EFFECT OF AIR STAGING ON A COAXIAL SWIRLED NATURAL GAS FLAME

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Abstract

In the framework of a research program to investigate air staging applied to swirling flames, an experimental investigation aimed at studying pollutant emissions is reported. Staged combustion is accepted as an effective way to reduce nitrogen oxides in gas turbine combustors and, in the present study, is applied to a swirled flame fuelled by natural gas, to analyse the potential for further reducing nitrogen oxides emissions in a coaxial, non-premixed combustor under overall lean conditions.

The results indicate that the full benefits of air staged combustion in swirling flames depend mainly on the method of fuel injection. The most common method of axial injection of a premixed jet into a co-axial swirling airflow does not realize the required fast mixing. By radial injection of the premixed first stage in the secondary co-axial airflow, more efficient and faster centrifugal mixing is achieved, and hence shorter residence time and higher combustion intensity. This fuel injection strategy results in a more stable flame and dramatic reduction of NOx emissions when the first stage equivalence ratio is approaching the stoichiometric value. Still photographs of the flame and isothermal flow patterns are also reported to help correlate flame morphology and mixing features with nitrogen oxides emission.

Introduction

Staged combustion is accepted as an effective way to reduce nitrogen oxides in gas turbine combustors, particularly when burning biomass- or coal-derived gas from integrated gasification combined cycle plant. Although premixed natural gas and air combustion has become a valid method for controlling NO_x emissions, non-premixed combustion is preferable with syngas, due to the high content of hydrogen and the potential for flashback of the flame. The diluted non-premixed combustion has a chemical kinetic limit since the increase in dilution will cause flame instability. To further reduce NO_x emissions, the selective catalytic reduction (SCR) method will not work if the sulphur cannot be removed from the syngas. Among the strategies available for NO_x control, those based on aerodynamically modified combustor design have the advantage of being easy to maintain once installed and staged combustion has been suggested as one of the most effective way of reducing the NO_x emissions, maintaining other pollutants at low levels [1, 2].

Staged combustion can achieve lower NO_x emissions by staging the injection of either air or fuel in the near burner region. The present study is concerned with the first strategy where the combustion air is introduced by two stages, and is aimed at investigating the Rich-Quench, Lean Combustion (RQL) concept, which has been successfully applied for nitrogen oxide reduction in aircraft gas turbine combustors [3]. The RQL idea is to burn the fuel under rich conditions in a premixed primary zone, and then quickly mix with the secondary combustion air in the lean combustion regime. The mixing of the secondary air has to be as quick as possible to minimize combustion residence time near stoichiometric conditions and to avoid thermal NOx formation. Several approaches have been explored, including cross-flow, coaxial mixing, wall-jet configurations [4].

This paper is motivated by the fact that although staged combustion seems to be a well established concept for NO_x reduction, it has not been studied sufficiently. The work is intended as a preliminary effort for the design of low emission micro gas turbines for distributed electrical power generation fuelled with syngas, and the main objective is to investigate air staging applied to coaxial swirling flames to analyse the potential for further reducing nitrogen oxides emissions in a non-premixed burner under overall lean conditions. In our application the coaxial swirled geometry of a pilot-scale burner is used by issuing rich premixed gases in the inner pipe and secondary swirled air in the outer concentric annulus. The specific objectives were: (1) to test the effect of coaxial swirling air on staged combustion, and (2) to test the RQL concept in a simple coaxial geometry.

Since the early times swirling flows have been employed to establish a recirculation zone which entrains the hot combustion products and creates a low velocity zone of sufficient residence time and turbulence levels such that the combustion process becomes self-sustained [5]. The presence of swirl results in a rapid rate of mixing between the incoming air and fuel which reduces the flame temperature and hence lowers NO_x formation. It is also well known that coaxial air provides a significant reduction of the NO_x emission index of a simple jet flame, since it shortens the flame length and reduces the residence time for thermal NO_x to be produced [6, 7]. The simultaneous presence of coaxial airflow and swirl changes the whole dynamics of a jet flame and makes the resulting flow very complicated. It is assumed that swirl increases the rate of fluid entrainment and mixing which significantly reduces the flame temperature below the adiabatic value and hence lowers NO_x formation and increases the flame stability limits [8]. A further important aspect is the method of fuel injection, which affects flame morphology, development and rate of mixing in the primary zone of the burner and pollutant emissions at the exhaust [9, 10]. It has been found that radial (cross-flow) injection produces lower NO_x levels with respect to the most common axial one [11, 8]. The challenge is the selection of the appropriate swirl level and equivalence ratio which, combined with air staging and injection strategy, could ensure the best performances and reduction of NO_x formation at variable thermal power.

