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Diagnostics on-line of Unsteady Combustion in an Industrial Burner Model and Development of an Active Control

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Abstract

The paper summarizes experience matured by ENEA to develop and test an Active Control for Combustion System for controlling fluid dynamic and thermo-acoustic combustion instabilities.

It is well known that combustion in gas turbines may exhibit pressure oscillations due to poor flame stability. Flame anchoring is, in fact, a major concern for future combustors, as they will tend to reduce NO_x emissions using premixed combustion.

Under certain operating conditions, burners can be characterized by self-excited oscillations or instabilities. It is widely accepted that it is the coupling between fluctuations of the **heat release rate** and **pressure oscillations**, that drives combustion instability. Self-excited oscillations need a feedback mechanism to induce growing amplitude oscillations of pressure. Usually (but not always) this feedback is determined by the acoustics of the system: pressure waves make the incoming fuel flow rate fluctuate; in turns this drives a further oscillation of the heat release rate, and this induces a new pressure wave. According to Lord Rayleigh postulate, if this pressure wave is in phase with the prior sound pressure oscillation, a closed loop is established and self-amplification of the pressure field can be observed. Rayleigh's criterion indicates also that it is possible to damp the instability by exciting pressure waves that are 180 degrees out of phase with respect to the heat release-driven pressure oscillations.

This coupling between fluctuations of the heat release rate and pressure oscillations may become dangerous when self-amplified causing undesirable noise emission in low power systems, and mechanical damage in high power systems. Other possible effects may be thermal destruction of the liner, due to the increased frequency of velocity oscillations, leading to increased and cyclic heat transfer to combustor walls, and the blow-out or flashback, in case of high amplitude oscillations.

In order to limit the thermo-acoustic combustion instabilities, the damping combustion instabilities and hence extend the stable operating range of combustion process, an **Active Control** techniques has been investigated.

Measurements can help scientists to understand physics hidden in what observed. A lot of techniques, such as LDA and thermocouples, give average quantities; a few, such as PIV, instantaneous fields. While spatial resolution can be fine enough, it is not the same for time resolution. Frequency analysis performed by means of LDA can capture frequencies up to 1 kHz; hot wire anemometer can reach higher frequencies but it cannot be used in flames.

Recently ENEA has patented a new instrument called **ODC (Optical Diagnostic of Combustion)** [1], resolving up to 10 MHz and over. This technique is on-line, very economic and absolutely not intrusive because it needs only a hole to introduce an optic fiber.

This technique was installed on a combustion chamber equipped with quartz windows. The burner operates with a methane-air mixture at atmospheric pressure.

The natural unstable motion of the flame is analyzed by measuring the spontaneous light emitted by the flame and by means of the variations of the flame's surface area.

Capturing physics and dynamics of turbulent flames, this new ODC instrument can develop and test new control strategies to increase efficiencies, reduce noise and pollutants emissions.

Key words: Active control, combustion diagnostic, frequency analysis, photodiode, chemiluminescence, ODC, LDA, PIV.

Introduction

The main drawback of aeronautical and mechanical systems is the rising of instability, which can be limited by a recirculation of hot products, achieved by means of a bluff-body placed at the exit section. As shown in [2] and [3], the recirculation zone acts like a heat source since fresh mixture is preheated in the shear layer.

In order to reduce further the fluid dynamic instabilities and the amount of pollutants, often correlated to noise, an active control strategy on the actual burner has been tested. The control methodology consists in perturbing the flame by means of air jets exhausting from holes located on a ring surrounding the burner exit section. Such a method has been designed and numerically simulated by Giacomazzi and Bruno [4] for the Active Control of a non-premixed flame: they obtained good results in terms of flame stability and pollutant emissions by pulsating the auxiliary air jets.

Experimental results of our analysis represent a basis for developing Active Control strategies for turbulent flames, a task which is presently underway by the authors.

Experimental set-up

Annular burner

All the experiments have been conducted at the combustion fluid dynamic laboratory of C.R. Casaccia of ENEA (Italian Agency for Energy and Environment). The burner model is formed by two parts, the base (premixing zone) and the top (outlet zone). The base consists of a Bunsen burner modified for the forced inletting air. The air gets along the vertical walls and crosses the incoming fuel. Downstream the mixing zone there is the outletting zone with a variable area section, conceived to avoid flame flash-back. The exit of the burner (quarl) is formed by two parts: an external pipe with a diameter D of 25 mm and an inner inverted cone fixed to a 7 mm axial rod coming from the outlet zone [5]. The maximum diameter of the bluff body (d) is 15 mm.

In order to obtain a good premixing level before combustion, four circular ducts of 8 mm of diameter, symmetrically positioned with respect to the axis of the burner, inject air into a current of fuel which moves in a duct of 10 mm of diameter and 100 mm of length.

