Aerospace Science and Technology 49 (2016) 41–51

Contents lists available at ScienceDirect

Aerospace Science and Technology

www.elsevier.com/locate/aescte

# Image processing for the characterization of flame stability in a non-premixed liquid fuel burner near lean blowout ☆

Maria Grazia De Giorgi *,[1], Aldebara Sciolti [2], Stefano Campilongo [2], Antonio Ficarella [3]

*University of Salento, Dept. Engineering for Innovation, via Monteroni – 73100 Lecce, Italy*

A R T I C L E I N F O

*Article history:*
Received 30 June 2015
Received in revised form 26 October 2015
Accepted 22 November 2015
Available online 30 November 2015

A B S T R A C T

In the present work, an experimental investigation was performed by varying the fuel/air ratio of a liquid-fuel gas turbine derived burner in the non-premixed mode, until an ultra-lean combustion condition was reached. In this condition, flame instabilities occur with negative impacts on combustion efficiency. Two high speed visualization systems in the visible range and in the infrared spectral region were used. Moreover, they were supported by an OH* chemiluminescence measurement and by gas exhaust measurements. Different techniques were used starting from the luminosity signal of each pixel: the Wavelet Decomposition to calculate the wavelet energy, the frequency analysis of pixel intensities of the flame images to estimate the dominant frequency, finally the statistical analysis to calculate the pixel intensity variance. Both the statistical and frequency analyses were applied to the OH* chemiluminescence data. One of the most important results of the present work regarded the capability of imaging techniques to individuate the instability insurgence and to be used as a predictive tool. Furthermore 2D maps of some parameters, extracted by the wavelet-based analysis of flame images, permitted to investigate local unsteadiness in the flame area.



## 1. Introduction

One of the most important driving factors for the scientific and technical development of modern aeronautical burners is the environmental pollution limitation. In particular, the Nitrogen Oxides ($NO_x$) reduction is a substantial challenge of the actual combustion research. $NO_x$ reduction can be obtained by controlling the air/fuel ratio until lean and ultra-lean conditions are attained, achieving lower temperature combustion [1]. Unfortunately, “lean” combustors are subject to transient flame holding problems, such as flame instability. The reduction of the flame’s equivalence ratio leads to extinction events and the lean limit for stable operation (i.e., Lean Blowout LBO) may be reached [2–4]. Hence the flame stability and in particular lean blowout is a serious problem for aircraft engine operability, for example, during power reductions involved in approach and landing. To avoid the negative effects of the combustion instabilities [5], the recognition of the instability occurrence will play an important role, preferably using automatized methods for the individuation of the flame regime of stability/instability, especially for the real-time control techniques. The proximity to LBO could be determined on the basis of empirical quantities related to low-frequency combustion oscillations [6].

Most commonly used methods for instability sensing involve acoustic detection using a microphone or pressure sensor, and optical emission measurement from OH*, CH*, or $CO_2^*$ [7,8].

However, microphone sensors for pressure fluctuations are sensitive to background noise (from vibration or flow) and require careful calibration before operation. Furthermore, traditionally the instability occurrence is individuated through the frequency analysis of the pressure measurements in the combustion chamber to highlight the frequency peaks [6]. This method is able to individuate when instability occurs but not to preview it or to permit to activate the control system to prevent it.

Several approaches based on optical signals (through narrow- and broadband, single sensors and CCDs) have been also applied to relate optical emissions with meaningful combustion parameters, including stability [9].

☆ *Referred to by* Maria Grazia De Giorgi; Aldebara Sciolti; Stefano Campilongo; Antonio Ficarella “Experimental Data Regarding the Characterization of the Flame behavior near Lean Blowout in a Non-Premixed Liquid Fuel Burner” Data in Brief, http://dx.doi.org/10.1016/j.dib.2015.11.051.

* Corresponding author.
*E-mail addresses:* mariagrazia.degiorgi@unisalento.it (M.G. De Giorgi), aldebara.sciolti@unisalento.it (A. Sciolti), stefano.campilongo@unisalento.it (S. Campilongo), antonio.ficarella@unisalento.it (A. Ficarella).
[1] Tel.: +39 0832 297759.
[2] Tel.: +39 0832 297783.
[3] Tel.: +39 0832 1835172.

http://dx.doi.org/10.1016/j.ast.2015.11.030
1270-9638/

**Abreviations**

| | | | | | |
|---|---|---|---|---|---|
| $E_i$ | $i$th detail component wavelet energy | – | $\dot{m}_{air}$ | air flow rate | g/s |
| $\Phi$ | equivalent fuel/air ratio | – | $\dot{m}_{fuel}$ | fuel flow rate | g/s |
| $f_a$ | frequency level for PSD evaluation | Hz | $L$ | number of acquired images for each condition | – |
| $f_{DOM}$ | dominant frequency | Hz | $N, M$ | pixels matrix dimensions | – |
| $f_s$ | sampling frequency | Hz | PMT | photomultiplier system | |
| $I(x, y, t)$ | temporal series of the pixel intensity | – | PSD | power spectral density | – |

Yi et al. [10] used OH* chemiluminescence by single sensor to detect the lean blowout in partial premixed, liquid fueled, multi-swirl stabilized gas turbine combustor. Two statistical quantities, such as the normalized root mean square and the cumulative duration of LBO precursor events, were extracted for lean blowout prediction.