On our pilot-scale burner, the swirled non-premixed flame has been already characterised, using a variable mixture of hydrogen and natural gas and the emissions performances explored by varying equivalence ratio and hydrogen content [12]. For the present investigation, air staging has been introduced to study the effect on pollutant formation. In particular, the emissions of NO_x and CO were examined for the effect of several parameters: method of fuel injection, primary jet fuel to air equivalence ratio ranging from the non-premixed reference case (natural gas only) to the near stoichiometric condition, coaxial air-fuel jet momentum ratio (from 140 to 0.3), overall equivalence ratio (from 0.2 to 0.9), thermal power (from 3 to 16 kW), and air swirl level (from 0.8 to 2.1). The changes in these parameters influence not only emissions, but also combustion performances, including flame stability, radiant heat release, mixing of fuel and air, primary flame zone residence time, and flame morphology. It follows that it is quite difficult to isolate the effect of a single controlling quantity. Nevertheless, the investigation has provided useful information on combining staged or RQL combustion and swirling flames, and has enabled clear identification of the influence of the injection strategy, swirl level and associated axial recirculation on the jet mixing in the primary zone. Tests have also been conducted in order to correlate NO_x emissions with flow patterns, combustion efficiencies and flame stability limits. Natural gas was used as a reference fuel to investigate the potential of staged combustion in minimizing pollutant emissions on a high-heating value fuel. In addition to providing more insight into the potential of staged combustion, the results of these studies are also needed for the validation of prediction models.

Experimental set-up

The model burner consists of a central fuel pipe surrounded by an annulus supplying swirled air and characterized by a converging nozzle intended to increase the swirl strength. Fig.1a depicts a schematic drawing of the burner. It has no quarl cone, which is suitable for obtaining full optical access to laser measurements in the close vicinity of the burner exit, and allows the use of two injection typologies of the fuel, axial or radial (Fig.1b and 1c). In the axial configuration, the fuel is injected axially at the centre of the swirling airflow through the inner pipe (L/d ≈ 35, outer diameter 15 mm) which terminates with a diverging nozzle (d_0 = 13 mm) located at the exit plane of the coaxial outer pipe (inner radius, R_b= 18 mm). Radial (transverse) injection is obtained by closing the axial exit and inserting 8 holes, each 4 mm in diameter, symmetrically spaced on the periphery of the pipe. The holes were designed to maintain approximately the same total exit area of the axial nozzle and are located 3 mm upstream from the exit throat of the burner.

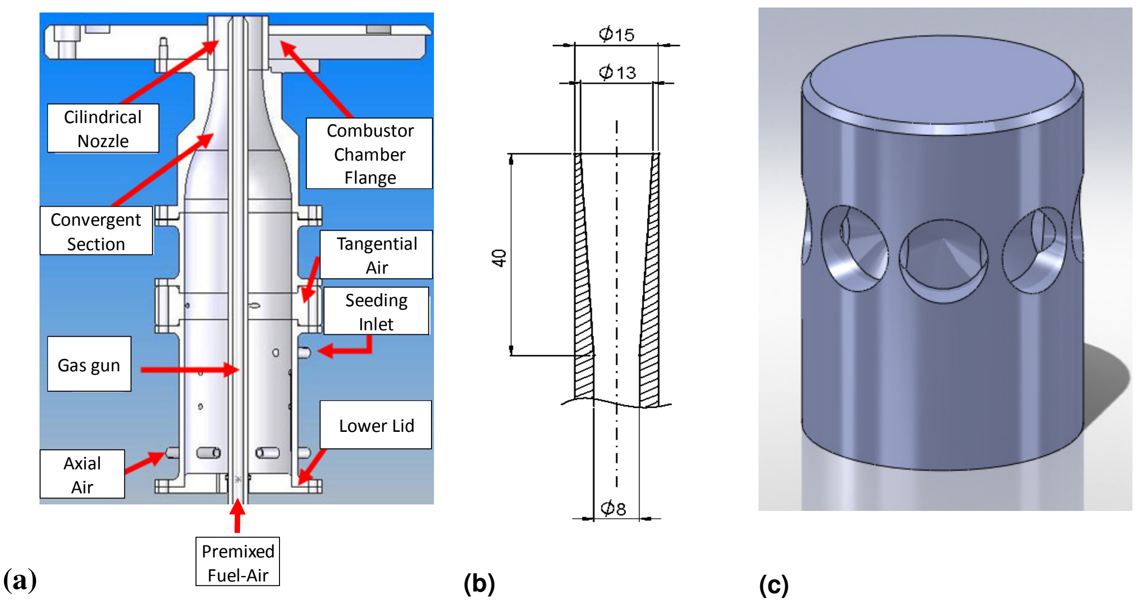


Figure 1. Layout of the burner (a) with two injection typologies: (b) co-axial and (c) radial.

