DETECTION OF COMBUSTION INSTABILITIES IN GAS TURBINE RQL COMBUSTOR

Dener Silva de Almeida, dener@ita.br
Pedro Teixeira Lacava, placava@ita.br
Aeronautical Institute of Tecnology, Marechal Eduardo Gomes Square, 50, São José dos Campos – SP, Brazil

Cristiane Aparecida Martins, cmartins@ita.br
Aeronautical Institute of Tecnology, Marechal Eduardo Gomes Square, 50, São José dos Campos – SP, Brazil

Abstract. *The focus of the present work is a new Rich – Quench – Lean – RQL gas turbine combustor. The combustion happens in two phases; the first one with oxidant deficiency, or fuel rich combustion, and the second one is a fuel lean combustion. This combustion structure allows the conciliation of low NOx emissions and partial oxidation combustion products, as carbon monoxide, unburned hydrocarbons and soot. The idea of the traditional RQL combustors is the staged reactants injections through the chamber, providing some unfavorable regions for NOx formation. But in the new concept proposed here, these unfavorable combustion conditions for NOx formation are reached through the dynamic control of reactants mixing process into the chamber, favoring some advantages in relation of traditional RQL process. However, for the lean combustion in the secondary chamber, depending operational combustion parameters, some acoustic oscillations happen. Therefore, the present work is concerned about the influence of these operational parameters: equivalence ratio, fuel jet Reynolds number, swirl number, and primary chamber length/diameter ratio (L/D), in the acoustic instabilities. The results show that increasing swirl number, and reducing fuel jet Reynolds number, the combustion oscillations can be attenuated. In addition, the highest L/D ratio investigated was 3, and for this situation good results were observed for instabilities attenuation. In the spite of the difficulties to understand the complex phenomena of combustion instabilities, this work presents some recommendation to control the oscillations in RQL gas turbine combustors.*

Keywords: Combustion, Gas Turbine, Combustion Instability

1. INTRODUCTION

The reduction of pollutants has became the main objective in the design of gas turbine engine, both for aeronautical use and industrial applications (power generation) by the expansion of its use in both situations. However, reduce emissions in these equipments isn't an easy task, since that operate in a wide range of power and environment conditions.

Among the various concepts developed for this purpose, is the LP (lean premixed) combustion system. This allows the NO_x reduction by reducing the flow rate of fuel and consequently the reduction of flame temperature peak (Kang *et al*., 2007). Althoug the LP concept allows significant reduction of NOx emission, various practical problems are associated with your implementation, including the washing of the flame (blowout), self-ignition e flame return (flashback) (Lyons, 1981).

Another technology to control the formation of NOx, besides UHC and CO in gas turbines, is the RQL (Rich-Quench- Lean) combustion system. In such cameras, a limited amount of air is introduced into the primary zone allowing a rich mixture with equivalence ratio ranging between 1.2 and 1.6. (Wulff and Hourmouziadis, 1997). However, the success of this concept is in uniform and effective cooling (quench effect) which is required for the transport of the mixture rich (hot) to the poor zone of the combustor, where the rest of the fuel is oxidized. Then more air is added to the poor zone with the objective of reducing the temperature and control the composition, which, with an appropriate residence time, will supplement the consumption of CO, UHC and soot formed in the rich zone. The point where the additional oxidant is injected is often called a stage of rapid mixing of an RQL combustor (Straub et al., 2005). The RQL concept, such as LP, is very promising in the NOx reduction, but like any new technology presents problems. Due to considerable amount of soot formed in the rich zone and consequently the drastic increase in the transfer of heat by radiation to the walls of the combustion chamber, the RQL concept requires the presence of a complex system of air film cooling. Furthermore, the poor zone needs to operate hot enough to burn soot, CO and UHC from the primary zone. This could limit the equivalence ratio to minimum values, *ie,* between 0.5 and 0.7 (and Hourmouziadis Wulff, 1997).

Gas turbines combustion is also object of research and technological development for the combustion group of the Aeronautical Institute of Technology - ITA, composed of teachers, researchers, engineers, technicians and students, who accumulate experience in design of the gas turbine combustion chamber and in the development of new cameras that incorporate technology for low emissions, mainly NOx.

