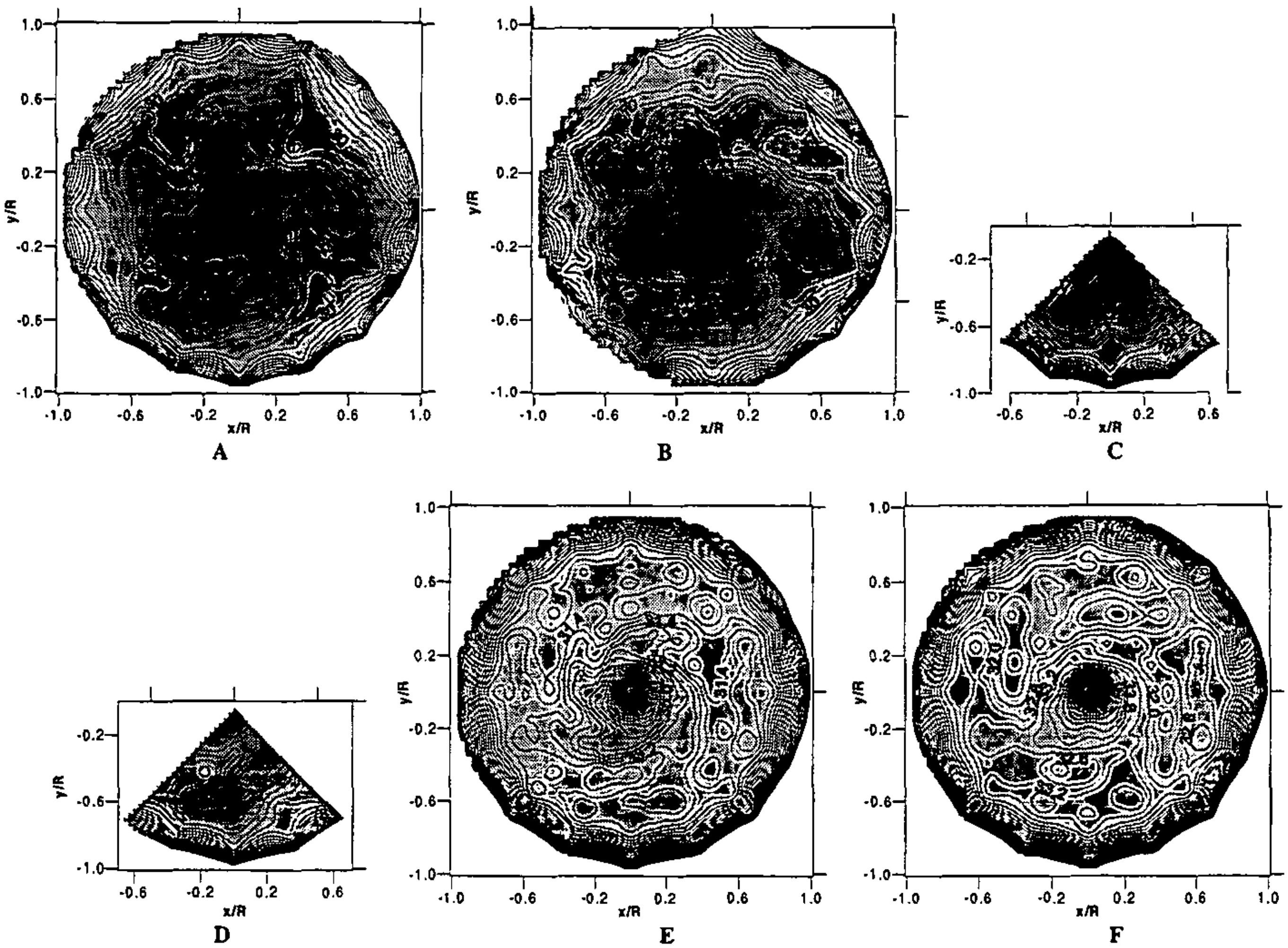


Fig. 5 Gas mixing at the exit plane: velocity distribution [m/s] (nozzle A through F)

single channel architecture with a predictive/adaptive filter to reduce noise.