The reacting mixture flows through a circular duct of 25 mm of diameter with a conic bluff-body of the diameter of 15 mm to the center. A scheme of the head of the burner is reported in Fig.1.

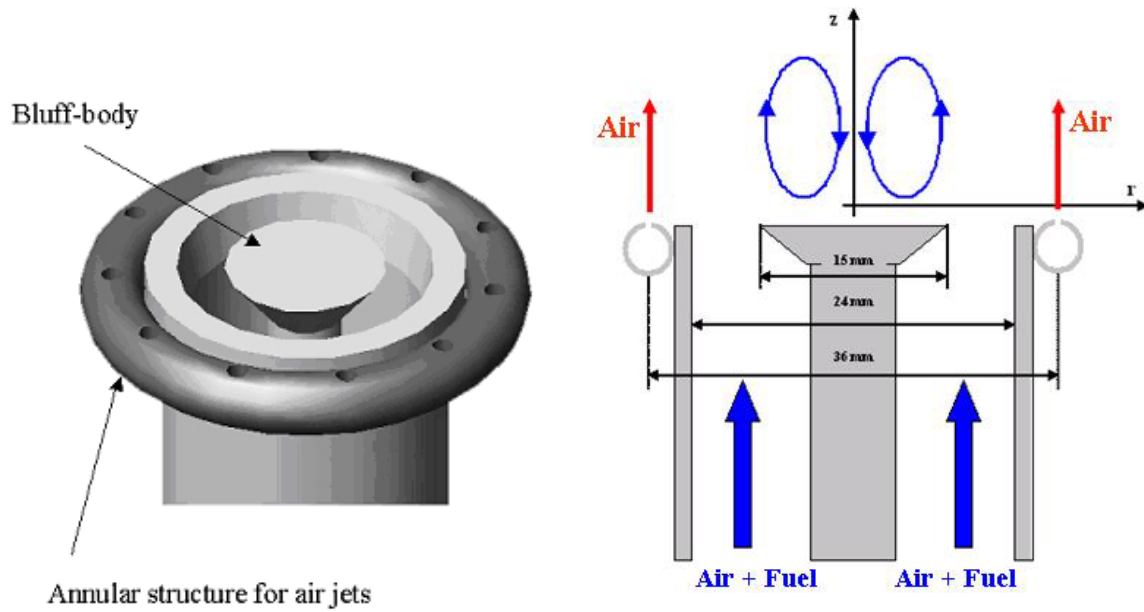


Fig. 1: The annular burner DG-25-15-CON.

The flow rates are metered by two Venturi tubes: one for the air and one for the fuel. The ring surrounding the burner has 12 holes of 2 mm of diameter and it is used as actuator for the control strategy that modulates the flow rate of its air jets. The annular burner and the Active Combustion Control System were installed on a combustion chamber at atmospheric pressure, equipped with quartz windows to have a direct optical access to the flame. The annular burner is positioned inside an axisymmetric test chamber with a cross section diameter 40 times larger than the burner diameter and a height of 1100 mm.

Optical set-up

Two different types of photodiodes (Fig.2) are used in our experiments. Their characteristics are shown in Tab.1.

Photodiode IPL 10530 DAL	Photodiode OSI 1-300k/10M
<ul style="list-style-type: none"> • Frequency response 12 KHz • Spectral Enhancement UV→IR • Field of view 12° • Diameter of lens 8.33 mm • Active area 1.75 mm² • Low thermal drift 	<ul style="list-style-type: none"> • Frequency response 10 MHz • Spectral Enhancement UV→IR • Active area 1 mm² • Low thermal drift • Diameter of quartz fiber 1 mm

Tab. 1: Characteristics of the two photodiodes used.

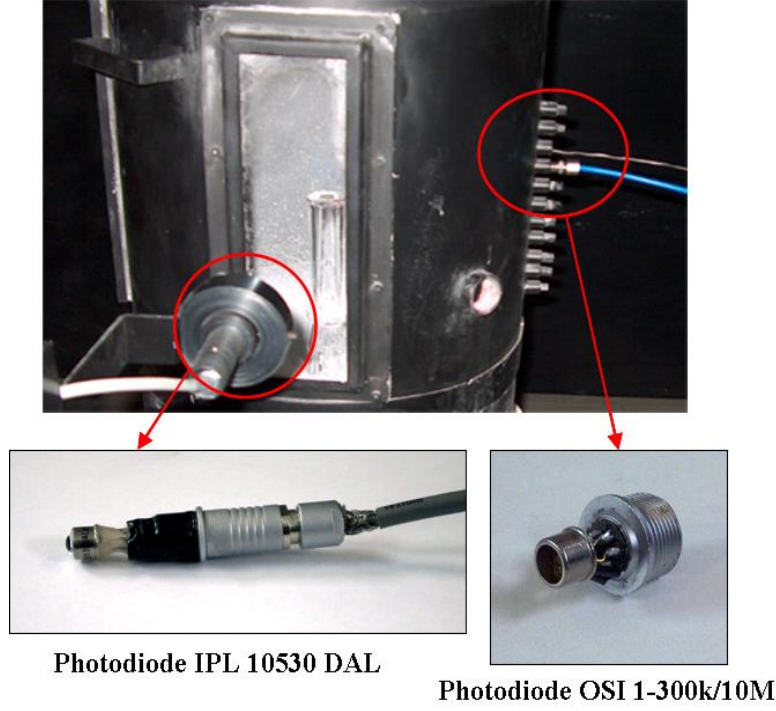


Fig. 2: The two type of photodiode used in these experiments.

