

# A LASER DOPPLER ANALYSIS OF THE IMPACT OF FLOW BOUNDARY CONDITIONS ON THE PERFORMANCE OF A MODEL LEAN-PREMIX COMBUSTOR

By

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## ABSTRACT

The increasing regulation of pollutants emissions from aero-engines has stimulated the development and test of new technologies. In particular, the demands for low  $\text{NO}_x$  emissions and high combustion efficiency has led to designs which involve the combustion of premixed fuel and air at equivalence ratios which are close to those of the lean flammability limit. This, in turn, has led to problems of flame stability and pressure oscillations within the combustor and associated ducting.

This paper is aimed to improve the knowledge of physics of typical flows in prevapourising and premixing ducts and of the subsequent lean combustion process, and presents an experimental study of the flow in a “Lean Premix Prevaporising Combustion”, LPP, gas-turbine model combustor. These experiments, addressed the reacting flow in a laboratory model combustor at atmospheric pressure and was intended to provide a simple case to analyse, the interactions between the flow conditions in the fuel preparation duct, the flame stabilisation process and the downstream combusting flow, in practical aero-engines combustors.

The experimental results obtained showed that, is possible to achieve together low  $\text{NO}_x$  emissions and high fuel efficiencies in Lean Prevaporised Premixed combustors operating at very lean conditions, applying to high turbulence flow levels (swirl flows). The effect of the residence time is not relatively important in Premixed lean-flames for temperatures below  $1400^\circ\text{C}$ , which can be used to optimise the fuel efficiency of the combustor. Results obtained for different flow conditions have showed that, a change of turbulence level did not result in a change in  $\text{NO}_x$  emissions.

For premixed lean-flames close to the flammability limit (temperatures below  $1300^\circ\text{C}$ ) the contribution of Thermal and Fenimore  $\text{NO}$  mechanisms formation to the total  $\text{NO}_x$  formed was found to be relatively small. The  $\text{N}_2\text{O}$  pathway can be the dominant route to  $\text{NO}$  formation under these conditions.

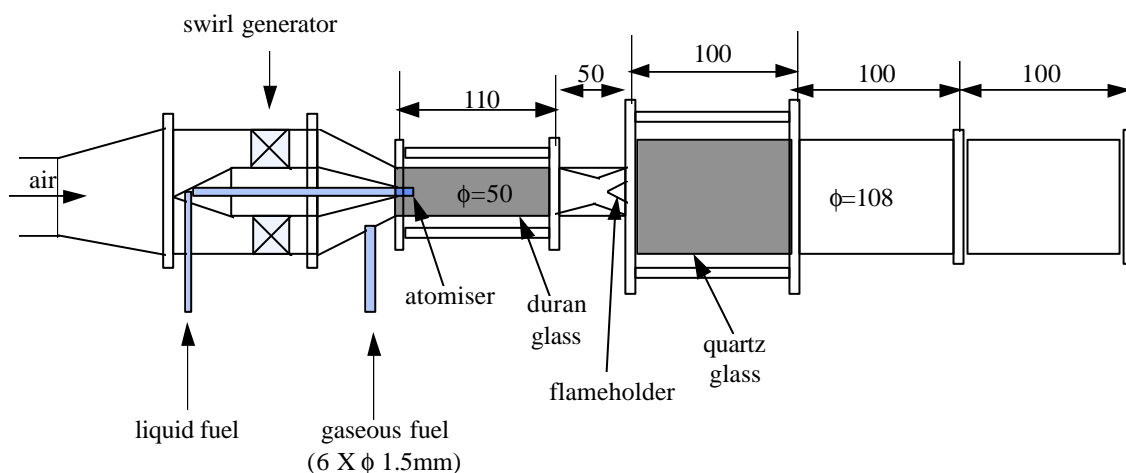


Figure 1 – Schematic drawing of the test rig

## 1. INTRODUCTION

A major consideration in the development of advanced high performance gas turbine engines for aircraft applications is to reduce pollutant emissions while increasing fuel efficiency. This is especially true as combustor temperatures and pressures are increased in order to improve engine efficiency, since both of these factors result in increased oxides of nitrogen ( $\text{NO}_x$ ) production. Significant system design improvements are needed to reduce  $\text{NO}_x$  emissions, because of their harmful effect on the earth's atmosphere, particularly in terms of the destruction of ozone layer in the upper atmosphere (Johnston et al., 1989 and Wuebbles and Kinnison 1990) and the ozone formation in the lower atmosphere (which is known as photochemical smog).

