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DETECTING ENVIRONMENTAL FEATURES IN AN EXPERIMENTAL COMBUSTION CHAMBER OF GAS TURBINE: ADVANCED IMAGING PROCESS AND ACCURACY

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Abstract: The quality of combustion process has an impact on combustion itself and mainly on emissions. This1 latter is one of the major concerns in an environmental viewpoint; for instance, the amount of oxygen is an indicator of bad and good combustion. It is also a constraint for regulating pollutant production, in particular dust that is also a vector transporting harmful micropollutants. The paper illustrates combustion quality detection by means of imaging. The work aims at retrieving possible precursors of combustion deterioration, and instability and allowing decision makers to provide accordingly. Images have been taken from an experimental setup.

Keywords: Environmental measurements, gas turbine, pollution detection, combustion chamber, myriad smoothing.

1. INTRODUCTION

In the last years digital imaging and image processing techniques vision based monitoring and characterization of combustion flames are of great interest.

Imaging devices based on digital charge coupled device (CCD) array constitute an array of photo-sensors that might be suitable to be applied in combustion monitoring, control, and burner's engineering project.

The good correlation between the combustion process and the light absorption-emission phenomenon permits to use optical techniques provided by chemiluminescence optical sensors (phototubes and cameras) as real time and non-invasive measurements [1,2,3]. Changes in the burning conditions have an instantaneous effect on emissions and thus in the light that reaches the sensor.

These techniques enables the observation of the spontaneous emission of electromagnetic radiation by some radicals, which are generated during the combustion. Since the decaying time of these radicals from the excited status to the basic one is much shorter than the characteristic time of the diffusive or convective motions present in the flame, chemiluminescence sensors might be used to investigate the flame dynamic. Chemiluminescence of excited radicals such as OH* and CH*, can be acquired as signatures of the burning conditions , of the heat volumetric release and of the spatial flame distribution [4, 5, 6]. In fact the hydrocarbon flame color, captured by photo-sensors, is related to the relative densities of these emitters.

In previous works [7,8,9] it was found a good correlation between the flame features extracted by the images acquired by high speed camera and the flame behavior in proximity of lean operating conditions.

For high temperature combustion that is carried out in dedicated chambers or kilns, direct sensing has some limitations due mostly to devices and instrumentation thermal drift. That is why accurate imaging through appropriate glass window can help to determine the quality of flame within the given chamber. This issue comprises two aspects; the first one is related to the quality hardware and the second deals with imaging and its processing. The second aspect offers a plenty of software solutions that exploit: image deblurring, image segmentation, advanced image filtering…Some transformation are also viable as Hough transform, for example.

In the present work high speed CCD camera has been used as photo-sensors. An image processing methodology has been implemented to diagnose the spatial distribution of burning conditions along the flame front, applied to the lean flame of a liquid-fuelled swirling gas-turbine derived combustor.

2. EXPERIMENTAL SETUP DESCRIPTION

Experiments were performed in the 300 kW liquid-fuelled swirling gas-turbine derived combustor [7,8,9], shown in Fig. 1. The combustion chamber has an internal diameter of 0.14 m and a length of 0.29 m. Preheated air enters from one site of the burner head and then splits in two ways: a coaxial one (primary air) and a swirled one (secondary air, eight-septa 45° swirler). The fuel is injected directly into the chamber using a central injector (one hole, 0.5 mm diameter). The air has been preheated up to 500 k and the pressure in the chamber (without combustion) was 1 bara. The fuel and air mass flow rates were set in order to investigate ultra lean conditions.

The total air flow rate was fixed at about $85*10^{-3}$ kg/s with a ratio of 1:11 between primary and secondary air flow respectively while the fuel flow rate was 1.54 g/s.

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Fig. 1. The Green Engine burner.

The cooled optical accesses of the combustor, three circumferential and one frontal optical windows, permit to use imaging technique for the flame characterization acquiring the visible and the UV chemiluminescence emissions.

CH* chemiluminescence emissions images were acquired from the frontal windows of the burner by using the Phantom Miro M320S® High-Speed Digital Camera [10] equipped with an intensifier by Lambert Instrumentation® [11] and two interference filters with central wavelength of 307 nm and 431 nm respectively, with a full width at half maximum (FWHM) of 10 nm. The intensifier gain was set to 250 for the CH* emissions. The sensitivity and the quantum efficiency (QE) of the Intensifier are respectively 74 mA/W and 21% for the CH*.

Optical lens was a ultraviolet/visible 105 mm lens, having light transmission efficiencies higher than 85% in the near-ultraviolet/visible range (250-650 nm).

The UV images were taken with a resolution of 651 pixels x 407 pixels, a frequency of 1 kHz and a flame view area of 59 mm (h) and 36.8 mm (v).

