AIR STAGING IN A SWIRLED NATURAL GAS BURNER WITH RADIAL INJECTION

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Abstract
The present work describes the experimental investigation on NO_x emissions of partially premixed flames characterised by air staging through radial injection of premixed jets into a co-flow swirling air. NO_x emissions were found to increase with increasing partial premixing and reach a maximum value at $\Phi_p \approx 5$, followed by a dramatic decrease as Φ_p approaches values ≈ 3. In the most favourable conditions, single digit NO_x levels were reached without penalizing combustion performances or increasing CO emissions. The effects of staging on the amount of NO_2 found at the exhaust were also examined and the results corroborate the idea that NO_2 is formed in the turbulent mixing region, favoured by the increasing cooling rate of the combustion gas by entrainment of cold unburned gas. PIV measurements of the isothermal flow field are used to confirm the analysis and to better understand how the emissions are related to the turbulent mixing of the premixed first stage with the secondary swirling air.

Introduction
Staged combustion has been suggested as an effective way to reduce nitrogen oxides in gas turbine combustors, particularly when burning low calorific value (LCV) gas derived from agricultural wastes [1-7] or coal-derived gas from integrated gasification combined cycle plant. Staged combustion can achieve lower NO_x emissions by staging the injection of either air or fuel in the near burner region. Mixture formation can be improved by burning in a swirling flow and employing the recirculation region to control fuel-air mixing and promote flame stabilization [8-10]. The primary objective of our research project is to investigate air staging obtained through radial injection of premixed jets into a cross-flow swirling air. Staged combustion has been already explored by testing two different methods of fuel injection [11] and the results indicate that appreciable benefits of air staged combustion in swirling flames can be obtained by transverse injection of the premixed first stage in the secondary swirling cross-flow.

Experimental set-up and procedures
The pilot-scale air-staged swirl burner used in the present investigation has been already described [11]. It is composed of two concentric pipes separately supplied by the fuel mixture and a surrounding swirling co-flow of air. The fuel is supplied along the inner pipe ($L/d \approx 35$, 8 mm i.d. and 15 mm o.d.) into an injector which

can be varied in geometry and shape, allowing to explore different injection strategies and mixing tipologies, i.e. axial or radial staging. The radial injection, used in the present investigation, is obtained by blocking off the axial exit and inserting 8 holes, each 4 mm in diameter, symmetrically spaced on the periphery of the pipe, and located ~ 4 mm upstream from the exit throat of the coaxial annular duct. Natural gas (non-premixed flame) or a variable mixture of air and natural gas (air staging configuration) are feed through the holes to inject fuel or premixed jets normally into the swirling cross-flow. The premix air and the fuel flow-rates are metered and stabilised by calibrated thermal mass flow-meters and controllers (accuracy ~ ±1%). The flame is confined in an optically accessible, water-cooled cylindrical combustion chamber (i.d.=194 mm, L=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, extracts flue gas to measure the global emission performance of the burner. The probe is connected to a gas analyzer for measuring oxides of nitrogen (chemiluminescence), carbon monoxide (infrared absorption), and oxygen (paramagnetic). The sampling line is preheated and insulated to prevent condensation of post-combustion products. The analyzer is calibrated against known concentrations of the gas to be measured.

Particle image velocimetry (PIV) is employed to characterise the near field flow patterns under non-reacting conditions. More details on the PIV system are reported in [10]. Still photographs of the flames are also taken to document the large variations of flame morphology and to compare with the PIV maps. The burner is operated at atmospheric pressure and nominal inlet gas temperature of 300 K, in overall lean conditions (equivalence ratio, $0.6 < \Phi_g < 0.95$), with input thermal power ≈ 10 kW and swirl numbers in the range $0.6 < S < 2.1$. We introduce an overall fuel to air equivalence ratio, Φ_g, based upon the measured mass flow rates of the fuel (natural gas) and total air (primary in the inner pipe plus secondary in the coaxial annulus), and a premixed equivalence ratio, Φ_p, defined based on the flow rates of the fuel and the primary air. At each test condition the premix air flow rate was increased from zero (non-premixed flame) to values close to the stoichiometric one, until flame blow off occurred, and the coaxial air flow was decreased accordingly, in order to maintain Φ_g = const. and S = const.

In the cross-flow geometry, the value of the momentum flux ratio (fuel or premixed gas to swirling air flowing in the concentric annulus), ore better its square root, is commonly used to characterize the jet penetration and mixing regime [12, 13]:

$$J = \sqrt{\rho_J U_J^2 / \rho_{AS} U_{AS}^2} \tag{1}$$

where ρ and U are average fluid density and axial velocity and the subscripts *J* and *AS* refer to the normally discharging premixed jet and the swirling secondary air. This quantity, together with the swirl number, S, are used to characterise the test

conditions. In all the investigated cases, the variation of the primary air affects both the momentum flux ratio and the equivalence ratio of the premixed jets, and thus the two parameters cannot be varied independently and the effects of mixing and stoichiometry cannot be separated in our experiments. In any case Φ_p decreases when the momentum of the inner jet increases.