A number of strategies have been considered for reducing  $\text{NO}_x$  emission from gas turbine engines (Bahr, 1995). Of particular interest in this paper is the Lean Prevaporized Premixed (LPP) concept. This low  $\text{NO}_x$  combustor concept is based on the fact that thermal NO formation is reduced when operating away from stoichiometric conditions. If the fuel is completely vaporized and mixed before the flame, the overall fuel lean conditions result in a very low  $\text{NO}_x$  production. In practice, however, it is difficult to achieve a complete fuel-air mixing. As a consequence, fuel non-complete vaporization and spatial non-uniformity and/or temporal fluctuations in the equivalence ratio, can result in locally near-stoichiometric conditions which produce NO in excess of what is produced under perfectly mixed conditions (Lyons, 1982 and Fric, 1992).

The development of future generations of ultra low  $\text{NO}_x$  engines requires the understanding of NO-formation mechanisms at very low temperatures, where Thermal NO production is not dominant (Michaud et al., 1992 and Correa 1992). The chemistry of  $\text{NO}_x$  formation in laminar flames has been studied for a long time, and the major reaction mechanisms are well understood (Miller and Bowman, 1989). At present, the effect of turbulence on  $\text{NO}_x$  formation remains unclear, some authors reports considerable  $\text{NO}_x$  reduction in turbulent premixed flames (Fujimoto et al., 1985) and others found higher rates of  $\text{NO}_x$  formation in turbulent flames when compared with laminar flames at the same temperature (Semerjian et al., 1977).

In premixed fuel-lean flames, the contribution of the Zeldovich and the Fenimore mechanisms to the  $\text{NO}_x$  formation becomes small when the combustion temperature is below  $1500^\circ\text{C}$  (Michaud and Westmoreland 1992, Steele et al., 1995). It is proposed that most of the  $\text{NO}_x$  is formed by the nitrous oxide ( $\text{N}_2\text{O}$ ) mechanism (Michaud and Westmoreland 1992, Steele et al. 1995). However, few experimental data are available on evaluation of the mechanisms.

This paper focuses an experimental parametric study on  $\text{NO}_x$  formation mechanisms in premixed lean-flames, as well, the study of flow characteristics in a LPP model combustor at atmospheric pressure.

The model combustor and experimental techniques are briefly described in the following section. Section 4 presents and discusses sample results obtained. The main conclusions of the work are summarised in section 5.

## 2. EXPERIMENTAL CONDITIONS

The experimental configuration consists of a single fuel injector positioned in the centre line of a cylindrical premixed-prevapourising duct, with flame stabilisation provided by a conical bluff-body or by the sudden expansion at the combustor entrance. The premixing chamber is a cylindrical duct with an inner diameter of  $d=50\text{mm}$  and a length of  $150\text{mm}$ . The fuel, Jet-A1, is atomised by commercial nozzles with different spray angles. Gaseous fuel can also be injected. The combustor itself, consists of a cylindrical stainless-steel duct with an inner diameter of  $D=110\text{mm}$  and a total length of  $300\text{mm}$ . The combustor modules include sections that provide the necessary optical access, to allow the use of laser techniques to visualise and quantify the inner flow.

The experiments were conducted in a test facility at atmospheric pressure. A pre-heater, deliver non-vitiated air up to  $T_0=500^\circ\text{C}$ , and a maximum air mass flow rate up to  $0.1\text{kg/s}$ . The swirl generator has a variable geometry, which allows to shift the angle of the vanes between  $0^\circ$  and  $60^\circ$ , in order to control the swirl level of the flow. Figure 2 shows a schematic drawing of the test rig.

The experiments performed in the model combustor, allow the representation of important features of the premixed chamber and of the primary zone of practical gas turbine combustors. The Reynolds number, based on the mean axial velocity at the inlet section of the combustor, is about  $10^5$ . The work

involves also the analysis of the effects of incomplete premixing and prevaporisation on flame stabilisation, propagation and pollutant formation under overall lean burning conditions.

Velocity was measured by a single component laser-Doppler velocimeter. Temperature measurements were obtained with fine platinum-13% rhodium-platinum thermocouples. Mean concentrations of major species were measured using a stainless steel gas sampling probe and a conventional analysers system. Flow visualisation included the use of different techniques.

Four different flow conditions were selected for detailed studies, as described in table1. Results presented also include parametric studies of pollutant formations.

