ANALYSIS OF THE IMPACT OF FLOW BOUNDARY CONDITIONS ON THE PERFORMANCE OF A LEAN-PREMIXING COMBUSTOR MODEL

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Abstract. *The increasing demands for low NO_x emissions and high combustion efficiency has led to the combustion of premixed fuel and air at equivalence ratios which are close to those of the flammability limits. The paper aims at improving the knowledge of physics of typical flows in premixing ducts and lean combustion process, presenting the development of an experimental rig of a "Lean Premixing", LPM, gas-turbine model combustor. The study assesses the development of a swirling reacting flow in a laboratory model combustor, intending to analyse the interactions between the flow conditions in the mixing duct, the flame stabilisation process and the downstream combusting flow, in practical aero-engines combustors. The experimental configuration consists of a fuel injector centred in a cylindrical premixed duct, UV-visible optical access sections, and a variable geometry swirl generator, allowing controlling the swirl level by rotating the vanes between 0º and 60º. The experiments depict important features of the premixed chamber and of the primary zone of practical gas turbine combustors. The work involves also the analysis of the effects of premixing efficiency on flame stabilisation, propagation and pollutant formation under overall lean burning conditions. The results associate flow conditions with mean values of temperature, velocity and concentration of main chemical species measurements and chemiluminescent imaging of visible flame chemiluminescence emission.*

Keywords: Lean Premixing Combustion, Swirling Flow, NOx formation, Gas Turbine

1. Introduction

The necessity to guarantee stability and high levels of combustion efficiency and to anchor the flame in a given part of the combustion space requires the use of specific methods of flow management. The main principle of combustion stabilization is to define a region where the local velocity is equal to the flame propagation velocity. This is achieved either by using a stabilizer in the form of a bluff body (Glassman, 1996), or by means of swirl (Syred and Beer, 1974). Flame stabilization by the later is a common feature of many combustion systems (Halthore and Gouldin, 1986, Jones and Wilhelmi, 1989, Bicen et al, 1990), whereas many fundamental aspects of the complex interaction between swirl and flames have been studied.

Otherwise, the increasing regulation for NOx emissions is promoting the design of combustors to be operated with lean premixed flames.

In the context of low emissions combustors, as defined by Bahr (1995), the recent work of Anacleto and Heitor (2001) in a *Lean Premixed Prevaporized*, LPP, model combustor provides evidence of very low NOx emissions at high fuel efficiencies by means of a central recirculation zone formed due to breakdown of a highly-swirled jet. This has motivated the present work, mainly because the effect of a swirling condition on combustion performance has been shown to depend on several factors, such as the fuel supply and mixture ratio (Syred & Beer, 1973; Bertrand & Michelfelder, 1976; Gupta et al., 1984; Froud et al., 1995; Coats, 1996), thus affecting overall combustion performance in practical combustors.

In this paper, experimental results of combustion in swirl flow conditions are reported. It aims at providing an improved understanding of the combustion process in the open swirl-stabilized premixed flames as well as to give sufficiently detailed information on the velocity, temperature and composition fields in a larger combustion domain.

2. Experimental Methodology

The experimental configuration consists of a single fuel injector positioned in the center line of a cylindrical premixing duct, with flame stabilization provided through a bluff body at the combustor entrance (Figure 1). The premixing chamber is a cylindrical duct with an inner diameter of d=50mm and a length of 150mm. Gaseous fuel (propane) was supplied before premixing duct (Figure 1). The combustor itself is made of cylindrical stainless-steel ducts with an inner diameter of D=184mm and a total length of 500mm. The various combustor modules include sections that provide the necessary optical access to the flow, to allow the use of laser techniques to visualize and quantify the inner flow, as also described in detail by Caldeira-Pires et al. (2003).

The experiments were conducted at atmospheric pressure. The swirl generator has a variable geometry, which allows shifting the angle of the vanes between 0º and 60º, in order to control the swirl level of the flow. The flow rate was measured with calibrated rotameters. The swirl number was defined through the swirler geometry according to Gupta et al. (1984).