The outputs are provided to a computer through a RS232 communication port. Precision in the NO concentration measurement is as low as 1.0 ppb. The mean values of the concentration are obtained averaging on 60 seconds for each measurement point. Preliminary tests show that this time is long enough to provide a good statistical estimation. The results are presented in terms of distribution on a plane of the equivalence ratio:

$$\phi = \frac{\alpha_{st}}{\alpha}$$

where α is the measured air fuel ratio,
α_{st} is the stoichiometric air fuel ratio

The overall equivalence ratio values, corresponding to the AFR considered. are ϕ=0.73 and ϕ=0.44 (Table 1) and are chosen accordingly to preliminary combustion tests. These values lie in the range where uniformity of the mixture plays a significant role in NO_x emission, as shown by Lyons (1981).

The fuel, introduced inside the nozzle by the central injector through four equally spaced holes, comes into rotation dragged by the main airflow. Once the rate of fuel is determined, by the value of the AFR, still the dimension of the fuel holes has to be defined. This can be done keeping in similarity the strength of the penetrating fuel jets between the model and the real nozzle for one operating condition. A commonly used parameter in this case (Matsuzaki, 1992) is the momentum-flux ratio (ratio of the specific kinetic energy of the fuel and air), defined as:

$$J = \frac{\rho_f U_f^2}{\rho_a U_a^2}$$

where ρ_f is the density of the fuel,
ρ_a is the density of the air,
U_a is the velocity of the air,
U_f is the velocity of the fuel.

the higher J the stronger the impingement of the fuel jets. The results, reported in Fig. 4, clearly show the effect of the different AFR: for the lower one (24) the momentum-flux ratio is higher thus giving more impetus to the fuel jets. As a result the fuel distributes outward making a spatially periodic pattern composed of four spots. This fact justifies why the analysis in the configuration C and D is restricted to a single quarter. In the other case (AFR=40), the fuel remains confined in the center following a more uniform distribution. The effects of the various internal bypasses are not so strong as it was shown in the absence of the fuel jets (Burattini, 1998). In this case, the dimension of the internal by-pass plays a significant role. However, it is clear that when the air flows through the internal aperture the momentum ratio is somehow weakened. This in turn brings a slightly narrower fuel distribution. Finally in the same figure it can be seen that the external by-pass has a negligible effect on the concentration distribution.

These observations can be quantified by means of the segregation factor (Flagan, 1990):

$$S = \frac{\sigma_\phi}{\bar{\phi}}$$

where σ_ϕ is the standard deviation of the equivalence ratio spatial distribution,

and $\bar{\phi}$ is the mean value of the equivalence ratio spatial distribution

A low value of S (zero as minimum) indicates good mixing. This parameter turns out to be very useful since it can be easily demonstrated that it does not depend on the absolute value of seeding concentration. In Table 2 the values of S calculated for some of the configurations are reported. In terms of spatial homogeneity the case with AFR=24 seems better. Moreover, little difference is made by the by-passes. The degree of mixing seems to be in either cases insufficient so one of the improvement to be verified in combustion tests will be the increase of the number of fuel orifices. Obviously their dimension will be varied accordingly to maintain the same momentum-flux ratio of nozzle A.

Finally it should be pointed out that, due to the intrusiveness of the sampling probe, which has an outside diameter of 1.3 mm, and the relative large size of the sampling point, the differences among configurations with same AFR probably faded a little.

	Nozzle name			
	A	B	E	F
S	0.40	0.45	1.02	1.00

Table 2 Segregation factor for different configurations (gas mixing results)

VELOCITY MEASUREMENTS

Velocity data are taken with an LDV system seeding the main air flow with an aerosol fog upstream of the premixer. The tracer is an aerosol fog obtained by vaporization of an oleos liquid with a density of 1013 kg/m^3. The aerosol particles, having a mean diameter of 2 μm, mix up with the fuel jets giving accurate values of axial velocity at the exit plane at several stations as was demonstrated in Burattini, (1998). LDV data are obtained in coincidence mode with a window width of 1.0 μs in order to obtain high-quality correlation between the velocity components. Except in the peripherical zones of the jet a satisfactory data-rate of 5000 samples/s was obtained. The tangential velocity range examined and particle size used assure that the inertial effects on the tracer particles are negligible (Burattini, 1998).

