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DIAGNOSTIC AND CONTROL OF LEAN PREMIXED COMBUSTION WITH ALTERNATIVE FUELS

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Abstract
The use of alternative fuels is a new challenge for lean premixed combustion. Their low calorific value and their variability pose additional difficulties to achieving low NOx emissions and, at the same time, avoiding the risk of combustion oscillations. The present work describes some novel approaches for the supervision and control of lean premixed combustion with alternative fuels. The methods proposed are based on the collection and analysis of different flame signals, and the use of such information for the monitoring and optimisation of the combustor.

INTRODUCTION

Lean premixed combustion is becoming a common technology in gas turbines, due to its low NOx emissions. This requires, however, working close to the lean flammability limits and the combustor needs to be carefully adjusted in order to achieve a clean, pulsation-free operation. The technology in this field is mature enough to ensure a good performance for conventional fuels, which generally include natural gas, diesel oil or kerosene. Nevertheless, the risk of combustion instabilities exists and is still motivating significant scientific and technological efforts.

A new dimension is arising in this field: the use of ‘alternative fuels’, such as gasification products, methanisation gas or other by-products (e.g., refinery gas). These new fuels, in many cases with low calorific values, require the adaptation of the gas turbine. But, probably, the main difficulty is the variability in their properties. The quality of the traditional fuels oscillates within narrow limits, and even small changes can cause significant drifts in the performance of the gas turbine. For alternative fuels, the range of variation can be significant (e.g., depending on the operating conditions or the fuel being fed to the gasifier). Assuring an optimised and safe operation with this type of fuels becomes, therefore, a difficult task.

Any attempt to adapt the operating conditions to the characteristics of the fuel is thought to require, as a first step, some diagnostic of the actual situation. This is, most probably, the main obstacle, as direct information on the combustion process is very limited. The development of monitoring techniques for lean-premixed combustors has been addressed in a number of works. Refs. [1, 2], among others, explored the use of emission spectra to estimate the equivalence ratio. In other cases, radiation sensors working in narrow or wide bands have been used for similar purposes [3, 4]. The signals from pressure transducers, commonly installed in industrial engines, can be also used to monitor the actual combustion condition, as shown by Rea et al. [5]. This sensorial information might be then applied to develop closed-loop controls designed to optimise the performance of the system, as reported in refs. [3, 4, 6].

The present work explores the capabilities of different flame sensors for the development of real-time monitoring systems. Some examples on the application of these methods in control strategies are also shown. Blends of natural gas with CO_2 are used to illustrate the cases of variable and poor fuels.

EXPERIMENTAL FACILITY

The tests were performed in a combustion rig designed to reproduce the main features of lean-premixed combustors, with thermal inputs up to 50 kW. A quartz tube (L=250 mm, i.d.=120 mm) configures the combustion chamber and allows for unrestricted optical access to the flame. The fuel-air mixture is injected as an annular jet (o.d.=40 mm, i.d.=25 mm), with a swirling motion imparted by 60° vanes. The fuel is injected into the air stream through 12 radial orifices, located 320 mm upstream of the chamber, in order to achieve a homogeneous mixture. The feeding holes for both fuel and air have small dimensions (high acoustic impedance) to minimize the coupling between combustion-generated pressure fluctuations and mass flow rates. The quartz tube is surrounded by a water-cooled steel vessel were the optical instruments are assembled. Three optical sensors have been installed: a spectrometer, a photomultiplier and a silicon photodiode (further details are given below). Each of them is fitted into a window through the steel vessel, oriented radially and cooled by a small air flow.

The test programme includes variations in the following settings:

- Equivalence ratio, ER=0.58-0.96
- Mass flow rates of natural gas in the range 2.5-4 Nm^3/h
- Dilution of natural gas with different amounts of CO_2, representative of gaseous fuels obtained from waste methanisation processes. X_{CO2}=0-50%

Fig. 1 displays the influence of these parameters on NOx and CO emissions. For a given fuel, the results display the usual behaviour in premixed combustors: low equivalence ratios lead to higher CO emissions and reduced NOx levels. Optimal performance is obtained at ER~0.68 with natural gas. Dilution of the fuel with CO_2, which is expected to reduce the flame temperature, lowers NOx emissions for a given

ER. As the amount of CO_2 is increased, both the CO curves and the blow-off limit are gradually displaced towards higher ERs.