This work deals with combustion instability phenomenon in a double-stage swirl combustor, which in this case is a kind of hybrid configuration between RQL and LP concepts, however, without pre-mixing of the LP combustors and without the staged air addition as happen in the RQL chambers. In this assembly, the dynamics of the reactants and burned gases flows prevent the occurrence of regions favorable to the NOx formation. The combustion occurs in two steps or two cameras. At first the fuel is injected through a central lance and the air that participates of the overall combustion process is forced to cross a swirl, where acquires tangential component of velocity. A yellow sooting flame is observed in the region of interaction between the jet fuel and the rotational air flow. This absorbs the intense heat transferred by radiation of the sooting flame and acts as a film cooling natural. At the end of this primary zone, transition zone, there is a sudden increase in the chamber diameter and the rotating air flow loses the wall effect, expanding itself radially. This causes the pressure decrease in the central region, which in turn allows the reversal of the air flow and consequently the creation of a intense recirculation zone mixing the remaining air with the products of combustion of the rich zone (effect quench). Only in the second stage (secondary camera) a poor pre-mixed flame is established.

Despite the NOx reduction provided by this experimental assembly, it is observed for certain working conditions, the occurrence of acoustic combustion instabilities, being the analysis of the influence of the main parameters controlling the combustion process on the occurrence of this phenomenon the objective of this work.

2. EXPERIMENTAL SETUP

2.1. Combustion chamber

The tests were performed at atmospheric pressure in a laboratorial scale combustor. This was made of stainless steel, does not require refrigeration, since, as mentioned in the previous section, the air from the swirl works as a kind of film cooling. The primary chamber, where the burning occurs rich, has three lengths, 10, 20 and 30 cm, with an only diameter of 10 cm. This variable geometry to make possible analyze the influence of the ratio L / D on the flow dynamics. Already the secondary camera shows length and diameter of 50 cm and 20, respectively. Figure 1 shows the schematic diagram of experimental assembly.

The fuel was injected through an injector nozzle located in the central region of the primary chamber. It was used three different diameters for the injector nozzle: 2.35, 3.20 and 7.8 mm, which provided fuel jets with Reynolds numbers of 50,000, 40,000 and 15,000 respectively. Thus, to observe the influence of Reynolds number, for a swirl number and ratio L / D wasn't necessary to change the fuel flow, which was kept constant at 1 g / s for all experiments. The air, from two blowers is conducted axially to the swirl at the entrance of the primary chamber. To allow that the air flow, when emerge of the swirl with extremely high tangential velocity component, concentrate around the cylindrical wall of the primary zone and only a small part of this flow interacts with fuel jet that occupies the central region the chamber, forming a rich flame, the camera and the crown of the swirl have the same diameter. The swirl is composed of 8 blades, which whit the axial direction form angles between 0 ° and 80 °, and thus the swirl number was modified by changing the angle between the swirl blades, not being necessary to change the air flow passing through this device. The maximum air flow achieved was 100 g / s.

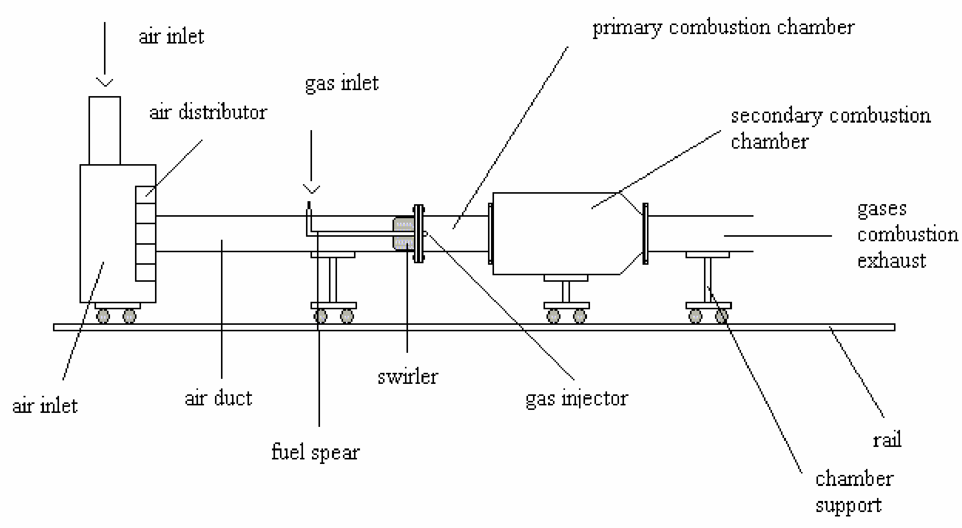

Figure 1. Schematic diagram of the experimental setup

2.2. Flow measures

Both working fluid mass flows were obtained through the use of orifice plates and pressure gauges of the type U. In order to make sure that the flow rates obtained by the orifice plates system weren't in disagreement with the experimental reality, since a calibration to check the accuracy of this system (according to ISO 5167 is 0.8%) was not possible, Rivas (2005), using the same orifice plates set, compared to gas natural combustion equivalence ratio with air in a cylindrical chamber of 1.5 m long and 0.5 m in diameter, through the plates data flow and through the O2 analysis in the output of the camera. The comparison was made for different conditions of equivalence ratio and gas injection diameters. Upon satisfactory agreement observed between the results for both methods in all experimental conditions, assumed that the flow rates obtained by the plates are right, although the calibration was not performed.