The co-flowing air stream is supplied through axial plus tangential inlet slots, a solution already applied [12, 13], which allows the degree of swirl to be changed by varying the axial and tangential flow rates of air. The axial air enters through four radial inlets in the cylindrical chamber and passes through a honeycomb flow straightener to produce a uniform axial stream. The tangential air is introduced through four tangential inlets to impart angular momentum, upstream from the burner throat. The air is supplied by the laboratory air compressed line and is divided into two separately metered streams to allow continuous control and regulation of the swirl strength at the burner exit. The central jet is either natural gas (non-premixed flame) or a variable mixture of air and natural gas to generate a premixed flame at the nozzle exit, in the air staged version. The premix air and the fuel flow-rates are metered and stabilised by calibrated thermal mass flow-meters and controllers characterised by good accuracy (~ ±1%). The flame is confined in an optically accessible, water-cooled cylindrical combustion chamber (i.d. = 194 mm, H = 600 mm) and a conical exhaust hood is placed directly above the cylinder, with a 4:1 area contraction. A stainless steel probe, mounted on a cylindrical extension of the conical hood, is connected to a gas analyzer for sampling exhaust gas and measuring oxides of nitrogen (chemiluminescence), carbon monoxide (infrared absorption), and oxygen (paramagnetic). The analyzer is calibrated against known concentrations of the gas to be measured.

Particle image velocimetry (PIV) was employed to characterise the near field flow patterns under non-reacting conditions. It has been observed that such patterns give similar trend of the reacting case [9] and therefore isothermal flows were investigated extensively to better understand the mixing of the primary premixed flame with the secondary air and to correlate it with pollutant emissions. PIV measurements were obtained with a double pulsed Nd-YAG laser and a double frame CCD camera, using oil seeding droplets in the 0.2 – 1 μm size range. The cross-correlation algorithm was applied for evaluating the velocity vectors and mean flow maps were obtained averaging 200 instantaneous vector fields. More details on the PIV system are reported in [10]. Still photographs of the flames were also taken to document the large variations of flame morphology and give an idea of residence times.

In the co-axial burner geometry, when the fuel or premixed gas and swirling air are supplied through concentric pipes, the value of the momentum flux ratio (coaxial air to inner jet) $M = M_{ca} / M_j = \rho_{ca} U_{ca}^2 / \rho_j U_j^2$ (where ρ and U are fluid density and axial velocity and the subscripts *j* and *ca* refer to the inner premixed jet and the coaxial air) is commonly used to characterize the mixing regime, together with the swirl number, S. In the present investigation S has been evaluated using axial and tangential velocity profiles measured by laser Doppler velocimetry (LDV) at $h/d_0 = 0.1$, downstream from the exit plane of the burner, with the inner jet switched off. The following equation has been used [5], which assumes that the fluctuating terms are small in comparison with the mean axial and tangential velocity terms, a condition experimentally verified in our case.

$$S = \frac{2\pi\rho \int_{r_i}^{R_B} UW\, r^2 dr}{2\pi\rho\, R \int_{r_{i1}}^{R_b} \left[U^2 - \frac{1}{2} W^2 \right] r dr} \tag{1}$$

In eq.(1) U and W are the axial and tangential mean velocity components of the co-flow air stream; r_i and R_b are the radius of the inner and outer pipe, respectively, and ρ is the air density. With axial plus tangential swirl generators it has been found [14] that it is possible to linearly relate the swirl number S to a geometric swirl number S_g which is defined through the mass flow rates of the axial, m_A, and tangential air, m_T, the total area of the tangential air inlets, A_T, and the radius, R_0, of the burner cylindrical body where tangential air is injected:

$$S_g = \frac{\pi R_0 R_b}{A_T} \left(\frac{m_T}{m_T + m_A} \right)^2 \tag{2}$$

A calibration has been performed by comparing the values of S and S_g at several different conditions and through this calibration we were able to change the total co-flow air rate without changing the swirl number, by adjusting the relative amount of air in the axial and tangential entries.