The distributions of the mean axial velocity U and of the longitudinal rms velocity fluctuations, taken at the point locations of Fig. 3, are shown in Fig. 5 and Fig. 6.

Several features appear from these figures. For instance, concerning the AFR=24, it can be noted that where the mean concentration of the fuel is high, both mean and fluctuating axial velocity present relatively low values. This characteristic might have an important role in the combustion process. It can be argued that the four jets can preserve, for a certain period, an individuality in terms of composition and momentum. However, this phenomenon is not visible for the higher AFR where both velocity and concentration distributions are much more uniform showing relatively high values close to the jet axis. Moreover, the overall turbulence level is lower.

From the same figures it can be assessed that, for both AFR, the distributions of the mean velocity present their maxima close to the center especially in the configurations that have an higher AFR. This is probably related to the fact that in this case the fuel jets have less momentum to weaken the rotating motion of the main flow. The peak in the mean velocity is thought to originate from the squeezing of the streamlines caused by the variation in the section area encountered by the swirling flow. This effect was first analytically demonstrated by Batchelor (1967).

From the combustion point of view, it is advisable to have a uniform and stationary velocity distribution that can help to stabilize the flame without running into flashbacks, while a proper turbulence field can step up the mixing process. These preliminary measurements show that both the dimension of the internal by- pass and the number of holes in the fuel injector are parameters which could be used for a fine tuning of the premixer flow characteristics.

VISUALIZATION OF THE FUEL MIXING

Data presented in the gas mixing section and reported in Fig. 4 require a long time to be gathered. For this reason, a different technique, capable to give an instantaneous qualitative assessment of the fuel distribution on the entire plane, has been used. In this case the fuel is simulated likewise in LDV measurements. The method utilizes a pulsed laser sheet (10 Hz), as a light source, together with a CCD camera to take single snapshots, which are subsequently saved on a computer hard disk.

Nozzle name	internal by-pass	external by-pass	AFR
B	Open (1%)	open	24
F	Open (1%)	open	40