Velocity was measured by a bi-directional hot-wire anemometer, temperature measurements were performed with bare-wire Pt-Pt/Rh thermocouples and the mean concentration of the main chemical species were sampling and analyzed by a combustion gases analyzer. (Gonzalez, 2004).

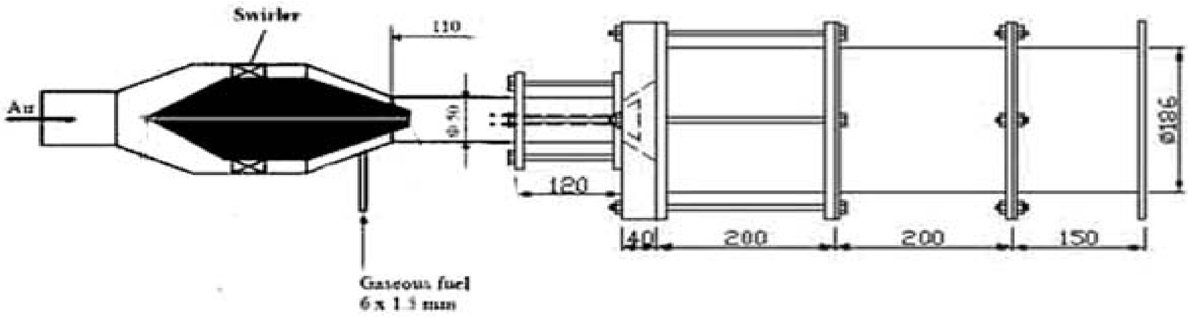


Figure 1: Schematic Diagram of the Swirler and the LPM Combustion Chamber

2.1. Swirl number evaluation

An alternative calculation for the swirl number in an axial flow in a tube with vanes (as presented by Figure 2, where the vane thickness is negligible) can be provided by Equation 1.

$$S' = \frac{2}{3}\left(\frac{1-\left(\frac{r_h}{r_b}\right)^3}{1-\left(\frac{r_h}{r_b}\right)^2}\right)\cdot \tan(\alpha) \tag{1}$$

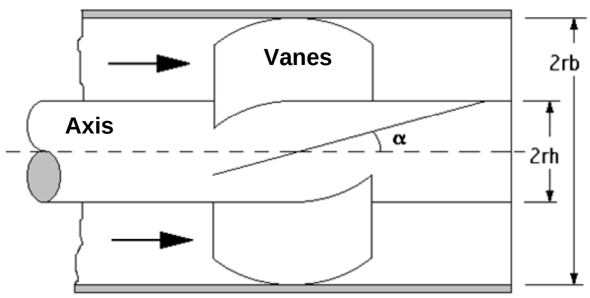


Figure 2: Axial Vanes Swirler

The evolution of swirl number with geometric parameters of the swirler, as calculated trough Equation 1, is presented by Figure 3.

Comparison of the values obtained with equation 1 with data calculated through geometric characteristic of swirler device (Gupta et al., 1984) demonstrates a fair agreement with theoretical definition (Equation 2). In our paper we use geometrical swirl number.

$$S_v = \frac{\int_0^\infty \rho\, u\, w\, r^2\, dr}{R\int_0^\infty \rho\, u^2\, r\, dr} \tag{2}$$

In this context, there were used three different vanes angle configuration, 0°, 45° and 60°, which correspond to swirl number, S, accordingly Equation 1 of 0.00, 0.88 and 1.52, respectively.