An overall fuel to air equivalence ratio, Φ_g, was calculated based upon the measured mass flow rates of the fuel (natural gas) and air (primary in the inner pipe plus secondary in the coaxial annulus). A premixed equivalence ratio, Φ_p, was defined based on the flow rates of the fuel and the primary air. The burner was operated at atmospheric pressure and nominal inlet gas temperature of 300 K, in overall lean conditions (equivalence ratio, $\Phi_g < 1$), with input thermal power of less than 16 kW and swirl numbers in the range 0.8< S <2.1.

Experimental procedures

Table 1 and 2 summarizes the representative test conditions selected to illustrate the experimental results with axial and radial injection, respectively. For both the two method of fuel injection, three main parameters were varied independently: the fuel flow rate (thermal power) m_{NG}, the overall equivalence ratio Φ_g and the swirl strength, S. An experimental run proceeded as follows: at each test condition, the thermal power, the overall equivalence ratio and the swirl number were kept constant, while the premix air flow rate was increased from zero until flame blowout occurred and the coaxial air flow was decreased accordingly, in order to maintain Φ_g = const. and S = const. In all the experiments Φ_p varied over a wide range from the non-premixed flame (reference case) to values close to the stoichiometric one.

Table 1. Experimental test conditions with the axial injection.

Test n.	Φ_g	**S**	m_{NG} **[Nl/s]**
1.1	0.48	1.5	0.17
1.2	0.48	2.1	0.17
1.3	0.48	0.9	0.17
1.4	0.62	2.1	0.22
1.6	0.24	1.5	0.08
1.7	0.38	1.5	0.13
1.8	0.71	1.5	0.25
2.1	0.21	1.5	0.10
2.2	0.28	1.5	0.13
2.3	0.58	0.8	0.42

Table 2. Experimental test conditions with the radial injection.

Test n.	Φ_g	**S**	m_{NG} **[Nl/s]**
3.1	0.79	1.9	0.25
3.2	0.62	2.1	0.22
3.3	0.71	1.5	0.25
3.4	0.62	0.9	0.22
3.5	0.60	0.8	0.25
3.9	0.60	0.8	0.16
3.10	0.62	1.5	0.22
3.13	0.62	0.6	0.22
3.14	0.71	0.9	0.25
3.15	0.86	0.9	0.30
3.16	0.95	0.9	0.33

With axial fuel injection, the variation of the primary air in the inner tube affects both the momentum ratio and the equivalence ratio of the premixed jet, and thus the effects of mixing and stoichiometry cannot be separated in our experiments. Fig.2 shows the relationship between Φ_p and M for a selected set of conditions at fixed swirl strength and variable global equivalence ratio. It can be noticed that in any case Φ_p decreases when the momentum of the inner jet increases. The increase of M_j has significant influence on the swirl induced central recirculation zone (CRZ) and the selection, in the present experiments, of high swirl levels, above the critical value for the inception of the CRZ, was intended to maintain a sufficient recirculation even at low Φ_p and high premixed jet momentum flux. The decrease of M has also important consequences on the mixing of the inner jet with the co-flowing secondary air; larger values of M implies faster mixing and shorter flames. With radial fuel injection, the momentum ratio has a different meaning since it indicates the penetration of the jets into the co-flowing secondary air, although it can still be related to the mixing efficiency.

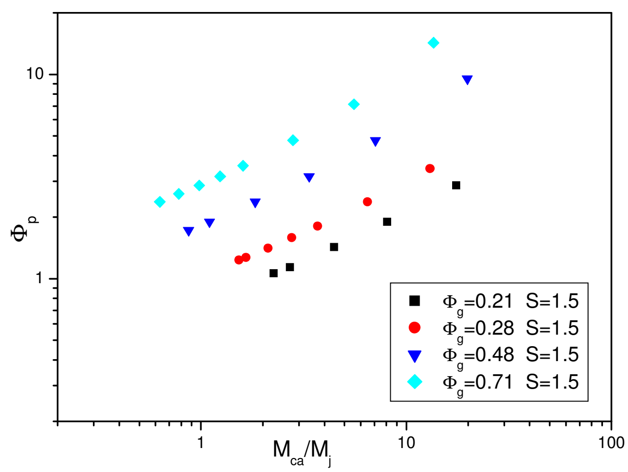


Figure 2. Relationship between Φ_p and M for a set of conditions at fixed swirl strength (S=1.5) and variable global equivalence ratio Φ_g. Axial injection.