Laser techniques

The PIV system consists of two Nd:Yag pulsed lasers (Quanta System) with 532 nm wave length, a cross-correlation unit type Dantec PIV-2000, a CCD camera (1280x1024 pixels), two monitors, a personal computer Pentium 3, with PIV synchronization software (Flow Map 3.50), an alumina seeder system (5 μm mean diameter).

LDA system consists of a Dantec 7 Watt Argon laser (with three components) and two Dantec Burst Spectrum Analyzer (BSA), a master and a slave, for the measurements of two velocity components (radial and axial).

Test-matrix

Combustion regimes and flow conditions are characterized by means of two global nondimensional parameters, the equivalence ratio (Φ and Φ_{tot}) and the Reynolds number (Re):

$$\text{Re} = \frac{U \cdot D_{\text{equ.}}}{\nu}$$

$$\Phi = \frac{\left(\frac{\dot{m}_{\text{fuel}}}{\dot{m}_{\text{air_princ}}} \right)}{\left(\frac{\dot{m}_{\text{fuel}}}{\dot{m}_{\text{air_princ}}} \right)_{\text{st}}}$$

$$\Phi_{\text{tot}} = \frac{\left(\frac{\dot{m}_{\text{fuel}}}{\dot{m}_{\text{air_princ}} + \dot{m}_{\text{air_in}}} \right)}{\left(\frac{\dot{m}_{\text{fuel}}}{\dot{m}_{\text{air_princ}}} \right)_{\text{st}}}$$

where U is the flow velocity at the exit burner, $D_{\text{equ.}} = \sqrt{D^2 - d^2}$ is the equivalent diameter of the burner, ν is the kinematic viscosity, \dot{m}_{fuel} is the fuel mass flow rate, $\dot{m}_{\text{air_princ}}$ is the mass flow rate of the main stream, $\dot{m}_{\text{air_in}}$ is the mass flow rate of the control air flow. Operating conditions analyzed in this work are summarized in Tab.2.

	Stable jets off	Stable jets on	Unstable jets off	Unstable jets on
\dot{m}_{air_princ}	$2.61 \cdot 10^{-3}$ kg/s	$2.61 \cdot 10^{-3}$ kg/s	$2.15 \cdot 10^{-3}$ kg/s	$2.04 \cdot 10^{-3}$ kg/s
\dot{m}_{fuel}	$9.55 \cdot 10^{-5}$ kg/s	$9.55 \cdot 10^{-5}$ kg/s	$9.55 \cdot 10^{-5}$ kg/s	$9.55 \cdot 10^{-5}$ kg/s
\dot{m}_{aria_in}	/	$2.35 \cdot 10^{-4}$ kg/s	/	$2.35 \cdot 10^{-4}$ kg/s
Re	9600	9600	8025	7585
Φ	0.63	0.63	0.75	0.79
Φ_{tot}	0.63	0.58	0.75	0.72

Tab. 2: Investigate conditions.

Control Software

The interface between the thermo-fluid dynamic field and the control algorithm was implemented in LabVIEW platform and a Virtual Instrument (VI) was developed to interface LabVIEW to real-time Active Combustion Control. The brightness signals are analyzed by using this VI.

The ODC system [1] consists of a photodiode, a computer that performs data analysis, a DAQ and a charge amplifier. The sampled brightness spectrum contains information related to chemistry and turbulence:

- chemical kinetics, because radiant energy is sampled at very high frequency, i.e., 500 kHz (order of MHz can be easily reached and at low cost);
- turbulence dynamics, because radiant energy is detected in a wide range of wave lengths, from 300 to 1100 nm; therefore, the radiant term in the energy equation is sampled and it roughly balances time derivative, convective and diffusive terms, and describes the turbulent dynamics of a passive scalar.

Control Hardware

The control hardware modulates the flow rate of the control ring surrounding the burner exit section. It consists of an array of 5 branches. In each branch there is an electrovalve on/off and a tap (Fig.3). The taps consent to calibrate the flow rate in the respective branches.



Fig. 3: Valve array for the air jets modulation.

Experimental Results

Characterization of flow field

An exhaustive characterisation of the burner and the effects of the control air jets was performed before proceeding to the diagnostic and control experiments.