2.3. Data acquisition and treatment

To detect the occurrence of instabilities, a Kistler 7261 piezoelectric pressure transducer, was attached to the primary zone of combustion chamber in the vicinity of the swirl. This position was chosen because of low temperature on the outside of the chamber, facilitating the cooling of the transducer (approximately 350k). Moreover, some preliminary tests showed that in this position the transducer can easily detect the instabilities, especially the first mode of oscillation, approximately 75 Hz, which is the frequency more pronounced for all experimental conditions. A Kistler 5006 charge amplifier, model 5006, was used to amplify the signal from the piezoelectric transducer, which is monitored by Tektronix 763 oscilloscope. The specifications of the transducer are: measurement range - -1 to 10 bar, maximum pressure - 12 bar, resolution - 1.5x10-5 bar, sensitivity - 2200 pC / bar. The amplitude and frequency uncertainty measures were determined by calibration. The transducer used in this work with a standard transducer were coupled into a chamber fed by a pulsating flow, and the results compared for different frequencies and amplitudes. The uncertainty is calculated for the 95% probability point in the curve "Student t", and for the results presented here the maximum error for the frequency is 1% and for the amplitude 5% of the measure.

The system used in this work to the data acquisition and analysis is LabVIEW, composed of a AT-MIO 16E4 plate with acquisition speed of 1.25 MS, 4 digital and 8 analogical channels, a low-pass filter with cut-off frequency of 2 Hz to reject noise of 60 Hz, set the gain from 1 to 100 and a termistor used as a sensor for compensation of cold joint. For each position, the value presented is the average of 1000 samples. The electrical signals were acquired by only 1 transducer at a rate of reading of 3200 points per second. To treatment of these data was used an analysis based on Fourier Transform (amplitude).

3. RESULTS

To better understand the results and attribute the operation parameters influences in the occurrence of instabilities, was tried to make some tests to determine the origin of them. In many situations this may not be of the responsibility of the combustion process, with the heat addition the role intensify of them. Furthermore, in experimental assembling study here, the instability could be associated with primary or secondary camera. Thus, there were the following tests: 1) burning for the whole set, *ie*, with the presence of primary and secondary chamber, 2) combustion only with secondary chamber, 3) complete assembly with absence of reactive flow. For this chosen as reference the situation L / D = 2, Re = 40000, α = 60 ° and different equivalence ratio, because, depending on the overall equivalence ratio high amplitudes of oscillation were observed for this condition. The results are met in Fig.2. Note that even for equivalence ratios where large amplitudes are reached with combustion, which for this study are lower than 0.3, ie the poor zone, there isn't instabilities for combustion situation. The combustion systems operating with theoretical equivalence ratios extremely low are more likely to combustion instabilities, which is proven in several published studies. There isn't also instability when the secondary combustion occurs open to the atmosphere. Thus, this comparison shows that the instability origin is inherent to the combustion process and the secondary chamber, *ie*, is related to interactions between energy addition, the reactive flow structure and the acoustic characteristics of the same. The average oscillation frequency when instability regimes are achieved was always close to 80Hz.

Energy addition oscillations are associated with speed, pressure, temperature fluctuations and reagents composition, which are present simultaneously in combustion systems. In gas turbines combustion chambers, some investigations showed that these oscillations behave like Helmholtz resonators. These instabilities are attributed to the pressure oscillation difference between the air and the combustor, causing an acceleration and deceleration of the air flow through the burner and, therefore, alternating rich and poor pockets mixture patterns. When these pockets reach the reaction zone, density fluctuations are generated, which in turn lead to speed fluctuations and thus keep the pressure oscillations. In favorable conditions, periodic heat addition fluctuations combine with the natural resonant frequency of one or more combustor geometric components or natural mechanisms related to the fluids mechanics.

