Experimental Investigation of the Temperature Profile at the Outer Wall of a New Concept of Two Stages Combustor for Gas Turbine

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Abstract. *The present work reports an experimental investigation about a new concept of a two stage combustor for gas turbines. It is based in low emission of NOx by the control of operational parameters like primary chamber length/diameter ratio (L/D), equivalence ratio, swirler blades angle and fuel jet Reynolds. Therefore, the variation of these parameters was made with the purpose of determining the influence of these parameters on the heat transfer to the combustor wall and to asure that the new concept of combustor satisfies one of the principal objectives of its creation, which is, to reduce the high temperature to which the walls of the combustor are submitted to. The result shows a general behavior in which high values of acoustic amplitudes and low swirler blades angles produce an increase in heat transfer to the outer wall. Also, higher L/D ratio and lower equivalence ratio generate lower temperature profiles and finally lower fuel jet Reynolds numbers have a tendency to increase the temperature values.*

Keywords*: Temperature, heat transfer, Combustor chamber, gas turbine.*

1. INTRODUCTION

Nowadays, gas turbines for energy generation are considered of great interest due to numerous factors such as complex cycles that can have an efficiency of 50%. The benefits derived from its very high construction, which offsets the initial investment (Correa, 1991). It can burn a variety of fuels and be adapted to use when the supply of coal gas decreases (Newby and Bannister, 1993). However, one of the main problems of using this type of turbine is the high emissions of pollutants such as nitrogen oxides in general (NOx), carbon monoxide (CO), unburnt hydrocarbons (UHC) and soot (Becker *et al.*, 1986).

Generally the traditional gas turbines operate under conditions where the reactants enter into the combustor separately, for reasons of security and control of the mixture. However, this leads to obtain high levels of thermal NOx, obtained at high temperatures and in regions near the stoichiometric mixture of reagents. At the same time, due to how the regents are introduced into the combustion chamber, it is difficult to control the process of mixing (Almeida, 2007a).

This leads to a high production of soot in the flame primary zone, which in turn increases the rate of heat transfer to the walls of the chamber, and therefore makes necessary the use of complex refrigeration systems. Some of the traditional methods used to reduce the high temperatures and the formation of thermal NOx has been the injection of water and water vapor (Brewster *et al.*, 1999). However, the injection of a great percentage of air to cool the turbine, combined with a corresponding decrease in the amount of air available for combustion has a direct influence on the profile of exhaust gas temperature. Moreover, the effect *Quench* decreases by the high presence of not burned air, reducing the combustion efficiency and increasing emissions of CO and UHC.

Among the various technologies developed for the reduction of NOx are the combustion system of the type pre-mixed low (LP-*Lean Premixed*) for gaseous fuels and combustion pre-steamed and pre-mixed poor (LPP-Vaporized and Lean Premixed Combustion) for liquid fuels. A striking feature of this system is the complete evaporation of the fuel in case of liquid and the complete mixing of reagents prior to the combustion region. This type of technology has serious problems associated with combustion instabilities, blowout and flashback (Almeida, 2009b).

Another technology used for the reduction of NOx is the combustion of type Rich-Quench-Lean. This is based on a two-stage combustor where the reagents are injected directly into a primary chamber, which allows a better control of the burning process, leading to a mixture rich combustion (Corr *et al.*, 1991). In this new technology, the air enters the chamber passes through a swirl, creating a tangential component of high speed that adheres to the cylindrical wall of primary chamber, thus forming a film cooling. This allows only a small amount of air conducted to the center of the chamber to be mixed with the incoming gas, resulting in a rich burn. In this area the airflow absorbs the intense heat transfer by the radiation product of the soot in the flame.

After the first stage, the gas enters in a chamber of a large diameter, where the wall effect produced by film cooling is lost, and the flow tends to expand rapidly in the axial direction creating a zone of low pressure in the center of the chamber called Central Zone of Recirculation (CZR). This allows the mixture of not burned air with the products of combustion from the primary zone (*Quench effect*) and also creates a homogeneous mixture of intense poor combustion (Ronceros, 2005).

Using a laboratory scale model of the combustion chamber, the Aeronautical Institute of Technology, Brazil, has been studying the effects of parameters regulating the combustion process like the length/diameter of the primary chamber (L/D), equivalence ratio (ϕ) , swirl number (S'), Reynolds number of reagents (Re) and acoustic instabilities in the combustion process on the temperature profiles, registered from the wall of the chamber, to determine if this new configuration is able to reduce NOx emissions and heat transfer to the combustor wall, with the purpose of obtaining maximum efficiency in the combustion process. The configuration of the combustor used both RQL concept and LP to control emissions, without pre-mixtures, a characteristic of the combustor LP and without additional stages of air to work, a characteristic of the RQL combustor.