3. LINEAR SMOOTHERS FOR IMAGING

The use of imaging is a useful approach for the purpose of this paper because in combustion chambers, especially for gas turbine instability regime, and in presence of undesired values of oxygen, affects the yield and may be not help to avoid pollution increasing . This regime cannot be studied using Gaussian models because of impulsive processes due to the superposition of small independent effects. That is why stable distributions are welcome thanks to their accuracy to have the theoretical underpinnings in modelling. Linear smoothers can address this goal and among them we encounter a special approach called Weighted Myriad filters [12] justified by the need of a flexible filter category having an increased efficiency in impulsive environments. The majority of linear smoothers obey to cost functions belonging to the following class

$$\rho(x) = \log[K^2 + x^2] \qquad (1)$$

where K is a variable parameter with a certain range of variation . Myriad filter has a large applications thanks to the variation of K that gives to it, under certain constraints, capability to operate also in Gaussian modelling. Myriad filter uses the well know Cauchy distribution.

If we have an observation vector $X(n) = [X_1(n), X_2(n), ..., X_N(n)]$ and a fixed positive (tunable) value of K, the running myriad smoother output a time n is calculated as

$$\begin{aligned} Y_K(n) &= MYRIAD[K; X_1(n), X_2(n), ..., X_N(n)] \\ &= \arg_\beta \min \prod_{i=1}^{N} [K^2 + (X_i(n) - \beta)^2] \end{aligned} \qquad (2)$$

The myriad $Y_k(n)$ is the value of β that minimizes the cost function recalled in Eq.(1) includes the free-tunable parameter K called also as linearity parameter. The Eq.(2) can be expressed in another manner, considering the fact the log function is monotonic, that is, the myriad can be also defined as

$$Y_K(n) = \arg_\beta \min \sum_{i=1}^{N} \log[K^2 + (X_i(n) - \beta)^2] \qquad (3)$$

Eq.(2) and Eq.(3), that are cost functions, have minima that lead to a unique value for a determined value of K. However there are cases the myriad is not unique for. That is not of critical significance.

If one decides to implement an algorithm based on myriad filter, he should try to tune the value of K but he encounters a decision to assess if a given K is large (or small) enough for the linear property to hold approximately. At this effect, it is wise to consider the myriad as the maximum likelihood location estimator generated by Cauchy distribution with dispersion K.

4. RESULTS PRESENTATION

Treating with instability during the combustion process, we consider the flame and smoke as a dynamic process with instability. Now we present some preliminary results within the scope of the project which final goal is to establish a relationship between thermodynamic states and chemical/physical components. Given the four image samples below, the myriad filter locates the generating distribution in a position where the probability of the sample set to occur is maximum. Since we have two categories of images from the combustion chamber: visible and chemiluminescence capturing. Both categories, even related to the same gas turbine chamber, obey to different image displaying, hence the value of K changes accordingly because of the wavelength. The preliminary results are only related to chemiluminescence that is an alternative way of capturing environment and that is compatible to the smoother process used in the present paper. Fig.2 and Fig.3 as original ones are connected to different instants of combustion. The algorithm of previous section is applied to both original images. After the algorithm application, clear

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features are now reverted to the readers, depicting flame displacement within the chamber cockpit. In both processed images we see a centred space with high density due to stable high temperature and a peripheral/surrounding 2D flame displacement with homogeneous consistency. The myriad smoothers with specific *K* values allow to see this consistency in a "2D " since we are able to see the deepness of the evolution [13].