Combustion Results

The presentation of the results is divided in two sections relative to the axial injection mode and the radial one. The NO_x emissions and the flame morphologies resulted very different and need a separate discussion. In all the cases the measured NO_x and CO levels were referred to 3% excess oxygen on a dry basis. Time mean values averaged over a period of 60 s are reported; the measurements were checked for repeatability and the maximum deviation was within ±3% of the full scale.

Axial injection

The flame morphology changes drastically from the reference case of non-premixed coaxial flame with the progressive increase of the air flow in the inner tube to generate a reach premixed first stage. The photographs shown in Fig. 3 illustrate the transformation from the non-premixed swirl dominated flame (Fig.3a) into a jet-like partially premixed flame (Fig.3b), almost insensitive to the swirl motion, as indicated by the reduction in the initial cone angle. Increasing the premix air flow rate, that means going toward a leaner condition (Φ_p = 2), the soot region disappears and the flame length reduces significantly (Fig.3c).

a) non-premixed, M =50 **b) Φ_p = 10.7; M = 7.2** **c) Φ_p = 2.4; M =0.63**

Figure 3. Photographs of the flame with axial injection: S = 1.5; Φ_g = 0.71; exp. time =10 s.

In this type of flames, the NO_x concentration at the exhaust follows a common trend: it increases or stays almost constant with the progressive addition of air to the central fuel jet, and consequent decrease of Φ_p and M, and then shows a slight decay for a fuel equivalence ratio of the premixed jet around $\Phi_p = 2$. Similar behaviour has been already observed in laminar [15] and swirled [16] partially premixed flames. Some indicative cases are reported in Fig.4, relative to four different global equivalence ratios and a swirl level S = 1.5. In the range $1 < \Phi_p < 2$, we found the blowout limit of the investigated flames, due to the increasing strain rate with increasing primary air. The limit is reduced by the air co-flow velocity and improved by the air swirl as already observed in turbulent jet diffusion flames [7, 17].

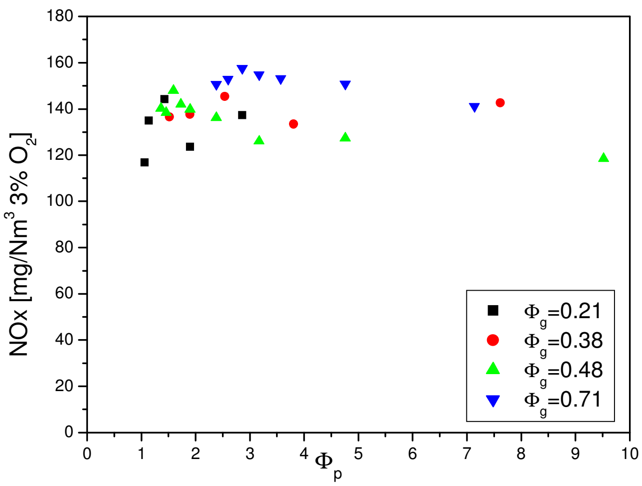


Figure 4. Concentrations of NOx (referred to 3% excess oxygen) vs equivalence ratio of the premixed jet, for several global equivalence ratios, at fixed swirl: S = 1.5.

It has been observed in coaxial flames [6] that NO_x are substantially reduced with increasing the momentum ratio $M=M_{ca}/M_j$ and this reduction is attributed to the decrease of the residence time. Recent studies on hydrogen jet flames with coaxial air [18] also indicate that the NO_x concentration decreases as M increases due to mixing enhancement. All these considerations hold when M > 1 which is not always the case in our experiment. Other differences with the present case are due to the air staging configuration, the presence of swirl and the use of natural gas as fuel. Nevertheless, we also found that the NO_x emissions are related to the momentum ratio M, indicating a strong influence of the mixing process between the inner jet and the co-flowing secondary air stream.

The entire set of measurements performed with axial fuel injection is summarized in Fig.5, and the results show that the momentum ratio, defined at burner exit without combustion, is the main parameter affecting the NO_x formation, more than the swirl level and the global equivalence ratio. It can be observed that NO_x emissions generally increase, with different slopes depending on the operating conditions, when M decreases down to M ~ 1, where they reach a common maximum value. For M < 1 the NO_x emissions start to decrease, following the same trend, independently from the swirl level and the global equivalence ratio. Obviously the momentum ratio is strictly related to the equivalence ratio of the premixed jet and depends also on the global equivalence ratio, as previously shown in Fig.2. A similar trend was found in a staged hydrogen flame [19] and this suggests that the NO_x emission mostly depends on the mixing rate of the premixed flame with the coaxial air in the secondary combustion zone. Actually, the condition M ~ 1 is the worst from the point of view of mixing of two coaxial streams. When M decreases further below unity the premixed jet will tend to entrain the coaxial air and thus the inner flame is sustained by more oxygen, becomes shorter (more intense combustion) and more similar to a premixed flame (see Fig.3c).