**TABLE 1 - Flow conditions for detailed combustor analysis**

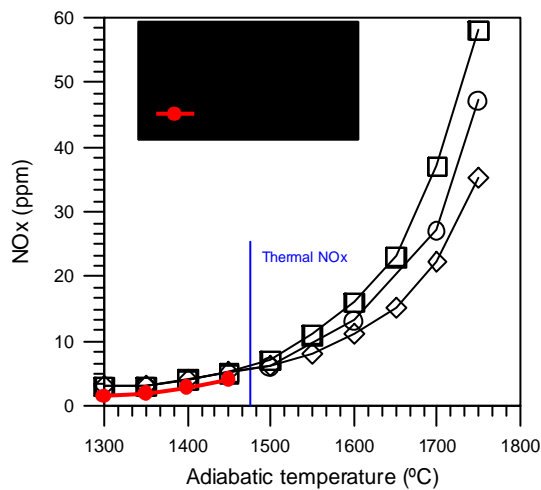
$m_{air}$ (Kg/s)	$T_o$ (°C)	$\Phi$	Blade angle (°)	s swirl n°	Flame stabiliser	Fuel	Run
0.05	300	0.5	45	0.56	Cone	Jet A1	1
0.05	300	0.5	0	0	Cone	Jet-A1	2
0.05	300	0.5	45	0.64	n. a.	Jet-A1	3
0.05	300	0.5	0	0	n. a.	Jet-A1	4

n.a. (not applied)

### 3. RESULTS AND DISCUSSION

#### 3.1 Parametric studies

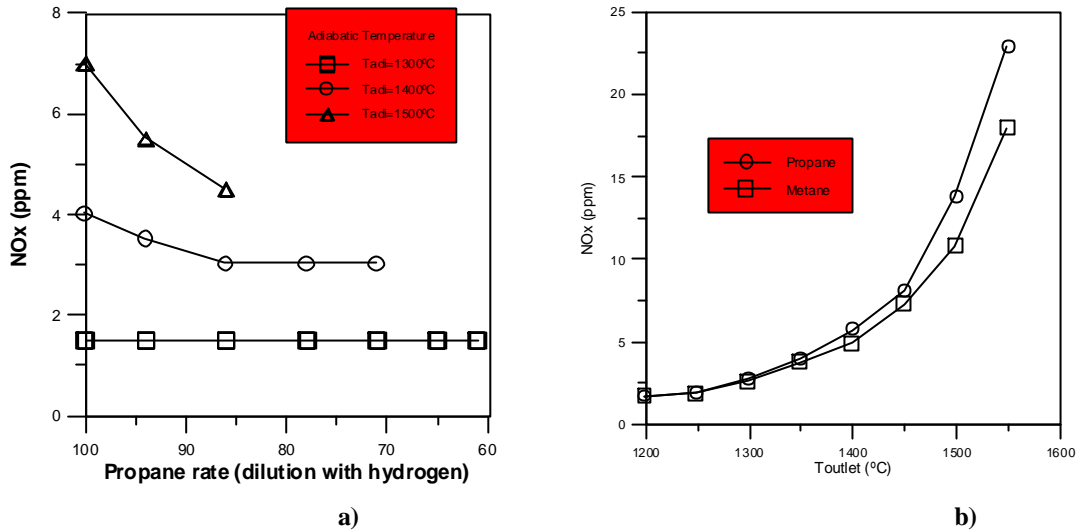
In premixed flames  $NO_x$  production is a strong function of flame temperature (mainly for temperatures above 1500°C), which varies with the equivalence ratio and the preheating of the combustion air. The effect of the combustor residence time in  $NO_x$  production as a function of the gases temperature, are shown in figure-2. The effect of the residence time is negligible for gases temperatures below 1500°C. Therefore, for these conditions the Thermal  $NO$  mechanism formation is not dominant, as for lean premixed flames with gases temperatures above 1500°C. The preheating of the combusting air, allows less  $NO_x$  production for similar exhaust gases temperature, which denotes the effect of the concentration of intermediate species in the  $NO_x$  formation mechanisms at low temperatures.



**Figure 2 -  $NO_x$  emission at combustor exit for different air mass flow rates and combustor exhaust gases temperatures.**

To address the question of which  $NO_x$  mechanisms formation becomes more important at lower temperatures, experimental data are shown in figures 3a and 3b. Figure-3a shows  $NO_x$  emissions for different exhaust gases temperatures and different levels of hydrogen dilutions. In this experiment, the exhaust gases temperature was kept constant and increased proportions of propane has replaced by hydrogen. The results show a decrease of the  $NO_x$  emissions with the propane concentration reduction, for temperatures above 1300°C. These results suggest that, the Prompt  $NO$  mechanism formation (Fenimore, 1971), which depends of the radicals HCN, have some importance in an intermediate range of temperatures. For temperatures below 1300°C the Prompt  $NO$  mechanism is negligible in comparison with other or others mechanisms. Figure-3b shows  $NO_x$  emission for different exhaust

