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MEASUREMENTS OF THE FLOW BEHAVIOR AND THE EMISSIONS GENERATED BY LOW SWIRL INJECTORS IN A LEAN PREMIXED GAS TURBINE COMBUSTOR

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Abstract. *Low swirl injectors for low emission gas turbine have been experimentally studied in atmospheric rig test to investigate the flow field, pressure oscillation and NOx and CO emissions. The flames generated by low swirl injectors were enclosed in a combustor with optical access ranging the swirl number from 0.6 till 0.03 and operated with premixed natural gas-air. The operating condition has been varied changing the equivalence ratio from the lean-blow off limit up to stoichiometric ratio in three levels of thermal power. The optical diagnostic measurement technique was applied to measure the instantaneous planar reacting flow field using particle image velocimetry (PIV). Gas analyzer was used to measure emissions at the combustor exit and a pressure transducer were used to determine the pressure oscillations inside of the combustor. Results show low levels of NOx and CO emissions at the stable operating conditions and the behavior of pressure oscillations and flow field for a wide range of swirl number, equivalence ratio and thermal power.*

Keywords: *Gas Turbine Combustor,* NO_x*, Low Swirl Injector, Lean Premixed*

1. INTRODUCTION

Stringent environmental standards drive gas turbine manufacturers to developed new design for combustion chamber, in order to reduce pollutant emissions. In the past two decades, lean premixed combustion has become the leading technology for controlling NO_x emissions from gas turbines of all sizes. Modern premixed combustion systems are highly optimized to exploit specific properties of fuels such as gas natural or propane (Day *et al*., 2012; Davis *et al*., 2013). Premixed fuel and air eliminates local stoichiometric and fuel-rich zones in the combustor, which can eventually lead to local "hot" regions when mixed with additional air, leading to the production of thermal NO (Seo, 2003). However, lean premixed combustors are inherently susceptible to combustion dynamics, which are sustained high amplitude pressure oscillations, resulting from the resonant coupling between the system acoustics and the unsteady heat release (Kim *et al*., 2010). Structural fatigue, increased combustor core noise, and/or possible system failure could result if these oscillations are not controlled (Stone and Menon, 2002). These oscillations affect the operating range, reliability, and lifetime of an engine and impose additional design requirements (Giezendanner *et al.*, 2005). Besides, there are another problems associated with LP concept application, such as blow-out, autoignition and flashback (Lyons, 1981). These phenomena involve complex interactions of unsteady flow structures and chemistry, which are still not well enough understood today, and are, strongly, dependent on the interaction of flow field and flame (Stöhr, *et al*., 2011).

In conventional gas turbine combustors, swirlers are commonly used so that the flow entering the combustor has not only axial component of velocity but also tangential and radial velocity. Swirl provides hot gas recirculation zone at entrance to the combustor for better mixing of the reactants and enhanced flame stability (Khalil and Gupta, 2011). In general, gas turbines use high swirl intensity to stabilize the flame by formation of a strong recirculation zone. But,

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recent developments in this devices show that is possible achieve a specific regime by decreasing swirl with an appropriate geometry. This geometry was defined, firstly, as low swirl injector by Cheng (1995). In this regime, the flame stabilization is performed within a low velocity region, i.e. exploits the "propagation wave" nature of a premixed turbulent and does not rely on flow recirculation to anchor the flame (Legrand *et al.*,2009; Cheng *et al*.,2000). In addition, these injectors present the advantage of avoid upstream hardware overhating, once they exhibit a lifted flame configuration (Legrand *et al*., 2009). Overviews and detailed description of the laser measurement technique applied in this work can be found in Kohse-Höinghaus (2002).

The present work analyze NOx and CO emissions, the dynamic behavior through the pressure oscillations measurement inside of the combustor and characterizes the flow fields applying optical combustion diagnostics for different levels of swirl intensity, equivalence ratio and thermal power in low swirl injectors operating in a lean premixed gas turbine combustor under atmospheric rig test.

2. EXPERIMENTAL SETUP

Experiments were performed using low swirl injectors designed based on Cheng concept (Cheng *et al*, 2000). The injectors are composed by swirler vanes made on a cylindrical center channel, a perforated screen positioned at the inlet of the center channel and an external tube, as presented schematically in Fig. 1.

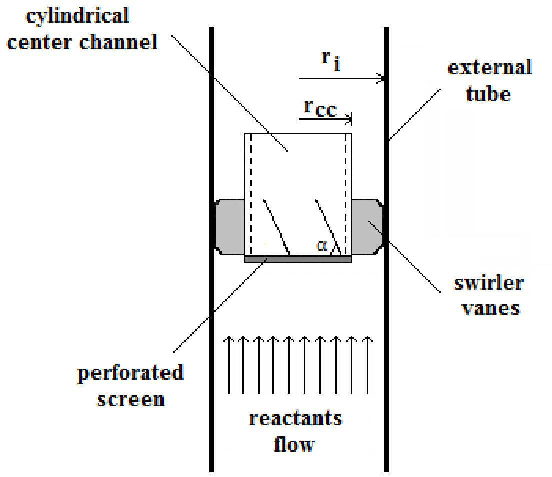

Figure 1. Schematic of the low swirl injector

The dimensionless ratio that characterizes the swirler intensity is given by swirl number, S, defined as the relation between axial flux of angular momentum and axial flux of linear momentum. The model used to calculate the swirl number is proposed by Cheng *et al* (2008):

$$S = \frac{2}{3} tan\alpha \frac{1 - R^3}{1 - R^2 + m^2\left(\left(\frac{1}{R^2}\right) - 1\right)^2 R^2} \tag{1}$$

where R is the ratio rcc/ri and m represents the ratio mcc/ms being mcc the unswirled flow through the center channel and ms the swirled flow. Three low swirl injectors with swirler blade angles of α = 45°, 40° and 35° were designed. Each injector, that has several perforated screens, with twenty orifices each one, is positioned at the inlet of the cylindrical center channel in order to vary the blockage ratios of unswirled flow from 68% till 26% to provide swirl numbers from 0.61 till 0.03. The outer radius of the center channel r_{cc} = 12 mm, the inner radius of the injector r_i = 18 mm and the lengths of the injectors were kept the same for all injectors. The swirler blade angles and orifice diameters of the perforated screens for the injectors evaluated are presented in Table 1.