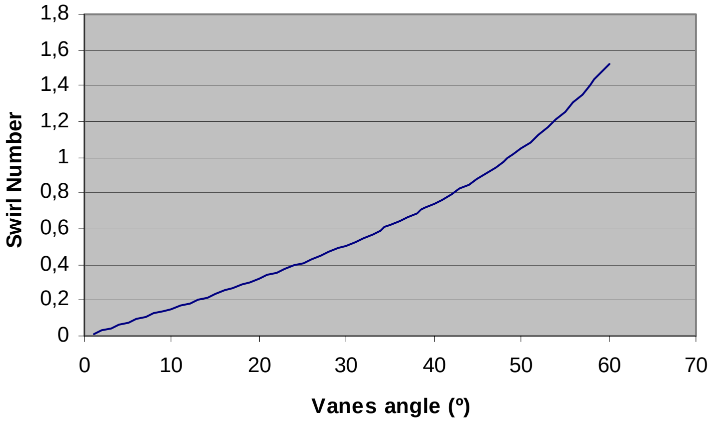


Figure 3: Association among Swirl Number and vanes angle

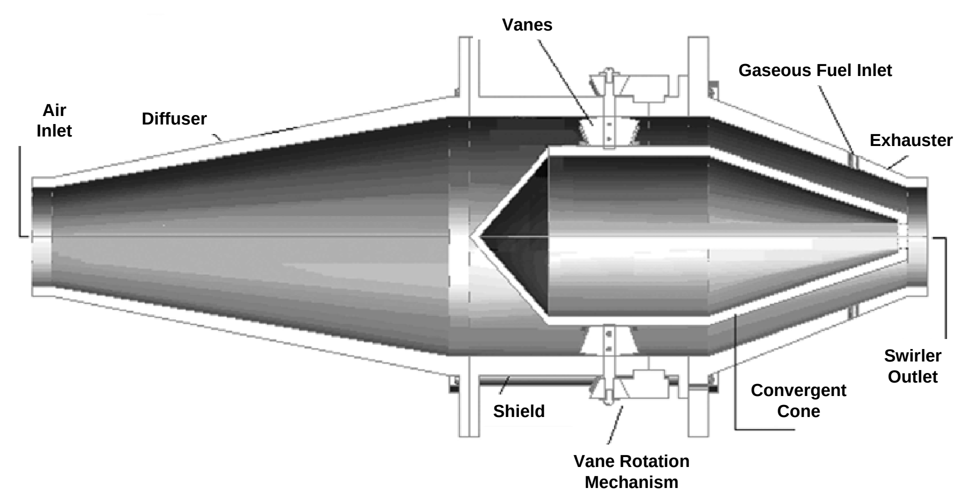
2.2. Swirler design

It is accepted that the swirl number is the key parameter for structure of swirl flow in a chamber that allows to provide effective control over working processes (Hoekstra et al., 1999; Zhou et al., 2000).

In this context, it was designed a swirler device to provide swirling flows at controlled conditions to the combustion chamber. Namely, the swirler encompasses a diffuser, a non-bluff body, a shell, a power transmission ensemble and vanes, and an exhauster. These components are responsible for:

- Diffuser: increases the static pressure keeping the boundary layer intact;
- Non-bluff body and exhauster: recover the flow dissipated energy when the flow passes through the vanes. At the exhauster there are six inlets for the gaseous fuel;
- Shell: external structure;
- Power transmission system: to control the vanes angle, through several conic devices/axis and double crow connection;
- Vanes: to add the tangential component of the velocity.

This system is presented through Figure 4 and 5, namely by a general diagram, an exploded diagonal vision and a horizontal one, and two photos of the vanes assembling detail.



Swirler`s transversal section

Diagonal exploded view of Swirler

Figure 4 - Detail of Swirler

3. Swirling flow structure

Flow visualization with video recording demonstrated that at the exit of premixing chamber a zone of recirculation flow is formed at its boundary. On this regard, a 8bits CCD digital camera is placed perpendicular to the UV-quartz (up to 60% transmittance at 220nm) section of the combustor, obtaining radial views of the flame. The video output signals were connected to a frame grabber, and used for the acquisition of independent monochromatic video signals. A commercial 105mm UV lens (f = 1.4) allowed a cone collection of light of 20^o, minimizing the distortion due to wide-angle imaging.

The experiments were performed at equivalence ratio of 0.6, at a fuel mass flow rate of 0.7g/s, at normal atmospheric conditions.