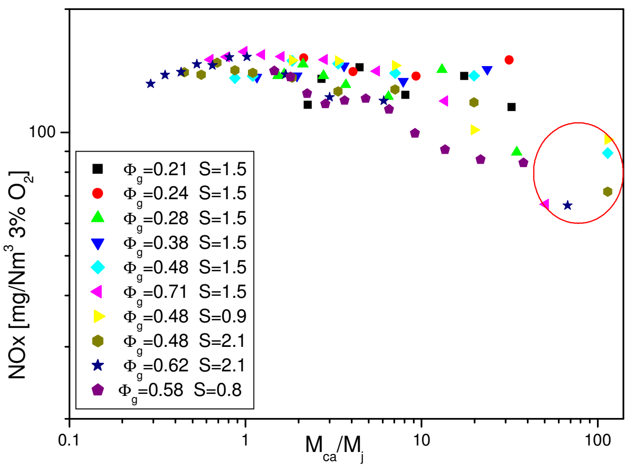


Figure 5. NOx emissions (referred to 3% excess oxygen) vs. the momentum flux ratio (air to jet) for all the investigated conditions with axial injection. The points enclosed in the red circle refer to the non-premixed reference case.

It must be noticed that the original NO_x level of the reference cases (non-premixed flames) is always lower than that measured in the present staged flame configuration with axial injection. The relative values are reported in Fig.5, enclosed in the red circle. In all the above cases the CO concentration resulted relatively high in the non-premixed flames (with maxima of the order of 3000 mg/Nm^3), but rapidly reduces to values lower than 200 mg/Nm^3 as the equivalence ratio of the premixed jet reduces down to the stoichiometric value.

Radial injection

The radial injection of fuel or the mixture of fuel and air produces a different morphology of the flame as illustrated by the photographs of Fig.6 for three values of the equivalence ratio of the premixed stage. As a general result, the pictures show no visible soot emission, the flame is compact, maintains a tulip shape due to the axial recirculation induced by the swirl, and reduces in size when the flow rate of the premixed air increases. An additional observation is that the flame becomes more stable as the premixed air fraction increases and the reaction zone moves upstream toward the burner throat.

a) **Non-premixed** **b)** **Φ_p = 8** **c)** **Φ_p = 2**

Figure 6. Photographs of the flame with radial injection: S = 0.9; Φ_g = 0.86; exp. time = 10s.

The visible flame volume is also indicative of the residence time and its progressive decrease with Φ_p should anticipate a parallel reduction of the NO_x emissions. This is actually observed, independently from the global equivalence ratio, as indicated in Fig.7. The NO_x

emissions firstly increase when Φ_p decreases, but then show a very rapid and dramatic reduction (almost one order of magnitude) when Φ_p ranges between 2 and 4. In this range, the NO_x values are much lower then those measured in the reference case of the non-premixed flame and the emission reduction is more effective when Φ_g is larger than 0.7. The abrupt reduction of NO_x formation rate when $\Phi_p < 4$ cannot be only explained with the residence time in the reaction zone. More complex explanations should be necessary implying chemical kinetics and fluid dynamics of the mixing between the premixed flame and the secondary coaxial air. It seems that the RQL concept works with this particular mode of injection which combines with the swirl to assure a fast and efficient mixing.

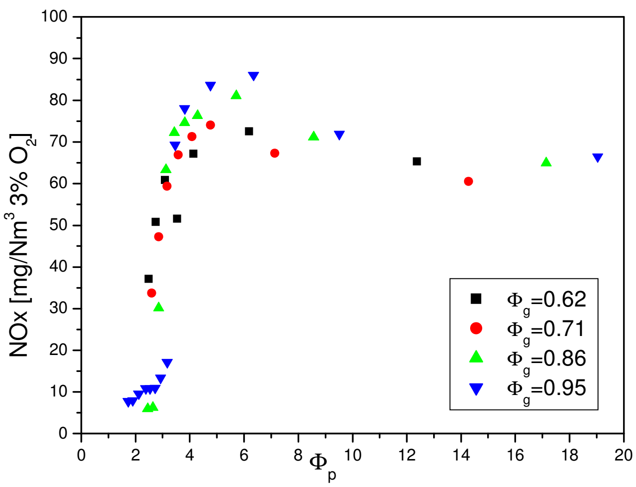


Figure 7. NOx emissions vs equivalence ratio of the premixed jet for various global equivalence ratios and fixed swirl: S = 0.9. Radial injection.