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Table 1. Geometric features of the injectors

Swirler blade angle (degree)	Diameter of the orifices (mm)	Swirl number (S)
45	2.5	0.6
45	2.7	0.5
40	2.8	0.4
40	3.0	0.3
35	3.1	0.2
35	3.4	0.1
45	3.8	0.03

The injectors were mounted in an optically accessible square combustor (600 x 600 x 600 mm) with four quartz windows (300 x 300 mm) all of them made in stainless steel and connected to a premixing section, to ensure a homogeneous mixture, and fired at the ambient pressure conditions. The air, which comes from an air blower, and natural gas enter at the premixer section and are monitored by the thermal flowmeters. To detect the pressure oscillations inside of the combustor, a Kistler 7261 piezoelectric pressure transducer was positioned at the top wall of the square combustor. The transducer signals were amplified by a Kistler 5006 charge amplifier. The LabVIEW software was used for data acquisition, i.e. to determine the amplitude and frequency of the flame oscillation in terms of pressure for this combustor geometry. The flow fields information for low swirl injectors were obtained using a LaVision PIV – particle image velocimetry system. This system consist of double 380 mJ Nd:Yag laser pulses at 532 nm, a digital camera with 2448 x 2050 pixels, a camera lens f = 50 mm, f/5.6, a narrow band filter (532 nm) and a cyclone type particle seeder. The PIV seeder flow, composed by 1 µm TiO_2 particles, was monitored by electronic mass flow controllers. The optical capture a field of view of 200 x 250 mm covering the inner flow field of the flames. The light-sheet produced by the 20 mm cylindrical lens was approximately 1.0 mm thickness and the interframe times to freeze the out-of-plane motion of seed particles were 55 µs (20 g/s) and 35 µs (30 g/s). Data acquisition and analysis were performed using the software Davis 7.2. Sets of 170 image pairs were recorded for each experiment corresponding to the minimum criterion required to produce stable mean and rms velocity. The PIV data were processed using 64 x 64 pixels cross-correlation interrogation regions. The combustion gases concentration acquisition was carried out by GreenLine 8000. The flue gas sample probe was coupled to the exhaust duct. The Greenline 8000 is accompanied by the DBGas 2004 software that assists data management and storage. The gases concentration is corrected to 15% of O_2. Figure 2 shows a schematic diagram of the experimental setup.

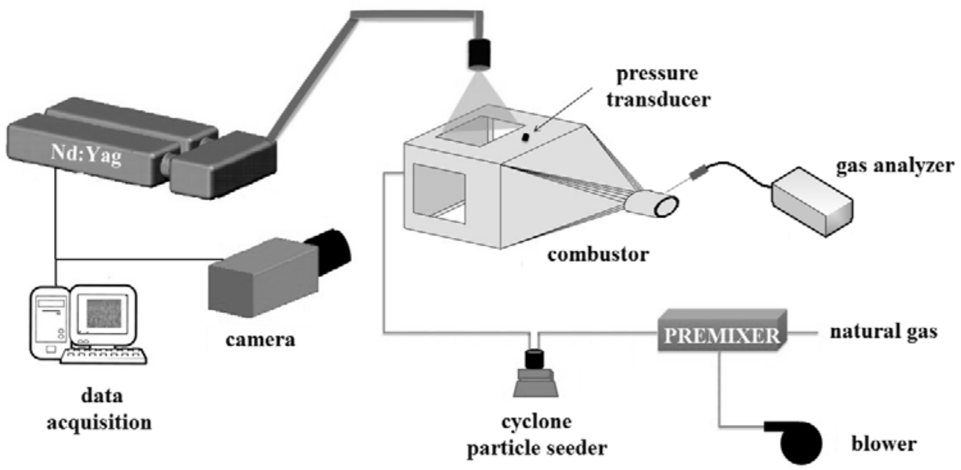

Figure 2. Schematic diagram of the experimental setup

3. RESULTS AND DISCUSSIONS

In order to provide different levels of swirl intensity to premixed natural gas-air flames low swirl injectors were designed and manufactured with lengths and radii constants. To control a portion of the reactants which remains unswirled the blockage ratio was varied and, consequently, the axial flux of linear momentum is controlled. The swirler blades angle was also varied to control the axial flux of angular momentum. The angular and linear momentum were combined in order to obtain the swirl intensity from 0.6 till 0.03. The lean blow-off was determined by maintaining a constant mass flow rate of air, m_a, and incrementally reducing the fuel flow until the flame became visibly weaker and smaller and blew-off. The injectors were evaluated operating in two different mass flow rates of air: 20 g/s and 30 g/s. When the mass flow rate of air was varied from 20 g/s to 30 g/s the bulk flow velocity $Vb = m_a / A$, where A is the exit