High speed visualization systems, involving CCDs in the Visible (VIS), Infrared (IR) or Ultra-violet (UV) spectral ranges, are particularly suitable to determine flame shape, brightness, oscillation frequency, which are related to combustion efficiency and flame stability. The relationships between flame features that are extracted through the processing of digital images and combustion performance parameters represent a "signature" of the flame behavior, hence they might be used for monitoring and control purposes [8].

In the literature UV high-speed imaging of OH* of a methane/air swirl flame was already implemented in active control system to increase the safe operation of combustors near the lean blowout limit [11].

OH* chemiluminescence imaging was also applied by Zhu et al. [12] to investigate the differences in the mechanisms of LBO in pure methane and hydrogen-enriched premixed flames.

A LBO prediction strategy based on CH* chemiluminescence UV acquisitions and flame color CCD images, was developed by Chaudhari et al. [13] to characterize the flame behavior of a premixed swirl stabilized dump plane combustor.

High speed acquisitions in the infrared spectral range have been also performed to investigate thermoacoustic flame instabilities [14,15].

However acquisitions in the visible spectral range might be easier and cheaper than acquisitions in the UV or IR spectral range. Huang et al. [16] used VIS imaging to investigate the effect of the equivalence ratio on the flicker of a premixed flame by using the RGB and HSV color models and to calculate the characteristic flame frequencies [17].

Combustion diagnostics require proper processing of the acquired signals to correlate the extracted parameters with the physical quantities that characterize the flame behavior.

Flame instability is characterized by unsteady fluctuations; it means that spectral, statistical and wavelet-based methods are very promising for the analysis of combustion phenomena approaching to LBO [18,19], because they are particularly suitable to reveal unsteady flow structures and to recognize flow pattern [20–22].

In the past Cabot et al. [23] used the power spectral density (PSD) distributions of pressure signals and of CH* emissions for the characterization of the combustion behavior.

A weakness of Fourier domain and PSD based methods is that flame pulsations and flicker before the flame blowout might be not purely sinusoidal but random. Therefore, the detection of peaks in FFT plots might be very difficult [24,25]. Moreover due to the global character of the Fourier spectrum, the non-stationary nature of the signal, due to the flame unsteadiness near lean blowout, might suppress some properties of the power spectrum density. Furthermore a long acquisition time is required if a high resolution estimation of the power spectra is desired while the wavelet transform is not affect by this limit and the wavelet spectrum can be evaluated even for a limited length samples. The wavelet transform is a time-scale signal decomposition that produces a vector of key parameters, representative of the PSD, that are the energy distribution values over the defined frequency ranges.

Finally the wavelet analysis is based on a faster algorithm for computing the coefficients of the discrete wavelet transform with respect of the traditional Fast Fourier transform, and requires a smaller sample size [26,27].

In the work of Nair et al. [6] spectral, statistical, wavelet-based, and threshold-based techniques were applied to the acoustic data to detect blowout precursors. Wavelets were found to be particular suitable for the flame where time-localized events in the signal with low impact on the average spectra were more pronounced, as in swirl and bluff-body burners. In contrast, Fourier analysis was sufficient for the piloted burner where the overall average characteristics of the signal change.

In [28] wavelet domain signal processing methods were used for feature extraction from the signals acquired through a Pyroelectric Infrared (PIR) sensor based flicker flame detection system.

In this context the present work aims to investigate the lean blowout and the flame stability in a liquid-fueled swirling combustor in non-premixed operating mode. A methodology was developed for the analysis of flame images based on two-dimensional distributions and zonal analysis of significant flame features, extracted by statistical and spectral methods.

Wavelet based techniques were implemented to fast visible and infrared imaging (respectively taken at 10 kHz and 1 kHz, 8 bits) in order to characterize the flame fluctuations at different fuel/air ratios using the luminosity matrix associated to every image. From these data, statistical, frequency and functional information from both the single-pixel time-dependent signal analysis and the mean intensity value of every image were obtained. Wavelet energy and variance of the luminosity were evaluated and correlated with the combustion regime. Moreover, the OH* chemiluminescence emissions, recorded using the PMT, were also analyzed with the same statistical and frequency wavelet-based approaches used for the images. Exhaust gas analysis has been carried out using a complete analyzer system equipped with gas sampling, sample conditioning, analyzer and system control units.

The objectives of this paper are: (i) to visualize the alteration of the flame shape approaching the blowout conditions and (ii) to examine the blowout transient behavior by high-speed diagnostics.

## 2. The experimental apparatus

The experiments were carried out using the combustion test rig at the Green Engine laboratory of the University of Salento in Lecce – Italy, where a 300 kW liquid-fueled swirling combustor was used (Fig. 1a). The burner is a gas-turbine derived combustor, modified for research's investigations [29–31]. Fig. 1b shows the geometry of the burner chamber and fueling system. The inner diameter of the burner is 14 cm and its length is 29 cm. The air passage consists of two concentric annular air tubes. The inner one is equipped