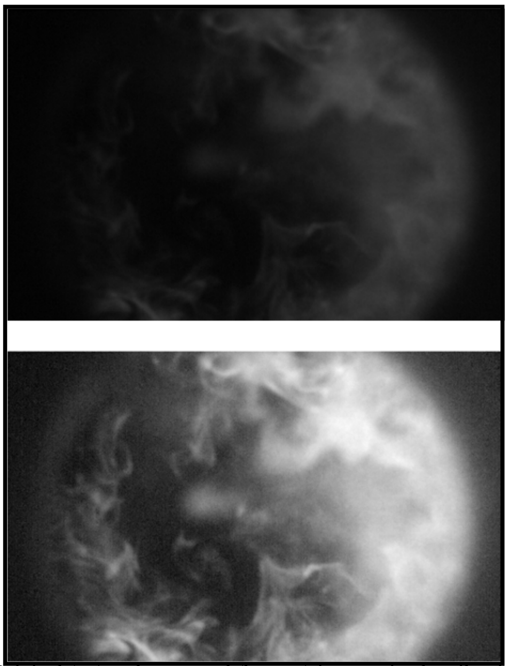

Fig. 2. Original (up) and processed (bottom) images in chemiluminescence capture

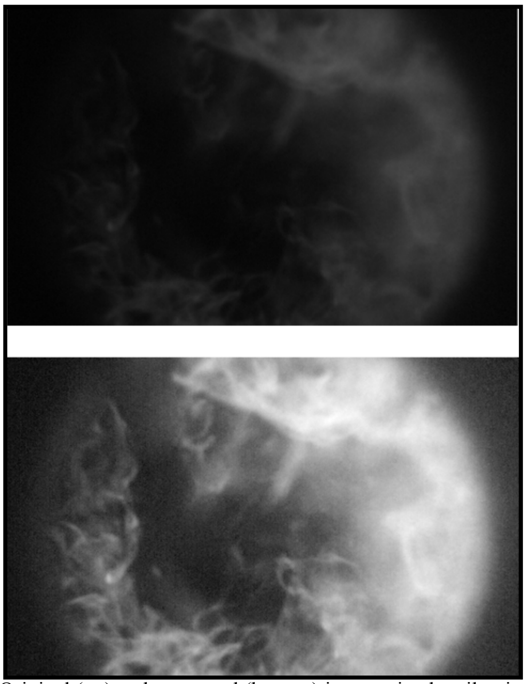

Fig. 3. Original (up) and processed (bottom) images in chemiluminescence capture

The deepness aspect permits to retrieve the inner part of the chamber where we have a high density as an area of stability.

This is an important issue in fixed combustion chamber or kiln. To control the features of the chamber, fluid injectors are located on the chamber at specific planar and angular distances in order to choose the instant for providing fluid injection; that is different from rotating combustion chamber in which the material to be burned is moved from the low temperature area to the high one.

Of course, a rotating combustion chamber is better than a fixed one. For the aforementioned images there is no need to use ROC (receiver-operating characteristic curve) expressing sensitivity versus specificity but in general it is. ROC [14] can be used as an analytical expression of the difference between quality before and after processing. The idea illustrated in this paper renders the fixed chamber viable and fluid dynamic characteristics interesting to understand in a clear way.

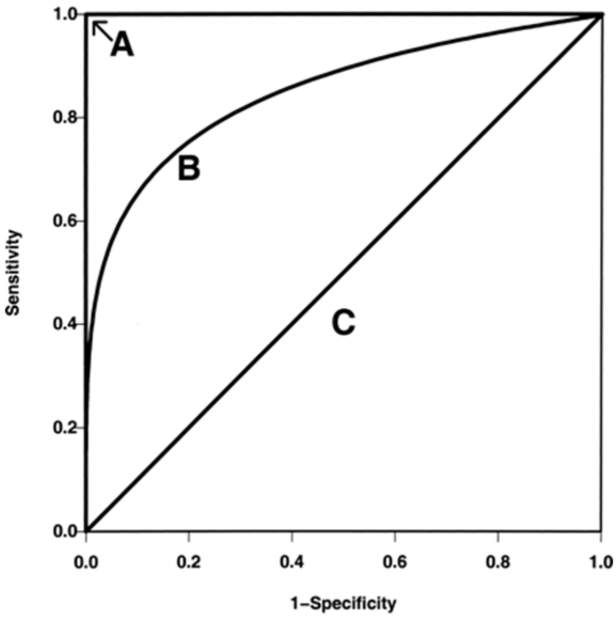

Fig. 4. An example of ROC curves used for the paper

As depicted in Fig.4, the gold standard is lines A on the upper and left axes, a typical curve is B, and a diagonal line indicating the random chance is C. For our cases the original images have curve on the left but near C while the smoothed images have curve on the left of the previous one, for example B. So ROC curves must lie between two extremes, C and A. The area under the ROC curve is a summary measure that averages diagnostic accuracy across the spectrum of test values.

5. FINAL COMMENTS

The paper illustrates preliminary results of applying imaging to understand combustion chamber performance and emissions. The detecting system is illustrated in section 2. Images undergo a preliminary background substraction to eliminate noises but most of processing is carried out by the algorithm illustrated in section 3. In the center of processed image we can see an area of "high density", that is defined with compactness or expanded crevice. This surface is provoked by most of the air-fuel mixture moving toward the bottom of the chamber by tumbling flow motion because the center velocity of the cylinder is high. Wrinkled flame fronts are very clear in the smoothed images since they imply turbulent flame. We have no direct and clear vision of OH radical when excited but that will be the topic of next improvement [15,16] using other technique for treating this kind of capturing. The further algorithm [17] could be useful for retrieving diverse species present in combustion chamber. This latter is chiefly used in some conditions to purify (" to wash") soot and emissions from industrial plants. Its main function is to oxide carbonaceous and organic and pollutant substances, transforming them in carbon dioxide aqueous vapour and nitrogen. The imaging [18] we study in this research must also be able to detect, by means of new algorithms the quality and the trend of the above species [19].

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