ISSN: 2321-0869 (O) 2454-4698 (P), Volume-15, Issue-1, January - June 2025

Characterization of Pollutant Emissions in Diffusion and Premixed Natural Gas Burners

Giulio Solero

***Abstract*— This paper describes the measurement of pollutant emissions (nitric oxides and carbon monoxide) in different natural gas burners: particularly, a swirl burner with different fuel injection typologies (co-axial and radial injection, with respect to the rotating air stream) and a premixed burner have been taken into account. As for the premixed burner, pollutant emissions have been related with thermal characterization of the reactant zone performed by thin thermocouples. In this case, a strong correlation with temperature and equivalence ratio has been observed. At the contrary, the swirl burner presents a strict dependence from the value of the air stream swirl number, which plays an important role for flame stabilization and fluid dynamic mixing process in the primary flame zone. Moreover, the radial injector in the swirl burner contributes to a general decrease of pollutant emissions, behaving similarly to the premixed burner, also as for the trend of CO and NOx emissions versus the equivalence ratio.**

***Index Terms*—Natural Gas Burners, Pollutant Emissions, Premixed Burners, Swirl Burners**

I. Introduction

Mixing process among fuel, air and hot flue gases controls the main combustion performances, such as flame stability and pollutant emissions. In fact, it is well known [1] that premixed combustion, in lean or ultra-lean conditions, improves combustion performance relatively to pollutant formation, with respect to a diffusion flame. That's why diffusion flames often require fluid dynamic strategies (swirl motion imparted to the air stream) to improve the reactants mixing process and ensure high combustion efficiency [2]. Environmental impact of combustion processes is nowadays one of the most important problems involving both scientific community and burner manufacturers. In the case of natural gas combustion, nitric oxides (NOx) reduction is the most critical aim to achieve, often requiring for industrial applications heavy and high-cost plant revamping (for instance, adoption of low-NOx burners or burned gases de-NOx treatment [3, 4]). Moreover, although NOx formation mechanisms are today quite understood [5], many unsolved questions are connected to the interaction between fluid dynamic and chemistry inside the burner device [6] and this makes the CFD codes not yet fully predictive.

II. Experimental Apparatus

This paper presents the results obtained as for pollutant emissions (nitric oxides and carbon monoxide) upon two different natural gas burner typologies: a swirl burner equipped alternatively with two different fuel injectors (co-axial or transverse with respect to the rotating air stream) and a premixed burner with a flame generated downstream a metallic grid. The analysis has been carried out varying the operating conditions of the devices (equivalence ratio, swirl number).

For both burners, burned gases have been sampled for analysis of the pollutant emissions through chemiluminescence for NOx and infrared analysis for CO. Moreover, a thermal analysis of the premixed burner behaviour has been performed by thin thermocouples, in order to relate the thermal field with pollutant measurements,

As for diffusion flames, the experimental apparatus is a laboratory-scale swirl burner (Fig. 1). The fuel is delivered by a central tube, while the swirling air flow is provided by a coaxial annulus. Details regarding the investigated burner typology are reported in [7]. Air swirl motion is imparted through an axial plus tangential air entry. The variation of the relative amounts of axial and tangential air flow controls the intensity of the swirl. The aerodynamic swirl number has been evaluated in isothermal conditions by integration of the velocity profiles measured at the efflux by LDV, as reported in [8]. Two different swirl intensities have been investigated: S=0.55 corresponding to medium swirl strength and S=0.84 corresponding to high rotation intensity with generation of a CTRZ (Central Toroidal Recirculation Zone) at the efflux, which enhances mixing efficiency between reactants and consequent flame stability, as reported in [9-10]. All tests were performed at ambient pressure, with the flame confined by a cylindrical quartz chamber (192 mm in diameter, 300 mm in height). The burner can be alternatively equipped with an axial or a radial injector that provides fuel admission transversal to the air stream and it is designed with eight circular holes. The radial injection creates a more stable flame in comparison to the axial injection. The different injection typologies are reported in Fig. 2.