Coherent large-scale structures also play an important role in combustion and, consequently, in energy addition form, through the reagents mixing control in the flame region. Interactions between these structures, acoustic resonant modes in the combustion chamber and the energy addition process are identified as the main causes of thermoacoustic instabilities. For swirl flows, the tangential velocity component addition changes the flow dynamics and can excite other types of instability. Reasonable modifications in large-scale vortices are important to control instabilities induced by swirl and increase the combustion efficiency.

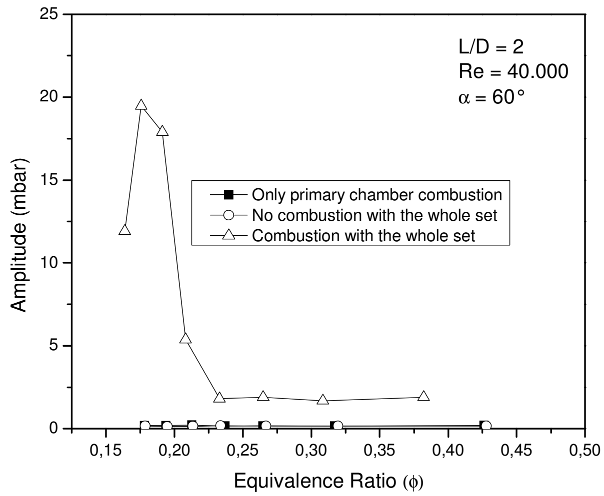

Figure 2. Results for L/D = 2, Re = 40,000, a = 60º and several global equivalence ratio.

The results for L / D = 1 are shown in Fig.3. Note that most of the instability occurs for equivalence ratios less than 0.3. The combustion systems operating with extremely low theoretical equivalence ratios are more likely to combustion instabilities, which is proven in several published studies such as Bradley *et al*. (1998), Lieuwen *et al*. (1998) and Cohen and Anderson (1996). In extremely poor combustion regimes, as already discussed and as expected for the secondary camera in this experiment, reagent mixture formation fluctuations lead to energy release rate alternations, which can cause pressure fluctuations, especially if the flame is close to its blowout limit. In the case of extremely poor mixtures, the flame propagation speed is very low, which does not allow an energy release recovery when equivalence ratio fluctuations are present (Stone and Menon, 2002).

Lieuwen et al. (1998) suggested that the poor mixing between the reagents in a poor global combustion condition causes equivalence ratio fluctuations, and they play an important role in the mechanism that induces the onset of combustion instability. Bradley *et al*. (1998) performed experiments with a flame formed by methane and air stabilized through swirl, kept constant the swirl number and the average axial entry speed, while the equivalence ratio was reduced. It was observed that low-frequency acoustic instabilities appeared for equivalence ratio values less than 0.6. However, for equivalence ratios above this value, the combustion remained stable. In general, it has been shown that equivalence ratio small disturbances (production of pockets) produce low-amplitude oscillations in stoichiometric mixtures, however, cause larger amplitudes oscilattations in poor mixtures, ie, in poor combustion conditions mixture reagent inhomogeneity induces energy release alternations leading to strong acoustic instabilities.

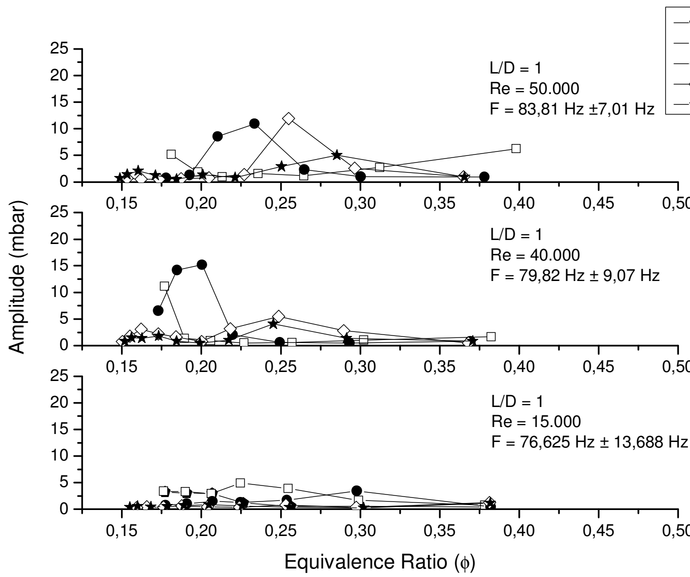

Figure 3. Results for L/D = 1

Another important observation is the influence of fuel jet Reynolds number. Comparing the results was found that with its increase there is a tendency for larger amplitudes oscillations. The explanation for this can is in the fact that the fuel injection with higher speed will produce a combustion gases central flow with a greater axial movement amount in the transition between primary and secondary chambers. Thus, there is a greater destruction of the secondary chamber recirculation structure.

