



A new proposal for analyzing combustion process stability based on the Hamming distance



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HIGHLIGHTS

- We studied combustion process stability.
- We analyzed the stability based on the Hamming Distance.
- We discuss the combustion efficiency.
- We observe chaotic behavior in the process.

ARTICLE INFO

Article history:

Received 11 April 2014

Received in revised form 20 June 2014

Available online 5 July 2014

Keywords:

Hamming distance
Combustion process
Cellular automata

ABSTRACT

In this paper, the concentration of soot during controlled combustion is analyzed using two fuels: acetylene (AC) and natural gas (NG). The stability was evaluated within the spatio-temporal standards generated by the system evolution, which was based on the measuring technique known as the Hamming distance (Hd). It was observed that Hd presented a transient state for AC at a 21% oxygen concentration for small time units and achieved a medium equilibrium value ($Hd = 0.035$), showing a significant increase in flame oxidation during combustion and ideal soot formation. For NG, at all oxygen concentrations, there was a tendency toward flame oxidation and an increase in soot formation, which suggests that Hd oscillates without a defined value with small pulses over time, indicating a decrease in flame temperature.

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1. Introduction

Understanding the combustion processes within soot formation (particles formed during the process of combustion) coupled with thermal radiation is important for steel industries. In this type of process, large quantities of energy are released in the form of heat and, consequently, light. Soot has an important role in the combustion process: its interaction allows knowing and consequently improving the thermal efficiency of the burners, thus increasing fuel economy.

The higher the process efficiency, the lower the NOX formation will be. Applications that use oxygen-enriched flame (OEF) aim to achieve higher efficiency in soot production and consequently better heat transfer and reduced pollution during the combustion process. Oxygen enrichment increases flame temperature, promotes soot formation and oxidation, and can decrease pollutant emissions.

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Wang et al. [1] presented a fluid dynamics model that included a detailed description of soot formation during the combustion process using OEF. The initial proposal of our work consists of studying small temporal variations in the soot formation process within confined flames using a measuring method known as the Hamming distance (Hd), which is based on the theory of cellular automata.

Cellular automata are simple mathematical models capable of explaining complex physical phenomena based on evolutionary dynamics. To study the physics of dynamic systems, Kauffman [2] considered a damage (perturbation) propagation method. This method essentially consists of monitoring the temporal evolution of two or more system configurations, given different initial conditions, subject to a specific dynamics and to the same thermal noise.

The stability analysis of the spatio-temporal patterns generated by the system's evolution relative to small perturbations, which are introduced in an initial state, evolve according to a simple rule known as cellular automata (CA)-type Wolfram class [3]. This automata model can be understood using an analysis technique called Hd or simply damage. Hamming applied a measurement parameter to correct the errors in telecommunication codes [4], and the same technique is used to measure the stability of cellular automata. This model has been employed in several scientific areas, for example, in biology, to explain how viral transmission of intraspecies evolutionary relationships occurs [5], and in chemistry, cellular automata can explain how molecules come together during a chemical reaction [6].

Because Hd can be used to explain evolutionary dynamics models and often complex models, a study using the theory of cellular automata will be performed considering Hd for two fuels using OEF. In this study, the combustion behavior of two enriched fuels will be analyzed using the theory of cellular automata evaluated by Hd.

2. Fractal geometry and cellular automata

A fractal geometry consists of a spatial set that expresses a scalar relationship between the number of its elements and its measuring class (size, density, or intensity). This definition applies to dynamic phenomena that can be spatially represented and hence measured. A physical structure with an irregular or fragmented shape at all measurable scales is also considered as a fractal, and scaling or geometric invariance under certain transformations is one of its characteristics. Scale invariance is known as self-similarity and presents the same visual aspect at any amplified or reduced scale.

Some structures present self-similarity but cannot be visualized at all scales, known as self-affine structures. Nevertheless, these structures are discussed under the scope of fractal geometry. For such natural forms, the concept of self-similarity should be considered carefully and should be seen as small parts belonging to the same structure or to an identical statistical distribution. A fractal characteristic is called self-affine if the set of system functions, when changed, still presents scalar symmetry. Notwithstanding, the reduction factor can be different for certain fractal dimensions [7] (i.e., it does not maintain the original form at all scales for the same altered scaling factor). However, certain temporal evolutions are discrete mathematical models in time, space, and dynamic variables whose evolutions are governed by rules, as in the case of CA.

A CA can be defined as a set of identical elements, usually located within a regular dimensional network [3]. Each element can have k states that can be altered over time, e.g., binary states. The values evolve in discrete time steps according to deterministic rules that specify the values in each cell in terms of the values of the neighboring cells. In other words, each unit influences the neighboring units by sending a response signal regarding its interaction. These evolutions obey a simple model that can be better understood through Wolfram classes, which can be described by Hd. CA may serve as useful models to describe complex systems, such as fractal characteristics. In fact, CA are complex systems composed of simpler units that interact strongly with each other as the system dynamically evolves. Wolfram automata [3] are categorized into four classes based on the temporal evolution patterns that describe the CA behavior, from a stable and homogeneous state to disordered patterns.