The control air jets reduce the scale of vortical structures (Fig.4b) and increase the mixing of the small scales.

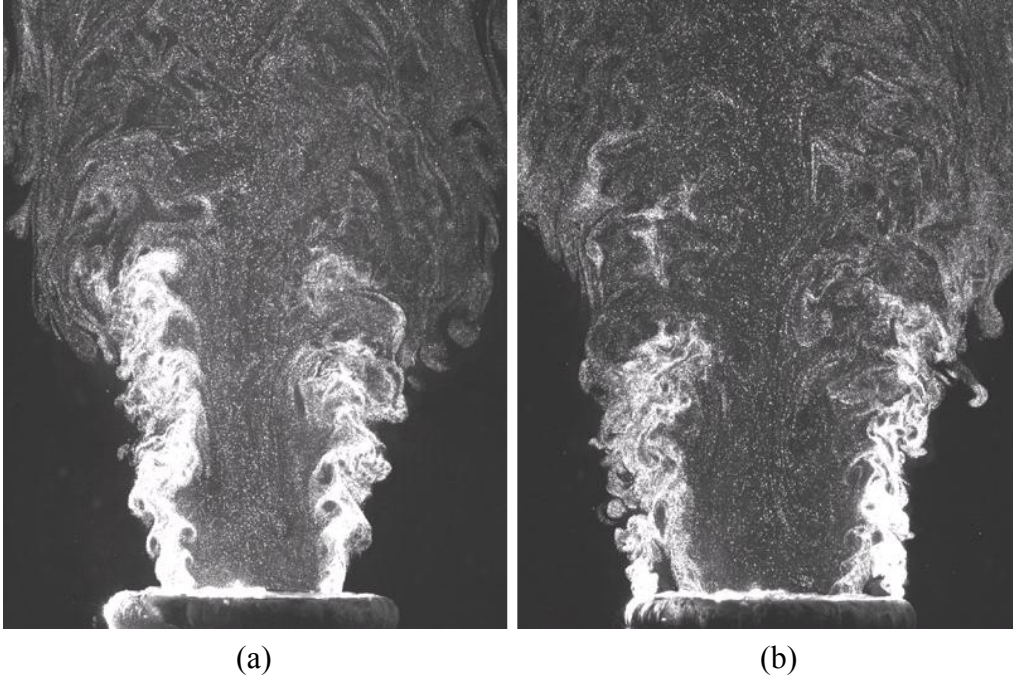


Fig. 4: Mie-Scattering images for Stable without (a) and with air jets (b) conditions.

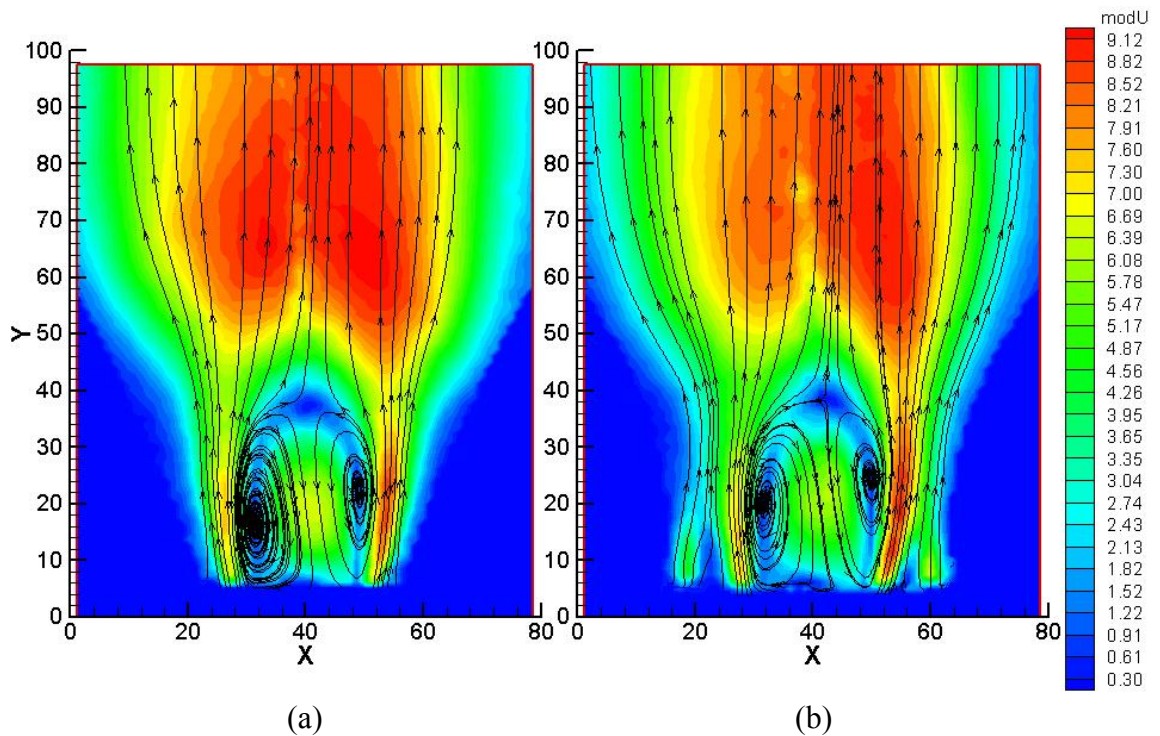


Fig. 5: Mean velocity fields for Stable without (a) and with air jets (b) conditions, averaging 200 samples of PIV images.