Figures 4 and 5 present the results to similar tests for L / D = 2 and L / D = 3, respectively. Qualitatively, it's noted that the same trends of influence on instabilities generation are observed for the global equivalence ratio, swirler angle and the jet Reynolds number. However, for L / D = 3 it can be seen clearly that there is a strong instabilities attenuation with relation to L / D = 1 and 2. Except in the case where Re = 50,000, for the two lower Reynolds numbers, the oscillations were less than 5 mbar for L / D = 3. Probably, the primary chamber longer, the axial movement amount of the partial combustion gases flow between the primary and secondary chambers is lower for other lengths. Thus, the partial combustion products are mixed with more homogeneous in the recirculation zone formed in the secondary zone. Obviously, for smaller Reynolds numbers, the amount of axial movement is more tenuous still.

.

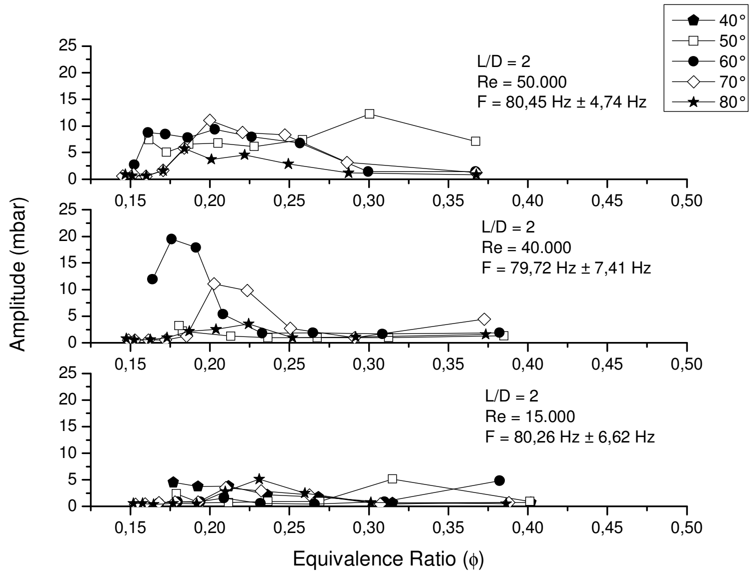

Figure 4. Results for L/D = 2

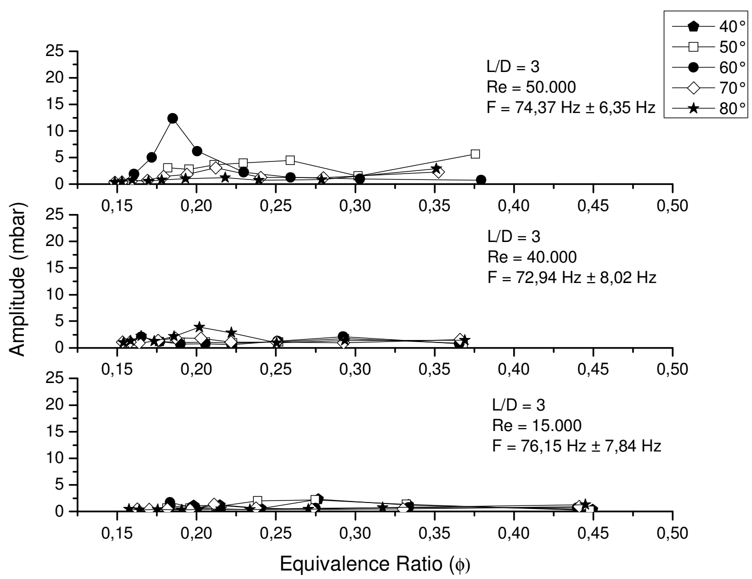

Figure 5. Results for L/D = 3

Results for L / D = 2, Re = 40000 and α = 60 ° (Fig. 5) represent the best combination for instabilities attenuation. Whatever the equivalence ratio and the swirler angle, the higher primary chamber length and a lower Reynolds number always able to establish a secondary combustion regime with conditions unfavorable to the instabilities generation. This shows that these two parameters, which influence axial movement amount in the transition between primary and secondary chambers, are fundamental to the instability appearance or not.

