Fractal aspects in O_2 enriched combustion

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HIGHLIGHTS

- We studied combustion process stability.
- We used Detrended Fluctuation Analysis (DFA).
- We discuss the combustion efficiency.
- We observe an auto-affinity in the time series.

ARTICLE INFO

ABSTRACT

In this study, we investigate the self-affinity of time series of thermal radiation from two fuels, natural gas (NG) and acetylene (AC), enriched with oxygen at 21%, 23% and 25% concentrations during the combustion process. We used the detrended fluctuation analysis method to evaluate the burning process of these fuels. We found a well-defined self-affine aspect for these gases in this dynamic process. Using the proposed method, we were able to characterize the time series of NG as a sub-diffusive process and the time series of AC as a process with persistent self-affinity.

The study of the technology of flame enrichment with oxygen, together with the study of soot formation coupled with thermal radiation, has attracted interest in industries that involve combustion processes where a large amount of energy is released as heat and, consequently, light. The main objective of combustion is maximize the heat while minimizing the production of polluting gases. It is necessary that this production be economical to maximize the combustion yield to obtain an energy potential with minimum dissipation. For this purpose, the air–fuel ratio must be optimized to obtain a perfect mixture. The air–fuel ratio has a fundamental influence on the combustions main state variables [1]. The more harmonic the union of these elements, the more efficient the combustion will be. The stoichiometry of the fuel composition provides a basis to calculate the required amount to be burnt in the reaction. Although there are existing studies on the mechanisms of soot formation and control, a more detailed understanding of these processes is important for technological advances in environmental impact (emission of polluting gases). Thus, we studied the radiation produced during the combustion of two fuels, acetylene (AC) [2] and natural gas (NG) [3]. The experiment was performed at different enriched oxygen concentrations in a combustion chamber equipped with gas analyzers and soot and thermal radiation detectors.

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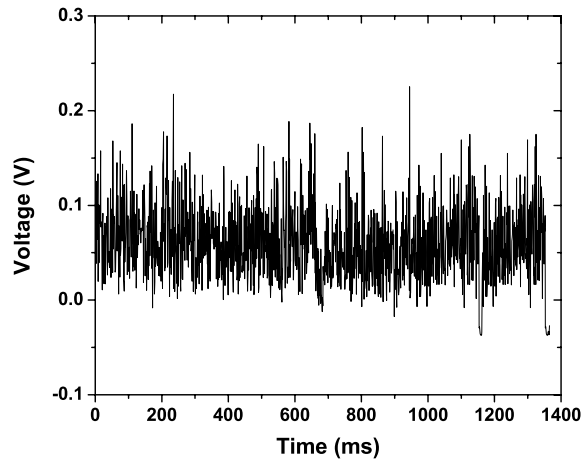E-mail address: mamoret@gmail.com (M.A. Moret).

Fig. 1. Time series obtained from data acquisition for *AC*21% with 1.0 degree of equivalence.

The Detrended Fluctuation Analysis method (DFA) [4] is an important tool for analyzing non-steady time series [5]. DFA has been used to analyze time series in different areas of scientific knowledge. For example, it shows the change in behavior in the liquid–vapor phase transition [6], the behavior of astrophysical systems [7,8], the dynamics of arterial pressure variations [9], the behavior of a waterway transportation system [10], economic series [11], meteorological factors [12,13], proteins [14], heartbeat fluctuations [15], and sunspots [16], vegetation [17], geomagnetic signals [18], fires [19], among other applications. The main objective of this article is to investigate the self-affinity of the oxygen content in the time series of the formation of soot in confined flames, to evaluate the temporal correlation of the measurements obtained from a combustion process, and to assess the efficiency of this process. DFA will be used to diagnose the behavior of the radiation fluctuation based on the voltage variation measured in a combustion chamber. Fig. 1 shows the time series of the analysis of the dynamic behavior of the burning of *AC*21% with degree of equivalence $\varphi = 1.0$.

Fig. 1 shows that there is a fluctuation in the intensity of the absorbed radiation that is sensitive to initial conditions, such as fuel concentration, degree of equivalence, and amount of oxygen in the mixture to be burnt.

