Abstract
The present work describes the experimental investigation on NO\textsubscript{x} emissions of partially premixed flames characterised by air staging through radial injection of premixed jets into a co-flow swirling air. NO\textsubscript{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 $\Phi_p$ approaches values $\approx 3$. In the most favourable conditions, single digit NO\textsubscript{x} levels were reached without penalizing combustion performances or increasing CO emissions. The effects of staging on the amount of NO\textsubscript{2} found at the exhaust were also examined and the results corroborate the idea that NO\textsubscript{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\textsubscript{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 \( \sim 4 \) 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 \( \sim \pm 1\% \)). 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 \( \approx 10 \) kW and swirl numbers in the range \( 0.6 < S < 2.1 \). We introduce an overall fuel to air equivalence ratio, \( \Phi_g \), 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, \( \Phi_p \), 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 \( \Phi_g = \text{const.} \) and \( S = \text{const.} \).

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

\[
J = \sqrt{\frac{\rho_j U_j^2}{\rho_{AS} U_{AS}^2}}
\]  

where \( \rho \) 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 \( \Phi_p \) 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 \( \Phi_p \), for variable global equivalence ratio \( \Phi_g \) and swirl strength \( S \). Fig.1 indicates that in the present experimental setup air staged combustion can provide a significant reduction of NO\(_x\) emissions when the premix equivalence ratio \( \Phi_p \) reduces to \( \approx 3 \), independently of \( \Phi_g \) 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 \( \Phi_p \) 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 \( \Phi_p \) 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 \( \Phi_p \) 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. \( \Phi_p \).](image1)

![Figure 2. CO emissions vs. \( \Phi_p \).](image2)
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 CO₂ conversion due to an increase in secondary air, decrease in residence times and localized extinctions. In non-premixed swirling flames a reduction in NOₓ 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 NOₓ 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 NO₂ found at the exhaust were also examined and Fig.3 reports the NO₂/NOₓ ratio measured in the flue gas. It can be observed that Φₔ has a marked influence on the NO₂/NOₓ ratio, particularly at higher values of Φₚ; in the leaner cases the ratio is always higher than 0.8. For Φₔ = 0.71 the ratio decreases with Φₚ, reaches a minimum around Φₚ = 3 and then increases. For higher values of Φₔ the trend is the opposite: the ratio remains low for Φₚ > 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 NO₂ remain very low, but their relative amount grows to more than 50% of NOₓ. Past studies on nitrogen dioxide formation in combustion systems provide evidence that it is mainly due to the HO₂ mechanism during the rapid cooling of hot combustion gas with cold air [15]. Actually, in our swirl burner the reduction of Φₚ 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](image-url)

**Figure 3.** The NO₂/NOₓ ratio at the exhaust vs. Φₚ for variable Φ₄ 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).

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 (\( J \approx 1.2 \)) 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, NOx 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\textsubscript{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\textsubscript{x} through reduced global residence time of the combustion products in the hottest zone and the formation of NO\textsubscript{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\textsubscript{x} emission down towards single digit values, with no significant increase of the CO production.

References