2. EXPERIMENTAL SETUP

The model used for the experimental assembly was made of stainless steel in a modular design in order enable a change in its configuration. It is divided into two areas easily differentiated: Primary zone (responsible for the rich combustion) has a diameter (D) and 0.1*m* length (L) of 0.1*m*, 0.2*m* and 0.3*m*, which gives L/D of 1, 2 and 3, respectively. Secondary zone (responsible for the lean burn) has a diameter of 0.2*m* and a length of 0.5*m*. Fig. 1 shows a schematic diagram of the experimental setup.

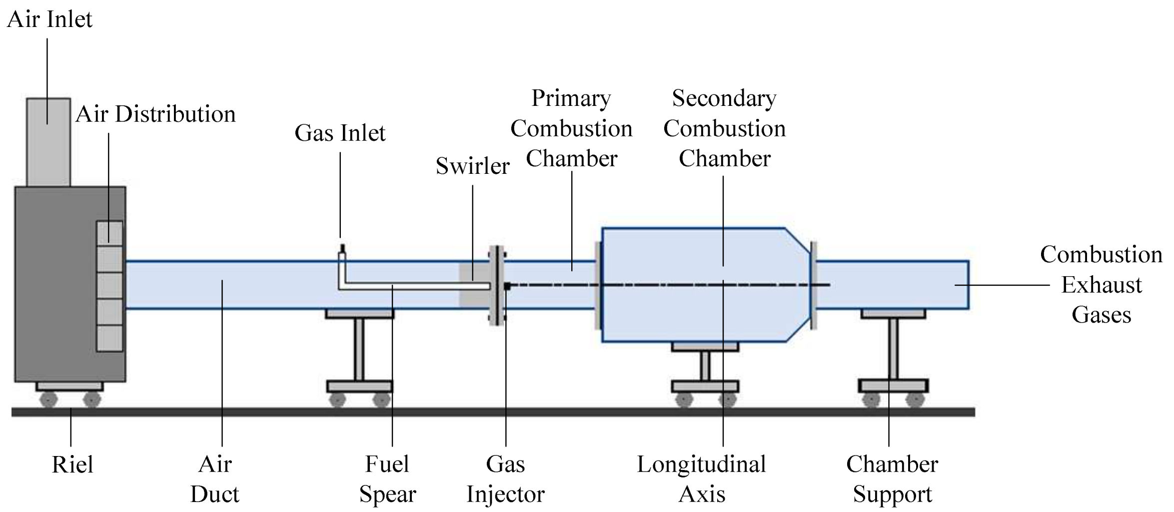

Figure 1. Schematic diagram of the experimental setup

With the purpose to vary the Reynolds number of the fuel flow (Natural Gas Vehicle, GNV), the mass flow rate was held equal to 1*g/s*, it was used three nozzles of various diameters, D (2.35*mm*; 3.20*mm* and 7.8*mm*) providing Reynolds (Re) of approximately 50,000; 40,000 and 15,000, respectively.

The axial swirl used has 9 blades of 0.014*mm* thickness. The angles used were 60° and 80° according to Lefebvre (1983) for these angles; instability and stability in combustion are experienced, respectively.

To obtain the mass flow rate of fluids (air and fuel), orifice plate systems were used. An orifice plate "Radius Tap" was used to obtain the mass flow rate of the air. To measure the mass flow rate of natural gas was used a plate of small diameter pipes (about 13*mm* to 40*mm*). Both mass flow rates were calibrated with a maximum error of 3% of the measure.

After the data acquisition of pressure and temperature, the program "Calculo do Numero de Swirl" (Rivas, 2005) was used in which mathematical equations suggested by Delmeé are implicit (1987), for calculating the mass flow rates (air and fuel), equivalence ratio, swirl number, Reynolds number, among others. The calculations of the Reynolds number and equivalence ratio are limited to the equation (1) and (2), respectively.

$$R_e = \frac{4\dot{m}}{\mu \pi D} \quad (1)$$

Where, $\dot{m}$ is the fuel flow mass, μ the viscosity of the fluid and D the diameter of the fuel nozzle.

$$\phi = \frac{(F/A)_{opera}}{(F/A)_{stoic}} \quad (2)$$

Where, $(\mathrm{F/A})_{\mathrm{opera}}$ represents the operating air-fuel ratio and $(\mathrm{F/A})_{\mathrm{stoic}}$ corresponds to the stoichiometric air fuel ratio, found as (Turns, 2000):

$$(\mathrm{F/A})_{\mathrm{stoic}} = {MW_{air}}/{MW_{fuel}} \quad (3)$$

Where, MW_{air} and MW_{fuel} are the molecular weights of the air and fuel, respectively.

To detect the Amplitude (A) and the combustion instability in each working conditions, a Kistler 7261 piezoelectric pressure transducer was positioned at 30*mm* above the swirl, at the primary wall chamber. This position was chosen due to the lower wall temperature, around 350*K* at the external side, facilitating the cooling transducer (Almeida, 2009b). For the results presented here the maximum frequency error is 1% and 5% for amplitude of the measure.