The swirl number influence on the oscillations amplitude for different Reynolds and L/D ratios is present more specifically in Figures 6, 7 and 8. In general, the results show that extremely strong swirl number, obtained here for swirler angle of 70º and 80º, regardless of Reynolds number, the equivalence ratio and the primary zone length, producing combustion conditions with more attenuated instabilities.

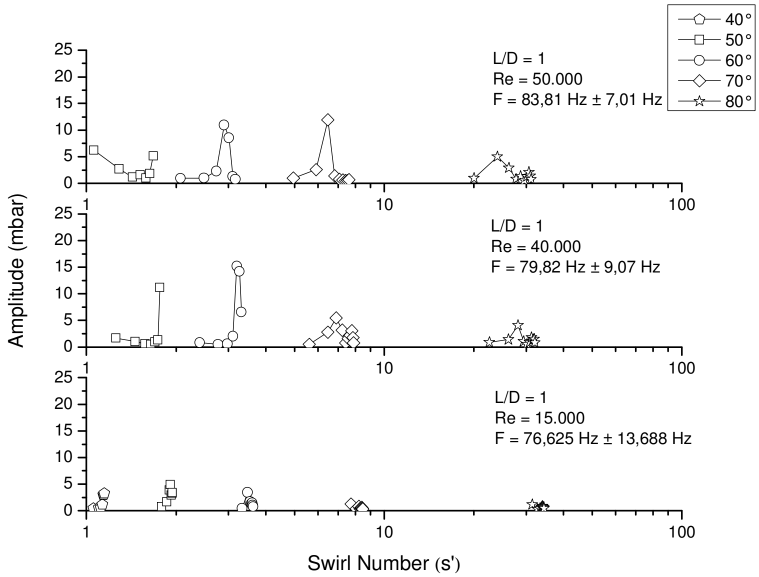

Figure 6. Results for L/D = 1

Swirlers flow can affect the instabilities appearance in two ways: influencing the reagents mixing or through of coupling between vortices disruption and combustion chamber acoustic characteristics. In the first case, as discussed earlier, increasing the swirl number enhances the recirculation structure, which promotes more homogeneous mixtures and less fluctuation in the energy release rate. In the second case, unstable large-scale movements arising from the instability of shear layers and the vortices breakdown as well as the center of the space alternating vortices (PVC – Precessing Vortex Cores) can attach themselves resonate with sound waves in the combustor and subsequently cause combustion instabilities (Huang and Yang, 2005). The occurrence of PVC is usually linked to the phenomenon of collapse of vortices and the presence of a recirculation zone, and their behavior and occurrence more complex during the combustion process, especially in poor combustion (Syred, 2006).

However, recent studies on the combustion instability in gas turbines using swirl indicate that high numbers of swirl tend to reduce the amplitude oscillations. According Syred (2006), high swirl number produces more strong and regular recirculation areas that are less susceptible to deformations imposed by pressure fluctuations. Huang and Yang (2005) also report on its work an amplitude instability reduction with the swirl number increase. Master and Benoit (1972) demonstrated by results of their experiments that a stable and efficient combustion in chambers with swirl can be achieved in a flow with a high swirl number. Broda et al. (1998) presented an experimental study of the combustion dynamics in a LP combustor stabilized by swirl, confirming the trend of reducing the instability magnitude with the swirl increase. The results of Tangirala et al. (1987) showed that the flame mixture and stability can be improved by increasing the swirl number to values close to unity. Abuaf and Lovett (1992) also showed that flames anchored by swirlers are less prone to instabilities of the flames stabilized by other types of anchoring.