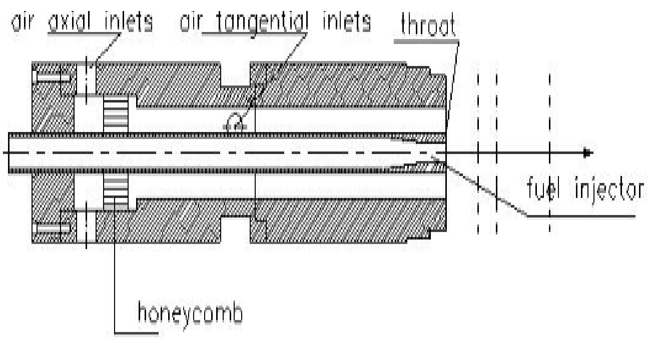

Fig. 1: schematic view of the investigated swirl burner.

Giulio Solero, Department of Energy, Politecnico di Milano, Milano, Italy,+39 02 23998562,.

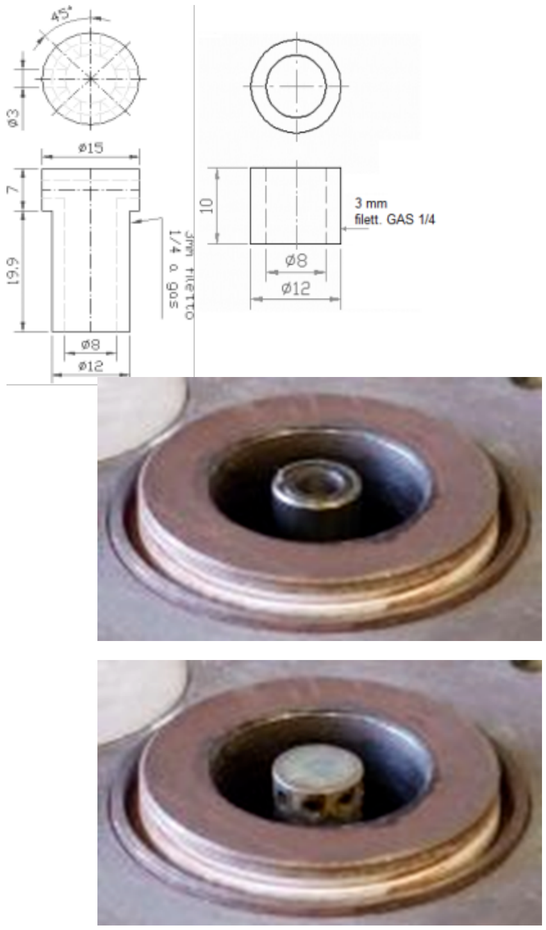

Figure 2: the radial and co-axial nozzle; dimensions are in millimeters.

Radial injector has been designed so as to reproduce (with respect to the axial one) similar Reynolds and momentum ratio. Tab. 1 reports the main operating conditions used for the experimental measurements described in this paper.

Air flow rate [g/s]	8.8
Reynolds number of air jet	20700
Reynolds number of natural gas jet	5600
Input thermal power [kW]	15
Air swirl number S	0.84 - 0.55
Fuel/Air Momentum ratio MR	0.91
Fuel/Air Equivalence ratio Φ	0.60 – 0.90

Tab. 1: main operating conditions of the swirl burner.

Fig. 3 a, b reports the image of the flame for the different injection typologies at a swirl number S=0.84. It can be observed the typical calyx shaped flame, due to high swirl intensity, and, for the axial injector, the formation of a central luminous region connected to fuel penetration inside the recirculating bubble, generating a fuel rich zone and giving rise to soot formation. This phenomenon, anyway sporadic for axial injector, is always absent for radial one.

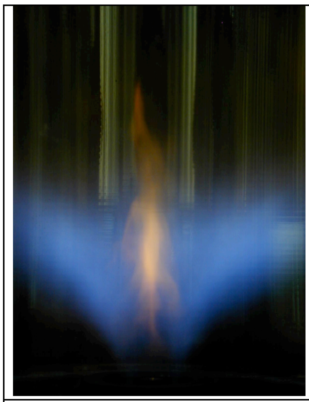

Fig. 3a: image of the flame for the axial injector.

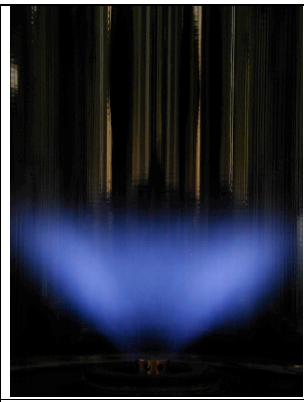

Fig. 3b: image of the flame for the radial injector.