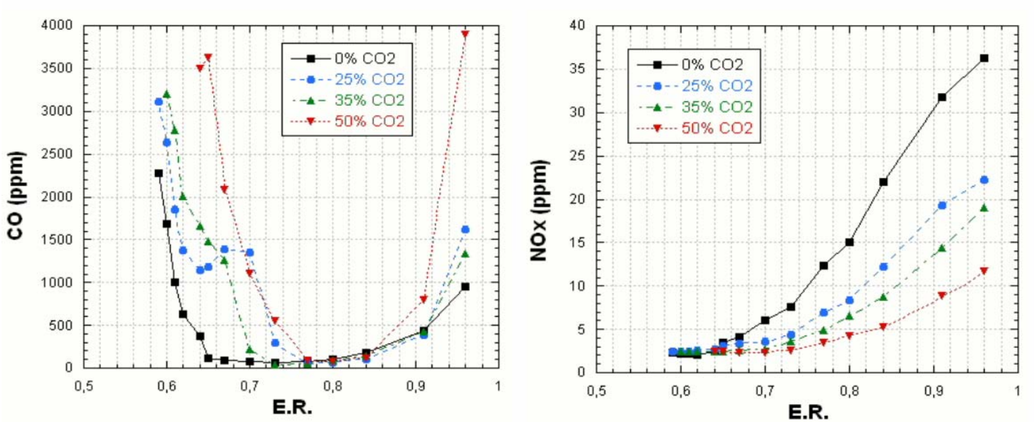

Figure 1 – CO and NOx emissions as a function of ER and X_{CO2}

FLAME SIGNALS

Different sensors were used to collect direct information from the flames.

Pressure transducer

A fast-response pressure transducer (PCB M106B) was installed on a semi-infinite guide, purged with nitrogen and connected to a tap in the combustion chamber. The magnitude of pressure fluctuations (expressed as its standard deviation, σ_P) varied widely with the operating conditions, as shown in Fig. 2. In all cases, the evolution with ER displays a similar pattern. As ER is reduced, σ_P increases gradually until a critical point is reached where combustion instabilities are triggered and σ_P rises suddenly. Further decrease in ER causes the detachment of the flame and σ_P drops. As the lean blow-off limit is reached, σ_P increases again until the flame is lost.

Blending of natural gas with CO_2 results in similar behaviours, but σ_P curves are displaced to higher ERs. It should be noted that, for a given ER value, variable amounts of CO_2 can cause operational problems. Namely, if the combustor is adjusted to ER~0.68 for optimal performance with natural gas, a gradual increase in the fraction of CO_2 could cause the onset of combustion pulsations. This case is discussed in a subsequent section.

Radiation sensors

Two radiation sensors were used to collect the light emitted from the flame:

- ❑ A photo-multiplier tube, Hamamatsu model R955, used in combination with a band-pass interference filter (310±10 nm). This instrument detects most of the radiation associated to OH* chemiluminescence.

- A Silicon photodiode, with a spectral response in the range 190-1100 nm. The signal is, therefore, representative of the 'luminosity' of the flame.

Radiation signals were processed to obtain statistical parameters (e.g., average and standard deviation) and frequency spectra. For brevity, only the results with the photomultiplier are shown in Fig. 3. The strength of the signal varies widely with both ER and amount of CO_2; the curves for the fluctuating component are similar to those shown for the pressure in Fig. 2.

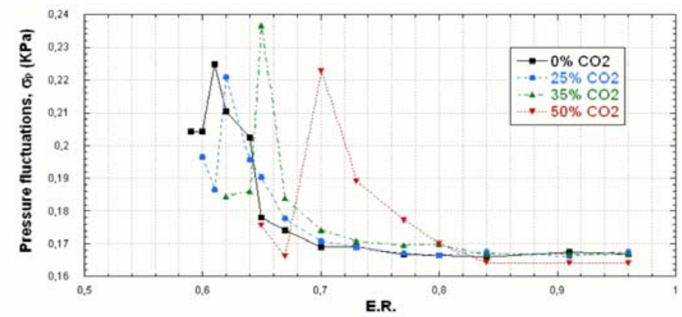

Figure 2 – Pressure fluctuations as a function of ER for blends of nat. gas with CO_2

