AN OPTICAL TECHNIQUE FOR THE IDENTIFICATION AND TRACKING OF COMBUSTION INSTABILITIES

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Abstract

Modern gas turbines tend to employ some form of premixing to operate with lean mixtures, thus reducing NO_x emission. Besides this design requirement of combustors, today the use of "hydrogen blends" is becoming usual, especially in IGCC (Integrated Gasification Combined Cycle) power plants. Both the presence of hydrogen and the use of lean mixtures enhance flame dynamics in terms of combustion instabilities, flashback and lean blow out. A diagnostic system for monitoring unsteadyness of the flow and for "early detection" of these phenomena would be desirable to provide significant payoffs. This article suggests a practical and cheap strategy named ODC (Optical Diagnostics of Combustion) to perform real time diagnostics, monitoring and, eventually, control in gas turbine combustors to operate them with leaner mixtures safely. Theoretical aspects at the base of the technique are briefly reminded. Example applications of thermo-acoustic instability detection and of effective tracing of the flame dynamics approaching blow out conditions are provided.

Introduction

It is well known that combustion in gas turbines may exhibit pressure oscillations due to poor flame stability. Flame anchoring and thermo-acoustic instabilities are, in fact, a major concern for modern and future combustors, as they tend to employ some form of premixing to reduce NO_x. Efforts are currently focused on fuel lean premixed combustors or partially premixed combustors with rapid mixing after fuel injection, with the tendency to operate close to the Lean Blow Out limit (LBO). However, these combustion strategies are less stable than conventional ones because lean mixtures imply weaker combustion processes and can therefore be easily perturbed, thus increasing the risk of flame blow out. This scenario goes against an acceptable operation of gas turbines.

Furthermore, today the use of CCS (Carbon Capture and Sequestration) derived fuels is becoming more usual, especially in IGCC (Integrated Gasification Combined Cycle) power plants. The big difference between these fuels (syngases or "hydrogen blends" in general) and natural gas is that they contain hydrogen. Hydrogen has particular molecular properties strongly affecting the features of fuels [1]. First, it tends to enhance flame stability in terms of increased flame speed, decreased ignition delay time, and enlarged flammability limits. This brings designers to use even more leaner mixtures to reduce NO_x. Second, "hydrogen blends", like syngases, have lower LHV (Lower Heating Value) with respect to natural gas. This brings designers to increase the fuel mass flow rate, and hence its injection velocity, to obtain a certain power. Besides these two issues, it has to be noticed that depending on the gasification process and which solid is gasified, substantial differences in the resulting syngas composition occur. Feeding lines contain fuels coming from different sites and inevitably gas turbines will have different thermal loads due to changes in fuel composition. All these design requirements and changes in composition enhance flame dynamics with respect to natural gas (thermo-acoustic instabilities, flashback, LBO, localized extinctions and reignitions) [2] whilst acceptable operation of gas turbines requires a "weak" dynamics.

Finally, combustion dynamics is expected to be "enhanced" in modern gas turbines operating with lean mixtures or with "hydrogen blends". This implies that undesidered and dangerous phenomena, such as combustion instabilities, flashback and lean blow out (LBO), are likely to occur not only in steady conditions, but also and more dangerously when rapid power changes are required. A fundamental question is to understand when and how pressure oscillations could make the flow dangerously unstable for engine operation. A diagnostic system for monitoring unsteadyness of the flow and for "early detection" of these phenomena would be desirable to provide significant payoffs. Instability precursor sensors would be also the main part of an active control system to operate present combustors with leaner mixtures safely.

Flame Radiant Energy and its Information

Total radiation emitted by flames consists of two type of sources. The first is chemiluminescence, while the other is thermal emission associated to the Planck function [3,4].

The intensity of light emission is proportional to the production rate of some molecules; this implies that chemiluminescence can be used to measure reaction rates [5] and heat release rate [6-8]. Chemiluminescence intensity ratio OH*/CH* has also been used to measure equivalence ratio in partially premixed flames [7] and it has been observed that chemiluminescence intensities C_2*/CH* may provide indication of strain rate in perfectly premixed flames with known equivalence ratio [7]. Furthermore, OH* has also been measured by means of PITLIF (PIcosecond Time-resolved Laser-Induced Fluorescence) and used as tracer of turbulent scales [9]; the capability of this tracing has been confirmed by LES simulations. On the other hand, the thermal contribution to the total radiation has been used to estimate temperature, soot volume fraction, and gas species concentrations [10,11].

Flame radiation has also been exploited as a tool to investigate flame extinction. In fact, both premixed and nonpremixed flames close to lean blow-off (LBO) are characterized by large scale pulsations [12,13] and lack of OH* radical for a significant amount of time [14,15]. The transition from stable combustion to LBO happens through a transient regime in which the flame experiences localized extinctions and reignitions; large scale pulsations produce noise, changes in radiative emissions [16-18], and cyclic thermal loads, that can be dangerous for the combustor walls and for the turbine blades located downstream of the combustor. These phenomena can be assumed as precursors for LBO; the number of precursor events in a given time window, and the duration of the event (usually defined as time spent outside of a threshold), increase as the LBO equivalence ratio limit is approached [15]. Furthermore, frequency analysis shows that energy content increases dramatically near the LBO limit, both in radiative [15-17] and acoustic [16,17,19] forms.