Comparing the averaged velocity fields with and without control (Fig.5) we note that the surrounding control air jets induce flame stretch. The mixing of the control fresh air with the hot gases outside the recirculation zone (Fig.4b), leads the mean temperature to decrease (Fig.6). We analyze the temperature fields by means of thermocouples.

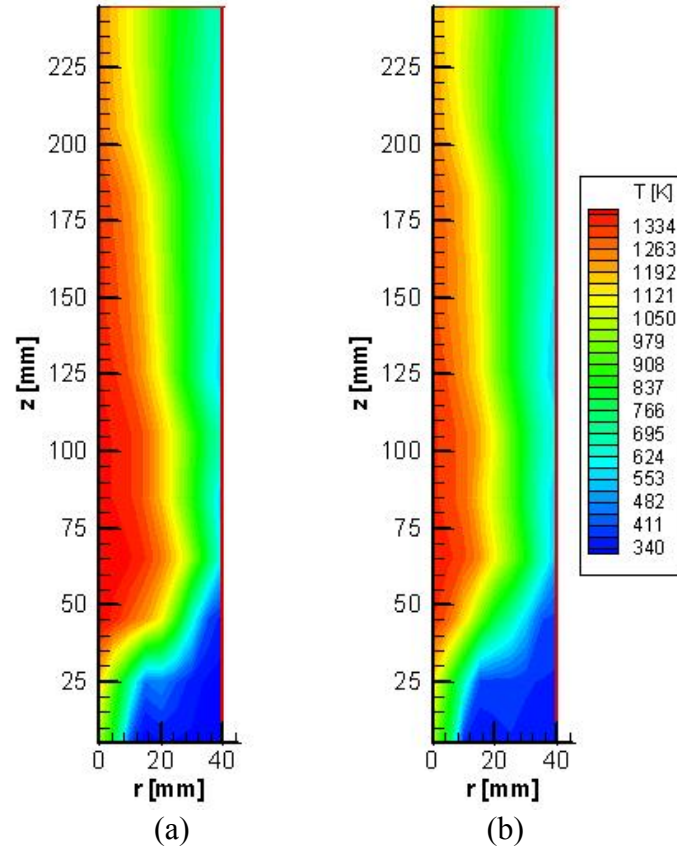


Fig. 6: Mean temperature fields for Stable without (a) and with air jets (b) conditions.

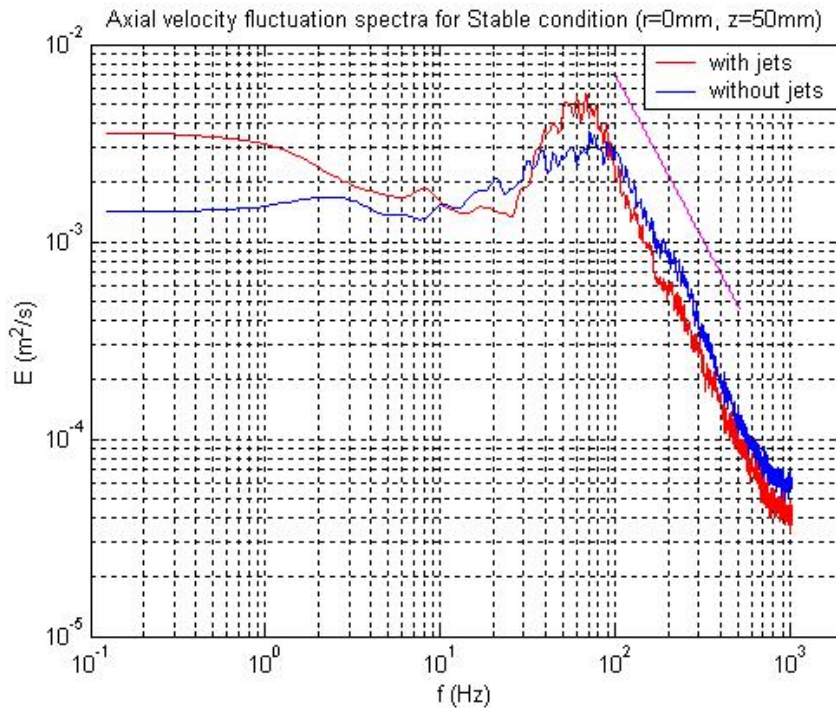


Fig. 7: Fourier spectra of the axial velocity fluctuations obtained by means of LDA technique for the Stable cases (50 mm downstream of the bluff-body along the burner axis).