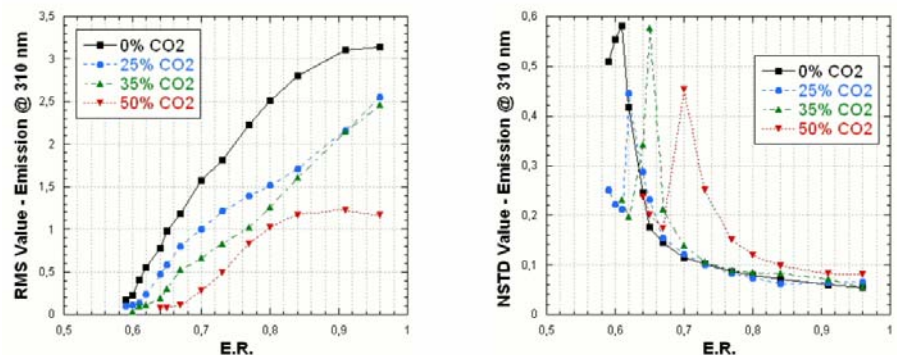

Figure 3 – Average and st. deviation of photomultiplier signal as a function of ER and X_{CO2}

Identification of flames

Figs. 2-3 demonstrate that flame signals vary with the operating conditions and the fuel type. Hence, it might be possible to use those signals as a signature of the flame, which could enable to identify the actual combustion conditions. A wide range of approaches have been tested in order to explore the possibility of developing a 'flame identifier'; i.e., an algorithm able to estimate the actual combustion conditions (ER, fuel type) using as the only input sensorial information from the flame.

Artificial neural networks (ANN) were one the methods selected for this purpose, due to their good capabilities for multivariate analysis with unknown and highly-nonlinear dependences. A two-layer backpropagation network (a kind of feed-forward multiple-layer network) was used, with a tan-sigmoid transfer function in the hidden layer (to stimulate a non-linear behaviour) and a linear transfer function in the output layer (to permit unbounded outputs). This is a powerful structure for unknown function approximation problems. In a first stage, the algorithm is 'trained' with a set of inputs+outputs obtained for a range of combustion conditions. The ANN so developed can then be used to yield estimations (e.g., of ER) using the flame signals collected for a given flame. Inputs include average and fluctuation (standard deviation) of the signals from the pressure transducer and the radiation sensors. The objective is to estimate operating conditions (ER) and emissions (CO, NOx) under 'arbitrary' operating conditions, using the flame sensors as the only inputs.

Some examples of identification tests are shown in Fig. 4, where the estimates of the ANNs for ER and NOx emissions are compared with the actual values as measured with the flowmeters and gas analysers. In this case, σ_P and the average and fluctuating magnitudes of the photodiode signal are the only inputs. The comparisons shown in Fig. 4 demonstrate that flame signals contain information that can be used as a diagnostic of the combustion process. Other combinations of parameters from the flame sensors have also provided similar results; it should be noted, nevertheless, that the fluctuating component ('flickering', for the radiation sensors, or 'sound level' for the pressure transducer) is a necessary ingredient to obtain good results. There are many ways in which these identification capabilities can be used; some examples are described in the next sections.

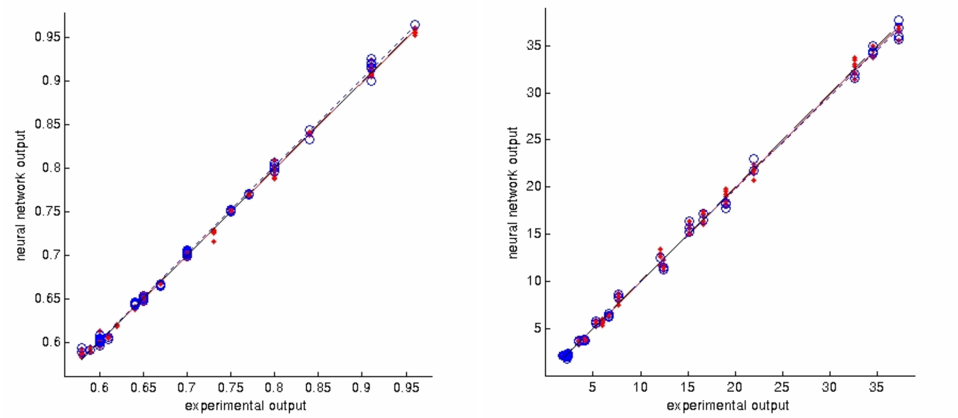

Figure 4 – Estimations of (left) ER and (right)NOx emissions using ANN and comparison with actual measured values.