Figure 6 displays photographies of the flame through the quartz tube (lateral) and Figure 7 the frontal view. These images were acquired with a digital camera with f=4.2 and exposition time of ¼ seconds. Figure 6 shows chemiluminescence averaged projections of the visible flame, and Figure 7 their respective frontal

The qualitative analysis of Figure 6 images suggests that the maximum luminous intensity locus approaches the bluff body as the swirl number increases. Otherwise, the flame concentrates near the chamber cylindrical wall as swirl number increases.

This concentration pattern can also be depicted at Figure 7, where the chemiluminescence emission locus moves toward the periphery of the combustion chamber, and simultaneously increases the temperature of the bluff-body as the flame approaches the chamber entrance.

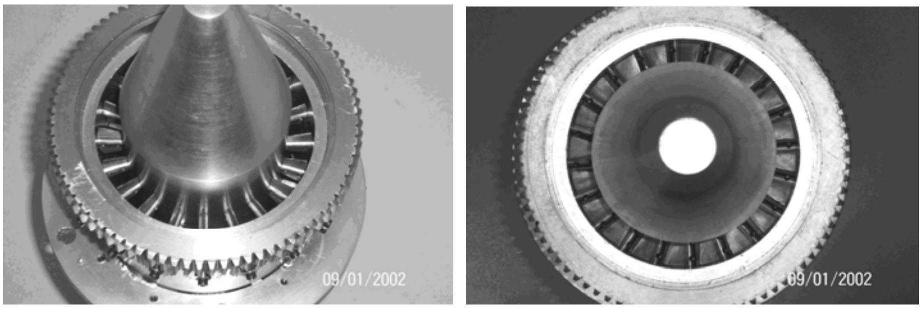
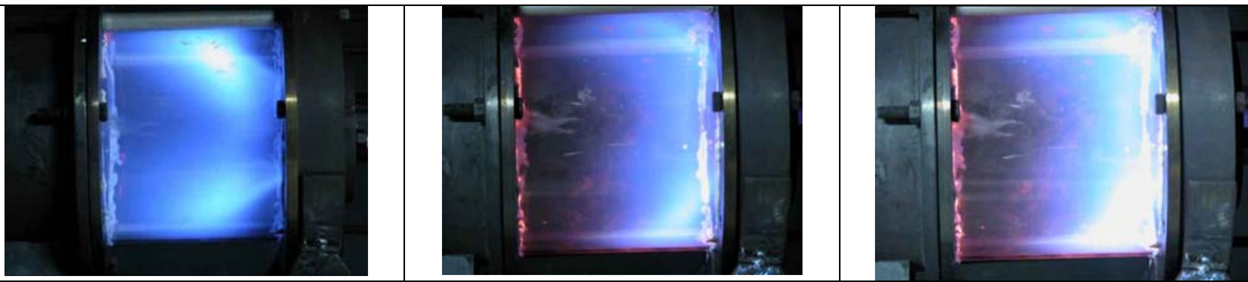
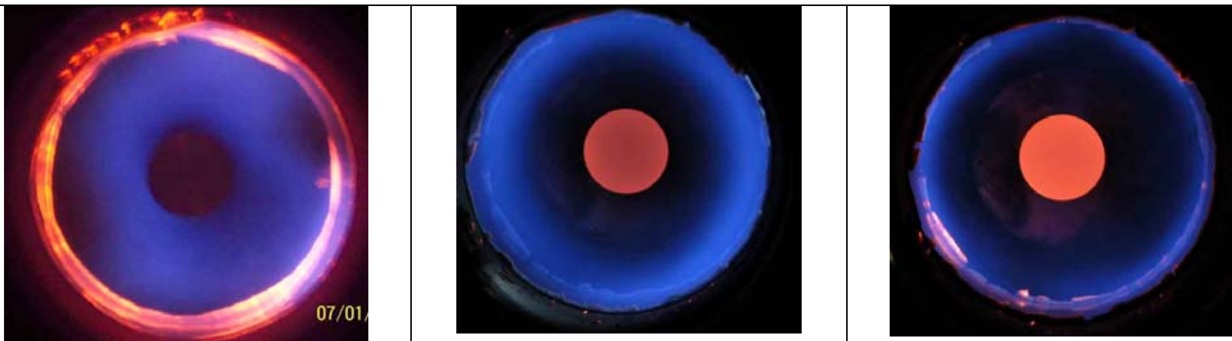