The spectral analysis of velocity signal (Fig.7) sampled by means of LDA (at 50 mm downstream of the injection along the burner axis), reveals a ~ 80 Hz dominant frequency for the reference stable case without jets. This peak is shifted at ~ 70 Hz in the stable case with jets. The inertial or Kolmogorov range (in this case it is in the range 100-500 Hz) have the typical slope of $-5/3$.

Diagnostic on-line of combustion

The spectrum of the chemiluminescence signal obtained by means of ODC is upper when jets are applied in the unstable condition and lower when the flow rate of the principal air is increasing. Surrounding air jets stabilize the flame, lowering the spectrum. The spectrum is lower when jets are applied to the stable condition.

Brightness spectra show that in the unstable case (the red condition in Fig.8, that is close to blow-off) the flame experiences large pulsations, resulting in the increase of amplitude spectrum at lower frequencies; furthermore, fast localized extinctions and reignitions increase the amplitude of high frequency components.

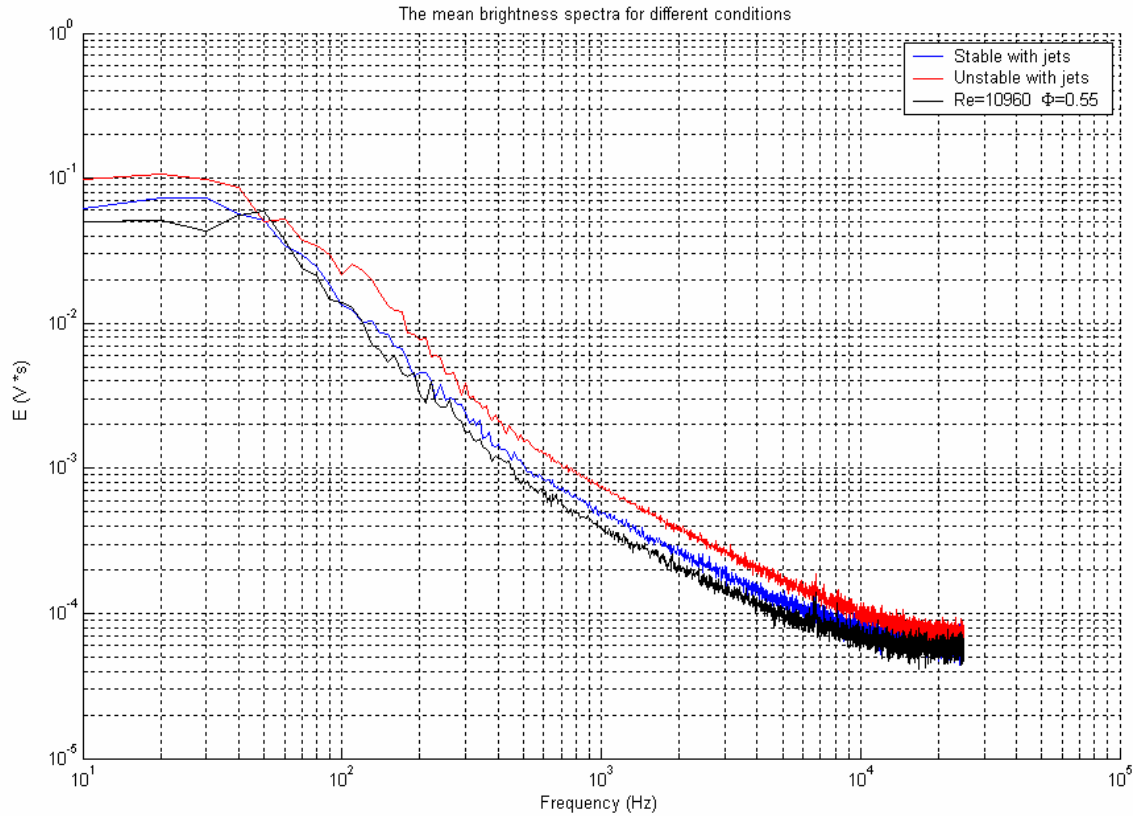


Fig. 8: Mean Fourier spectra of the chemiluminescence signals obtained by means of ODC for three different combustion conditions.

It is very interesting to compare the spectrum of chemiluminescence signal with the spectrum of axial velocity fluctuations (Fig.9). Both the LDA and the ODC spectra show characteristics of turbulence, i.e., the range of large eddies, the inertial or Kolmogorov range and the dissipative one (in this case the Kolmogorov scale is ~ 500 Hz); moreover, ODC can capture frequencies much higher than LDA, thus revealing effects of chemical kinetics. The brightness of the flame has the function of a nonintrusive and natural seed, whose dynamics is the dynamics of a turbulent passive scalar.