In summary, the DFA method consists of integrating the time series deviations and calculating the fluctuation for different boxes of size *n*, in other words, calculating the function $F(n)$:

$$F(n) = \sqrt{\frac{1}{N_{max}} \sum_{k=1}^{N_{max}} [y(k) - y_n(k)]^2} \tag{1}$$

where $y(k) = \sum_{i=1}^{k} [u(i) - \bar{u}]$ is the integrated deviation, and $y_n(k)$ is a polynomial fitted to $y(k)$ from which the trend is removed.

DFA allows analysis of the fluctuation in time series at different scales. The $F(n)$ function behaves as a power law of the $F(n) \approx n^{\alpha}$ type, where the exponent α is the exponent of the long-range correlation. In general, the physical interpretation of the problem must consider the behavior of the long-range correlation exponent, i.e., $\alpha < 1/2$—anti-correlated or anti-persistent signal; $\alpha = 1/2$—no correlation, white noise, does not have memory; $\alpha > 1/2$—has persistent long-range correlation; $\alpha = 1$—noise. For a higher exponent of long-range correlation values ($\alpha > 1$), the dynamics of the system is non-steady (transitory regime or transient conditions) [9] and closer to a random walk, in summary:

(a) $\alpha < 3/2$—sub-diffusive signal;
(b) $\alpha = 3/2$—diffusive signal;
(c) $\alpha > 3/2$—super-diffusive signal.

When the exponent α is equal to 0.50, it reveals that the data sequence is de-correlated, meaning that it is not possible to relate the past and future behaviors of the series because the process has no memory. An exponent lower than 0.5 indicates an anti-correlated expectation. For example, if the series has an anti-persistent behavior and there is a growing trend at a certain time, there will be a decreasing trend in the future fluctuation, and vice-versa. If the exponent is higher than 0.5, the series is called persistent, and the fluctuation behavior in the past tends to continue with time. Finally, if the exponent $\alpha > 1$, this value suggests a random walk, and the diffusion phenomenon [9] is established.

The diffusion phenomenon in time series occurs when the system shows periods tending to seasonality [9,10] or moments of sudden growth in the mean values of the observed physical magnitudes [6–10,16], such as the passenger demand increase on navigation systems during weekends and vacations [6] and the outbursts observed in x-ray binary systems [7]. As long as a diffuse process occurs, a set of observable elements and magnitudes, such as energy, linear momentum, pressure, number of molecules, or atoms, may change constantly (random character) [9].
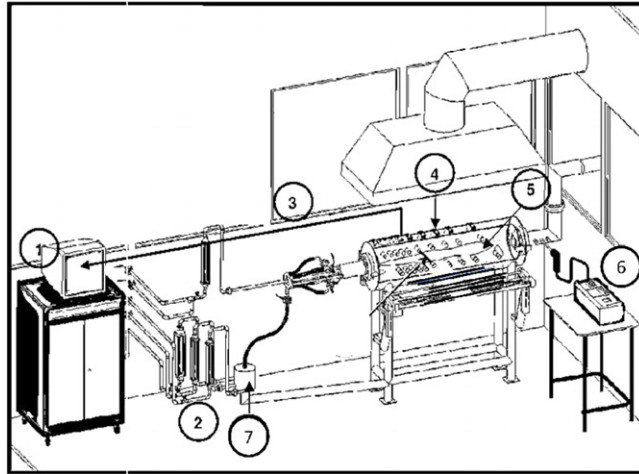
Fig. 2. Overview of the experimental device. Numbers correspond to (1) Data acquisition; (2) Rotameters; (3) Voltage signal; (4) Photo-detectors; (5) Flame; (6) Gas analyzer; (7) Air/O_2 pre-mixer.

Combustion data were obtained from an experiment performed in an apparatus consisting of a combustion chamber coupled with instruments to analyze gases and soot and to measure thermal radiation (Fig. 2) [20]. The experimental device has a burner composed of two concentric tubes where a flame is generated in the chamber. AC or NG flows in the internal tube, and pure or oxygen-enriched air flows in the external tube, as shown in Fig. 2.

The combustion air was enriched with oxygen at 23% and 25% proportions in the presence of AC and NG and tested with atmospheric air, without enrichment, with 21% oxygen concentration. This method consists of evaluating the effect of the enrichment on the flame (soot formation and oxidation).