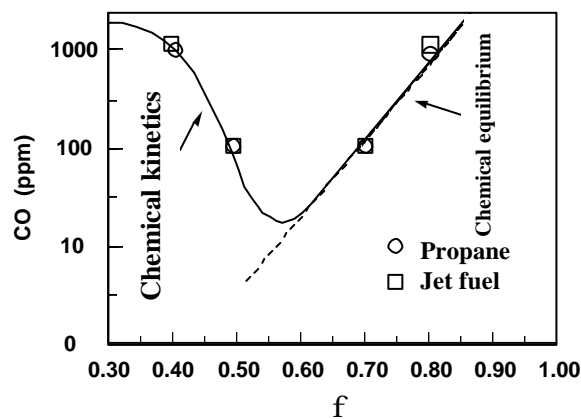
gases temperatures, with propane and methane gases fuels, keeping the combusting air mass flow rate constant. The data shows similar results of the previous figure, for temperatures below 1300°C there is no differences in NO<sub>x</sub> emissions between the two fuels, while for temperatures above that value the propane shows increased emissions in comparison of methane, mainly because of the Prompt NO mechanism (the C/H ratio is higher for the propane). These results show that, for temperatures below 1300°C the Prompt NO mechanism formation is relatively small to the total NO<sub>x</sub> formed, then another NO mechanism formation must be dominant under this conditions.



**Figure 3a - NO<sub>x</sub> emissions as function of hydrogen dilution; 3b - NO<sub>x</sub> emissions for propane and methane fuels.**

According several authors, chemical mechanism models based in the N<sub>2</sub>O pathway has shown good agreement with experimental results obtained for fuel-lean flames at very low temperatures (Michaud et al., 1992; Miller and Bowman, 1989 and Correa 1992). Experimental data about the effect of N<sub>2</sub>O addition of the flow, keeping other parameters constant showed dramatic increasing NO<sub>x</sub> emissions for several ranges of exhaust gases temperatures, which suggest that the N<sub>2</sub>O actuates like a radical in the NO process formation.

The CO emissions, as function of the equivalence ratio are shown in figure-4. The results show the effect of the restriction of chemistry kinetics, which prevent to achieve chemical equilibrium conditions for low temperatures. However, this restriction can be avoided by increasing the preheating air (for the same gases temperatures we have less fuel to react), by increasing the combustor residence time, or to increase the turbulence intensity at the front flame (applying to swirl flows). Reviewing figure-3 we conclude that, to increase the preheating air and keeping the exhaust gases temperature, will decrease the NO<sub>x</sub> emissions; for gases temperatures below 1400°C the residence time of the combustor do not affect the NO<sub>x</sub> production. The effect of the turbulence on NO<sub>x</sub> formation will be discussed in subsequent results (section 3.2).



**Figure 4 – CO emissions at exit combustor for different equivalence ratios**

### 3.2 Different flow conditions studied

Figure 5 shows flame visualization in the combustor for run's 1 to 4, respectively. The flow direction is from the right to left side. The flow visualization exhibits incomplete fuel vaporization in the premixing chamber for non-swirl motions (run's 2 and 4). In these conditions the fuel droplets impinge at the wall duct creating a liquid film, which reach the entrance of the combustor. The high air velocities at the combustor entrance are responsible for the break up of the remaining liquid film and the consequent fuel droplets formation, which will burn inside the combustor. However the big droplets can't burn completely due to the low residence time (they are convected by the high jet velocity at the combustor inlet) and blowout of the combustor, as shown in the flow visualization.