The higher stability and compactness of the flame in the case of radial injection is proved also by the results obtained by CH* emission spectroscopy from the flame front, resumed in Fig. 4. In fact, reaction zone (identified by the peak of CH* emission intensity) for radial injector is closer and more concentrated at the burner head (peak at h/Rb=1.3, where Rb=radius of the burner head=18 mm), with an initial steeper gradient.

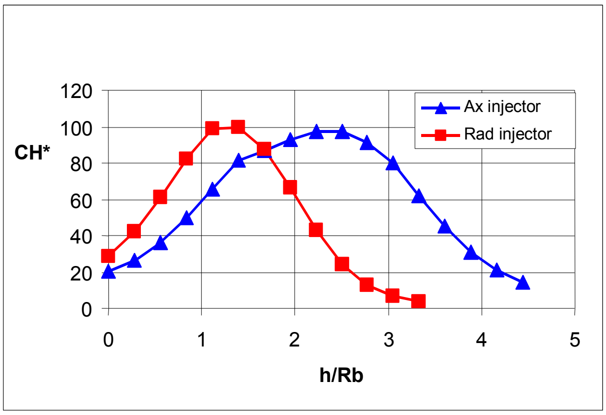

Fig. 4: CH emission intensity as a function of the distance h/Rb from the efflux.*

The premixed burner (Fig. 5) is mainly constituted by a mixing duct in which air + natural gas are injected and mix together: the duct terminates in a fine metallic grid equipped with an electrical ignitor. The premixed flame stabilizes downstream the grid and is confined inside a cylindrical combustion chamber.

Fig. 5: the premixed burner. The fuel-air mixing duct (left) and the outflow grid (right).

Fig. 6 reports the flame morphology as a function of equivalence ratio ER, from 0.6 (very close to blow-off limit) up to stoichiometric value. The nominal input thermal power of the burner is 10 kW.

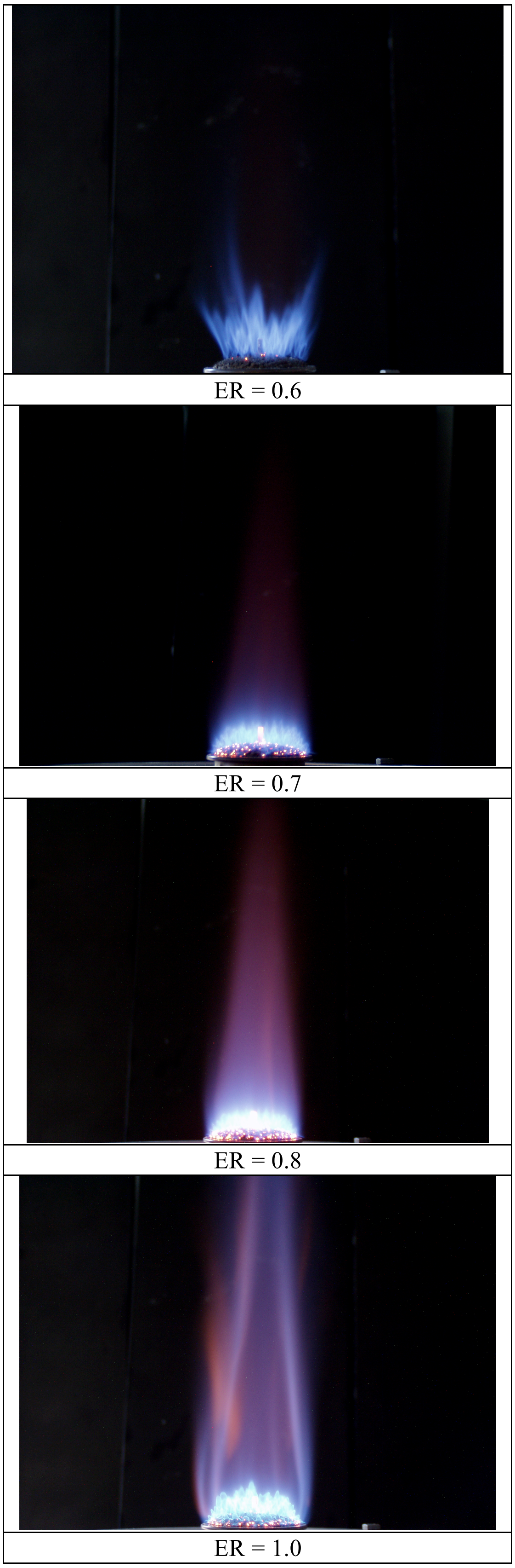

Fig. 6: flame morphology in the premixed burner as a function of equivalence ratio.