Table 3 Configurations and AFR tested with flow visualization

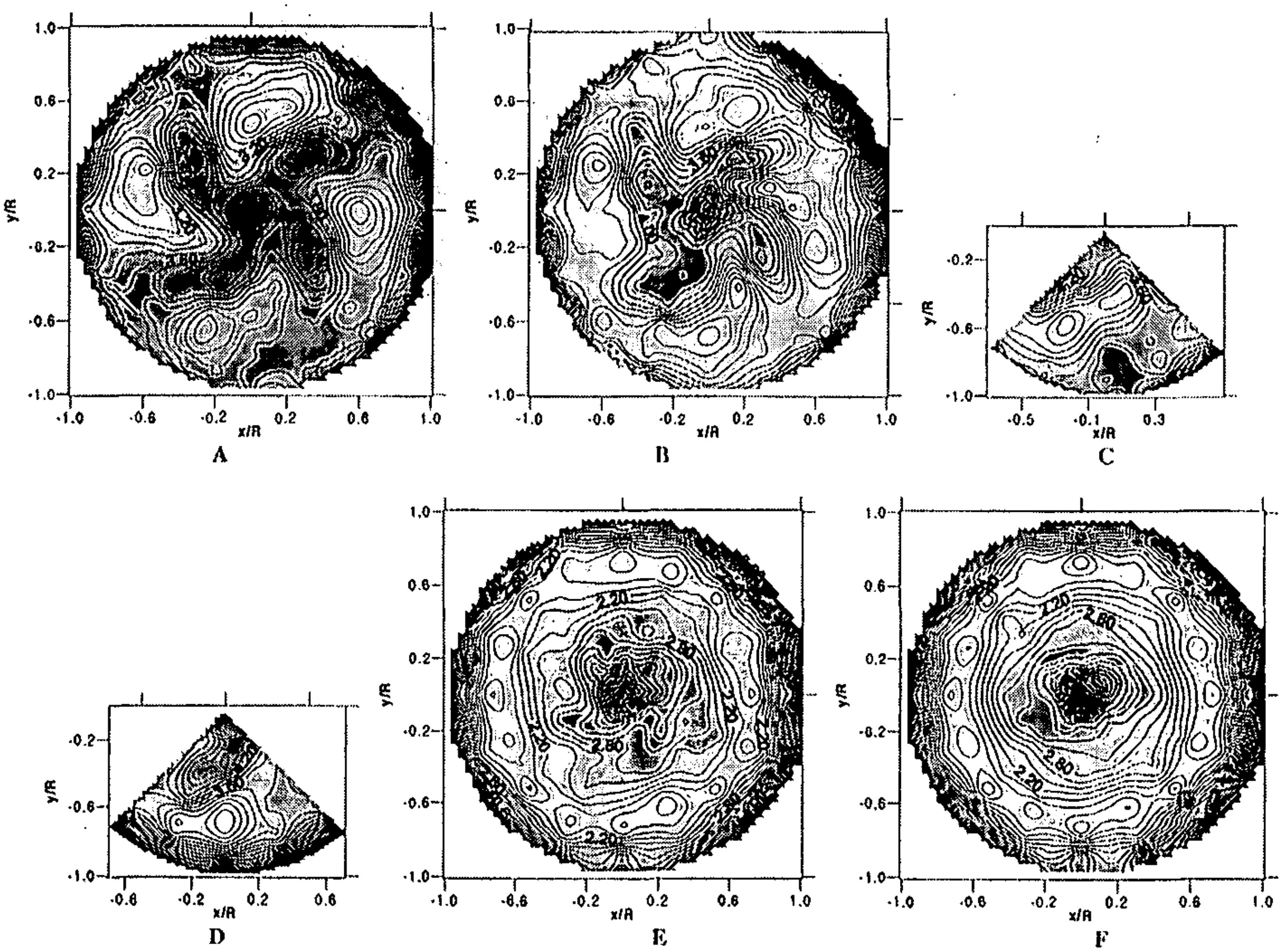


Fig. 6 Gas mixing at the exit plane: velocity RMS distribution [m/s] (nozzle A through F, see Table 1)

Off-line, an image post-processing of a picture ensemble can be performed to give average values, RMS and higher order quantities. This technique gives the opportunity to analyze the temporal statistics of the mixing process, which is in general non-stationary. This, in turn, can be related to, along with the spatial distribution seen above, the stability and emission characteristics of a lean premixed flame (Wang Ping Shih and Santivacca, 1996). The configurations presented are indicated in Table 3. The digital image processing is performed over 200 pictures.

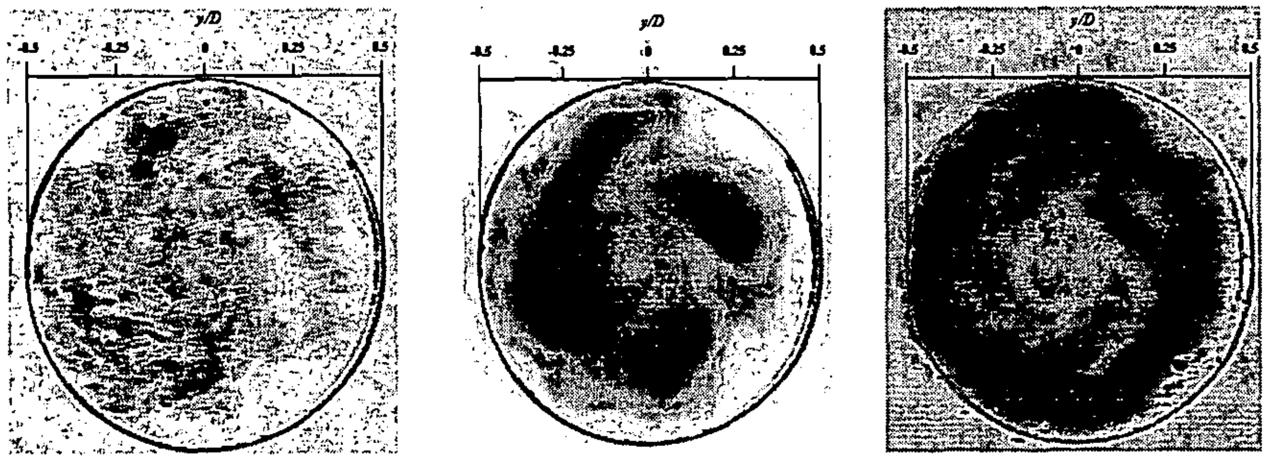
In Fig. 7 and Fig. 8 pictures representing single snapshots, averages, and fluctuations indices (ratio of the RMS and the average) for two configurations are reported. From these figures it can be noted the similarities between the mean distribution, showed in Fig. 8-9 (b) and the results, obtained with the sampling probe, reported in Fig. 4.