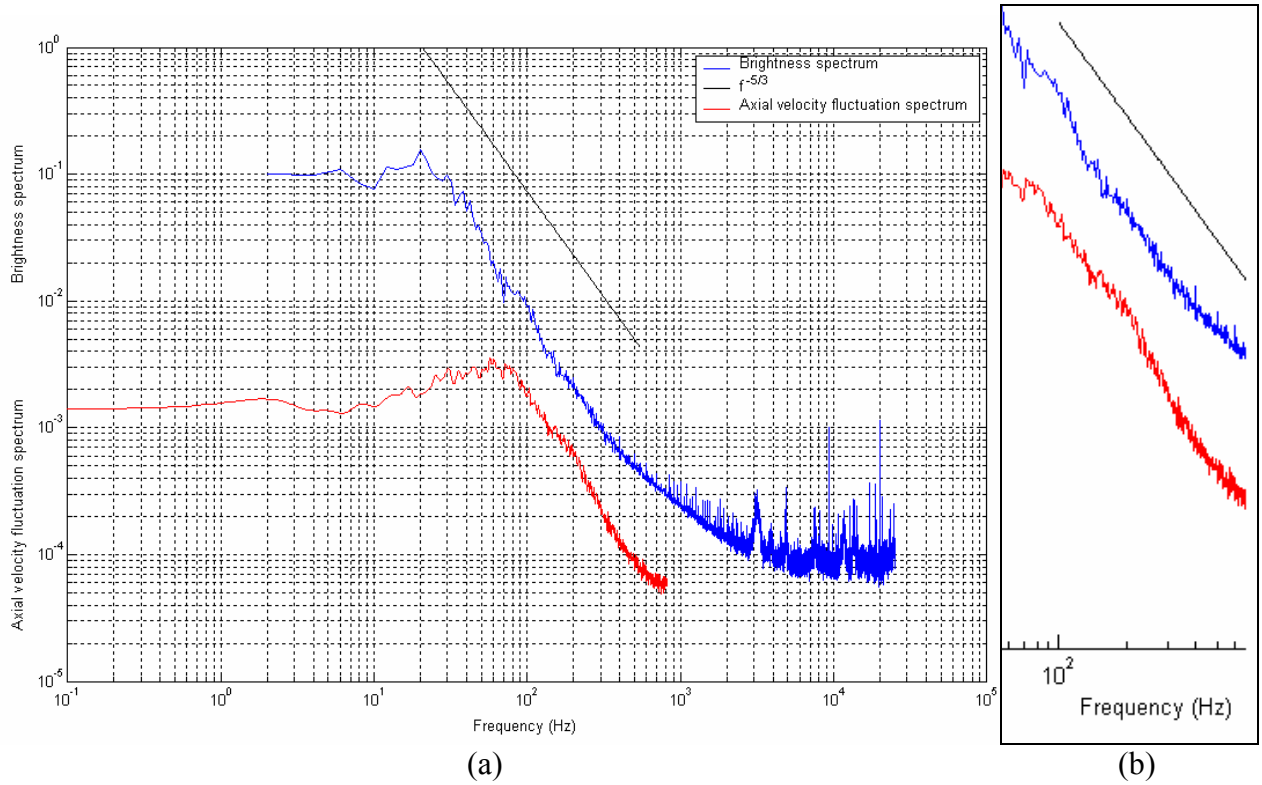


Fig. 9: Comparison (a) between the Fourier spectrum of the chemiluminescence signals (ODC technique) and Fourier spectrum of axial velocity fluctuations (LDA technique). In (b) there is a zoom of the inertial sub-range.

Active Control of combustion instabilities

The control variable is the change of the integral of the radiant energy spectrum in the fluid dynamic range 1-100 Hz; this change is calculated with respect to a reference mean radiant energy spectrum obtained by means of about 100 samples. This variable is multiplied by the control gain and then it becomes the control input. The gain is not linear but it is a sigmoidal function governed by three actuation thresholds.

In according to the instability level the ODC piloted the valve array and then the flow rate of the control ring.

In this work we modulate 32 different flow rates imposing a binary logic for the calibration of taps (Fig.3); in fact we can obtain 2^N levels of regulation, where N is the electrovalve's number. It permits a nearly continue regulation. With this solution the activation frequency of a single electrovalve is very low, about 1-2 Hz, although the activation frequency of the array is 10-40 Hz.

Figure 10 shows the effect of the Active Control in the raw-counts of the radiant energy acquired by ODC. We performed two identical experiences: without (Fig.10a) and with control (Fig.10b). The combustion process was operated first in a thirty seconds stable condition, then in a thirty seconds unstable condition and again in a thirty seconds stable condition.