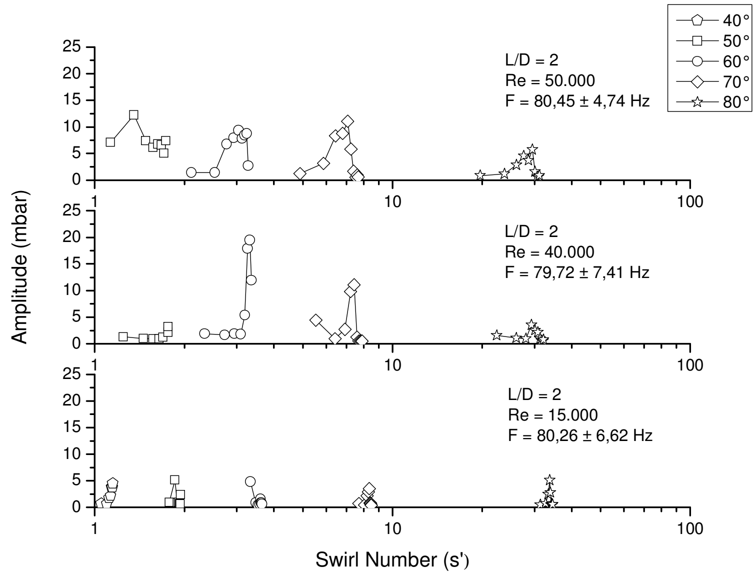

Figure 7. Results for L/D = 2

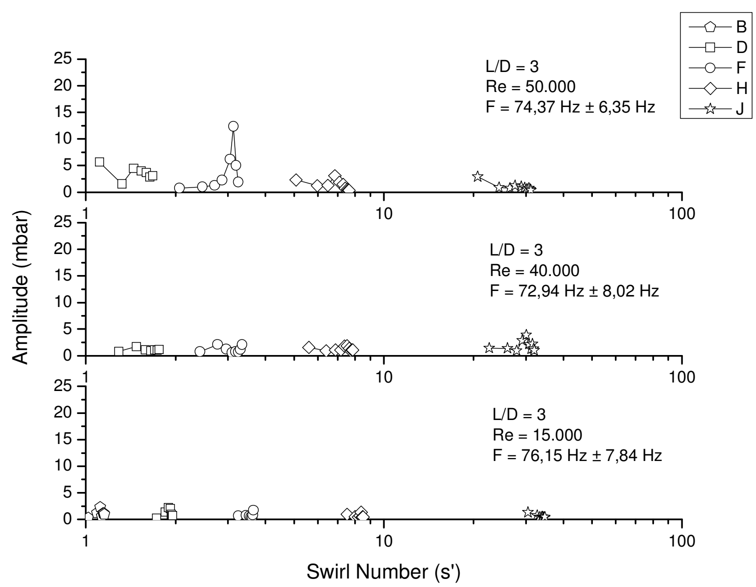

Figure 8. Results for L/D = 3

A high swirl number also tends to increase the turbulence intensity and consequently the flame speed, which in the poor combustion case may partially compensate the speed reduction due to low temperature, with this energy release fluctuations in the flame are less perceived.

Or by the mixture quality control or by unstable vortices effects attenuation, the results show that large swirl numbers are adequate to control the instabilities of combustion chamber studied in this work. The results also show that the swirl number exerts little influence on the acoustic frequency, which is related to the fundamental mode of the acoustic cavity, *i.e.*, the combustion chamber, but plays a key role in the oscillation amplitude.

4. CONCLUSIONS

The aim of this research was the experimental investigation of laboratory scale double stage swirl combustor operation parameters, namely: air flow swirl number, fuel flow Reynolds number, primary chamber L/D ratio and global equivalence ratio, and their influence on the combustion instabilities occurrence.

It was observed that the equivalence ratio exercises strong influence in the mechanisms that lead to instability. According to results of many studies in the literature, combustion systems operating with extremely low theoretical equivalence ratio are more likely to combustion instability. This is due to the fact that in poor combustion conditions, fluctuations in the reagent mixture formation lead to alternations in the energy release rate, which can cause pressure fluctuations. However, in general, the results showed that the oscillations will be reduced when the parameters studied contributed to creating a more homogeneous mixture in the secondary chamber.

A higher L/D ratio provides a more stable combustion, which can be attributed to lower axial movement amount of the gas burned jet in the transition between primary and secondary chambers, facilitating the air mixing in the recirculation area. The reduction of the fuel jet Reynolds number also reduces the oscillations. With lower speed, the jet fuel will have less influence on the destruction of the secondary chamber recirculation zone. For operating conditions with high swirl numbers (70 ° and 80 °), the combustion becomes more stable. With the angle increase, consequently of the swirl number, the recirculation zone at the exit of the primary chamber is intensified, that it can increase the occurrence of more homogeneous mixtures in this region and oscillations damping. Moreover, energy release fluctuations and, consequently, pressure fluctuations, because of the reagent mixture inhomogeneity is less felt by the flame, since a strongest recirculation zone increases the turbulent flame velocity, which compensate the decrease due to the extremely poor combustion.