A crucial assumption necessary to derive the fuel mixture fraction from the Mie scattering signal is that seeding particles mix and diffuse like fuel molecules. Again, it can be said that the inaccuracies induced by differences between molecular diffusivity and particle diffusivity are negligible since the mixing process is mainly controlled by turbulence (Dugué, 1994).

From the averaged picture (obtained at a sampling rate of 10 Hz) it is evident, in both configuration, the spiraling motion of the fuel embedded in the main flow. The fluctuation index, which is related to the time variation of the fuel concentration, shows a more uniform distribution for the higher AFR. Moreover, it is interesting to note that the fluctuations, in the lower AFR configuration, are concentrated in between the fuel jets. Outward, on either cases, fluctuations arise due also to a condensation process of the aerosol particles.

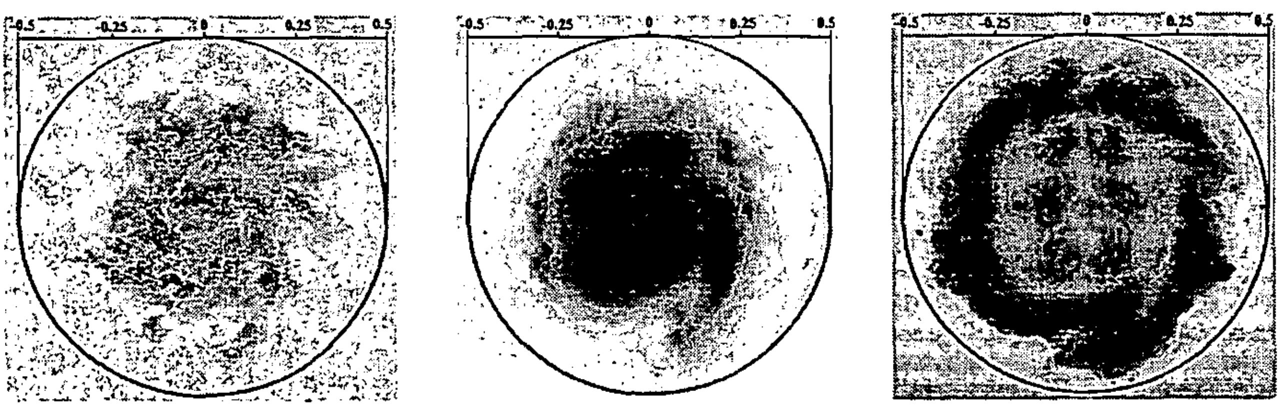
CONCLUSION

A preliminary study of the aerodynamic field and mixing characteristics at the exit of an isothermal model of a premixer is presented. Both of the aspects are strictly connected to NO_x production in lean premixed combustion. The results suggest some detail modification to be checked in future combustion tests. In particular a larger number of fuel injector holes will be examined aiming at a higher degree of fuel air mixing. A promising technique for obtaining gas-mixing picture has been successfully devised and tested.



a) snapshot b) average c) fluctuation index

Fig. 7 Visualization of the fuel mixing at the exit plane (nozzle B)



a) snapshot b) average c) fluctuation index

Fig. 8 Visualization of the fuel mixing at the exit plane (nozzle F)

	Nozzle name	
	B	F
S	0.45	0.69

Table 4 Segregation factor for different configurations (flow visualization results)

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