First analysis of flame radiation carried out in ENEA's combustion laboratory [20] using a photo-diode and considering data coming from different burners, fed with different fuels, revealed that ensemble average of time spectra gives evidence of a wide range of frequencies characterized by a clear scaling. And what is more curious is that this scaling, whose exponent is $-5/3$, is the same of turbulent kinetic energy in the inertial range of a homogeneous and isotropic non-reacting flow. In [20] a plausible explanation of such scaling law was attempted. Furthermore, considering a bluff-body stabilized CH_4/Air turbulent premixed flame, the comparison between the radiative emission spectrum and a velocity spectrum obtained by means of Laser Doppler Anemometry (LDA) at the center of the region seen by the photo-diode [21], revealed that both the spectra exhibit a clear range of $f^{-5/3}$ scaling and that the same main frequency, i.e., turbulent macro-scale, (10 Hz) is measured by both techniques. Finally, information about the dynamics of the large turbulent scales of the flow, its inertial scales and its small scales are gained. Small scales, being mainly related to combustion (heat release) and (high frequency) acoustics, may reveal critical in combustion instability detection.

It follows that flame radiative emission contains information related to both chemistry and turbulence, and it could be successfully used for monitoring flame stability and to detect flame blow out. Finally, the aim of this work consists in finding and propose a practical key of reading these information to guarantee more regular and continuous combustor operation.

Proposed Strategy and Sensor Set-Up

The main and direct output that an observer in front of a combustion process can capture are radiant energy, thermal energy and noise. The strategy proposed in this article to characterize the unsteadyness of a turbulent flame and to detect its stable or unstable state is based on an optical system called ODC (Optical Diagnostics of Combustion) that uses a photo-diode as sensor [22,23]. To monitor combustion dynamics it is suggested that radiant energy is not sampled point-like, but in a wide region of reacting zone, in order to capture eventual growing of instability precursors in different parts of the flame. By means of optical devices like photo-diodes, signal can be sampled at very high frequency (up to 10 MHz in the present version of the ODC system), thus providing excellent statistics and information about chemical and high frequency acoustic scales. Moreover, it is easy to implement efficient and fast diagnostic algorithm suitable for real-time control.

The issues of combustion dynamics analysis and instability detection were tested in several facilities (all located in Italy) at both laboratory and industrial scale:

- 250 kW Liquid Oil/Air Rapid Premixed burner in Savona Combustion Laboratory.
- 300 kW H2/O2 MICOS burner in ENEA Casaccia Research Center in Rome.
- 500 kW CH4/Air Centro Caldaie ANSALDO burner in Gioia del Colle (Bari).
- 3000 kW CH4/Air Centro Caldaie ANSALDO burner in Gioia del Colle (Bari).
- 5000 kW CH4/Air coal/water slurry ITEA flameless oxy-combustion burner in Gioia del Colle (Bari).

The first four burners can experience thermo-acoustic instabilities. An example of the analysis of the process dynamics towards instability and of the detection strategy of suitable instability precursors will be provided for the first combustor. In particular, it will be shown that the non-zero auto-correlation function of radiant energy signal identifies the onset of thermo-acoustic instabilities. Similar results were found for the other burners experiencing thermo-acoustic instabilities [24].

The main characteristics of the ODC system used in practical/industrial applications are sketched in Fig. 1. The present configuration of the system implements a photo-diode with a frequency bandwidth up to 10MHz (455HS version in the "Gain vs Frequency" plot) and with a spectral response in the range [300−1100] nm, i.e., from the UV range up to the near infrared (standard version in the "Spectral Response" plot).

The photo-diode and the diagnostic system is remoted far from the combustor by means of a monomodal quartz optical fiber. Quartz fibers have high flexibility; the monomodal feature permits also high lengths with low losses of signal. This fiber connects the photodiode, through a collimator, to the optical head consisting in a monomodal sapphire fiber with alumina protection and without cladding. The sapphire head has a view angle less than 10 degrees and can face temperatures slightly above 2000 K. Both the optical fibers have a diameter of 1mm. The two junctions require particular attention to avoid dramatic loss of signal.

The photo-diode signal is sampled by an acquisition system (DAQ) at 10 MHz. The present DAQ system can manage up to four sensors. The signals is finally elaborated by an in-house software on LABVIEW platform providing real time analysis of data.