The results presented in this paper show that conclusions about combustion thermoacoustic instabilities origin is not an easy task, due to a variety of complex physical processes involving this phenomenon. However, the conclusions obtained here should be bring with other project details, for example, the temperature profile at the exit of the combustor, the flammability limits for the entire engine, and low emissions. As future work it is recommended that tests similar to what was achieved in this work, but increasing the secondary chamber diameter. A higher chamber volume can act as a fluctuations buffer, in addition, a higher "step" between the primary and secondary chamber can strengthen the recirculation structure and improve the mixture between the partial combustion gases and air. Additionally, to understand the interaction between flows in the primary and secondary chambers with pressure oscillation, it is necessary to use images of OH radicals to secondary camera provided by PLIF or make use of the PIV analysis for the transition region. Finally the development of this type of camera setup should move towards tests with liquid fuels and pressures above atmospheric.

5. ACKNOWLEDGEMENTS

This work was sponsored by the Brazilian National Research Council - CNPq (research resource and grant of Mr. Lacava) and by The State of Maranhão Research Foundation – FAPEMA (grant of Mr. Almeida). The tests were carried out at the Professor Feng Aeronautical Laboratory, Aeronautical Technology of Institute.

6. REFERENCES

Bradley, D., Gaskell, P.H., GU, X.J., Lames, M. and Scott, M.J., 1998, "Premixed Turbulent Flame Instability and NO Formation in a Lean-Burn Swirl Burner", Combustion and Flame, Vol. 115, pp. 515-538.

Broda, J.C., Seo, S., Santoro, R.J., Shirhattikar, G. and Yang, V., 1998, "An Experimental Study of Combustion Dynamics of a Premixed Swirl Injector, Proceedings of the Combustion Institute, Vol. 27, pp. 1849-1856.

Cohen, J.C. and Anderson, T., 15-18 January 1996, "Experimental Investigation of Near-Blowout Instabilities in a Lean Premixed Step Combustion", In: 34th Aerospace Sciences Meeting and Exhibit, AIAA paper # 96-0819, Reno, Nevada, United States.

Couto, H.S., Muniz, W.F. and Bastos-Netto D., 11-15 December 1995, "Geometrical Parameters for Flows Across Axial Swilers", Proceedings of the 3rd Asian-Pacific International Symposium on Combustion and Energy Utilization, Vol.1, pp. 255-260.

Huang, Y. and Yang, V., 2005, "Effect of Swirl on Combustion Dynamics in a Lean-Premixed Swirl-Stabilized Combustor", Proceedings of Combustion Institute, pp. 1775-1782.

Kang, D.M., Culick, F.E.C. and Ratner, A., 2007, "Combustion Dynamics of a Low-Swirl Combustor", Combustor and Flame, Vol.151, pp. 412-425.

Lieuwen, T., Neumeier, Y. and Zinn, B.T., 1998, "The Role of Unmixedness and Chemical Kinetics in Driving Combustion Instabilities in Lean Premixed Combustors", Combustion Science and Technology, Vol. 135, pp. 193-211.

Lovett, J.A. and Abuaf, N., 1992, "Emissions and Stability Characteristics of Flameholders for Lean Premixed Combustion", ASME paper # 92 – GT- 120.

Lyons, V.J., January 1981, "Fuel/Air Nonuniformity-Effect on Nitric Oxide Emissions", In: 19th Aerospace Sciences Meeting, AIAA paper # 81-0327, Vol. 20, St. Louis, Missouri, United States.
Mestre, A. and Benoit, A., 1972, "Combustion in Swirling Flow", In: 15th International Symposium on Combustion.
Stone, C. and Menon, S., 2002, "Swirl Control of Combustion Instabilities in a Gas Turbine Combustion", Proceedings of Combustion Institute, Vol. 29, pp.155-160.
Straub, D.L., Castelon, K.H., Lewis, R.E., Sidwell, T.G., Maloney, D.J. and Richards, G.A., 2005, "Assessment of Rich-Burn, Quick-Mix, Lean Burner Trapped Vortex Combustor for Stationary Gas Turbines", Journal of Engineering for Gas Turbine and Power, Vol. 127, pp. 36-41.
Syred, N., 2006, "A Review of Oscillation Mechanisms and the Role of the Precessing Vortex Core (PVC) in Swirl Combustion Systems", Progress in Combustion and Energy Science, Vol. 32, pp. 93-161.
Tangirala, V., Chen, R.H. and Driscoll, J.F., 1987, "Effect of Heat Release and Swirl on the Recirculation Within Swirl-Stabilized Flames", Combustion Science and Technology, Vol. 51, pp. 75-95.
Wulff, A. and Hourmouziadis, J., 1997, "Technology Review of Aeroengine Pollutant Emissions", Aerospace Science and Technology, Vol. 8, pp. 557-572.

7. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.