III. Experimental Results

In the premixed burner the analysis has been carried out at constant input thermal power, varying the air flow rate and, consequently, the equivalence ratio ER. Fig. 7 reports an example of the thermal field in the premixed burner (radial semi-profiles at increasing distance from the efflux grid, corrected for radiative losses, as reported in [11]) for ER=0.80. As it can be seen, the field is characterised by a high uniformity in the main combustion region, with a steep decrease approaching the combustion chamber walls. The highest temperature values are reached along the burner axis, close to the efflux.

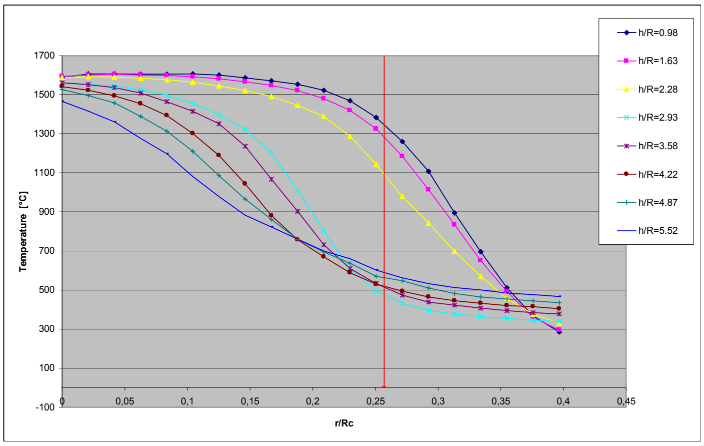

Fig. 7: thermal field in the premixed burner for ER=0.80.

Figgs. 8 and 9 report NOx and CO emissions measured at the exhaust (associated with the maximum temperature value measured in the profiles) as a function of ER. NOx formation is strictly temperature dependent with a peak in the correspondence of ER=0.83; at higher value of ER CO steeply increases, putting into evidence a possible combustion incompleteness with subsequent temperature decrease approaching stoichiometric value.

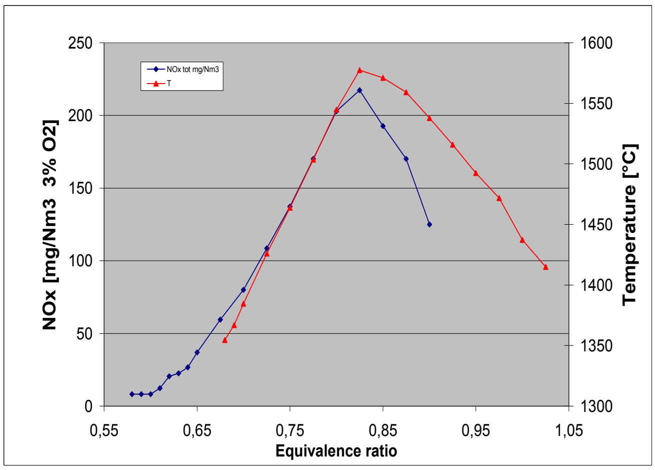

Fig. 8: nitric oxides emissions Vs equivalence ratio.

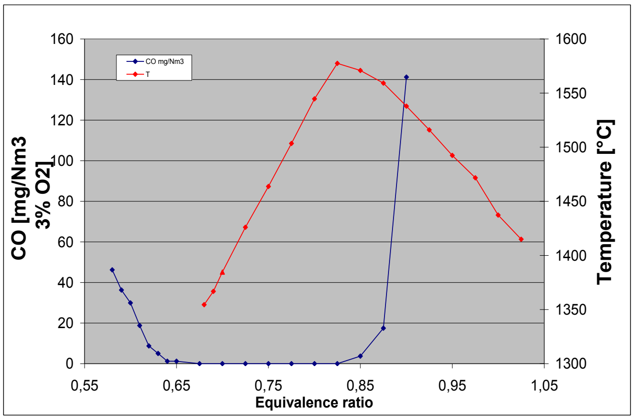

Fig. 9: carbon monoxide emissions Vs equivalence ratio.

As it can be observed, the premixed burner ensures lower NOx emission levels in a narrow operating range, in lean conditions (ER< 0.7). In the field 0.65<ER<0.85, CO emission is ultra-low for the premixed flame, but presents a steep increase outside this range.