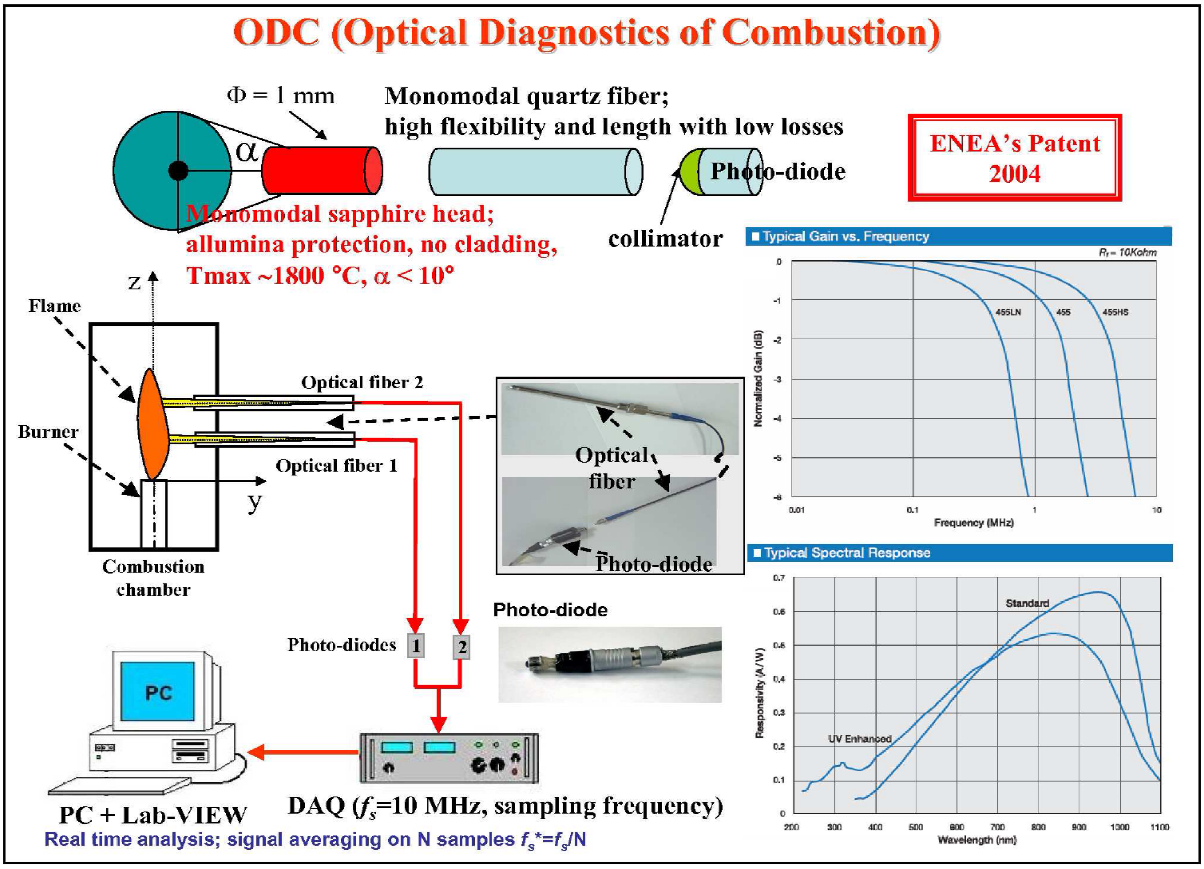

Figure 1. Sketch of the ODC system set-up and characteristics of the photo-diode currently used. Above, it is shown the connection of the diode with the quartz optical fiber and then with the sapphire optical head; the radius of the optical head and its actual angle of view are also reported. The experimental set-up on the left is generic and shows two photo-diodes, even though more diodes can be adopted depending on the DAQ system (in the present configuration it has four channels).

Thermo-Acoustic Instability Detection

Combustion instabilities occur especially in lean mixtures, and bring to dangerous operating conditions up to blow out. Nature of combustion instabilities can be fluid-dynamic or thermo-acoustic. The former are related to vortex - flame interaction. The coupling between fluctuations of the heat release rate and pressure oscillations drives thermo-acoustic instabilities [25-27]. Apart from Lord Rayleigh postulate [28] or some new formulations [29] there is still no reliable criterion to predict self-excited combustion oscillations.

It is interesting to observe that, although it is commonly accepted to think of precursor events of instabilities as intermittent peaks with growing frequency and amplitude when approaching unstable states, this is not confirmed by the present data. In particular, either peak detection with constant or variable threshold (e.g., for a data series in a 1 ms time window the local threshold can be assumed as its mean plus a percentage of its standard deviation), neither wavelet analysis, were able to identify instability precursors in terms of intermittent peaks or known waveforms. The present work shows that the non-zero auto-correlation functions of the flame radiant energy or of the pressure can be associated to precursor events of thermo-acoustic instabilities. The analysis also suggests to use the integral (normalized by a reference area) of the module of one of these auto-correlation functions as a thermo-acoustic instability factor.

The thermo-acoustic instability analysis performed on a 250 kW premixed liquid oil/air burner is here described as an example. This burner, sketched in Fig. 2, is the LRPM (Liquid Rapid PreMixer) facility in Savona Combustion Laboratory. This facility is equipped with an air compressor and an air preheater. The mixer length is 1.5 m, the combustion chamber length is 0.3 m, and the chimney length is 1.2 m. Air and liquid oil are uniformly mixed by means of the Rapid Premixer swirler. Ignition does not require any pilot flame. This facility was equipped with a photo-diode (ODC system) and a pressure transducer. Both the pressure transducer and the ODC were located in front of the flame, as shown in Fig. 2. This burner, when feeded by means of 288 g/s of air and 0.168 g/s of liquid oil, is in a stable mode. Increasing fuel mass flow rate up to 0.232 g/s, the operating mode switches to unstable; the type of instability is not fluid-dynamic, but thermo-acoustic. Air is preheated at 1073 K.