3. Model used

One technique used to study cellular automata stability consists of comparing the joint evolution of the original system to its replica, in which a perturbation was introduced into any of the cells (conversion from the active to inactive state). By comparing the trajectory of the original and perturbed configurations, the Hd between them can be defined. Hd is the total number of cells that differ from each other in the original and perturbed replica configurations divided by the total number of cells (N). Hd can be applied to compare genome sequences, where the class samples are measured with an Hd [8]; to solve the minimum cost flux problem, in which the modifications may be weighted using an Hd [9]; or to model infection scenarios, as the rules that govern infection can be described by a CA, and thus, the damage is described using Hd [10]. Hd is also extensively used in binary counter techniques [11].

For a unidimensional CA with N cells, Hd is given by Eq. (1).

$$Hd = \frac{1}{N} \sum_{i=1}^N |\sigma_i(t) - \beta_i(t)| \quad (1)$$

where $\sigma_i(t)$ and $\beta_i(t)$ are the states of cell i at time t of the original and replica configurations, respectively. In general, the fraction of Hd in the initial instants is small, and by considering that the system is sensitive to the initial conditions (chaotic characteristics), a small perturbation can lead the system to a different attraction from the original by propagating throughout its length. The Hd can present four configurations associated with the four Wolfram classes [3], as described below:

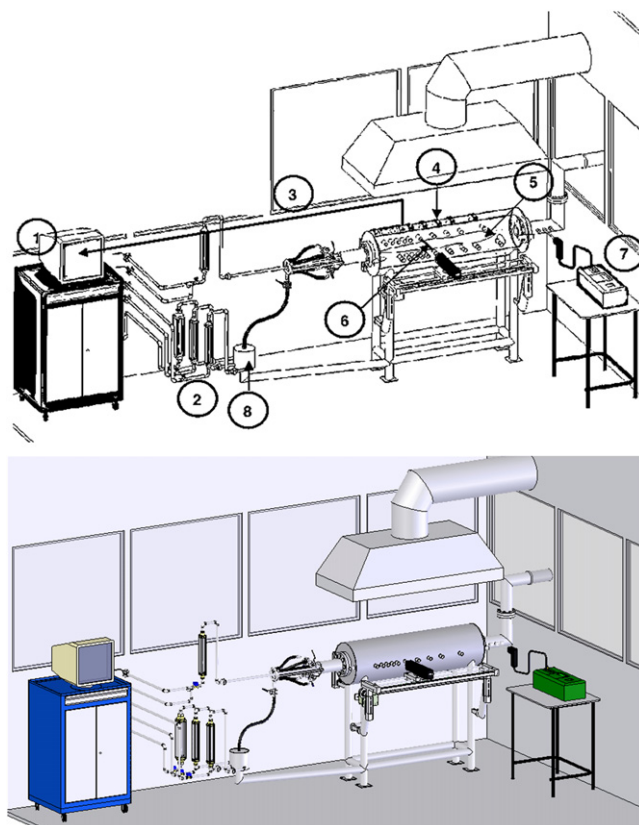


Fig. 1. General view of the experimental setup. (1) Data acquisition; (2) rotameters; (3) voltage signal; (4) photodetectors; (5) flame; (6) laser beam; (7) gas analyzer; (8) air/O₂ pre-mixer.

- **Class I:** the Hd vanishes with time. Therefore, the dynamics attractor is stable regardless of the perturbation.
- **Class II:** the Hd remains constant in time and is small.
- **Class III:** the Hd increases rapidly in time, generally reaching a high equilibrium value. In addition, even if the initial damage is minimal, it propagates throughout the CA chain. Therefore, Class III rules are unstable.
- **Class IV:** Hd has a long transient period before reaching its equilibrium value. The Hd increase is unpredictable. Moreover, its final value can vary greatly depending on the size and location of the initial damage. In general, the final Hd is similar to the case of Class II CA. Therefore, Class IV automaton dynamics features long chaotic transient periods before a stable periodic attractor is finally reached.

4. Experimental data

The experimental data were obtained using an apparatus consisting of a combustion chamber coupled with instruments for the analysis of gas and soot and for the verification of thermal radiation [12]. The experimental setup had a two-concentric-tube burner where the flame is generated within the chamber. These tubes have distinct diameters, where natural gas or acetylene flows through the smallest tube, while pure air or oxygen-enriched air flows through the region between the internal and external tubes, as shown in Fig. 1.

The flame was partially enriched with oxygen in the proportions of 23% and 25% in the presence of two combustibles, acetylene (AC) and natural gas (NG), respectively, and tested with atmospheric air without enrichment and with a 21% oxygen level. This enriching analysis method consists of evaluating the enriching effect on the flame (soot and oxidation formation) [13].