Figure 5 - Detail: Exposed Swirler



S = 0	S = 0.88	S = 1.52

Figure 6 Flame structure based on chemiluminescence emission (the photographies were taken perpendicular to the quartz cylinder)



S = 0	S = 0.88	S = 1.52

Figure 7 - Evolution of reaction zone with S (the photographies were taken from the end of the combustion chamber, co-axially to the experimental assembly)

3.1. Isothermal Flow Results

Isothermal flow characterization was performed by hot-wire (Pt-90%/W-10%, ∅ 5μm) anemometry (main unit: DISA M55001, dynamic signal analyzer: HP 35665A). This experimental rig is presented by Figure 8, displaying the schematic diagram and the photography of both hot-wire and thermocouple sensors positioned at the outlet of the swirler.

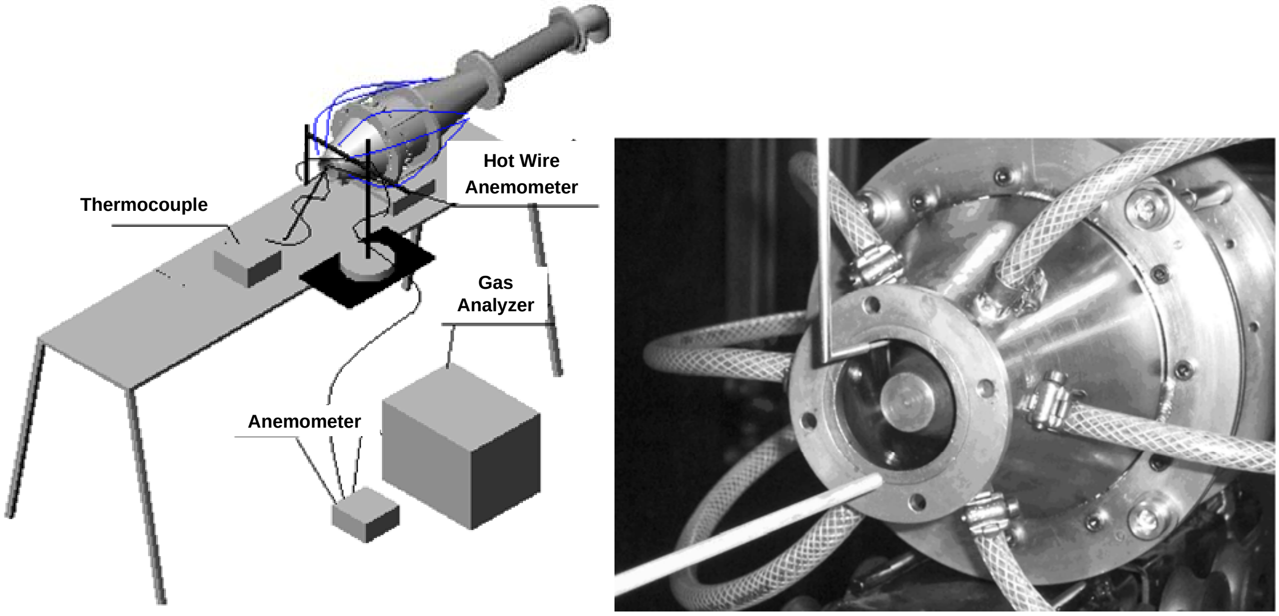


Figure 8 – Schematic diagram and photography of the hot-wire anemometry measurements installation

Figure 9 presents the results of the mean axial velocity, as measured at the outlet of the swirler, showing an increasing axial velocity at the border of the swirler, evolving from a flat pattern to a non-flat one, as the swirl number increases from 0.88 to 1.52.