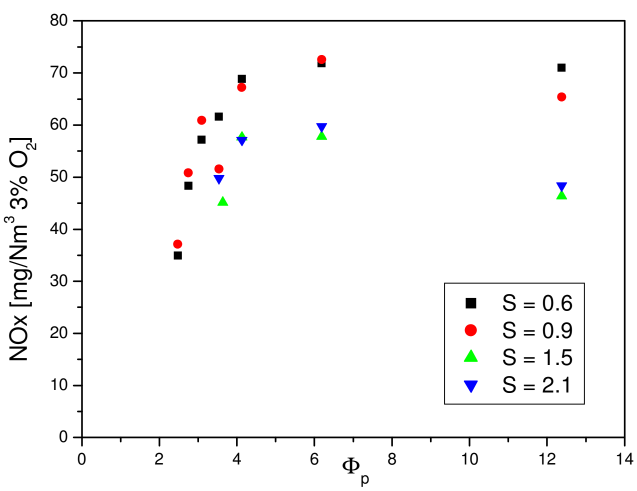


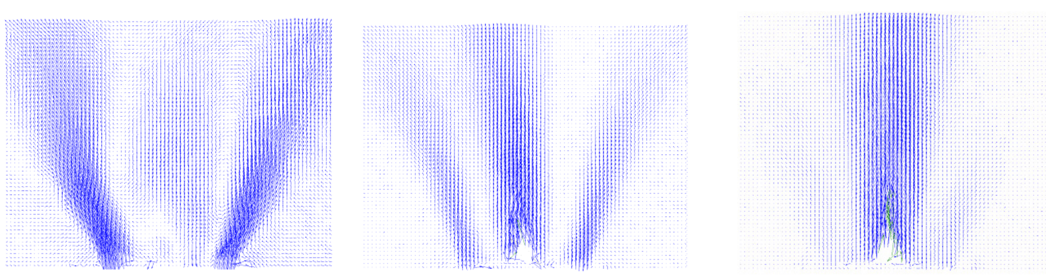
Figure 8. NOx emissions vs equivalence ratio of the premixed jet for various degree of swirl and fixed global equivalence ratio, Φ_g = 0.62. Radial injection.

The effect of swirl on the NO_x formation is illustrated in Fig.8. It is well known that the swirl intensity has a strong effect on non-premixed flames in which very low levels of NO_x can be obtained at higher swirl. The staging alters the NO_x concentration levels in different ways depending on the swirl strength, although a systematic rapid decrease of NO_x emissions for $\Phi_p < 4$ is a common feature of this type of flame. The decrease is proportionally larger when $S < 1$, also because the flame has a larger stability range extending down to $\Phi_p \cong 2$. Higher swirl levels tend to favour the flame blowout, particularly under lean global conditions and thus the operating range with very low NO_x emission levels cannot be reached.

In the case of radial injection, the CO concentration follows an opposite trend with respect to the axial injection. It was found always lower than 200 mg/Nm^3 in the non-premixed flames and remained very low as far as the premixed flame equivalence ratios was $\Phi_p \geq 2$. Just before flame blowout, it was observed a sudden increase to values close to 3000 mg/Nm^3, indicating a non complete combustion regime.

Flow Patterns Results

Particle image velocimetry (PIV) was employed to characterise the near field flow patterns under non-reacting conditions to better understand the mixing of the primary flame with the secondary air and to correlate it with pollutant emissions. Fig.9 shows the average flow patterns measured on a vertical cross-section of the burner in the case of axial injection, for different coaxial air to inner jet momentum ratios. In the reference case, the non-premixed flame (Fig.9a), the flow consists of a central recirculation zone (CRZ) surrounded by an annular jet containing the swirling secondary airflow. The high-velocity gradients enhance the shear forces at the secondary airflow boundaries, leading to higher mixing and combustion rates. These features are attenuated when M decreases, due to the increase of the premixed air, and the flow results in the intense inner jet associated with the premixed flame and almost insensitive to the swirling air (Fig.9b). The three PIV maps indicate a transition from the standard swirl flow of the non-premixed reference case to a jet flow for $M < 1$, corresponding to an equivalence ratio of the premixed flame, $\Phi_p = 1.5$ (Fig.9c). It has already been shown [9] that, as the central jet velocity increases, the strength of coherent structures formed by the co-flow swirling air are negatively impacted.



a) Non-premixed, M = 114 **b) Φ_p = 2.5 M = 1.8** **c) Φ_p = 1.5 M = 0.8**

Figure 9. Isothermal flow patterns in the near field of the burner for various equivalence ratios of the first stage, under axial injection mode. Test case n.1.1; S = 1.5.