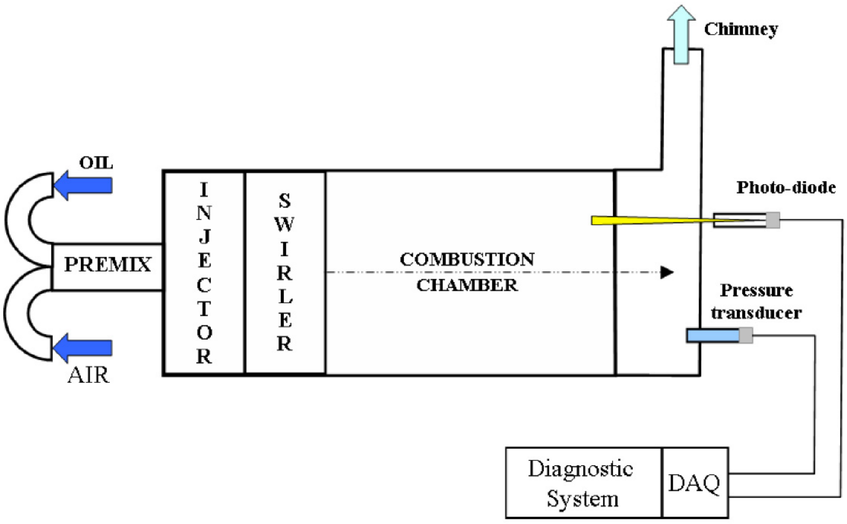

Figure 2. Sketch of the 250 kW Liquid Rapid Premixed burner in Savona combustion laboratory.

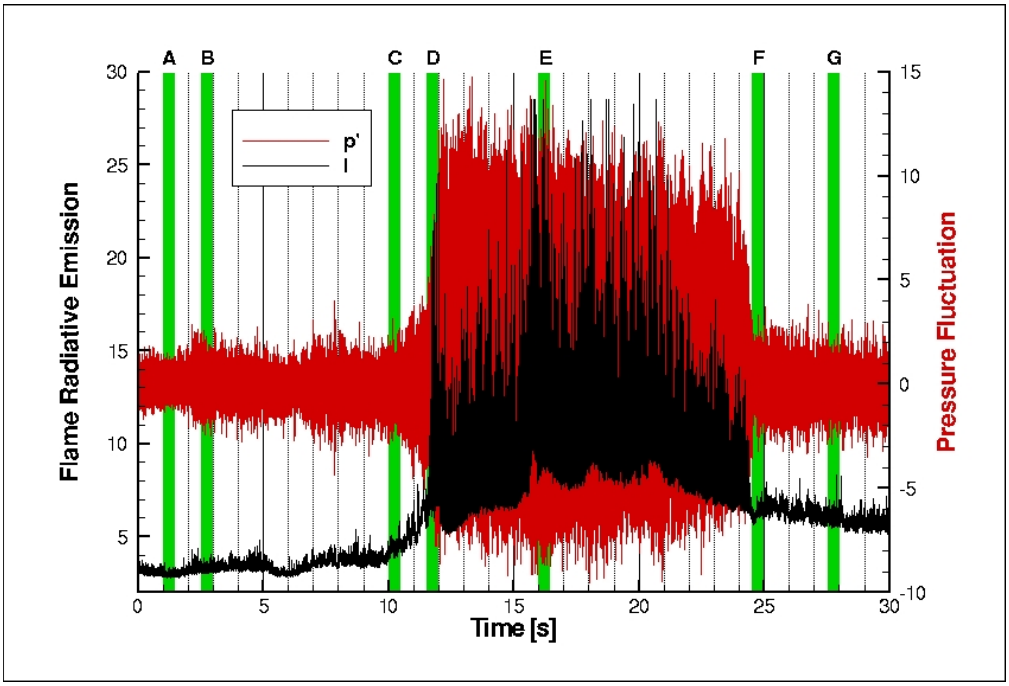

Figure 3. Characterization of transition from stable to unstable mode in the 250 kW premixed liquid oil/air burner located in Savona Combustion Laboratory (Savona, Italy). The red line refers to pressure signal, while the black one to radiant energy.

Figure 3 shows the time evolution of radiant energy (black line) and pressure (red line) raw signals in a 30 s time window during which there is the transition from stability to “humming”. The radiant energy signal increases slowly as the fuel mass flow rate is increased, meaning an increase of the averaged temperature inside the combustor. Seven time windows, each of 0.5 s and marked in the same figure from A to G, are here examined as representative of different operating conditions of the burner: they range from stability (A) to situations showing precursors of instability without (B) and with (C) temperature increase (drift), up to the quick onset of instability (D), then to “humming” (E) and then, through a quick exit from this regime (F), back to stability (G). These conditions are reached by firstly increasing and then decreasing the fuel mass flow rate.

Figure 4 shows some information associated to the intervals marked in Fig. 5. In particular, the first column from left (index 1) reports cross-correlations between pressure and radiant energy signals; the central column (index 2) reports auto-correlations for both signals (calculated without subtracting the average value of the signals in the time window considered, and normalized by their variance); the third column (index 3) reports semi-log plots of frequency spectra.