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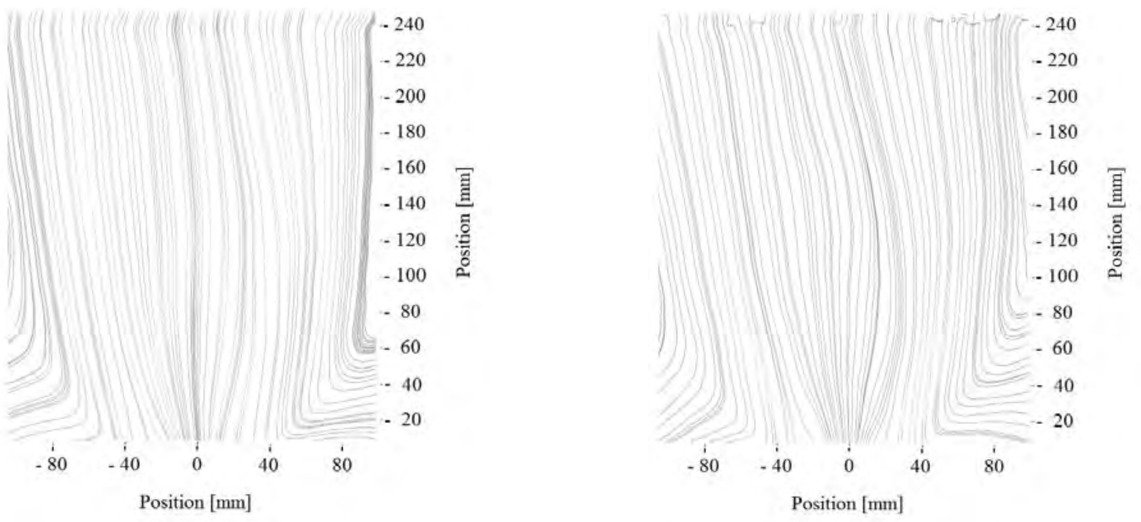
area of the injector, changed from 18 m/s to 27 m/s which correspond to the Reynolds number, Re, of 36,000 and 54,000, respectively, calculated based on the injector exit diameter. The equivalence ratio, ϕ, was also varied from 0.6 till 0.9 for each mass flow rate of air. The operating conditions of the experiments for each swirl number evaluated are presented in Table 2.

Table 2. Operating conditions for the experiments

Reactant flow		Equivalence ratio (ϕ)	Thermal Power (kW)
m_a (g/s)	m_f (g/s)		
20	0.73	0.6	35
	0.85	0.7	40.8
	0.97	0.8	46.6
	1.09	0.9	52.3
30	1.09	0.6	52.3
	1.27	0.7	61
	1.45	0.8	69.6
	1.63	0.9	78.2

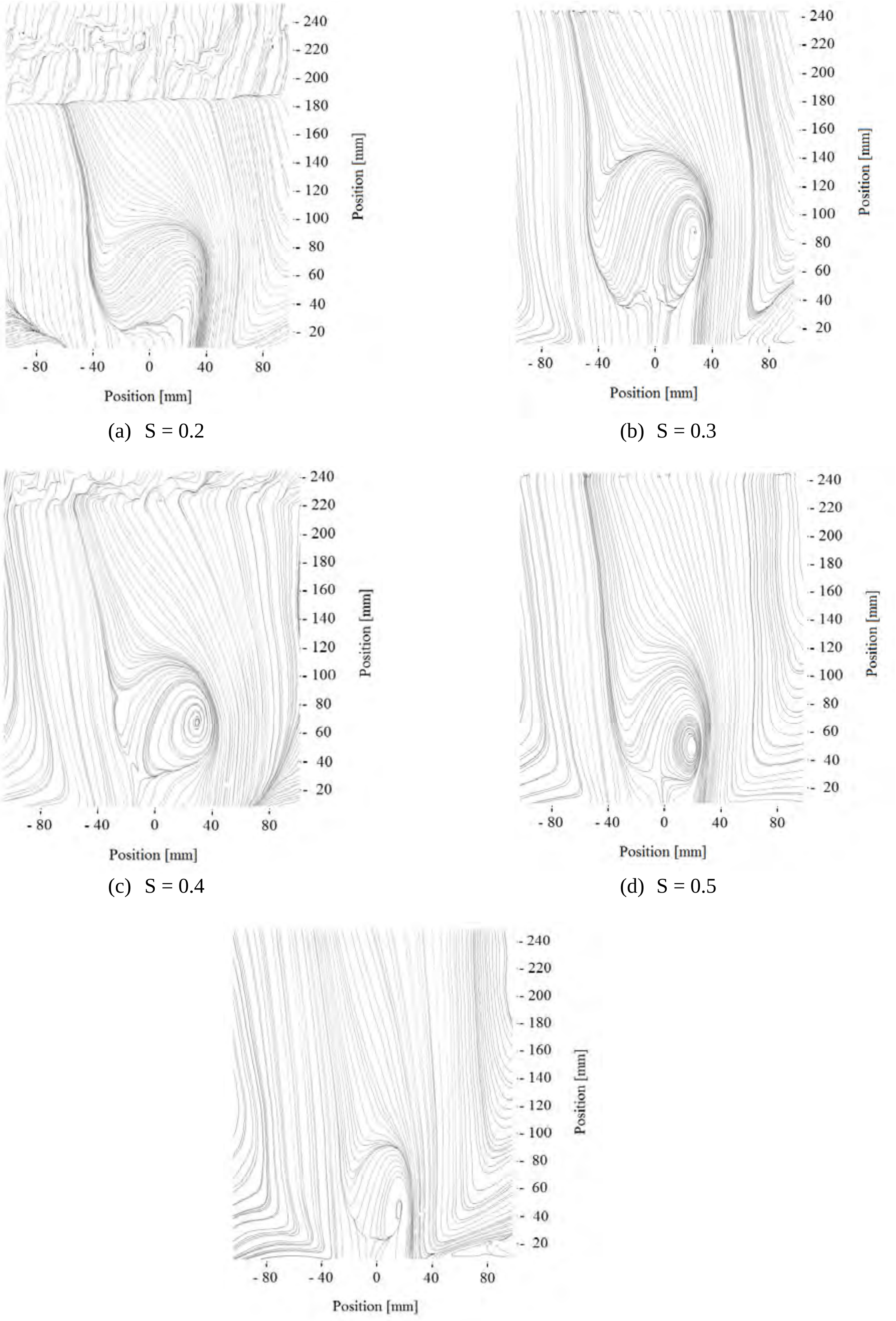
It was observed that varying the swirl intensity changes the flame shape and position. The flame shape became longer and thinner when the swirl intensity was decreased. This effect occurs due to the increase of the axial flux of linear momentum and reduction of the axial flux of angular momentum changing the gradient between the swirled and unswirled flows that in turns cause the flow divergence and the flame to reposition itself where the local mass flux equals the burning rate. The rate of divergence influences the precessing vortex core in the reaction zone. For the swirl numbers of 0.03 and 0.1 the flow fields showed no inner precessing vortex core in reaction zone and the streamlines presented only axial flow due to the weaker axial flux of angular momentum compared to axial flux of linear momentum. Figs. 3 (a) and (b) present the streamlines for the equivalence ratio equal to 0.7 and Re = 36,000 for S = 0.03 and S = 0.1, respectively.