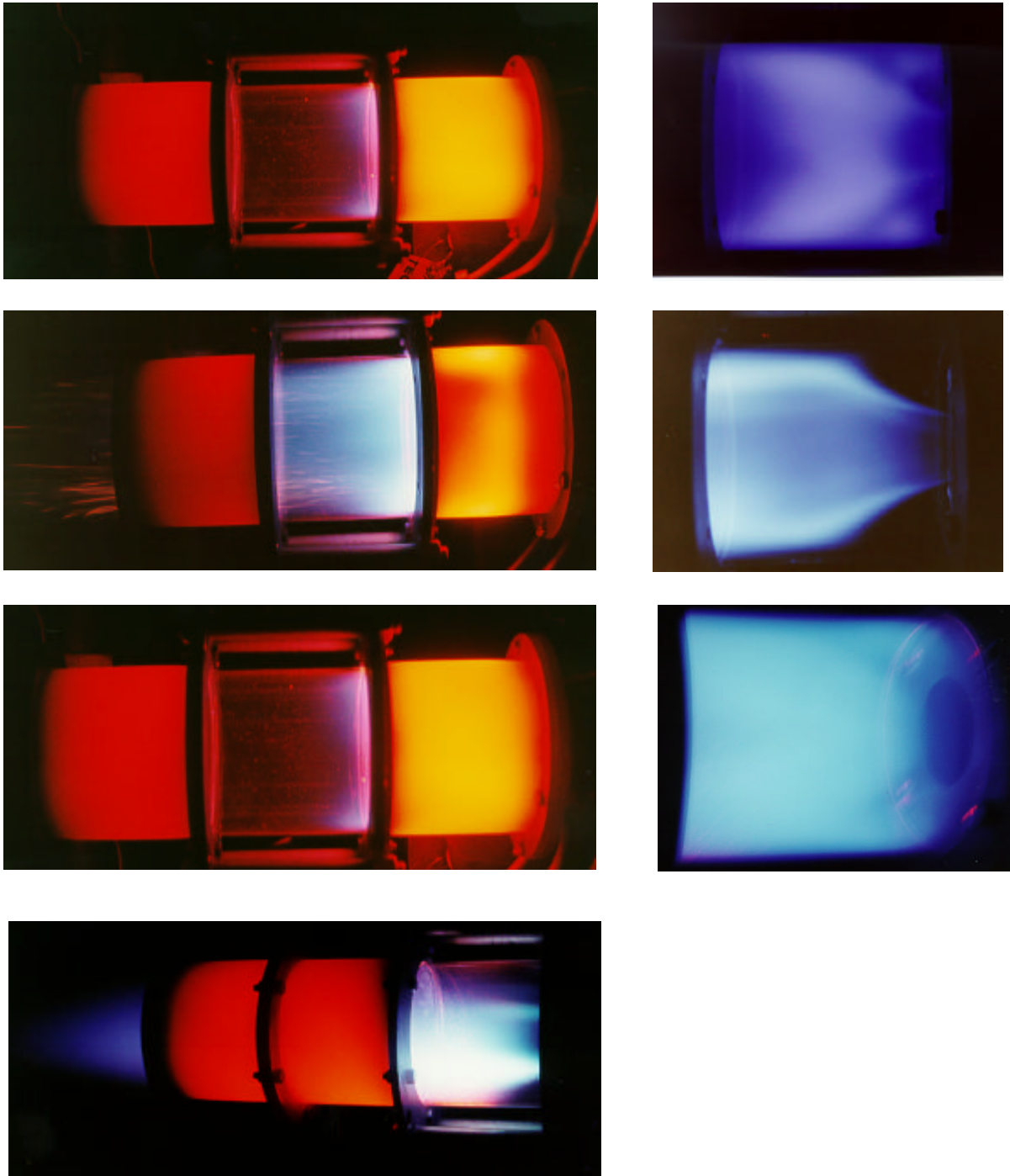
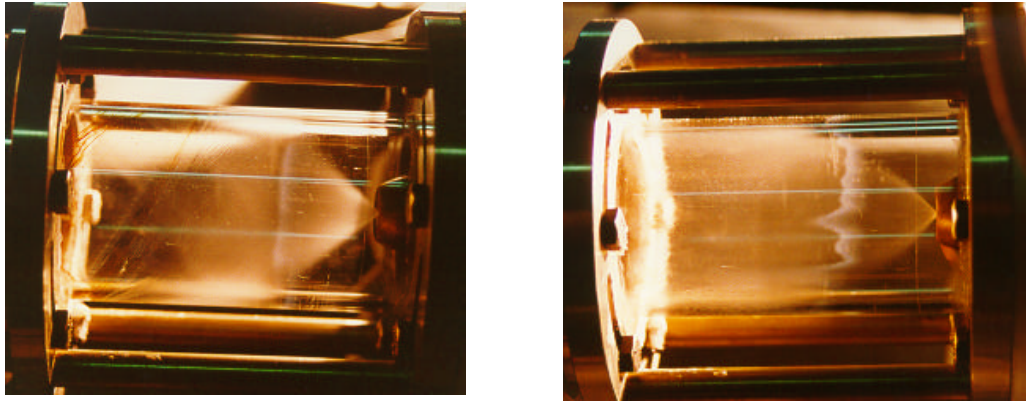