The air/fuel or fuel/air ratio admitted in combustion at a certain functioning condition is expressed by the $\varphi = \frac{A/C_{stoichiometric}}{A/C_{actual}}$ ratio, where φ is known as the equivalence ratio, A is air, and C is the fuel. The equivalence ratio φ measures the air–fuel ratio, which defines the characteristics of the combustion as follows:

$\varphi < 1$—Mixture with excess air or poor mixture (in fuel);
$\varphi = 1$—Stoichiometric mixture;
$\varphi > 1$—Mixture with excess fuel or rich mixture.

A voltage difference was observed due to the variation of the flame radiation intensity, and the concentration of particles formed during the combustion process was measured. This radiation was quantified by the photo-detector (orifices) located outside of the chamber, as described in Fig. 2. Part of the radiation emission underwent absorption and dispersion because of the formation of soot particles generated during combustion.

In this study, we proposed to analyze the relationship between the voltage measured in the detector and the combustion efficiency measured by the formation of soot in the flame. Two different fuels, AC and NG, were used. The voltage measurements obtained in the soot formation in the combustion process were analyzed. Ten time series were recorded for each proposed initial condition. We then applied the DFA method to each oxygen concentration measurement and to each degree of equivalence.

Our analysis consisted of researching the behavior of exponent α at each degree of concentration in the combustion. The first case was NG at 21% with φ equal to 0.7, 0.9, 1.0, 1.1 and 1.3. Ten measurements were taken for each φ in orifices located along the combustion chamber. Time series were generated for each gas (NG and AC) with different values of φ and oxygen concentrations (21%, 23% and 25%).

Fig. 3 shows the behavior of AC with $\varphi = 1.1$ and 23% oxygen enrichment. It is important to note that the power law behavior was obtained independently of the initial conditions for both gases (AC and NG), which characterizes this type of system as self-affine objects.

We can verify the correlation between the (α) coefficients and explain how their fluctuations occur by evaluating the soot formation process as a function of oxygen concentration increase during burning.

In Fig. 4, we show the long-range correlation coefficients (exponent α) for the AC (4(a)) and NG (4(b)) series. We verified the influence of the oxygen concentration on the flame for both fuels by fixing the measurement in each orifice of the combustion chamber. The value of exponent α as a function of φ in the combustion is described in Fig. 4.

Fig. 4(a) shows the behavior of exponent α obtained from AC as a function of φ. Exponent α for AC 21% maintains a mean value $\alpha > 1.0$, which indicates that the dynamics is non-steady and closer to a random walk. This result indicates that AC 21% is less efficient and is similar to the fluctuation behavior of NG. Therefore, it is less stable, as there was less efficiency in soot formation, and a seasonality trend was observed (Fig. 1). However, for concentrations of 23% and 25%, the mean exponent α is $\bar{\alpha} = 0.94 \pm 0.01$, indicating that the combustion process is persistent at these concentrations. In other words, the
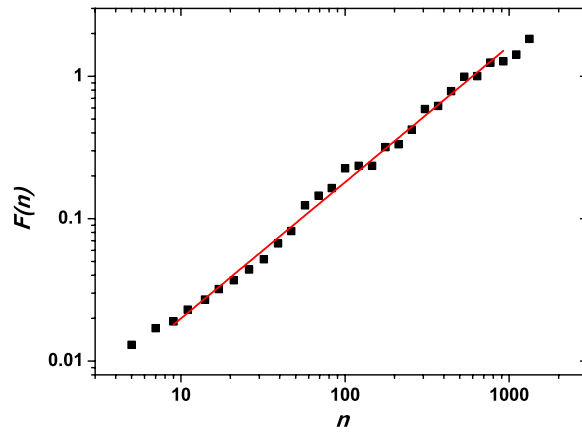
Fig. 3. Characteristic behavior of fuel-burning time series. In this case, AC with $\varphi = 1.1$ and enriched with 23% oxygen concentration exhibited $a = 0.96 \pm 0.02$, and the Pearson correlation index was $R = 0.99$.
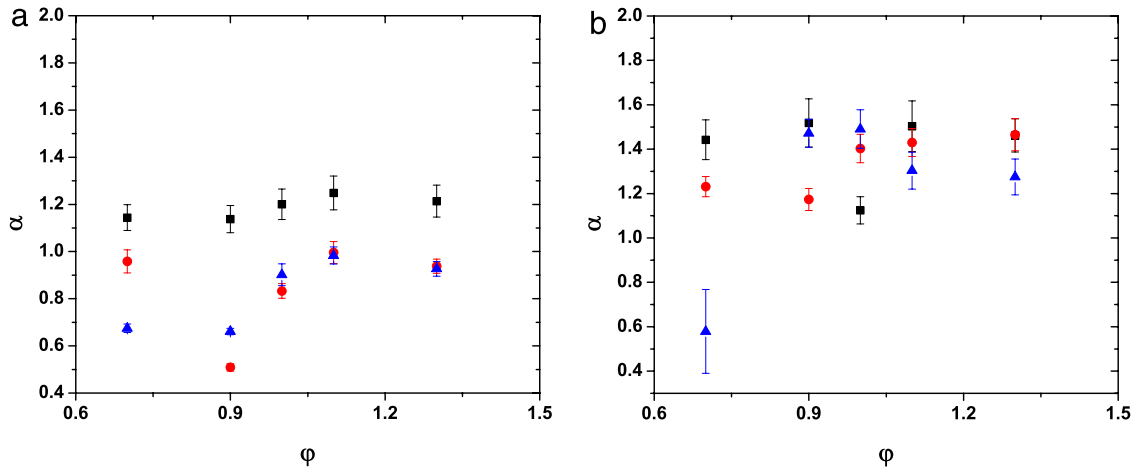