(a) S = 0.03 (b) S = 0.1

Figure 3. Flow fields at Re = 36,000 and ϕ = 0.7 for the swirl number S = 0.03 and S=0.1

The inner precessing vortex core appeared at the swirl number of 0.2 and vortex core leads to the recirculation zone in the reaction zone of the flame at the S = 0.3 as can be observed in Figs. 4 (a) and (b), respectively. For the swirl intensity from 0.3 till 0.6 the flame stabilizes closer to the injector exit than the swirl numbers 0.03, 0.1 and 0.2. When the swirl intensity is increased the flame is pulled closer to the injector exit. This dynamic behavior of the flame can be visualized through streamlines obtained by the PIV analyses for swirl numbers: 0.6, 0.5, 0.4 and 0.3 and are presented in Figs. 4 (b) – (e), respectively. It could be observed that the position of the inner recirculation zone was moved in reaction zone and became far from the injector exit when the swirl number was decreased from 0.6 till 0.3. For S = 0.6 the inner recirculation zone can be found near to 40 mm, Fig. 4(e), whereas its position for swirl numbers from 0.5 till 0.3, Figs. 4 (d) – (b), is moved up to 90 mm. The operating conditions for the streamlines showed in Figs.4 (a) – (e) were Re = 36,000 and ϕ = 0.7.



(a) S = 0.2 (b) S = 0.3 (c) S = 0.4 (d) S = 0.5 (e) S = 0.6

Figure 4. Flow fields at Re = 36,000 and ϕ = 0.7 for the swirl number from S = 0.2 till S=0.6

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The results of the pressure oscillations for the combustor used in this experimental investigation show that the swirl number presents small influence on the frequencies and amplitudes. However, the frequencies tend to increase slightly with the increasing equivalence ratio and it is related with the combustor geometry. The frequencies obtained for all operating conditions were found in the range from 50 Hz till 64 Hz, which is classified by many researchers as intermediate frequency, as can be visualized graphically in the Figs. 5 to 11. With the respect to amplitude, the flame showed a very stable operational conditions under Re = 36.000 presenting small oscillation amplitude which tends to decrease as the equivalence ratio increases. For Re = 54.000 the amplitude peak for $\phi = 0.6$ presented a value almost two times bigger than the amplitude for $\phi = 0.7$, although both presented small values. When the equivalence ratio increases from 0.7 till 0.9 a trend to decrease the amplitude could be observed, as presented in Figs. 5 to 11. The possible cause of the amplitude increases for $\phi = 0.6$ and Re = 54.000 is due to lean blow-off limit that occurred at $\phi = 0.56$ for Re = 36.000 and $\phi = 0.59$ for Re = 54.000.

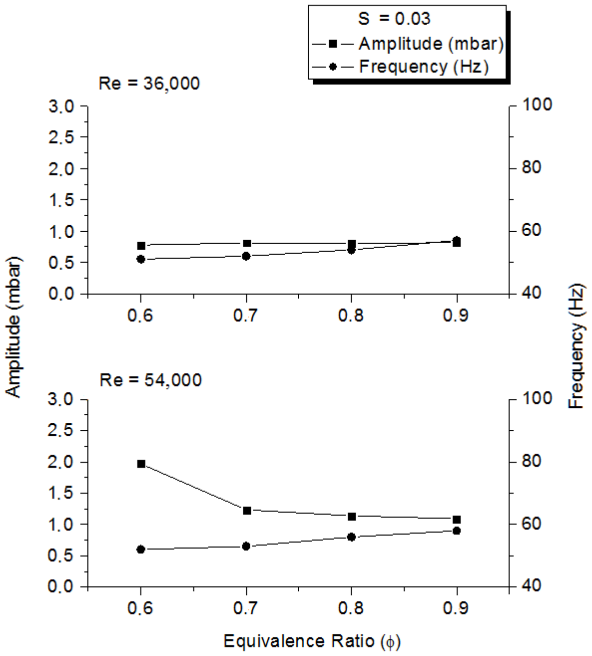

Figure 5. Pressure oscillations for different Reynolds numbers and swirl number 0.03