Looking at Fig. 4, it can be observed that when the burner is in the stable operating mode (A), pressure and radiant energy are not correlated (plot A1), nor auto-correlated (plot A2). Furthermore, this condition does not show any dominant frequencies, apart from some peaks with amplitude negligible with respect to those present in the other time windows (plot A3): 15, 39, 52 and 66 Hz for radiant energy and 17, 54, 74, 80 Hz for pressure. It is stressed that pressure peaks are at frequencies slightly higher than radiant energy ones.

While increasing the fuel mass flow rate, some precursors of instability intermittently appear, as in condition B, thus increasing correlation and auto-correlation of both signals (plots B1 and B2).When this condition is reached the system shows a dominant frequency at ~ 80 Hz (plot B3). It is interesting to note that this dominant frequency was in fact already present in the pressure field of the stable regime (plot A3) with a much lower amplitude; hence, increasing fuel mass flow rate forced radiant energy field to synchronize with pressure field, and this can be due to the pressure field modulating the inlet flow rates and consequently the heat release.

Unstable situations like the previous one are intermittent with short life-time: the system quickly tends to dampen these fluctuations. Continuing to increase the fuel mass flow rate more energy is released inside the system, and the temperature increases (as the radiant energy drift of Fig. 3 from C to D confirms). It is interesting to note that precursor events (like that in B) are not so frequent, as shown by the evolutions of the pressure–radiant energy cross-correlation and of the above defined (radiant energy) thermo-acoustic instability factor in Fig. 5. The dominant frequency evidenced in plot B3 (i.e., ~ 80 Hz) tends to become steady, being present (plot C3), although with lower amplitude, also when cross-correlation between pressure and radiant energy is negligible (plot C1). “Calm” situations like this may arise during transition to “humming”. In plot C3 radiation shows a richer frequency spectrum than pressure (as in A3), especially at frequencies lower than the dominant 80 Hz, with a peak at 32 Hz; the amplitudes of both signals are lower than in plot B3 by one order of magnitude, and by two orders of magnitude with respect to those in plot A3. Pressure is not auto-correlated (plot C2) while the auto-correlation of radiant energy is not negligible and its form is that associated to a drifting signal as shown in Fig. 3 from C to D. This observation suggests that the photo-diode is better than the microphone, since it can identify eventual drifts of the system energy. To gain this information with an acoustic sensor, a pressure transducer should be adopted. Removing the local average of signal in the 0.5 s time window used to calculate the auto-correlation (normalized by means of its variance) produces nil auto-correlation as for the pressure signal of the microphone.