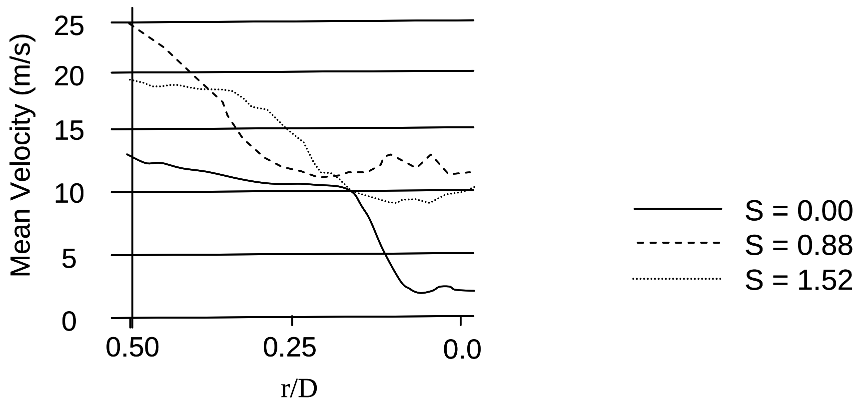


Figure 9 – Evolution of the radial profile of mean axial velocity at the outlet of the swirler with S (D=184mm)

4. Reacting Flow Results

The reacting flow characterization was achieved by means of chemical species concentration, making use of a gas analyzer, and temperature, assessed with type S thermocouples, both measured 400mm downstream combustion chamber entrance. Maximum temperature were measured at radial position r/D = 0 (D = 184mm, combustion chamber diameter) and the minimum at r/R ~ ±1, near the chamber wall.

The flame was obtained by burning LPG, at a mass flow rate of 0.7g/s, and air at 0,30 m^3/s, resulting in a equivalence ration of, Φ, 0.60.

Figure 10 display both schematic diagram and photography of thermometry and gas analysis. Temperature measurements were performed at the whole diameter of the chamber; otherwise, chemical species analysis were accomplished in a single radial position, namely at r/D=0.25.

Figure 10- Schematic diagram and photography of thermometry and gas species measurements schema

Radial temperature profiles evolution, as depicted in Figure 11, suggests that the maximum temperature of the flow does not vary significantly with S, although the peak of temperature moves toward the periphery of the chamber, following the same pattern observed at the reaction zone evolution at Figure 7.

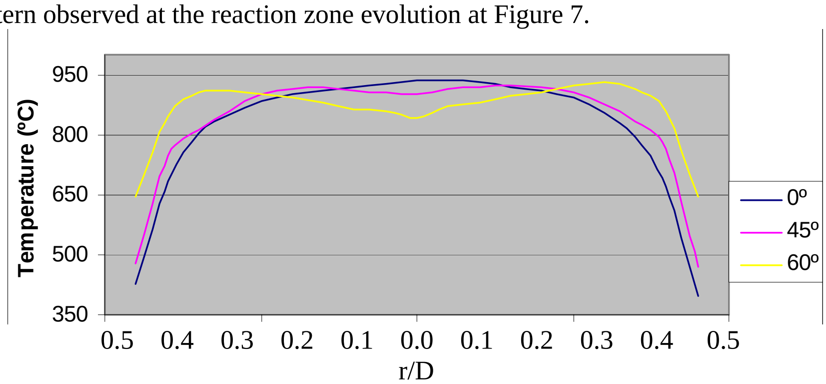


Figure 11 – Evolution of radial profiles of mean temperature at the exit of the combustion chamber with S

The results of chemical species concentration measurements, performed at the reacting flow on wet basis, are presented in Figure 12, which suggests that an increase in the swirl intensity leads to an increase of 30% of NOx and of 300% of CO at exit of the combustion chamber. It should be mention that the range of absolute values measured is within the confidence range for each chemical species measurements, namely the NOx concentration measurements precision are lower limited at 5ppm, which raises serious difficulties to guarantee the precision of these data.

Although these results did not characterize accurately the effect of swirl intensity on the combustion efficiency, the whole set of measurements demonstrated that modification on the flow velocity pattern alters the mixture efficiency, and therefore, the position of the reaction zone and the temperature and chemical species distribution within the combustion gases.