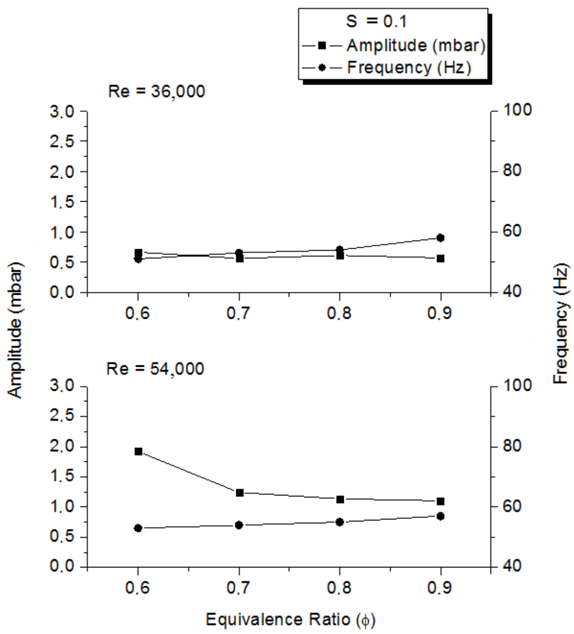

Figure 6. Pressure oscillations for different Reynolds numbers and swirl number 0.1

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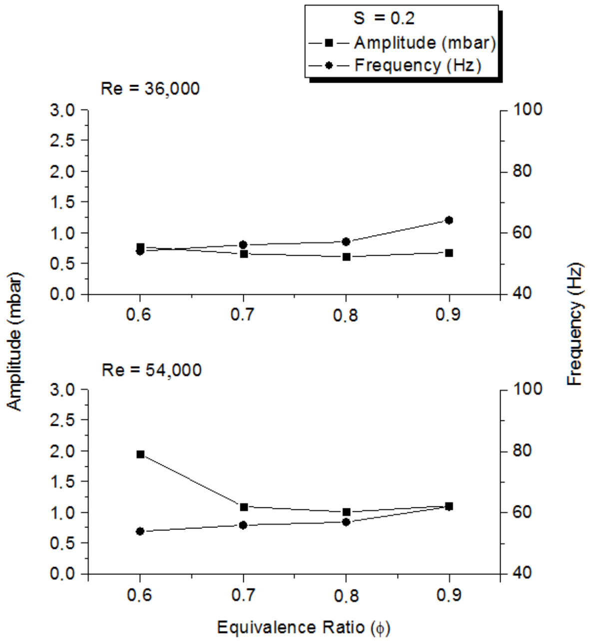

Figure 7. Pressure oscillations for different Reynolds numbers and swirl number 0.2

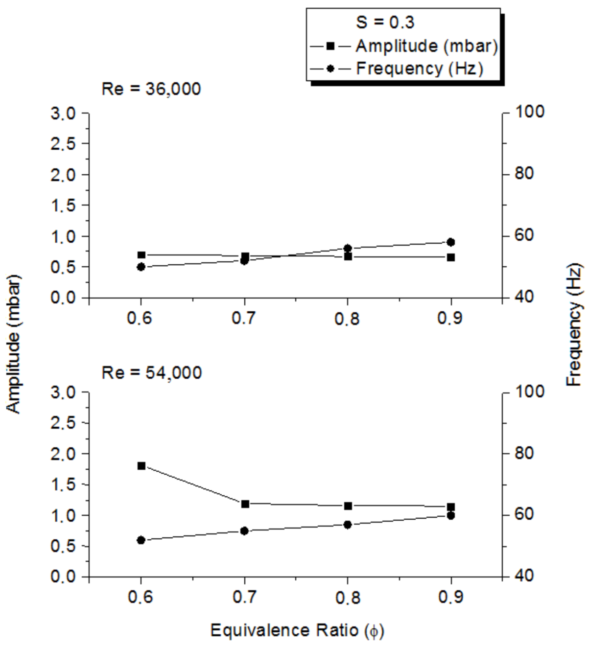

Figure 8. Pressure oscillations for different Reynolds numbers and swirl number 0.3

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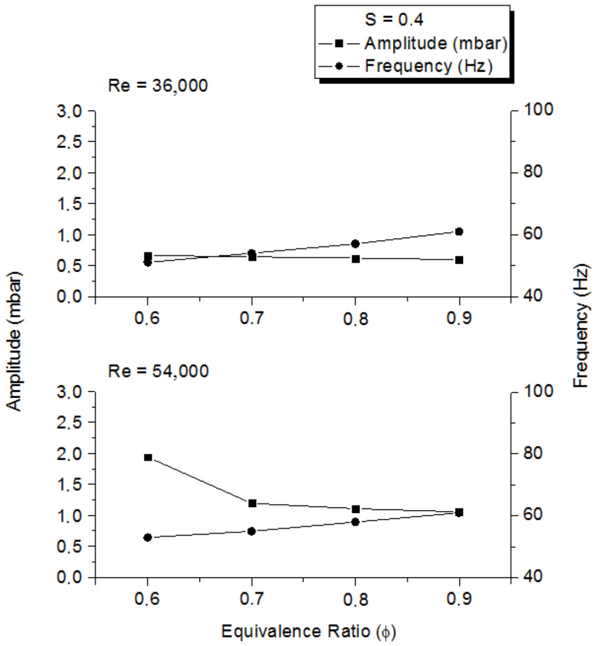

Figure 9. Pressure oscillations for different Reynolds numbers and swirl number 0.4