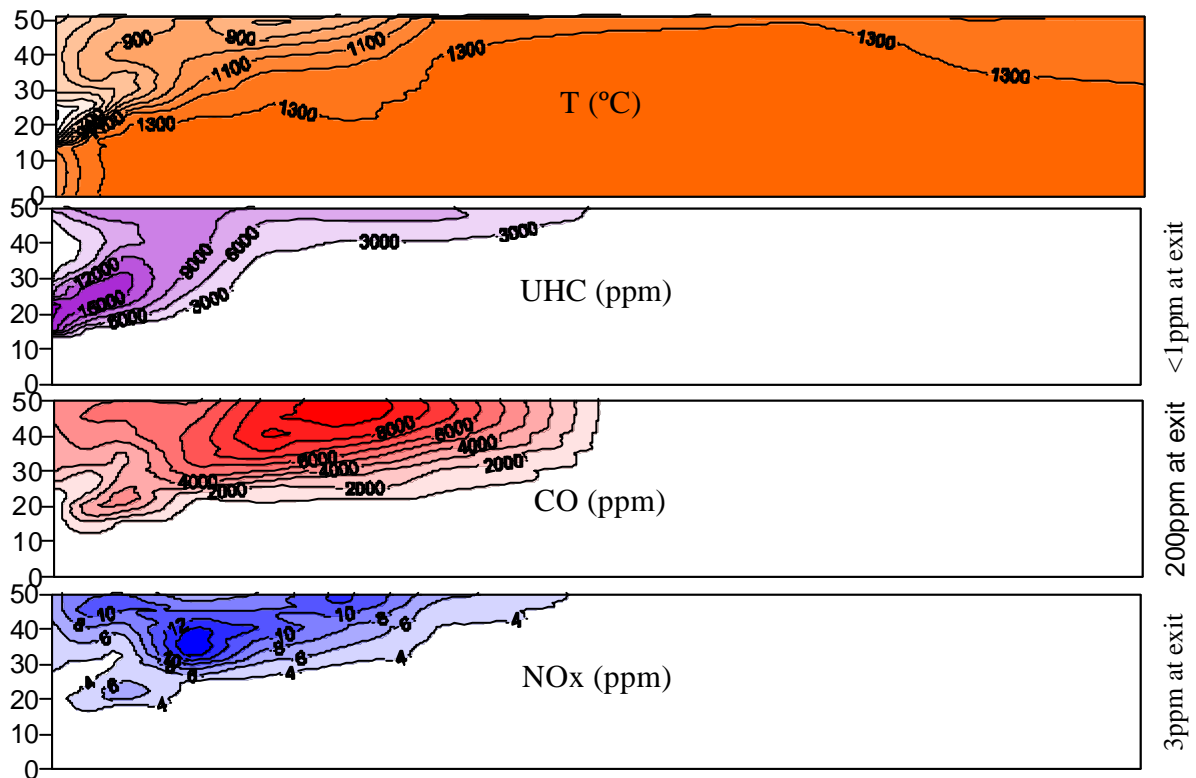
Figure 5 – Flame visualization for run'1 to 4, respectively

The fuel spray visualization inside the premixing duct for run'3 and 4 are shown in figure 6. The left side image shows the complete fuel vaporization in the premixing duct for run3 while the image on the right side shows the liquid film formation downstream of the droplets impingement at the wall duct in run4 flow condition, which reaches the combustor entrance.



**Figure 6 – Liquid fuel atomisation in the premixing duct.**

The mean temperature and major species concentrations fields for run's 1 to 4 are shown in figures 7 to 10, respectively. The results show a good performance (low  $\text{NO}_x$  emissions together with high fuel efficiency) of run 1 and 3, due to the homogeneous mixture achieved in the premixing duct