As for the swirl burner, pollutant emissions (CO and NOx) at the exhaust have been measured for the two injectors in different operating conditions, that is varying equivalence ratio, and for different values of air swirl number. As previously outlined, swirl number variation is possible modifying the axial-tangential split ratio in the swirl generator. Variation of the equivalence ratio has been obtained changing fuel flow rate and, consequently, input thermal power and momentum ratio, but maintaining constant the air flow rate and, as a consequence, the Reynolds number and the macroscopic fluid dynamic of the flow.

Subsequently, the behaviour of the two different burners operated at various input thermal powers, as for pollutant emissions, has been compared using emission index (EI) for NOx and CO. In fact, EI represents the grams of pollutant emission for kg of burned fuel and, consequently, is independent from the thermal power of the device.

Tha main results are reported in Figgs. 10-13.

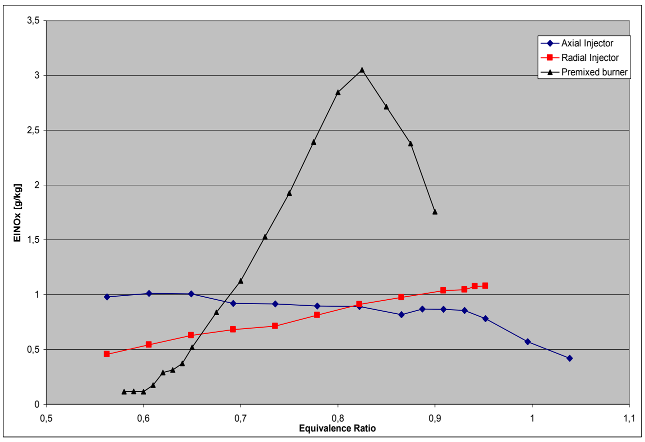

Fig. 10: comparison of EINOx vs ER at a swirl number=0.84.

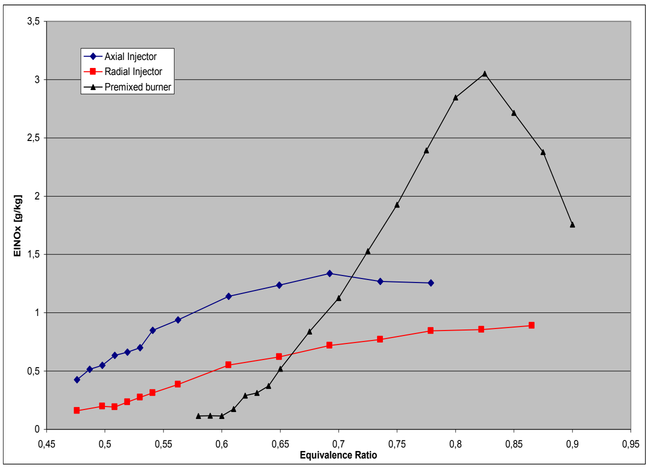

Fig. 11: comparison of EINOx vs ER at a swirl number=0.55.

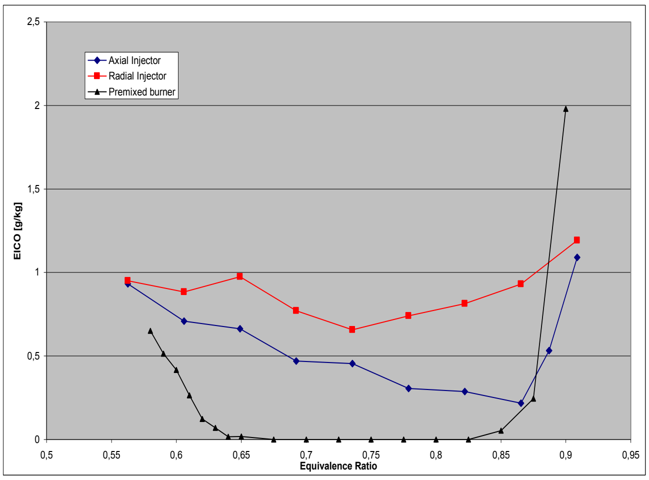

Fig. 12: comparison of EICO vs ER at a swirl number=0.84.