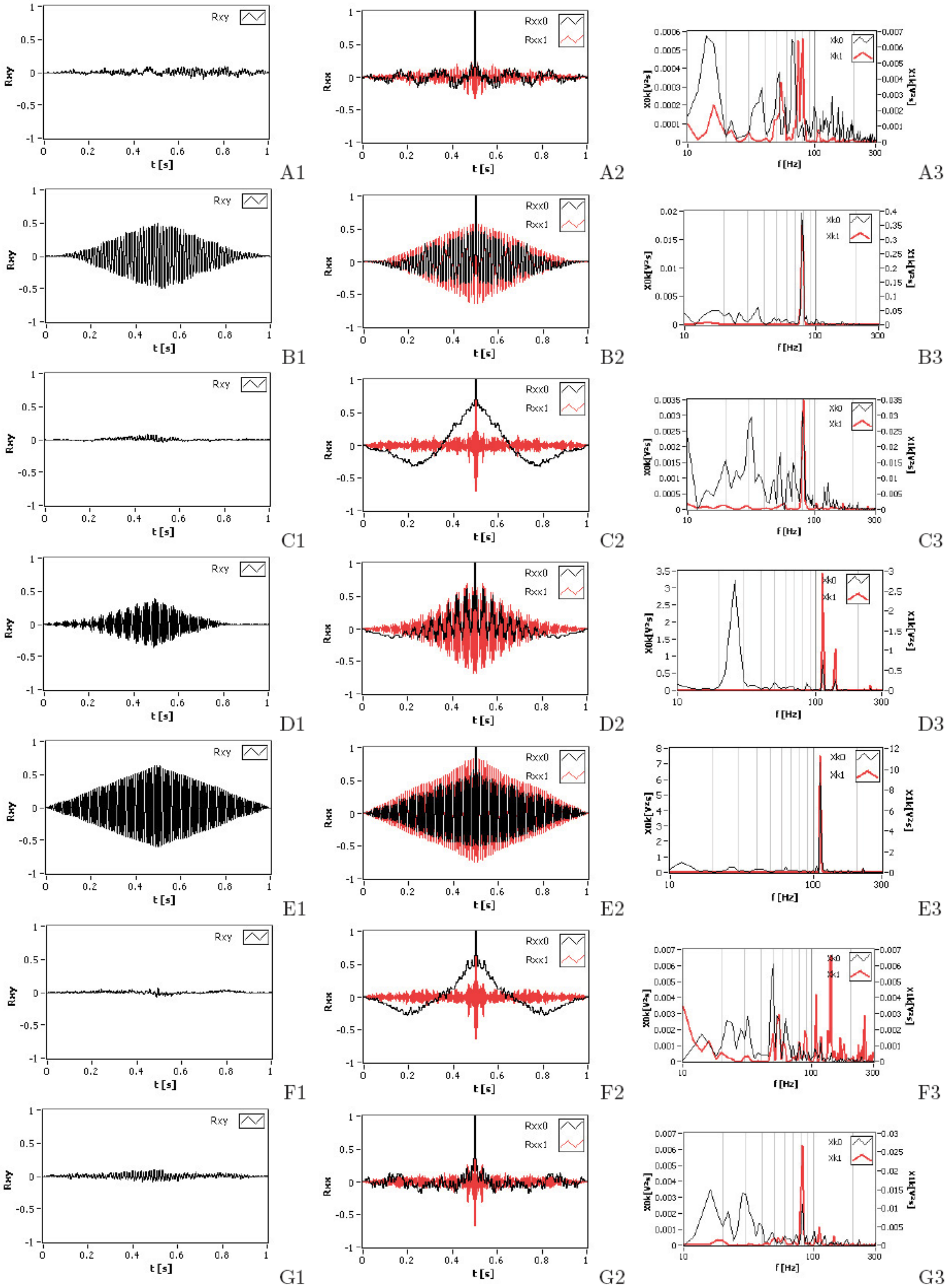

Figure 4. Characterization of transition from stable to unstable mode in the Liquid Rapid Premixed burner of Savona combustion laboratory. The letters from A to G refer to time intervals in Fig. 3. The first column from left (index 1) reports cross-correlation between pressure and radiant energy signals; the central column (index 2) reports auto-correlation for both signals; the third column (index 3) reports frequency spectra. In the last two type of graphics the red line refers to pressure signal, while the black one to radiant energy.

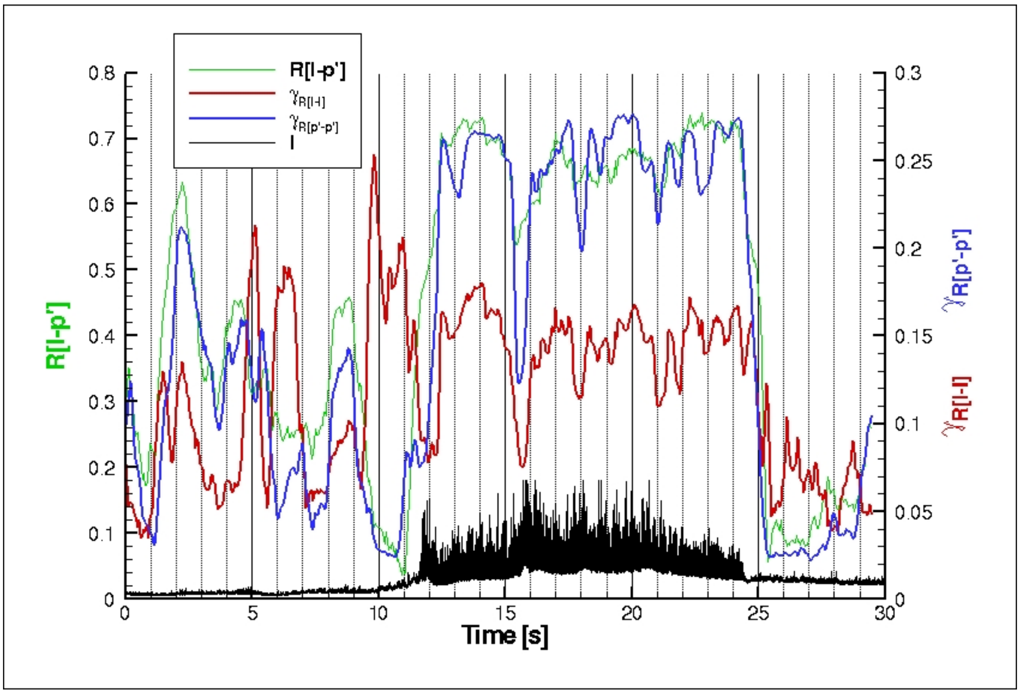

Figure 5. Liquid Rapid Premixed burner in Savona combustion laboratory: evolution of pressure–radiant energy cross-correlation and of the thermo-acoustic instability factors (defined as the normalized integral of the auto-correlation function module of the radiant energy and pressure signals) in the 30 s time window analyzed (see Fig. 3).

In correspondence of the steep radiant energy gradient (D) there is the onset of instability, i.e, the transition to a fully established unstable condition ("humming"): cross-correlation and auto-correlation grow (plots D1, D2, E1, E2); amplitudes increase at least by three orders of magnitude with respect to A3; characteristic frequencies are shifted (112 and 136 Hz in plot D3) according to the increase in temperature of the medium (that increases the sound speed, i.e., the propagation velocity of acoustic waves), and then "selected" up to the establishment of a single frequency (112 Hz in plot E3). It is observed that if the wavelength of the standing acoustic wave is assumed constant during the transition from B to E, it follows that the ratio between the dominant frequencies, i.e., 112/80 = 1.4, is equal to the ratio between the sound speeds; thus, the average temperature inside the chamber in condition E increased to T_E = 1.96 T_B. The growing temperature trend is also confirmed by the increase of the flame radiant energy amplitude in Fig. 3.