NOx and CO Emissions

The measured NO_x and CO concentrations, referred to 3% excess oxygen on a dry basis, are reported in Fig.1 and 2 as a function of Φ_p, for variable global equivalence ratio Φ_g and swirl strength S. Fig.1 indicates that in the present experimental setup air staged combustion can provide a significant reduction of NOx emissions when the premix equivalence ratio Φ_p reduces to ≈3, independently of Φ_g and S. However, flame blow off occurred at high swirl strength (S > 1) and low global equivalence ratio ($\Phi_g < 0.8$), before the critical value of Φ_p could be reached, confirming that leaner flames are more susceptible to blow off at the higher swirl [10]. Blow off may be ascribed to the presence of high strain and localized extinction as a consequence of the turbulent interaction of transverse injection into a swirling cross-flow. For all the test cases, the NO_x emissions present a maximum for $\Phi_p \approx 5$ and reduce steadily with increasing levels of Φ_p toward the non-premixed flame condition ($\Phi_p \rightarrow \infty$) indicated on the right side of the graphs. It can be observed that higher swirl is beneficial in reducing NO_x for non-premixed flames and flames with a rich premixed stage, higher than $\Phi_p \approx 5$. The trends in the variation of NO_x with Φ_p agree with those observed in other swirling flames [8], with the minimum reached at $\Phi_p \leq 3$. The decrease of NO_x may be attributed to a reduction of prompt NO through reduced residence time and flame temperature increase for $\Phi_p \leq 3$ which shifts NO_x production from prompt towards thermal [8].

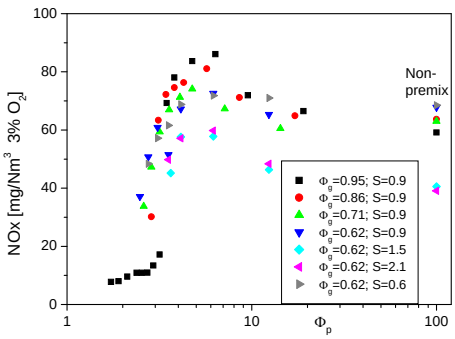


Figure 1. NO_x emissions vs. Φ_p.

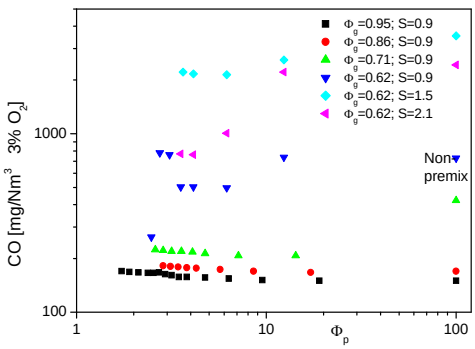


Figure 2. CO emissions vs. Φ_p.

The CO levels, shown in Fig.2, were found higher only in overall lean conditions and higher swirl strength, suggesting a quenching effect on the CO to CO_2 conversion due to an increase in secondary air, decrease in residence times and localized extinctions. In non-premixed swirling flames a reduction in NO_x is generally accompanied by an increase in CO emissions [14], while in the present case, the combination of a partially premixed first stage with swirling secondary air indicates that reduction of NO_x can be achieved at an optimum level of premixing before the CO emissions increases in the proximity of flame blow off.
The effects of staging on the amount of NO_2 found at the exhaust were also examined and Fig.3 reports the NO_2/NO_x ratio measured in the flue gas. It can be observed that Φ_g has a marked influence on the NO_2/NO_x ratio, particularly at higher values of Φ_p; in the leaner cases the ratio is always higher than 0.8. For Φ_g = 0.71 the ratio decreases with Φ_p, reaches a minimum around Φ_p = 3 and then increases. For higher values of Φ_g the trend is the opposite: the ratio remains low for $\Phi_p > 5$ and then increases abruptly in the region where a rapid decrease of the absolute value of NOx has been observed. Thus, the absolute values of NO_2 remain very low, but their relative amount grows to more than 50% of NO_x. Past studies on nitrogen dioxide formation in combustion systems provide evidence that it is mainly due to the HO_2 mechanism during the rapid cooling of hot combustion gas with cold air [15]. Actually, in our swirl burner the reduction of Φ_p implies an increase of the momentum of the premixed jets and a deeper penetration in the secondary swirling air. This induces a larger entrainment and faster cooling of the premixed flames in the secondary stage of the combustion process.