Fig. 4. Behavior of the long-range correlation exponent (α) as function of degree of equivalence (φ) for different oxygen concentration (21% (square), 23% (circle) and 25% (triangle)) for AC (a) and for NG (b).

increase in oxygen concentration in the flame makes the process more efficient, and the behavior of the radiation intensity fluctuation tends to remain the same over time.

Fig. 4(b) shows the behavior of NG at 21%, 23% and 25% concentrations. It is observed that the behavior of this process is practically the same at these concentrations with mean exponent α values $1.0 < \bar{\alpha} < 1.5$. Therefore, the process is sub-diffusive and non-steady [9]. Because NG has a lower efficiency and a tendency to form soot, these results suggest that the combustion behavior is independent of oxygen or air concentration in the flame because the process tends to always be diffusive and transitory. This result indicates that the process is less efficient, regardless of the oxygen increase (enriched combustion) or degree of equivalence (φ).

It is important to note that the first (1–3) and the last (7–10) orifices indicated fluctuations in the exponent α values in the $0 < \alpha < 3/2$ interval, without a defined pattern. This behavior may be related to the turbulence of the flame, especially in the initial and final states, where a zone is observed with a higher soot formation trend in the beginning of the flame and, consequently, higher oxidation in the final states.

In summary, a well-defined self-affine behavior was found for both gases, AC and NG, at any degree of equivalence (φ) and oxygen concentration in the combustion. The main difference was the behavior of this self-affinity. The AC tended to remain in a persistent regime independent of the φ and sensitive to oxygen concentration because when the oxygen mixture was poor (21% concentration), the regime tended to a sub-diffusive state. In contrast, NG remained in a sub-diffusive state regardless of the initial conditions.

In conclusion, NG has a lower efficiency and a higher tendency to form soot. This result suggests that the self-affine behavior of the time series of this fuel is independent of oxygen or air concentration in the flame and from φ because the process tends to be always sub-diffusive and transitory. Likewise, AC 21% exhibits a turbulent state (see discussion in Ref. [21]), tends to be less efficient, and exhibits fluctuation behavior similar to that of NG in that there was a lower efficiency of soot formation. However, for AC at 23% and 25% oxygen concentrations, the exponent α remained persistent,

which suggests that the combustion process tends to maintain the same radiation behavior over time. Our results indicate that AC is more efficient than NG at all initial conditions, as reported in the literature. However, for oxygen-poor mixtures (21%), the behavior of acetylene is similar to the behavior of natural gas.

Acknowledgments

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