When the fuel mass flow rate is decreased down to its initial value the system tends to exit from the unstable regime (F) in a way similar to its entrance (C). Pressure and radiation are not correlated any longer exhibiting rich frequency spectra of low amplitudes (plot F3); in particular, pressure spectrum spreads over a wide range of frequencies, while radiation is confined to frequencies lower than the ~ 80 Hz dominant in condition B. It is interesting to note that the acoustic frequencies 108 and 140 Hz, approximately already present in plot D3, appear again. Note that the non-zero auto-correlation of the flame radiant energy is again due to the drift of the system energy as in C.

Finally, the system slowly turns back to its stable initial configuration (G). Looking at Fig. 3, the averaged temperature level inside the combustor stays still high (in the 30 s time window analyzed), likely due to walls, now hotter than before "humming". This means that the backward transition to the stable mode is slow and that the system may turn back to "humming" easier than before, i.e., by a less increase of the fuel mass flow rate.

As concluding remark, it is stressed that precursor events tend to grow many seconds prior the fully establishment of instability; in particular, it is noted that the delay time between the condition where the first precursors are detected by the photo-diode (condition B, see plot B2) and the condition of fully established instability (condition E, see plot E2) is ~ 14 s. Furthermore, the auto-correlation of the radiant energy signal evidences some important drifts in the system energy not revealed by the pressure signal (coming from microphones), as in conditions C and F (see plots C2 and F2), since the radiant energy has a non-zero average value (as also the pressure has when sampled by pressure transducers). All these features are strategic for active control applications.

Figure 6 reports the distribution of pressure–radiant energy cross-correlations versus the time delay between the two signals in three time windows: before the full establishment of instability, within it and after it. It is observed that the delay time between the two signals becomes constant (~5 ms) when the instability is fully established. This confirms the pulsating mode of the instability (at 112 Hz, as shown in Fig. 4, plot E3). Due to the speed of light propagation, the radiant energy signal has zero delay time with respect to thermo-acoustic pulsations originating where acoustic waves and heat release are in phase. Since the delay time between radiant energy and pressure signals is ~5 ms, this will be the time taken by the thermo-acoustic pulsation wave to reach the microphone at the bottom of the combustor. If another microphone had been located upstream, it would be possible to estimate the average sound speed of the wave and then the location of the origin of the thermo-acoustic instability.

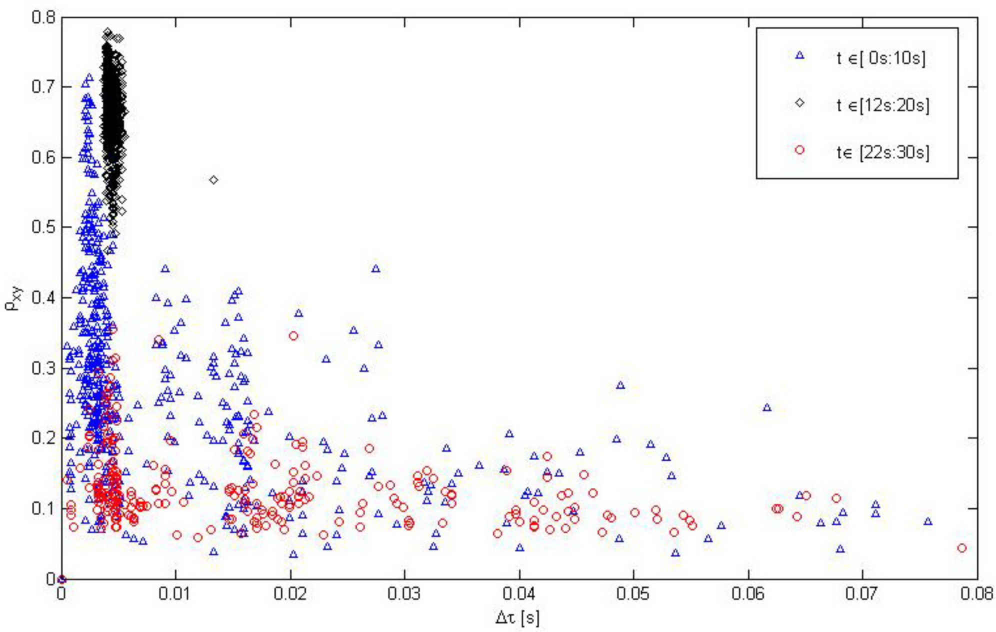

Figure 6. Liquid Rapid Premixed burner in Savona combustion laboratory: distribution of pressure–radiant energy cross-correlations versus the time delay between the two signals in three time windows, before the full establishment of instability, within it and after it.

Detection of a Generic Combustion Instability

Once understood that flame radiative emission is linked to both turbulence and chemistry, the ODC system can be used to identify and dynamically trace a generic combustion instability.

An axisymmetric burner equipped with a conical bluff-body to anchor a premixed CH_4/Air flame was operated in ENEA's combustion laboratory at a stable condition and at an unstable condition close to the blow-off. Fig. 6a shows the time averaged spectra of flame radiative emission acquired by the ODC system. The spectra were averaged over 60 spectra, each one sampled in a 1 s time frame. The blue spectrum refers to the stable case, while the red one to the unstable case.