3. Conclusions

The work presents data relating swirl intensity and reaction flow configuration downstream combusting flow within a LPM model combustor. The results are of interest to practical combustors in that flow regimes that may lead to low NOx emissions are primarily influenced by flow configuration. In fact, considering the design of combustors to be operated with lean premixed flames, it is evident that the target would be a regime with a steady recirculation zone and stabilized combustion. In general, the practical significance of the work is based on the evidence shown between the swirling flow parameters, which might be acquired by relatively simple techniques, and combustor performance. The effect shown of the rotation in the premixing chamber on flow development downstream of swirl jet is important to predict combustor regimes. Consequently, optimal LPP combustor design should be associated with swirling flow regimes with developed and stable recirculation zones. Accordingly, visualization illustrated the presence of a developed region in a primary zone of the combustor that provides the necessary condition for turbulent stabilization process.

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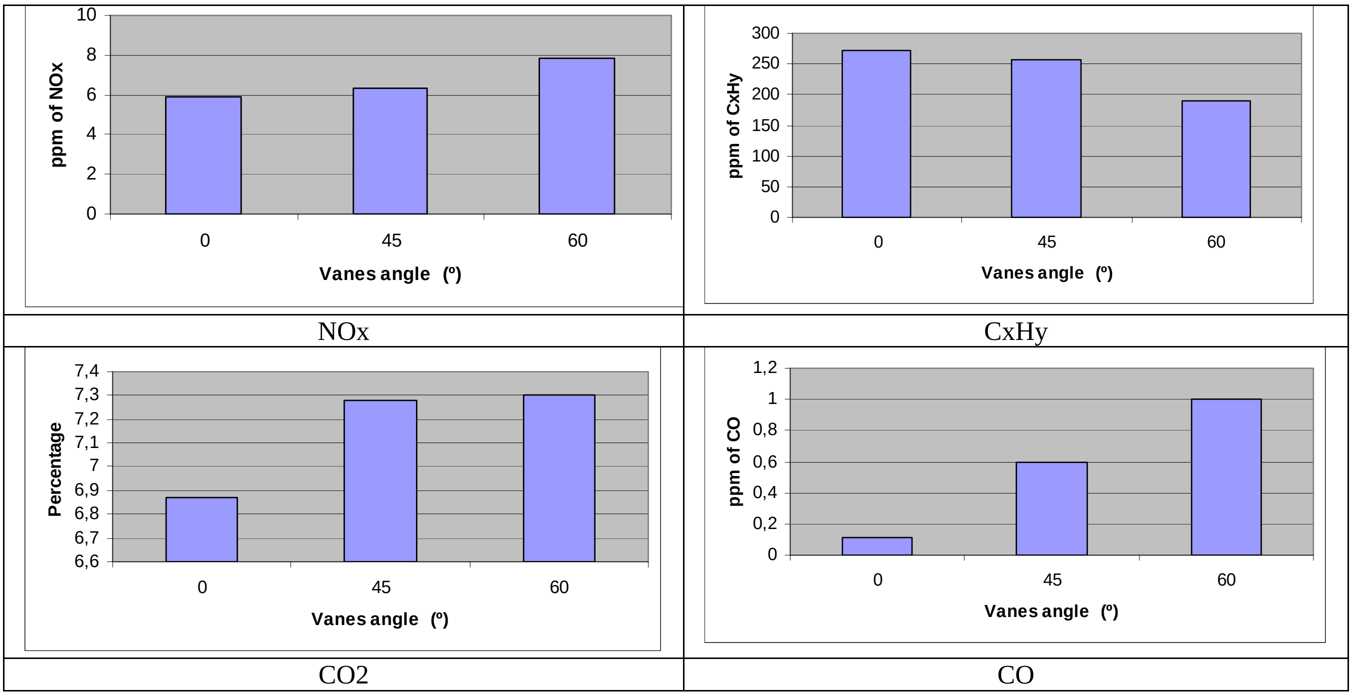

Figure 13: Variation of mean concentration of chemical species at the exit of the combustion chamber with S (single point measurements at r/D=0.25)

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