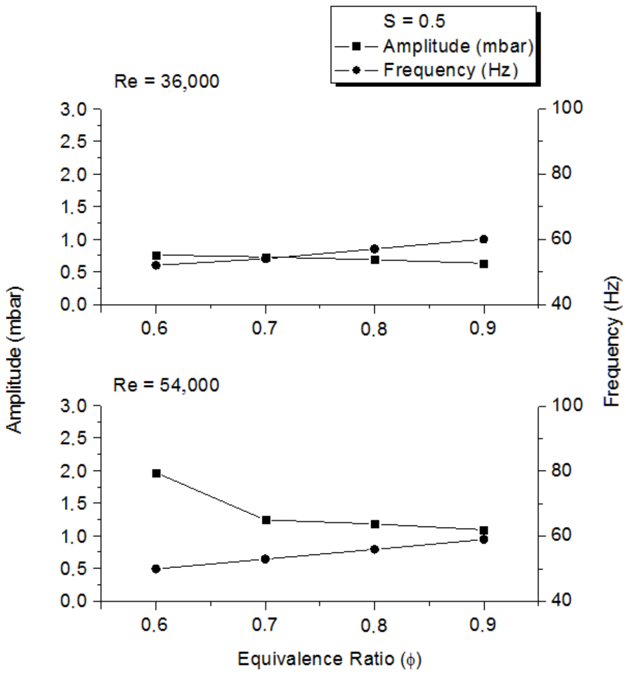

Figure 10. Pressure oscillations for different Reynolds numbers and swirl number 0.5

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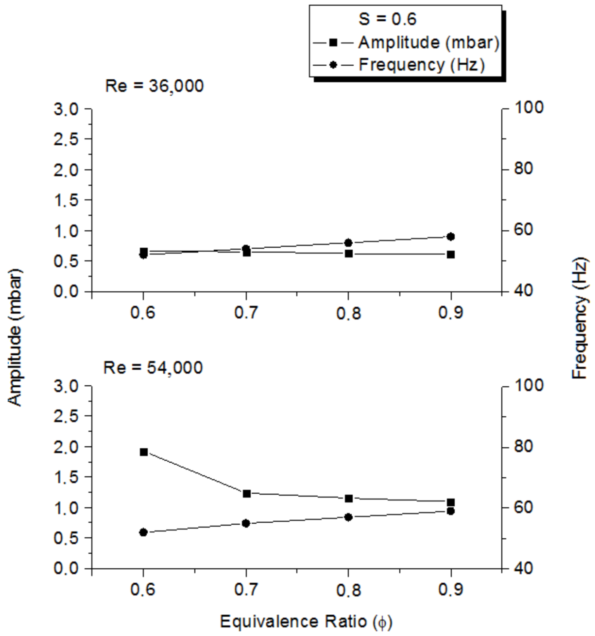
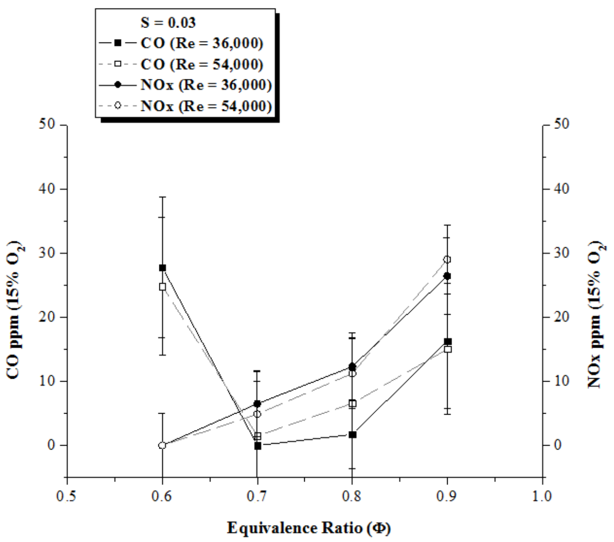
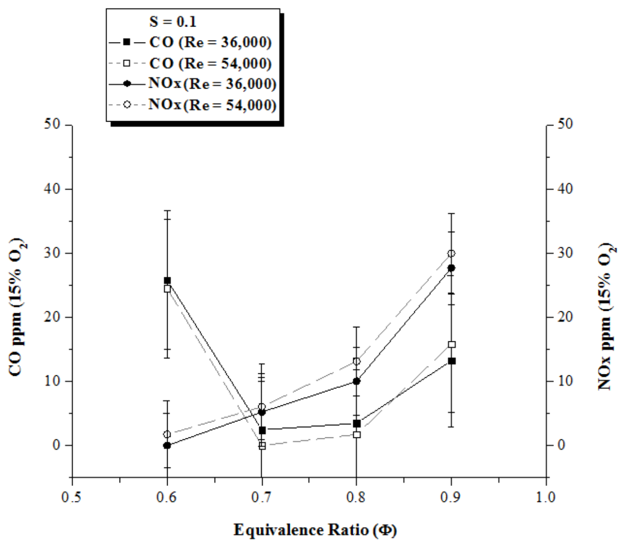


Figure 11. Pressure oscillations for different Reynolds numbers and swirl number 0.6

In spite of the low accuracy of the gas analyzer the results showed very low levels for CO and NOx emissions. It was observed the maximum value of CO at equivalence ratio equal 0.6 for all swirl intensity and Reynolds numbers. The CO decreases as the equivalence ratio increases up to ϕ = 0.8, as can be observed in Figs. 12 and 13, probably because the reaction in a lean combustion regime occurs at low temperatures, consequently, the conversion from CO to CO2 will be slow. Increasing the equivalence ratio for ϕ = 0.9 besides the combustion gases temperature increases, these gases will present a higher concentration of hydrogenated species, which in turn accelerates, considerably, the conversion from CO to CO_2. In addition, the CO oxidation by the OH radical is an important reaction, but slow. At low temperatures (low equivalence ratios) CO emissions will be high due to incomplete combustion and for very high temperatures, the levels of this pollutant will be high due to the carbon dioxide dissociation. NOx production is strongly dependent on temperature, pressure, residence time and reactants mixing degree. Among these, the flame temperature is presented as a major factor in the NOx formation. In situations where the temperature is above 1,800 K the NOx formation rate increases, rapidly, with the combustion temperature increase, as observed in this work and presented in Figs. 12 and 13. NOx emissions always reached maximum values for ϕ = 0.9, when the maximum flame temperature is achieved, and decreases up to ϕ = 0.6 presented levels near to zero when the flame temperature shows low values.