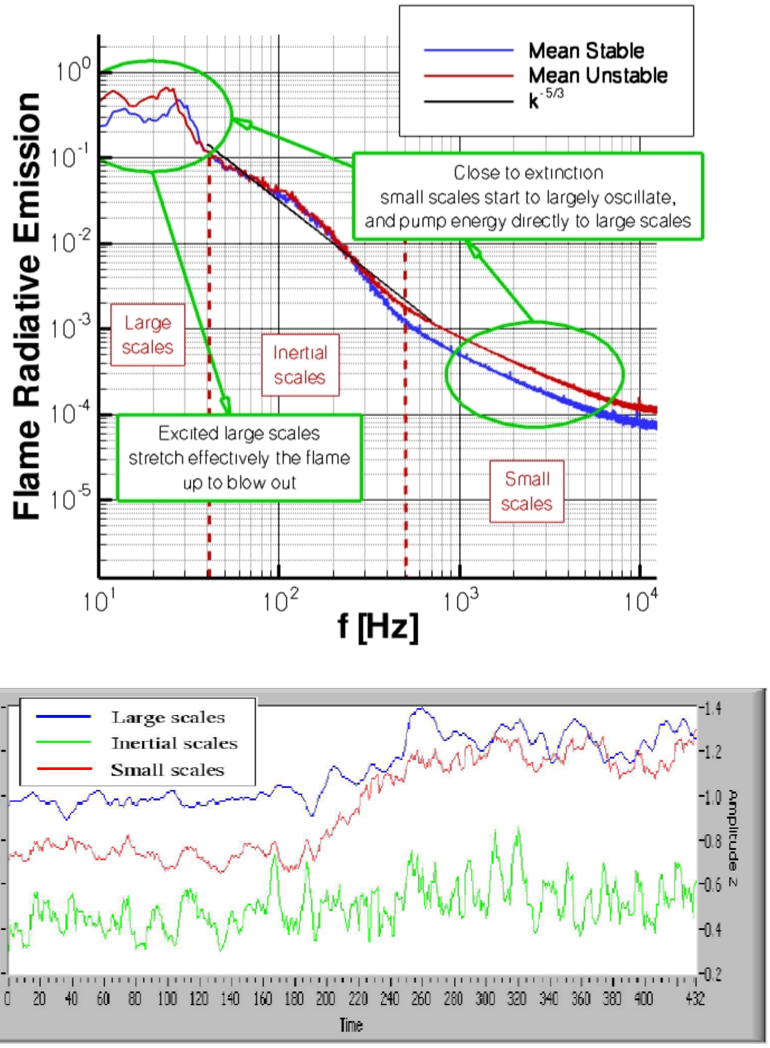

Figure 6. a) Time averaged spectra of radiative emission in a premixed CH4/Air flame operated in a stable (blue line) and an unstable (red line) configuration. The unstable case is close to blow out. The partition of the frequency range in large, inertial and small scales is also shown. b) Dynamics of the energy associated to the large, inertial and small scales evidenced in Fig. 6a when the flame approaches the extinction.

Upon measuring velocity fluctuation via LDA (Laser Doppler Anemometry) the turbulent Reynolds was calculated and used to estimate the dissipative scale. The frequency of this scale and the extension of the (average) inertial slope −5/3 were used to separate the investigated frequency domain in three ranges associated to the large, inertial and small scales, respectively. The two spectra are practically identical in the inertial range, while the unstable one has higher energy at the large and small scales. Hence, small and large scales interact non-locally in the wavenumber space; this does not happen in non-reacting flows.

Now, what are the first scales to be excited close to extinction? The small or the large ones? To address this problem the energy of the three ranges was tracked in the unstable case and Fig. 6b shows that the energy of small scales increases before that of the large scales when close to extinction. The small scales energy largely oscillates due to fast localized extinctions and reignitions. This pumps energy directly to the large scales without altering the inertial scales. Finally, the excited large scales stretch effectively the flame up to blow out. Hence, when a flame is stable, the large scale may drive small scale fluctuations, while in unstable conditions close to extinction the small scales drive large scale fluctuations via fast localized extinctions and reignitions.

Conclusions

An optical technique consisting in sampling flame radiant energy by means of a photo-diode has been suggested as a practical way for monitoring the dynamical state of combustion systems. The technique is able to detect the stable or unstable state of combustors and could be adopted in an eventual feedback control loop.

After having reviewed the fundamental theory at the base of the technique, two examples were provided, one related to a thermo-acoustic instability and another one to a chemical/fluid dynamic instability close to blow out. It was shown that the auto-correlation of the flame radiant energy or of the pressure signals (coming from pressure transducers and not from microphones) can be used to identify precursors of instability and to quantify the stable or unstable state of combustors. The proposed ODC technique, compared with pressure transducers, is more robust, standing higher temperature (2000 °C) than pressure sensors (900 °C), and has less intrusivity, due to its smaller size (1 mm optical fiber diameter). Moreover, pressure transducers needs an amplifier.

Acknowledgments

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