2.1 Data acquisition of temperature at the outer wall of the combustor

For data acquisition of temperature at the outer walls of the combustor, an optical pyrometer or infrared thermometer was used, IRtec Miniray 100, which captures infrared energy radiating from the bodies and focuses on a detector, which converts that in an electrical signal amplified and displayed on a digital display. This instrument has a watch with a circular laser with spot dimensions at 1m of 3.5*mm*, measuring range from 241*K* to 793*K*, capable to acquire data for a certain time and display averages of these measures, it also complies with ISO 9000 specifications, with a limit of error ±274.5*K* (from 241*K* to 296*K*) or ±1% of reading (from 296*K* to 793*K*). This was located at a horizontal distance of 1.50*m* and a height of 1.30*m* of the longitudinal center combustor in a variable position, allowing free movement along the longitudinal axis thereof.

The points at which temperatures were taken at the outer wall combustor were determined for the primary chamber according to its length, for 0.2*m* and 0.3*m* length was distributed to 25% separation, whereas the chamber 0.1*m* due to its short length, just found a measuring point (50%). For the secondary combustor 4 points of it were taken, each separated 0.10*m* (Fig. 2). At each point of temperature 20 measures at intervals of 10*s* were acquired, to make this half of temperature with a significant number of samples, providing a more accurate measure of the real value.

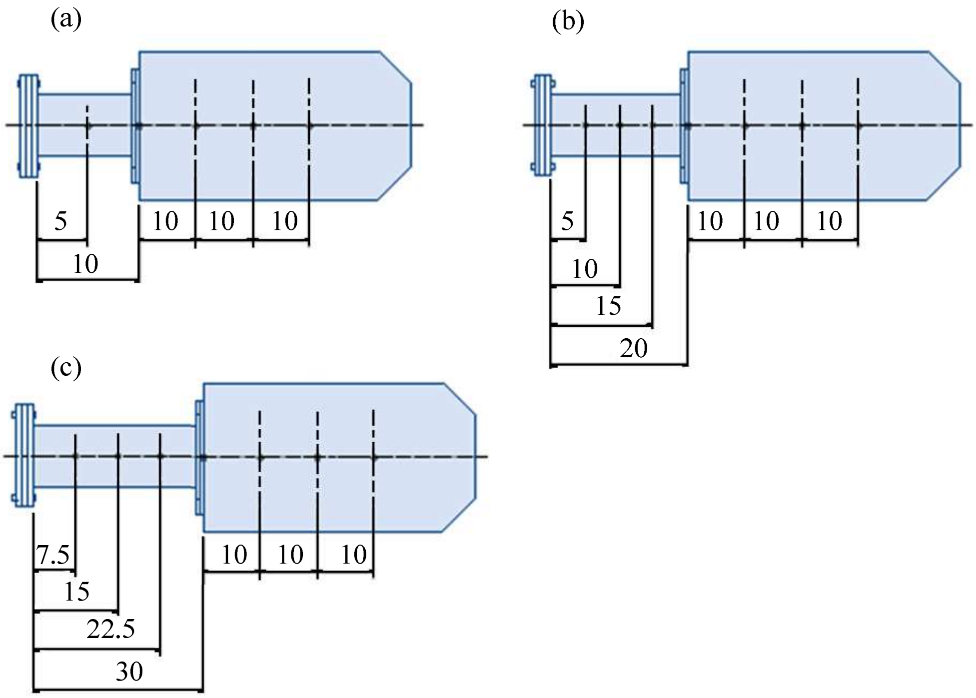

Figure 2. Temperature measurement points for different L/D: (a) Relation L/D=1, (b) Relation L/D=2 and (c) Relation L/D=3. All distances in $10^{-2}m$.

After defining the points for data acquisition of temperature at the outer walls were varied during the experiment parameters such as L/D ratio for the primary chamber, fuel jet Reynolds number, swirler blades angle (α) and the equivalence ratio, as commented before.

3. RESULTS

3.1 Influence of the number swirl and combustion instabilities on the temperature profiles obtained

Recently, a study with this combustor has shown that for angles below 50°, it failed to maintain a stable flame for fuel flow 1*g/s*, (Aponte, 2006). Moreover, according to Lefebvre (1998), by increasing the swirl's angle, there are less acoustic oscillations in combustion chambers for gas turbines, improving the quality of the mixture of reagents. This is the reason why we worked with angles representing 60° and 80°.

According to Stone and Menon (2002), for a small swirl number exists a small amount of tangential movement in the flow, this being a factor in the stability of the flame and consequently the combustion process. Theoretically, these parameters are crucial in enhancing heat transfer to the environment. In Fig 3 are shown the temperature profiles obtained for various conditions.

Comparing the temperature profiles with the values of amplitude in each condition applied, it can be observed that there are cases to swirl angle of 60^0, where the amplitude value was significantly high compared with the amplitudes obtained for the same L/D and D condition. These cases are presented in Tab.2.