OPTIMISATION METHODS

Optimisation can be seen as the search for extreme values of a mathematical function (*cost function*). In combustion, this function might be some combination of efficiency, emissions, stability …, with the independent variables including the burner settings or operating conditions that can be modified by the operator. In general, the relationship between controllable settings and cost function is not known. There are several mathematical methods that can be used when both values and gradients of the function are unknown. The Downhill Simplex method has been used in this work. This multidimensional minimization algorithm compares function values at the vertices of a general simplex, a geometrical figure that in one-dimensional minimization is a line and in two dimensions is a triangle [7]. The simplex adapts itself to the local cost function topology, elongating down long inclined planes, changing direction on encountering a valley at an angle, and contracting in the neighborhood of a minimum. The results reported have been obtained for only one variable setting (ER), and the simplex takes the form of a segment.

In order to optimise the performance of the combustor, the cost function has been defined as a combination of the NOx and CO emissions, having a minimum around ER=0.68 for natural gas. The downhill method has been successfully applied to find that minimum, starting at an arbitrary value of ER. However, from a practical viewpoint this method has some drawbacks, and some attempts to avoid them have been explored:

- ❑ The downhill algorigthm requires evaluating the function at several points, and the analysers need to reach a stable reading at each of the steps. The settling time for this type of measurements is relatively long, and the total optimisation time can reach several tens of minutes. The ANN estimators already mentioned have been used in order to improve the dynamic response.
- ❑ In all the tests with the downhill algorithm, the combustor had to enter instable regions with large pressure oscillations. A continuous monitoring of pressure fluctuations has been performed, and the set points were corrected when σ_P exceeded a certain threshold.

Fig. 5 shows the results of an optimisation test, incorporating both procedures. Minima search is relatively easy for the cost function used (a single valley), and a performance very close to the optimum is found in 15-20 evaluations. The two modifications yielded remarkably good results:

- ❑ As shown in Fig. 5(a), the cost function estimated using NOx and CO values produced by the ANN follows very well the actual emissions measured with the gas analysers. The ‘settling time’ for the photodiode+ANN chain is of the order of seconds, and the time required for an optimisation cycle can be 1-2 orders of magnitude shorter than with the gas analysers.
- ❑ Correction to the optimisation process according to the monitored pressure fluctuations was an effective way to prevent the onset of combustion instabilities, which otherwise were very common with the ‘raw’ downhill algorithm. As it can be appreciated in Fig. 6(b), the threshold of 0.17 kPa was only exceeded in a few cases; and even these overshootings probably might be reduced once the dynamic response of the supervision algorithm is optimised for this application.

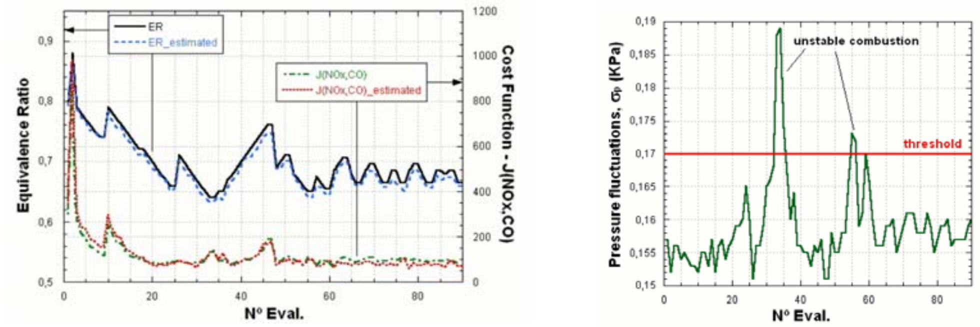

Figure 5 – Evolution of (a) ER and cost function and (b) σ_P during an optimization cycle. Both actual and ANN-estimated values of ER and cost function are shown.