In the radial injection mode the flow pattern is very similar to the previous one in the non-premixed case, but it looks substantially different when the premixed air is added and further increased. The cross-flow type of mixing of the individual jets penetrating into the coaxial stream alters the axial and tangential velocity distributions of the air co-flow, depending on the momentum ratio, but maintains the main features of the swirling flow, with the CRZ, as shown in Fig.10. Actually, the effect of increasing the premixed air flow is the reduction of the CRZ dimension and the formation of a double vortex very close to the burner exit. The effect of swirl on the size of the CRZ was found to be significant with this mode of injection due to the increased influence of centrifugal forces. Comparing with the photographs in Fig.6, it can be observed that the flame surface is confined by the inner boundaries of the swirling airstream and reduces in the same manner as the vortical structure when the premixed equivalence ratio reduces, approaching the stoichiometric value.

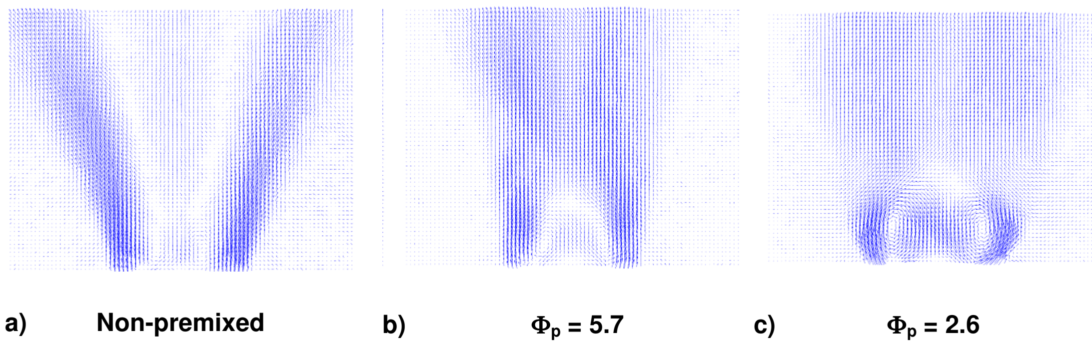


Figure 10. Isothermal flow patterns in the near field of the burner for various equivalence ratios of the first stage, under radial injection mode. Test case n. 3.15; S = 0.9.

Conclusions

An experimental investigation aimed at reducing pollutant emissions by air staging applied to swirling flames has been performed. Air staging has been applied to a swirled flame fuelled by natural gas, to analyse the potential for further reducing nitrogen oxides emissions in a coaxial, non-premixed combustor under overall lean conditions.

The results indicate that the full benefits of air staged combustion in swirling flames depends mainly on the method of fuel injection. The most common method of axial injection of a premixed jet into a co-axial swirling airflow does not realize the required fast mixing, while the radial injection in the secondary airflow results in a faster and more efficient centrifugal mixing. Hence, the Rich-Quench, Lean Combustion (RQL) concept is more properly satisfied. The radial fuel injection strategy results in a more stable flame, shorter residence time, higher combustion intensity and dramatic reduction of NO_x emissions when the first stage equivalence ratio satisfy the condition $\Phi_p < 4$.

Particle image velocimetry (PIV) was employed to characterise the near field flow patterns under non-reacting conditions and to correlate the mixing of the primary flame with the secondary air. This allowed to better understand pollutant emissions behaviour. The cross-flow type of mixing of the individual jets and the coaxial stream alters the axial and tangential velocity distributions of the air co-flow, depending on the momentum ratio and jet penetration at the fuel injection section, but maintains the main features of the swirling flow. The effect of increasing the premixed air flow is the reduction of the axial recirculation zone and the formation of a double vortex very close to the burner exit. Comparing with the photographs, it has been observed that the flame surface is confined by the inner boundaries of the swirling airstream and its volume reduces when the premixed equivalence ratio is reduced. This favours a reduction of the residence time.

Detailed study of chemical kinetics and fluid dynamics of the mixing between the premixed flame and the secondary co-axial airflow are necessary to fully understand the present results. Moreover, more work is needed to optimize the overall equivalence ratio and the swirl strength to achieve the best combustion performances with a minimum level of NO_x and CO emissions and wider operating range.

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