The figure shows the increasing of the combustion oscillations in the unstable regime (Fig.10a). The active control system leads the combustion process to a new different regime characterized by the same spectral energy distribution and lower brightness. The active control piloting the combustion oscillations reduce them (Fig.10b). The peaks in the unstable regime (in the red zone of Fig.10b) are due to the smaller control flow rates of valves chasing the intrinsic fluctuations of the flame.

The control strategy developed reduces the Lean Blow Off (LBO) limit of the actual burner, thus enhancing its performance.

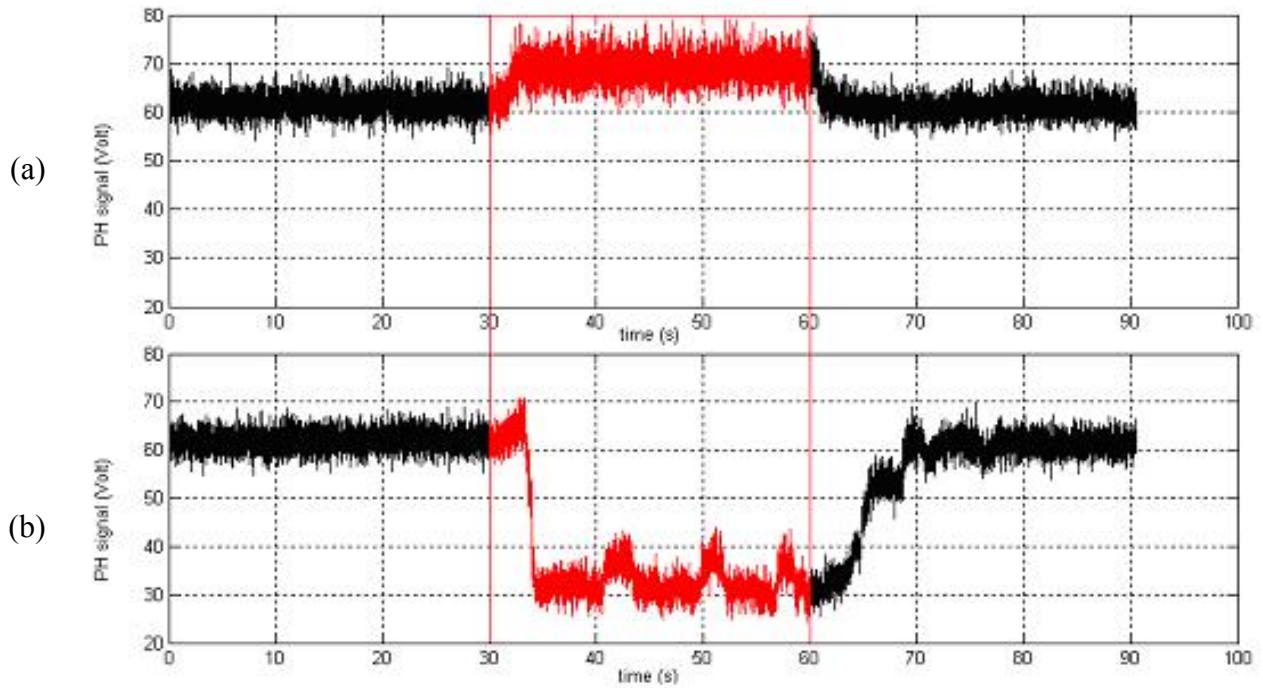


Fig. 10: Raw signals of the radiant energy obtained by the photodiode without (a) and with (b) control.

Conclusions

A control strategy, firstly developed and optimized by means of Large Eddy Simulation, has been implemented for the active control of a premixed methane/air flame in an industrial burner model. The governing parameters (e.g., equivalence ratio and Reynolds number) have been varied to reach operating conditions close to blow-off. This critical situation is automatically identified analyzing (in real time) the optical signal sampled by a photodiode sensor (ODC system). The flame is then stabilized again by activating coaxial air jets piloted by ODC. When the system is in the stable condition again, the jets are turned off.

Measurements have demonstrated that ODC provides the same frequency information obtained by means of LDA, and showed that the analysis of flame brightness can be used in diagnostics of combustion instabilities. The ODC system uses radiant energy as a nonintrusive and natural seed, thus capturing the dynamics of a turbulent passive scalar, i.e., the classical large scale, inertial and dissipative ranges of turbulence; moreover, due to the high sampling frequency, also chemical kinetics range, is captured. This last point is critical to detect combustion instabilities associated to fast localized extinctions and reignitions. All these information are provided at very low cost and in real time by using ODC, important features for the development of an Active Control strategy.

This work puts in evidence that it is possible to implement this Active Control of the combustion in industrial systems. Tests demonstrate its efficiency to identify the unstable changing modes in real combustion systems.

Further efforts are necessary. The most interesting research direction appears to be the development of an adaptive control algorithm. This will be the next step of our work.

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