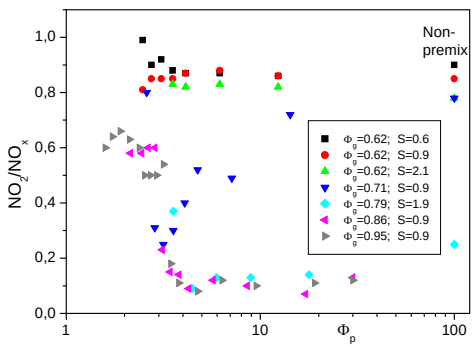
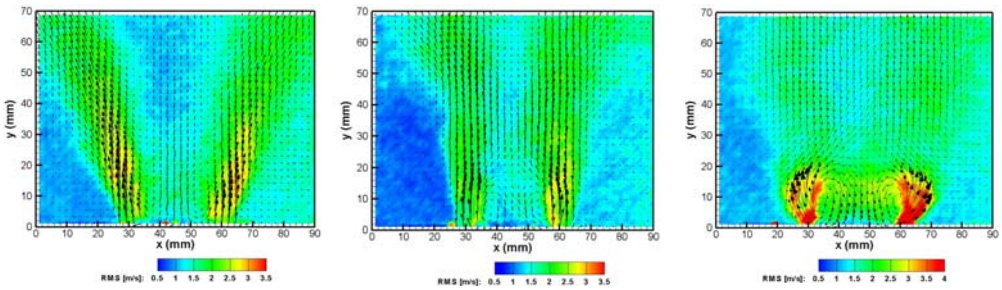


Figure 3. The NO_2/NO_x ratio at the exhaust vs. Φ_p for variable Φ_g and S.

Flow Patterns

In order to improve the understanding of these results, isothermal flow patterns measured by PIV in the mid plane of the burner have been acquired in the region near the burner throat and three representative examples are reported in Fig.4. At large values of the primary equivalence ratio corresponds a quite low momentum

flux ratio and thus the premixed jets experience poor penetration and low entrainment of the secondary airflow. This is confirmed by the flow pattern in Fig.4a showing that the recirculation zone at the burner exit, originated by the swirling motion, still remains intact and the disturbances created by the jets die off quickly. The corresponding flame has no visible soot emission and shows the typical tulip shape, quite similar to the non-premixed flame with normal injection [9]. Under this condition, the NOx emission is not affected by air staging and remains close to or higher than the corresponding non-premixed flame (Fig.1).



a) $\Phi_p = 12$; J = 0.7 **b)** $\Phi_p = 6$; J = 1.2 **c)** $\Phi_p = 2.4$; J = 2.8

Figure 4. PIV isothermal flow patterns; $\Phi_g = 0.62$; S = 0.9. Averaged 2-D velocities (arrows) and turbulence intensity (colours).

As far as the equivalence ratio of the premixed stage reduces ($\Phi_p \approx 6$), the momentum flux ratio becomes sufficiently large (J≈1.2) to provide larger penetrations of the premixed jets into the swirling airstream and this affects the flow structure and swirl strength. The effect, observed in the PIV pattern (Fig.4b) is a weakening of the flow rotation with a prevailing axial direction of the airstream and a decrease in the extension of the central recirculation zone (CRZ) which seems restricted to the wake of the central bluff body. The turbulence intensity is lower, indicating poor mixing. Similarly, the flame radial extension is reduced and the flame shows an elongated structure. Under these conditions, NO_x emissions have their maximum and air staging looks less attractive than the reference non-premixed combustion (see Fig.1).

Further increase of the momentum flux ratio (J=2.8) produces a deeper penetration of the primary jets into the swirling flow with higher entrainment rate and faster mixing. The corresponding flow map is shown in Fig.4c, together with the axial turbulence intensity, and suggests that the jets interaction with the swirling air flow reduce the intensity of the circumferential motion. The pattern reveals the formation of intense vortical structures in the wake of the jets, associated with strong turbulence on the external edges of the vortices and thus better mixing of the primary flames with the secondary air. The corresponding flame image shows individual premixed flames anchored to the surface of the inner pipe, extending

along the vortical structures. This condition is associated with the rapid decrease of the NO_x concentrations and could be attributed to an efficient attainment of the following condition: 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 measured flow field and the flame photographs corroborate the hypothesis of a reduction of NO_x through reduced global residence time of the combustion products in the hottest zone and the formation of NO_2 in the turbulent mixing region surrounding the vortical structures, favoured by the increasing cooling rate of the combustion gas by entrainment of cold unburned gas.
In conclusion, it seems that a range of conditions exists where air staging can significantly reduce NO_x emission down towards single digit values, with no significant increase of the CO production.

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