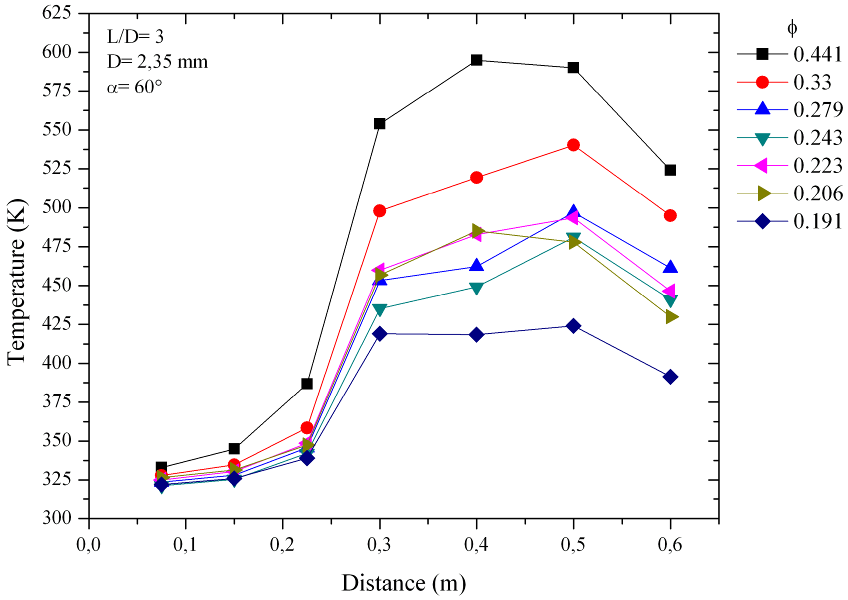

Figure 3. Temperature profiles obtained to relation L/D=3, Re= 50,000 and $\alpha=60^0$. The profiles with $\phi=0.206$ and $\phi=0.191$ has acoustic instabilities.

Experimentally, the high values of acoustics amplitude registered influenced the profiles obtained, presenting increases of temperature for low values of swirl number and acoustics instabilities in the combustion chamber. (see Fig. 3 and Tab. 1).

Table 1. Values of amplitude and swirl numbers obtained to relation L/D=3, Re= 50.000 and $\alpha=60^0$.

ϕ	$\dot{m}_{aire}$ (g/s)	S'	A (Pa)
0.441	38.006	1.754	113.3
0.33	50.252	2.273	212.1
0.279	59.799	2.569	74.7
0.243	68.495	2.762	231.9
0.223	74.567	2.897	452.9
0.206	80.968	3.000	802.2
0.191	87.695	3.078	771.9

As shown in Tab. 1, high values of instability were obtained for reasons of equivalence extremely poor (less than 0.206), which coincides with the theory of systems that operates with low theoretical reasons equivalence, these are susceptible to combustion instabilities, which consequently, increases the heat transfer system towards the combustor's chamber walls. According to Lieuwen and Zinn (1998), it is suggested that the processes of combustion with low swirl angles and deficient mixing between reagents of a poor global combustion, produce pressure oscillations that increase heat transfer.

In the cases stated in Tab. 1, the origin of the instabilities can be related to two factors as follows: The low swirl numbers obtained, which provide a drop in the quality of the reagents' mixing process and the observation of vibrations in the secondary chamber, which indicate the existence of a strong zone of destruction of vortices inside. This as a product of oscillations in the combustion process at the time of mixing the reagents from the primary zone to the secondary chamber, suggesting that the acoustic characteristics of that area are influential in the emergence of instabilities which increase the heat transfer on the combustor walls.

Such behavior can be attributed to the presence of differences across sectional areas between the diameter of the primary chamber and secondary chamber, which are 0.1*m*. and 0.3*m* respectively. There may not be space available to the mergence of a recirculation zone strong enough to absorb vibrations caused by the breakdown of vortices (Almeida, 2007a).

According to Aponte (2006), in studies of instabilities made to the same settings of two stages combustor, the secondary combustion chamber is responsible for the emergence of oscillations; it is because there is not uniformity in the reagents' mixture, which induces an increase in release of energy as heat.

Furthermore, comparing the temperature profiles obtained in Fig. 3 and Fig. 4, greater instabilities were obtained for low swirl numbers (for α=60°), while for high swirl numbers (for 80^0), the flame became more stable (Tab. 2), obtaining temperatures slightly higher for the primary camera that worked with high swirl number. This is due to the high tangential motion as the flow, which creates an increased air circulating in a spiral shape around the combustor walls, which reduces the burning area and the availability of air in the middle of it, producing a theoretically rich combustion (excess fuel) which causes increased presence of soot and increases the brightness of the flame radiant heat transmitted over the unburned circulating air, and increasing the heating temperature on the combustor walls.