CASE OF VARIABLE FUELS

Blending of natural gas and CO_2 was used to simulate a scenario of a fuel with variable properties. With this purpose, the fraction of CO_2 in the fuel (X_{CO2}) was varied in the interval 0-34%. Ramps of both ascending and decreasing X_{CO2} were implemented by sequentially adjusting the flow controllers (see Fig. 6).

Two different situations were reproduced in this way. First, the gradual increase in the amount of CO_2 at a fixed ER=0.7 eventually leads to a rise in pressure fluctuations. Fig. 6 displays the evolution of σ_P when no correction is performed. Ideally, the control system should be able to detect the drift and correct the operating conditions (i.e., ER) in order to avoid the onset of strong oscillations. In this case, an arbitrary threshold of 0.17 kPa was established, and the system reacted by increasing ER when this limit is reached. This simple strategy was sufficient to prevent the onset of pulsations and to bring σ_P back to safe levels (see Fig. 6).

Actually, similar approaches are used in industrial engines to prevent pulsations due to eventual drifts in some operating parameters. However, there exists no mechanism to reduce ER when the cause of the drift disappears; hence, the combustor is set to an ER above the optimal point, leading to high NOx emissions. This situation is simulated with a descending X_{CO2} ramp, starting at ER=0.78 (as required to limit pressure fluctuations with X_{CO2}=34%). When no correction is taken, decreasing the CO_2 amount results in a gradual rise in NOx from 4 to 12 ppm. During the control test, both NOx and σ_P were continuously monitored. When an increase in NOx is detected, the amount of air is modified in order to reduce ER. This operation is supervised in order to prevent any rise in σ_P. As shown in Fig. 6, this strategy enabled to maintain low NOx emissions throughout the test, with nearly constant σ_P.

SUMMARY

Several examples on the use of flame sensors for the diagnostic and control of lean-premixed combustors have been presented. The tests performed indicate that pressure and radiation signals can be used as a signature of the flame and, after suitable processing, can be exploited for identification purposes. Two different control scenarios have been explored: optimisation and adaptation to variable fuels. In both cases, it is likely that the combustor would enter regions of instability. In the tests performed, this problem could be avoided by monitoring the flame signals, which can also be exploited to speed-up the optimisation process.

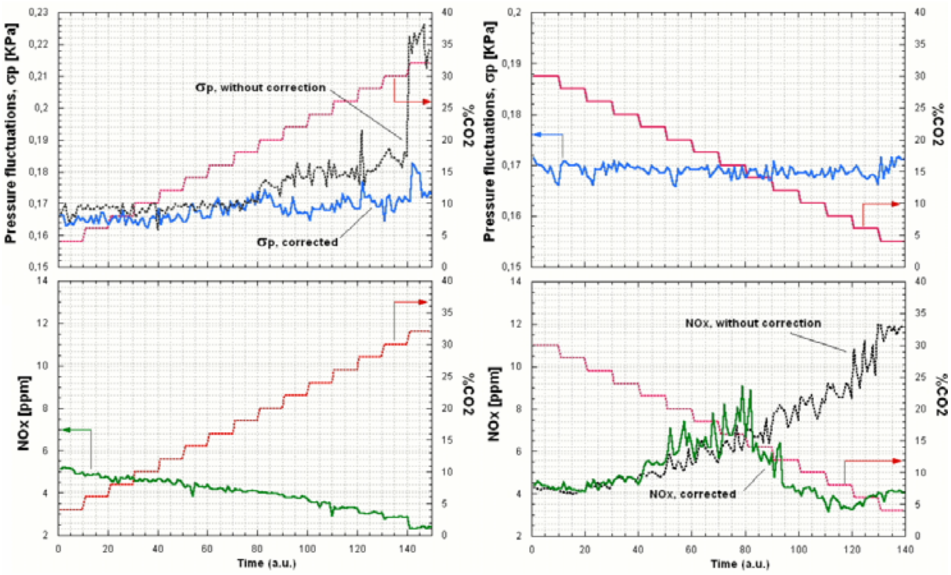

Figure 6 – Evolution of σ_P and NOx along ramps of ascending and decreasing X_{CO2}, without any correction (dotted lines) and when ER is regulated to improve performance (solid lines).

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