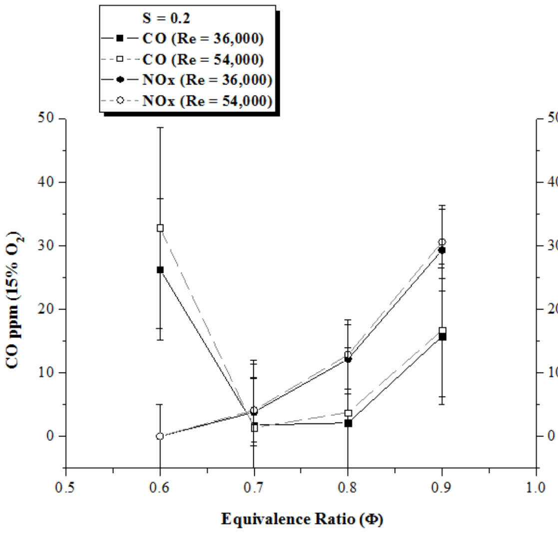


(a) S = 0.03

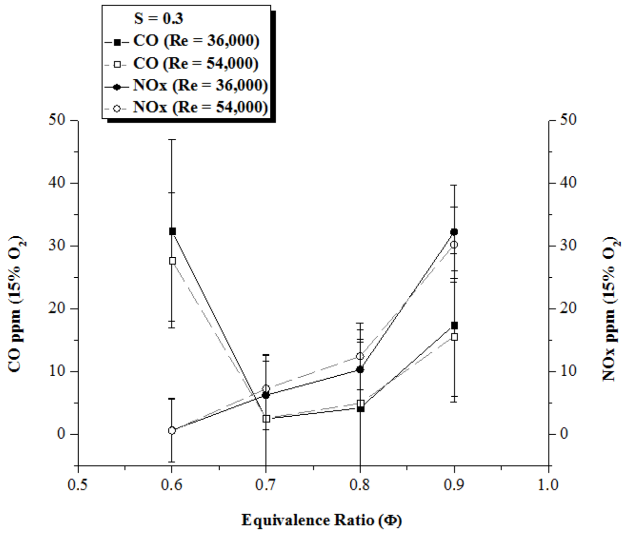


(b) S = 0.1

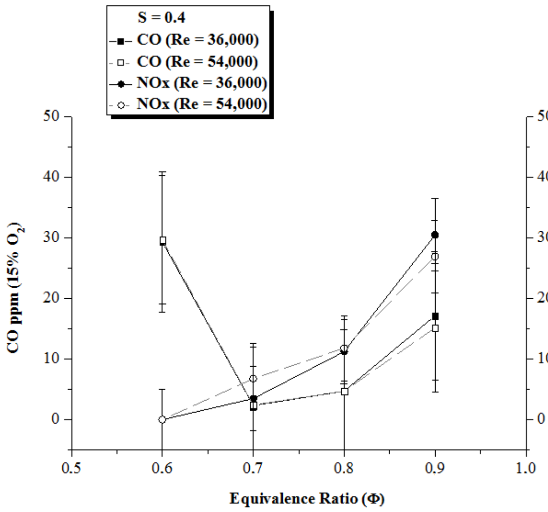
Figure 12. Rig test emissions measurements for S = 0.03 and S = 0.1 at atmospheric conditions



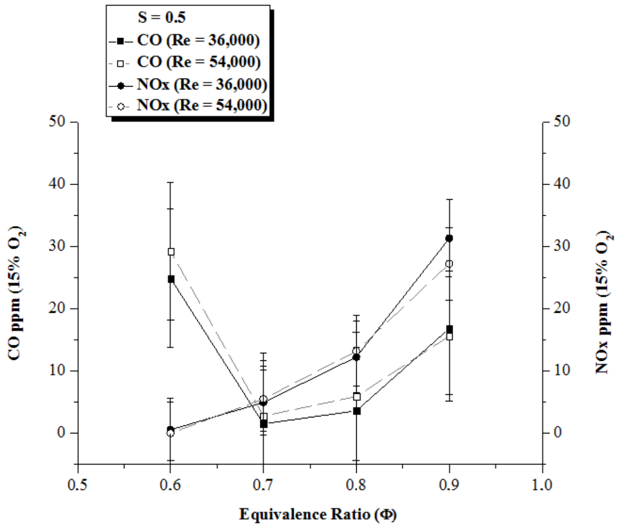
(a) S = 0.2



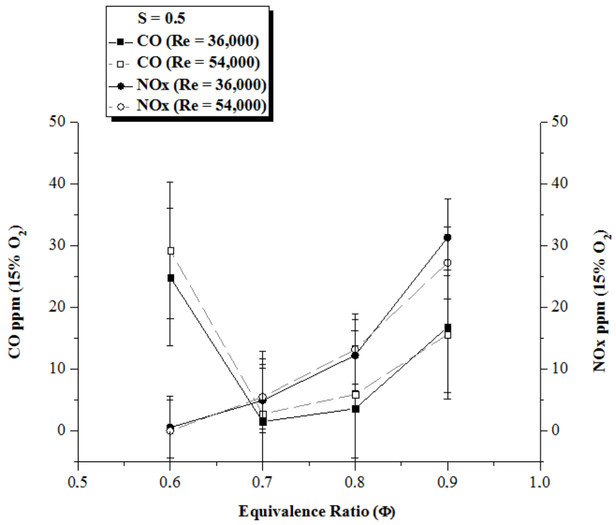
(b) S = 0.3



(c) S = 0.4



(d) S = 0.5



(e) S = 0.6

Figure 13. Rig test emissions measurements for swirl number from 0.2 till 0.6 at atmospheric conditions