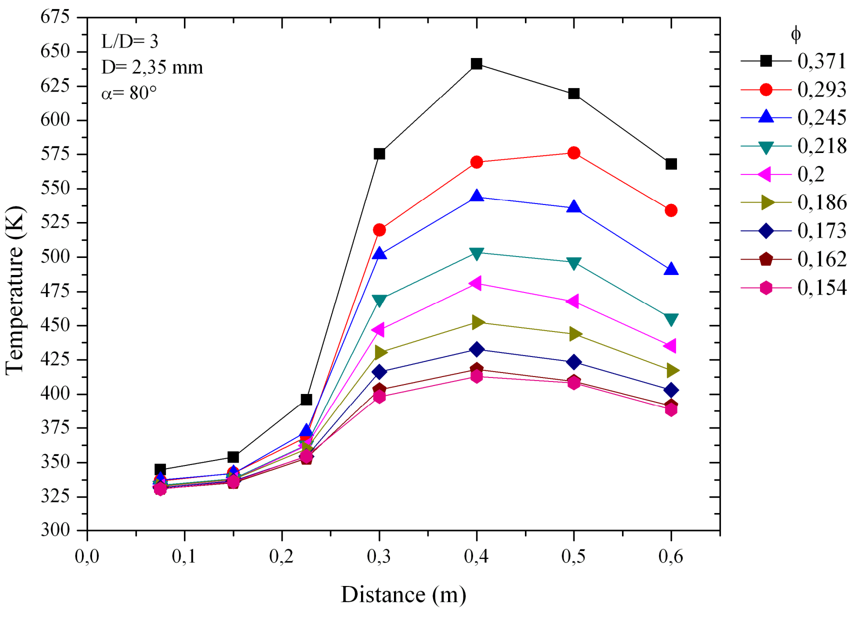

Figure 4. Temperature profiles obtained to relation L/D=3, Re= 50,000 and $\alpha=80^0$.

Table 2. Values of amplitude and swirl numbers obtained to relation L/D=3, Re= 50,000 and $\alpha=80^0$.

ϕ	$\dot{m}_{aire}$ (g/s)	*S'*	A (Pa)
0.371	42.67	19.775	347.9
0.293	53.549	23.669	69.3
0.245	63.193	26.116	107.3
0.218	70.591	27.446	70.7
0.2	77.184	28.538	113.8
0.186	83.2	29.349	86.3
0.173	89.747	29.96	64.3
0.162	95.791	30.462	54.9
0,154	100,4	30,835	314,0

Although it is difficult to predict a behavior for a secondary camera, it appears that once worked with high number of swirl, corresponding to 80^0 (Tab. 2) showed a tendency to present higher temperatures in the secondary cameras than the once worked with low numbers swirl (Tab.2). This can be seen in Fig. 3 and Fig. 4, where the effect was more marked for reasons of equivalence numbers, where there is less air injected for combustion.

For equivalence ratio extremely poor, the maximum temperatures obtained in the secondary chamber tend to be lower for $\alpha=80^0$ than the temperature obtained for $\alpha=60^0$, this is due to the presence of high amounts of oxidant around the walls of the secondary chamber, which acts as a film cooling to reduce heat transfer to the walls of this area.

3.2 Influence of the relation L/D to the temperature profiles obtained

Comparing Fig 4, 5, 6 and second Herbert (2002), an increase in the ratio L/D results in the decrease of the temperature in the primary chamber, because of the length enlargement, so there is more space available to dissipate the heat product of combustion.

According to Fig. 5, a chamber of 0.1*m* length (relation L/D= 1), has little space available, producing a rich combustion in a small space, therefore, it is released large amounts of energy (heat) to a small area, making this a condition for obtaining higher temperatures than in the longest primary cameras, consequently lower temperatures were registered for the primary chambers with L/D= 2 (Fig. 6) and L/D= 3 (Fig. 4).

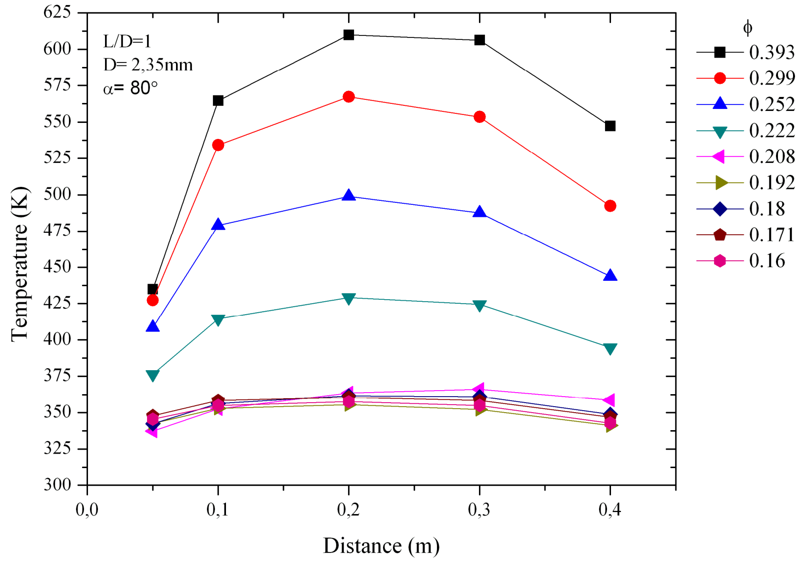

Figure 5. Temperature profiles obtained to relation L/D=1, Re= 50,000 and $\alpha=80^0$.