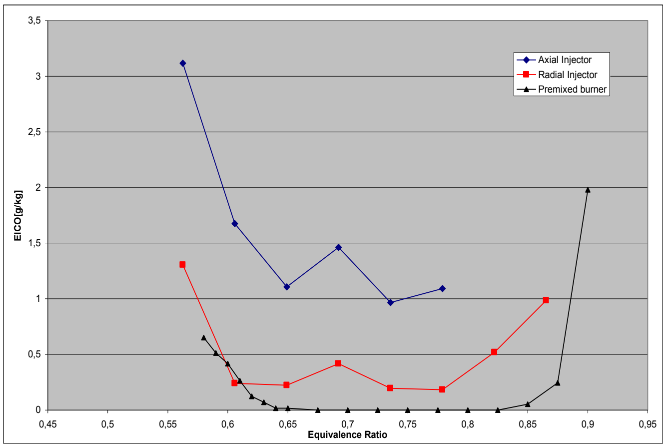

Fig. 13 : comparison of EICO vs ER at a swirl number=0.55.

As it can be observed for the swirl burner, pollutant emissions are quite insensitive to ER (especially for high swirl number) and, in general, radial injector seems to give rise to better performance, confirming the results obtained through qualitative flame imaging and flame spectroscopy. Moreover the higher swirl number ensures generally lower pollutant emissions, enhancing flame stability and widening the burner operating conditions.

IV. Conclusions and Future Work

Different natural gas burner typologies (a swirl burner with different fuel injectors and a purely premixed one) have been characterised under the point of view of pollutant emissions (NOx and CO).

The obtained results put into evidence that the premixed burner ensures ultra-low emissions (both for NOx and CO) in a very narrow operating field at ER≈0.7 (lean conditions). Outside this field the premixed burner gives rise to a steep increase of pollutant emissions.

At the contrary, the swirl burner presents a wider operating field under the point of view of flame stability and environmental impact. In fact, the analysis performed upon the swirl burner highlights the dependency of pollutant formation on the operating conditions of the device (swirl number, fuel injection typology and equivalence ratio).

The global results obtained during the experimental characaterization of the two different burners could be of interest to identify, from a practical point of view, the optimal operating conditions of the burners and to support, under a theoretical aspect, the validation of CFD codes. Off course, the results here described have to be considered as a preliminary aspect of the flame behaviour, that has to be deepened through further application of experimental techniques (for instance, local temperature, velocity and mixture fraction measurements).

References

[1] Fric, T.F. (1993): "Effect of fuel-air unmixedness on NOx emissions", Journal of Propulsion and Power, No. 9, p. 708

[2] T.C. Claypole, N. Syred: "The effect of swirl burner aerodynamics on NOx formation", 18th Symposium (International) on Combustion, The Combustion Institute, 1981, p. 81

[3] Kolb, T., Jansohn, P. Leuckel, W. (1988): "Reduction of NOx emission in turbulent combustion by fuel-staging: effects of mixing and stoichiometry in the reduction zone", 22nd Symp. (Int.) on Combustion, p. 1193, The Combustion Institute, Pittsburgh, PA

[4] Bosch, H., Janssen, F. (1987): "Catalytic reduction of nitrogen oxides: a review on the fundamentals and technology", Catalysis Today, Vol. 2, No. 4, p. 369-401

[5] Miller, J.A., Bowman, C.T. (1989): "Mechanism and modeling of nitrogen chemistry in combustion", Prog. Energy Combustion Science, Vol. 15, p. 287-338

[6] Bray, K.N.C. (1979): "The interaction between turbulence and combustion", 17th Symp. (Int.) on Combustion, p. 223, The Combustion Institute, Pittsburgh, PA

[7] G. Solero, A. Coghe, G. Scribano (2004): "Influence of natural gas injection procedure in a swirl burner", Joint Meeting of the Greek and Italian Sections of The Combustion Institute, Corfu, June 17-19 2004

[8] Solero, G., Coghe, A. (2000): "Calcolo del numero di swirl di correnti fluide da misure di velocità tramite LDV", Atti delle Giornate AIVELA, Ancona, 16-17 Settembre 2000

[9] Gupta A. K., Lilley D. G., Syred N. (1984): "Swirl flows", Abacus Press, Tunbridge Wells

[10] Coghe A, Solero G, Scribano G. (2004): "Recirculation phenomena in a natural gas swirl combustor", Experimental Thermal Fluid Science 2004; Vol. 28, p. 709-14.

[11] Morgan, T.V. (1991): "Thermal behaviour of electrical conductors", John Wiley and Sons