**Figure 7 – Mean temperature and concentrations fields for run1 flow**

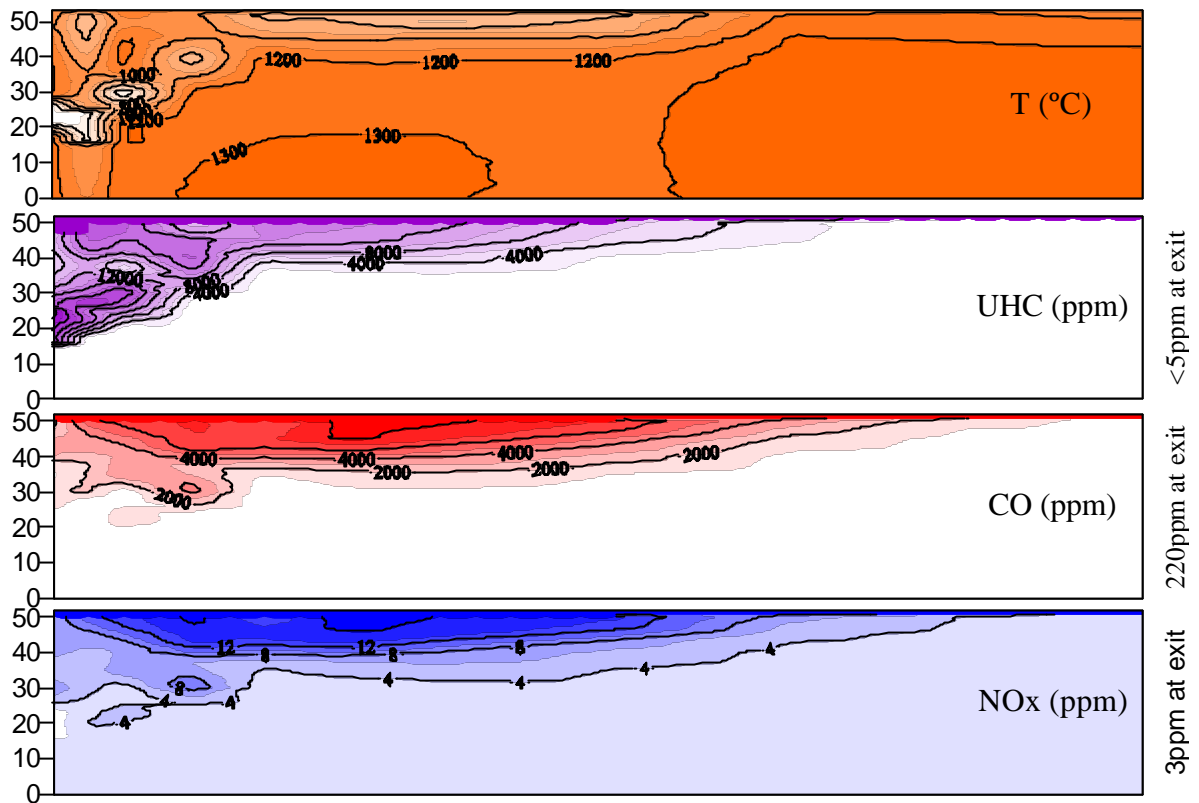


Figure 8 – Mean temperature and concentrations fields for run2 flow

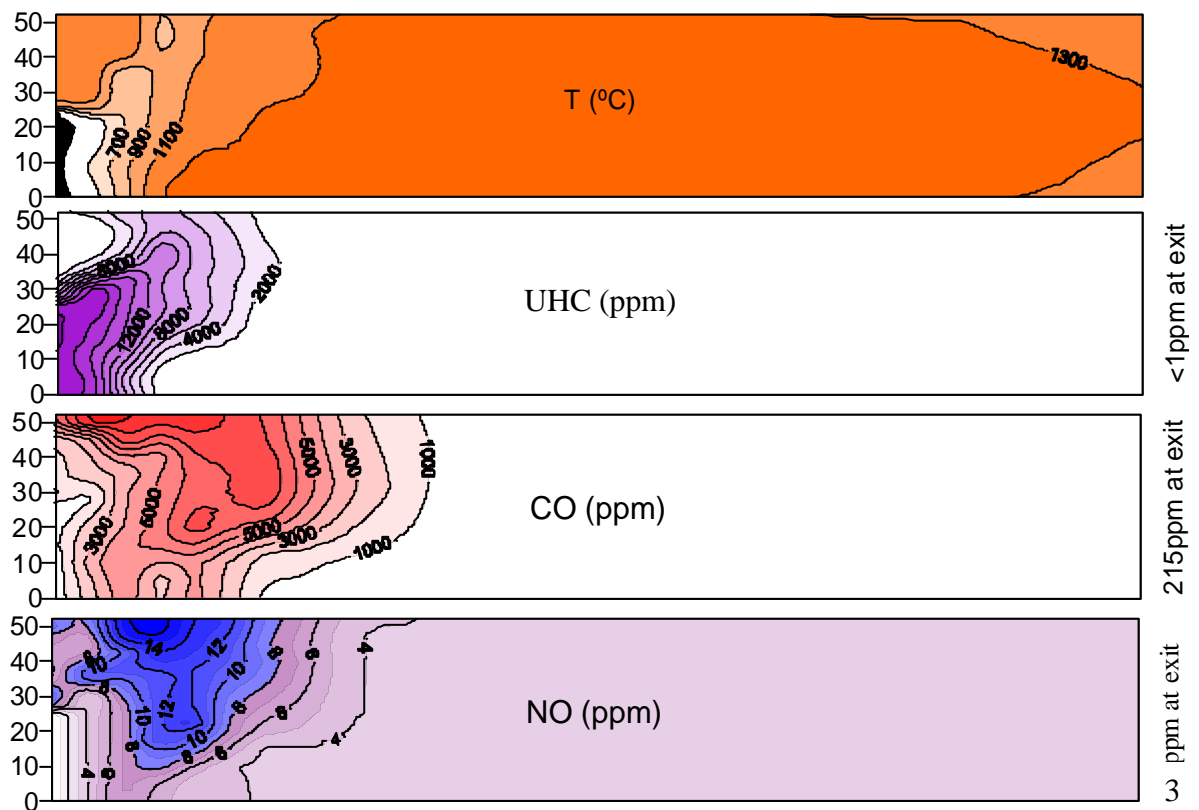


Figure 9 – Mean temperature and concentrations fields for run3 flow

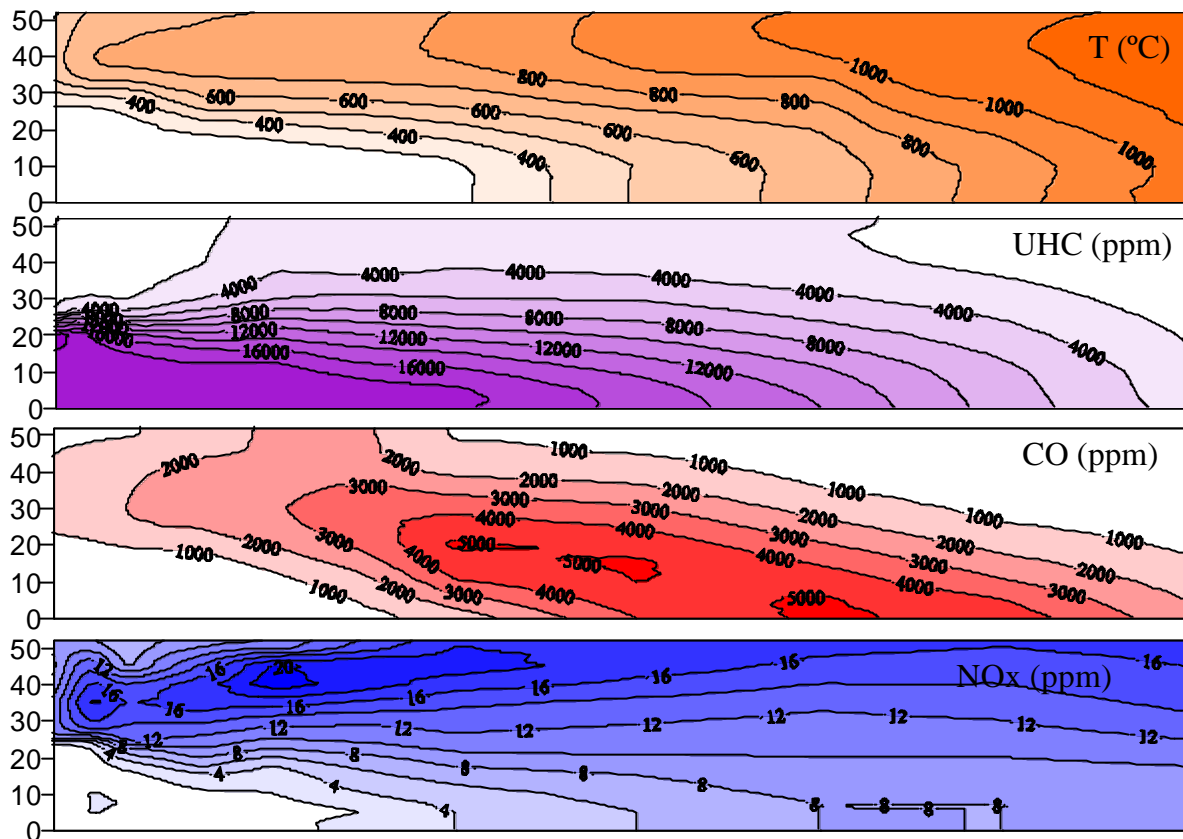


Figure 10 – Mean temperature and concentrations fields for run4 flow

#### 4. CONCLUSIONS

The experimental results obtained showed that, is possible to achieve together low  $\text{NO}_x$  emissions and high fuel efficiencies in Lean Prevaporised Premixed combustors operating at very lean conditions, applying to high turbulence flow levels (swirl flows) in the combustor.

The effect of the residence time is not relatively important in Premixed lean-flames for temperatures below  $1400^\circ\text{C}$ , which can be used to optimise the fuel efficiency of the combustor.

A good control of the equivalence ratio of the mixture and of the air preheating is necessary to assure lean stability close to the flammability limit, as well the use of high turbulence flows (swirl flows).

For premixed lean-flames close to the flammability limit (temperatures below  $1300^\circ\text{C}$ ) the contribution of Thermal and Prompt NO mechanism formation to the total  $\text{NO}_x$  formed was found to be relatively small. The  $\text{N}_2\text{O}$  pathway can be the dominant route to NO formation under these conditions.

A change in the turbulence level, between the different flows conditions, did not result in a change in  $\text{NO}_x$  emissions.

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