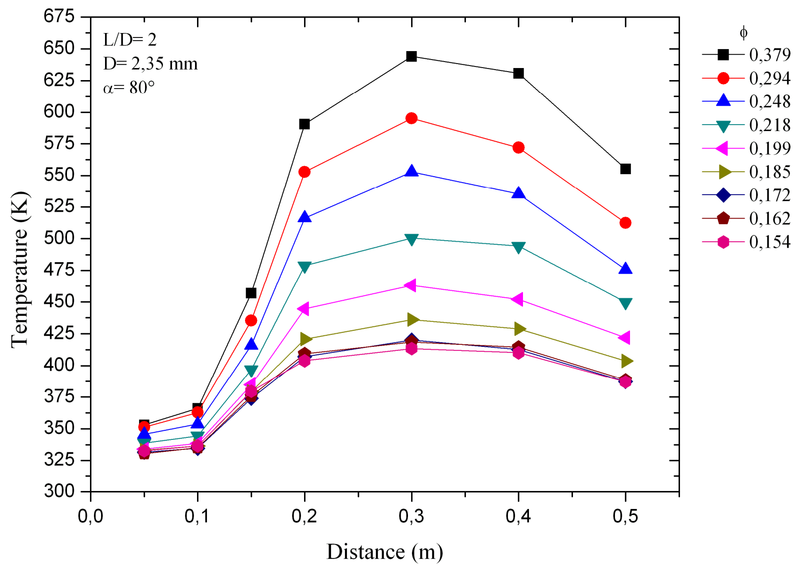

Figure 6. Temperature profiles obtained to relation L/D=2, Re= 50,000 and $\alpha=80^0$.

In the same order of ideas, analyzing the temperature profile behavior along the secondary chamber, it is noticed that despite there is not a followed consistent pattern in all profiles, there is a trend to lower temperatures for relations L/D = 1 as compared with L/D= 2 and L/D= 3 (compare Fig 4, 5, 6). This can be attributed to the fact that at higher temperatures experienced in the primary chamber, for L/D= 1, there is a greater amount of burnt reagents, thus to reach the secondary chamber there is little presence of fuel to be burned releasing less energy during the process.

3.3 Influence of the equivalence ratio on the obtained temperature profiles

By analyzing the general behavior of the graphs presented above, it appears that temperature profiles are obtained with lower temperature as it decreases the equivalence ratio of air/fuel injected in the combustion chamber, for example, in gradual works with poor equivalence ratio or remote to the stoichiometric ratio, less heat is transferred by radiation (flame) and convection (hot gas) to the combustor walls (Hebert, 2002). Such behavior is mainly due to increased mass flow injected to the combustor, allowing more air available for combustion and efficient cooling to itself.

The graphs presented above, show that the temperature results corresponding to the primary chamber, present a very similar behavior, that is, the temperature variations between each equivalence ratio is only a few degrees centigrade, which gives an indication that the changes in equivalence ratio, which enhance the mass flow injected, probably will have more influence on the temperature profile corresponding to the secondary chamber than the profile results of the primary chamber, lowering the temperatures for equivalence ratio with more presence of mass flow of air.

According to Fig 7, 8 and 9, to the temperature profiles obtained with $\alpha=80^0$, when the work conditions decrease get closed to extremely poor equivalence reasons. ($\phi \leq 0.209$ to L/D=1, $\phi \leq 0.188$ to L/D=2 y $\phi \leq 0.175$ to L/D=3, approximately)the profiles have less variation in temperature, behaving almost like a curve. In these cases, the mass flows of air were: 75.436*g/s*; 84.083*g/s* y 97.252*g/s*, approximately, suggesting that for high angles of swirl ($\alpha=80^0$) and $\dot{m}_{aire}$ high, near the highest capacity of the compressor (100*g/s*), temperature profiles are more dependent of the relation L/D and the diameter of the fuel injector (Re) than the equivalence relation.

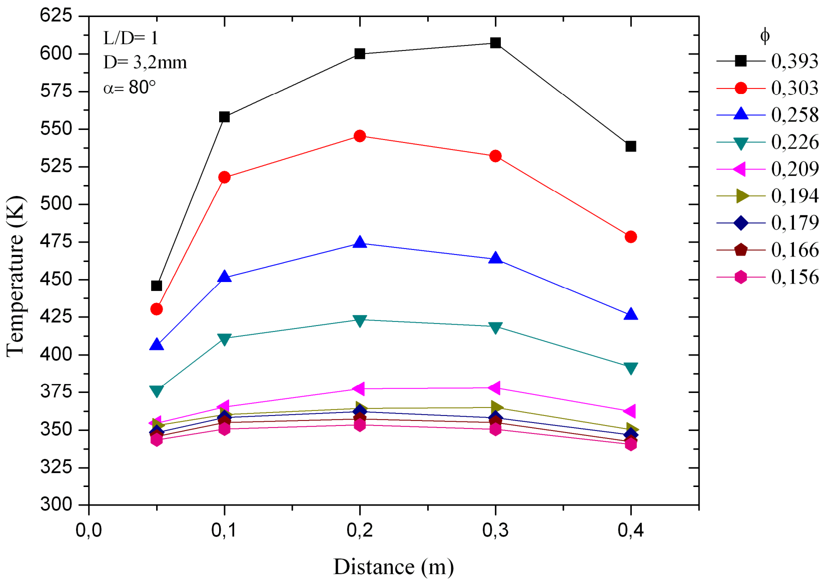

Figure 7. Temperature profiles obtained to relation L/D=1, Re= 40,000 and $\alpha=80^0$.