4. CONCLUSIONS

The present paper examined experimentally the influence of the swirl intensity on pollutant emissions and pressure oscillations in a lean premixed combustor under atmospheric conditions for equivalence ratio from 0.6 till 0.9 and Reynolds number of 36,000 and 54,000. In additional, the flow fields of the reacting flows were obtained for all operational conditions using the optical combustion diagnostics technique. Analysis of the PIV data have shown that the flames generated by low swirl injectors are devoid of inner precessing vortex core or recirculation zone for swirl intensities below of 0.2. The appearance of inner precessing vortex core occurs at S = 0.2. The changes in the flame shape position could be observed through displacement of the recirculation zone visualized by the streamlines for S = 0.2 till 0.6, for Reynolds numbers of 36,000 and 54.000, showing that the flames are pulled closer to the injectors exit as the swirl number increases.

Swirl intensity presented a quite small influence on the amplitudes and frequencies of pressure oscillations. The frequencies were measured in a range from 50 Hz till 64 Hz and it is probably related to combustor geometry. The high value of peak amplitude for Re = 54.000 and $\phi = 0.6$ compared to others equivalence ratios for the same Reynolds number is probably due to lean blow-out limit that for this condition occurs at $\phi = 0.59$. For pollutant emissions the swirl intensity not present a significant influence showing the same qualitative behavior for all swirl numbers evaluated. In spite of the low accuracy of the gas analyzer the values measured presented very low levels for CO and NOx emissions. These results suggest that low swirl injector is a potential concept to attain an ultra-low emissions target of NOx < 10 ppm and CO < 40 ppm for gas turbine combustor.

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6. REFERENCES

Cheng, R.K., Yegan, D.T., Miyasato, M.M., Samuelesen, G.S., Benson, C.E., Pellisari, R. and Loftus, P., 2000. “Scaling and Development of Low-Swirl Burners for Low Emission Furnaces and Boilers”, Proceedings of the Combustion Institute, Vol. 28, p. 1305-1313.

Cheng, R.K., 1995. “Velocity characteristics of premixed turbulent flames stabilized by weak swirl”. *Combustion and Flame*, Vol. 101, p. 1-14.

Davis, D.W., Therkelsen, P.L., Littlejohn, D. and Cheng, R.K., 2013. “Effects of hydrogen on the thermo-acoustics coupling mechanisms of low-swirl injector flames in a model gas turbine combustor”. *Proceedings of the Combustion Institute*, Vol. 34, p. 3135-3143.

Day, M., Tachibana, S., Bell, J., Lijewski, M., Beckner, V. and Cheng, R.K., 2012. “A combined computational and experimental characterization of lean premixed turbulent low swirl laboratory flames”. *Combustion and Flame*, Vol. 159, p. 275-290.

Kim, K.T., Lee, J.G., Quay, B.D. and Santavicca, D.A., 2010. “Spatially distributed flame transfer for predicting combustion dynamics in lean premixed gas turbine combustors”. *Combustion and Flame*, Vol. 157, p. 1718-1730.

Legrand, M., Nogueira, J., Lecuona, A., Nauri, S., Rodriguez, P.A., 2009. “Atmospheric low swirl burner flow characterization with stereo PIV”. *Experiments in Fluids*, Vol. 48, p. 901-913.

Lyons, V.J., 1981. “Fuel/air nonuniformity-effect on nitric oxide emissions”. Proceedings of the 19th Aerospace Sciences Meeting. AIAA paper # 81-0327. Saint Louis, Missoure, Unite States.

Seo, S., 2003. “Combustion Instability Mechanism of a Lean Premixed Gas Turbine Combustor”. *KSME International Journal*, Vol. 17, p. 906-913.

Stöhr, M., Sadanandan, R. and Meier, W., 2011. “Phase-resolved characterization of vortex-flame interaction in a turbulent swirl flame”. *Experiments in Fluids*, Vol. 51, p. 1153-1167.

Stone, C. and Menon, S., 2002. “Swirl Control of Combustion Instabilities in a Gas Turbine Combustor”. *Proceedings of the Combustion Institute*, Vol. 29, p. 155-160.

Giezendanner, R., Weigand, P., Duan, X.R., Meier, W., Meier, U., Aigner, M. and Lehmann, B., 2005. “Laser-Based Investigations of Periodic Combustion Instabilities in a Gas Turbine Model Combustor”. *Journal of Engineering for Gas Turbine and Power*, Vol.127, p. 492-496.

Khalil, A.E.E. and Gupta, A.K., 2011. “Swirling distributed combustion for clean energy conversion in gas turbine applications”. *Applied Energy*, Vol. 88, p. 3685-3693.

Kohse-Höinghaus, K., Applied Combustion Diagnostics, Taylor & Francis, New York, 2002.

R.K. Cheng, D.T. Yegan, M.M. Miyasato, G.S. Samuelsen, C.E, Benson, R. Pellizari, P. Loftus, Proceedings of the Combustion Institute 28 (2000) 1305-1313.

R.K. Cheng, D. Littlejohn, W.A. Nazeer, K.O. Smith. Journal of Engineering for Gas Turbines and Power 130 (2008) 021501.

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