It is observed that with increasing relation L/D, the effect of equivalence ratio on the decrease of temperature profiles is reduced, since for increasing the ratio L/ D required an increase in air mass flow that can create the same film cooling effect experienced for L/D= 1.

As it is known, the main objective of a combustion chamber is to achieve maximum efficiency, achieving the highest conversion rate of fuel inject to deliver energy to the turbine; this effect is to achieve a complete combustion. With a greater amount of air, combustion takes place with greater efficiency to take advantage of energy release. Moreover, air excess will reduce the final temperature and the amount of energy release. That is why for future studies would be air/fuel ratio as a function of temperature and combustion efficiency desired.

3.4 Influence of the Reynolds' number on the profiles of temperature obtained.

In this study, the Reynolds' number characterizes the level of turbulence in the flow of fuel inject into the combustion chamber (Almeida, 2007a), using diameters of nozzles of: de 2.35*mm*, 3.8*mm* y 7.8*mm* with Reynolds' numbers of approximately 50,000, 40,000 and 15,000, respectively.

By analyzing the results obtained from the variation of this parameter, the results were compared to the same relation L/D, varying the diameter of the fuel injector, where the following trends were registered:

Comparing Fig. 5, 7 and 10, that worked with relation L/D= 1 and fuel injector diameters of 2,34*mm*, 3,8*mm* and 7,8*mm* respectively, it is shown that for low turbulent Reynolds numbers (Re= 15,000) were obtained temperatures slightly higher than those obtained for higher Reynolds numbers, that is, by measuring the increase of turbulence fuel flow, lower temperatures were recorded on the combustor walls.

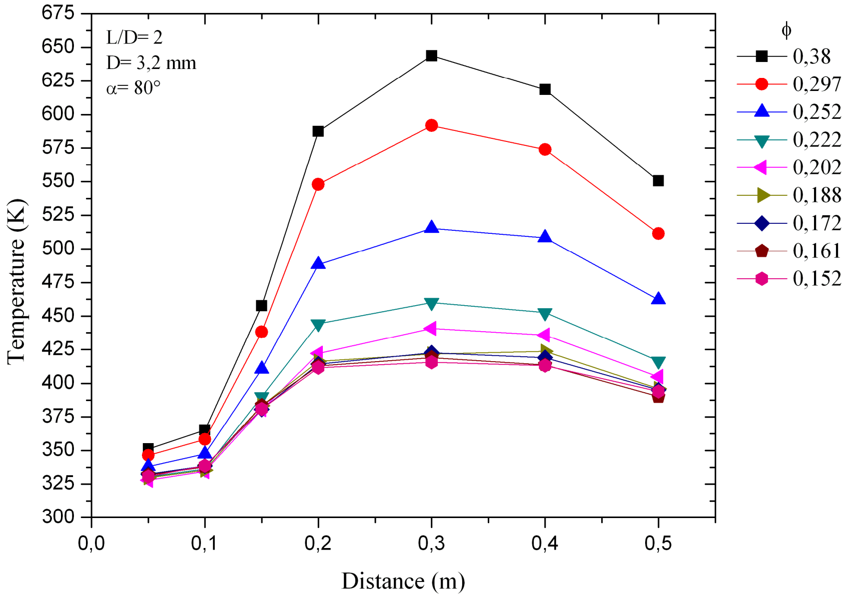

Figure 8. Temperature profiles obtained to relation L/D=2, Re= 40,000 and $\alpha=80^0$.

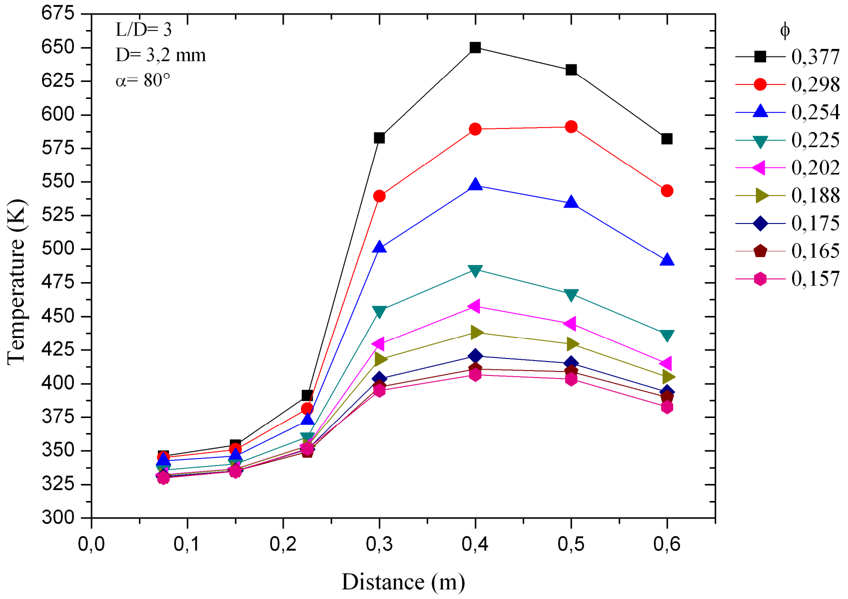

Figure 9. Temperature profiles obtained to relation L/D=3, Re= 40,000 and $\alpha=80^0$.

This effect is attributed to the fact that fuel flow with higher speed can produce a central flow in the combustion gases with a greatest amount of movement, it means, sufficient turbulent flows are able to create a homogeneous mixture between the reactants, increasing the effectiveness of the combustion process, otherwise, as studied in the three graphs listed above a little turbulent combustion will be done and with a deficient mixture of reagents, which results in increased formation of soot that increases the brightness of the flame and consequently the heat transferred to the combustor walls.

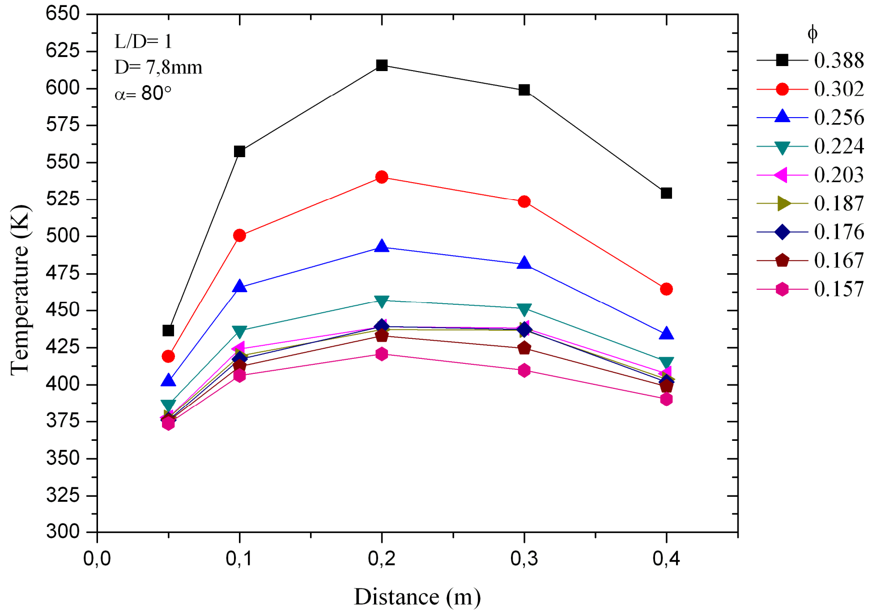

Figure 10. Temperature profiles obtained to relation L/D=1, Re= 15,000 and $\alpha=80^0$.

4. FINAL REMARKS

The present work shows the influence of operational parameters of the combustion process (relation L/D, equivalence ratio, swirl blade angle, fuel jet Reynolds number and acoustic instabilities) on the heat transfer to the combustor wall producing trends in behavior as shown below:

High values of amplitude influence the behavior of temperature profiles, it increases for low values of swirl number and acoustic instabilities in the chamber.

High swirl numbers increase the heat transfer to the chamber walls due to the high tangential movement given to the flow, it created a reduction in the burning area and the availability of air in the center itself, producing a rich combustion theory (excess fuel), which results in a increase in the production of soot transmitting more heat by radiation to the circulating air that does not burn, and increasing the temperature at the outer walls of the chamber.

The relation L/D = 3 shows temperature profiles lower than the relation L/D = 1 at the outers walls of the primary chamber, probably because there is more space available for the occurrence of combustion and the energy dissipation product of that process.

It is possible to obtain profiles with lower temperatures for lower air/fuel ratios. For conditions of operation with poor equivalence ratio or distant to the stoichiometric ratio less heat is transferred by radiation (flame) and convection (hot gases) to the outers combustor walls.

Low Reynolds numbers show a trend to increase temperatures at the outers combustor walls due to the low turbulence provided the flow, which hinders the process of mixing, increasing the formation of soot and the heat transferred to the walls of the chamber .

Finally, the results show that general behaviors like high values of acoustic amplitudes and low swirler blades angles produce an increase in the heat transfer to the outer wall. Also, higher L/D ratio and lower equivalence ratio generate lower temperature profiles and finally lower fuel jet Reynolds numbers have a tendency to increase the temperature values.

5. ACKNOWLEDGEMENT

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