The admissible air/fuel or fuel/air relation admitted in a combustion, for a given functioning condition, is expressed by the relation $\varphi = \frac{A/C_{\text{stoichiometric}}}{A/C_{\text{real}}}$, where φ is the equivalence ratio, A is the air, and C is the fuel of the burning process. The equivalence ratio measures the air-fuel proportion, and its value defines the combustion characteristics as follows:

- $\varphi < 1$: mixture with an excess of air or poor mixture (in fuel);
- $\varphi = 1$: stoichiometric mixture;
- $\varphi > 1$: mixture with an excess of fuel or rich mixture.

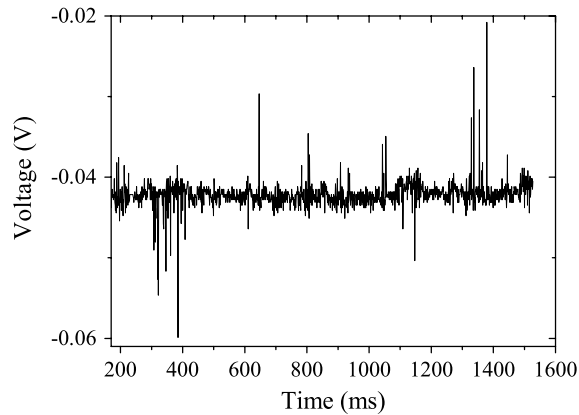


Fig. 2. Temporal series of the measurements obtained by the data acquisition for 23% NG with a 0.7 degree of equivalence.

A laser beam was emitted towards the flame to measure the concentration of particles formed in the combustion process. The radiation emitted by the laser was quantified by the photodetector (holes) outside the chamber, as shown in Fig. 1. Part of the emitted laser radiation was absorbed or dispersed. The absorption and dispersion were directly related to the formation of soot particles. Therefore, the maximum incident laser signal was obtained by reading the signal from data acquisition before the formation of the flame in the burner. Thus, the laser signal was focused towards the flame, which, in turn, was detected by a signal from the other side of the flame. Knowing the initial laser intensity, it is possible to calculate the difference between the emitted and received signals, thus determining what part of the laser radiation was absorbed or scattered due to the formation of soot during the combustion, as shown in the temporal series obtained in the natural gas experiment with 23% NG for the first hole with a 0.7 degree of equivalence (Fig. 2). With this data, it is possible to observe the temporal evolution of this system and evaluate it based on Hd.

5. Experimental results

Given the results, and using Eq. (1), Hd was calculated for the AC and NG with oxygen concentrations equal to 21%, 23%, and 25%. The quantity of air during combustion was varied, measured by the degree of equivalence, where $\varphi < 1.0$ indicates an excess of air in the flame, $\varphi = 1.0$ indicates the ideal condition (stoichiometric condition), and $\varphi > 1.0$ indicates a lack of air within the flame. As each cell represents a measure (hole), the number of cells is $N = 10$.

The category shown in Fig. 3 (a) and (b) denotes that the automata follow the same pattern for the AC fuels with an oxygen concentration of 21% for different equivalence ratios. It can also be observed that in the beginning of the combustion process, the Hd oscillates within a very small interval ($0.01 < Hd < 0.16$) until the distance is reached, following what corresponds to a Wolfram Class IV. This behavior leads us to believe that the soot concentration reaches a stationary state when Hd reaches a mean value of $Hd_m = 0.035$. In this case, when Hd reaches this value, a progressive reduction of soot concentration can be observed during the combustion process. This observation shows that when oxygen is added to the AC flame, there is a gain in fuel combustion, in other words, an increase in radiation.

Note also that the degree of equivalence of the flame is not influenced by the enriching process. However, this pattern is only observed for AC 21% because when the oxygen within the flame is increased for AC 23% and AC 25%, (Fig. 3(c) and (d)), Hd does not vanish but remains small in a diverse state and does not reach an equilibrium condition. Thus, no class is observed. This result shows that the increase of oxygen in the flame initially creates greater soot formation, and due to the higher soot concentration and OEF, there is an increase in the thermal radiation emitted by the flame.

When evaluating the NG experiments (Fig. 3(e) and (f)), we observed that the behavior of Hd indicates that NG does not follow any Wolfram class. This result means that when Hd oscillates within defined intervals with weak pulses, there is a tendency for minimal soot formation. NG does undergo soot formation (there is an increase of soot); however, compared to AC, NG soot formation is less, thereby reducing the radiation emission and possibly accounting for this behavior of Hd.

In general, the degree of equivalence does not influence Hd. Oxygen concentration does influence Hd, but only in the presence of 21% AC.

6. Conclusions

Based on these results, we conclude that for the AC gas, Hd remains initially small, oscillating within an interval of 0.0–0.12, and ultimately reaches a mean equilibrium value ($Hd_m = 0.035$), indicating that this behavior can be described as Wolfram class IV. However, this feature is only observed for 21% AC; in this case, Hd evinces a strong tendency to oxidize the flame, increasing its radiation and consequently decreasing the combustion temperature. Thus, upon reaching the stationary state, Hd indicates soot reduction and a higher combustion efficiency.

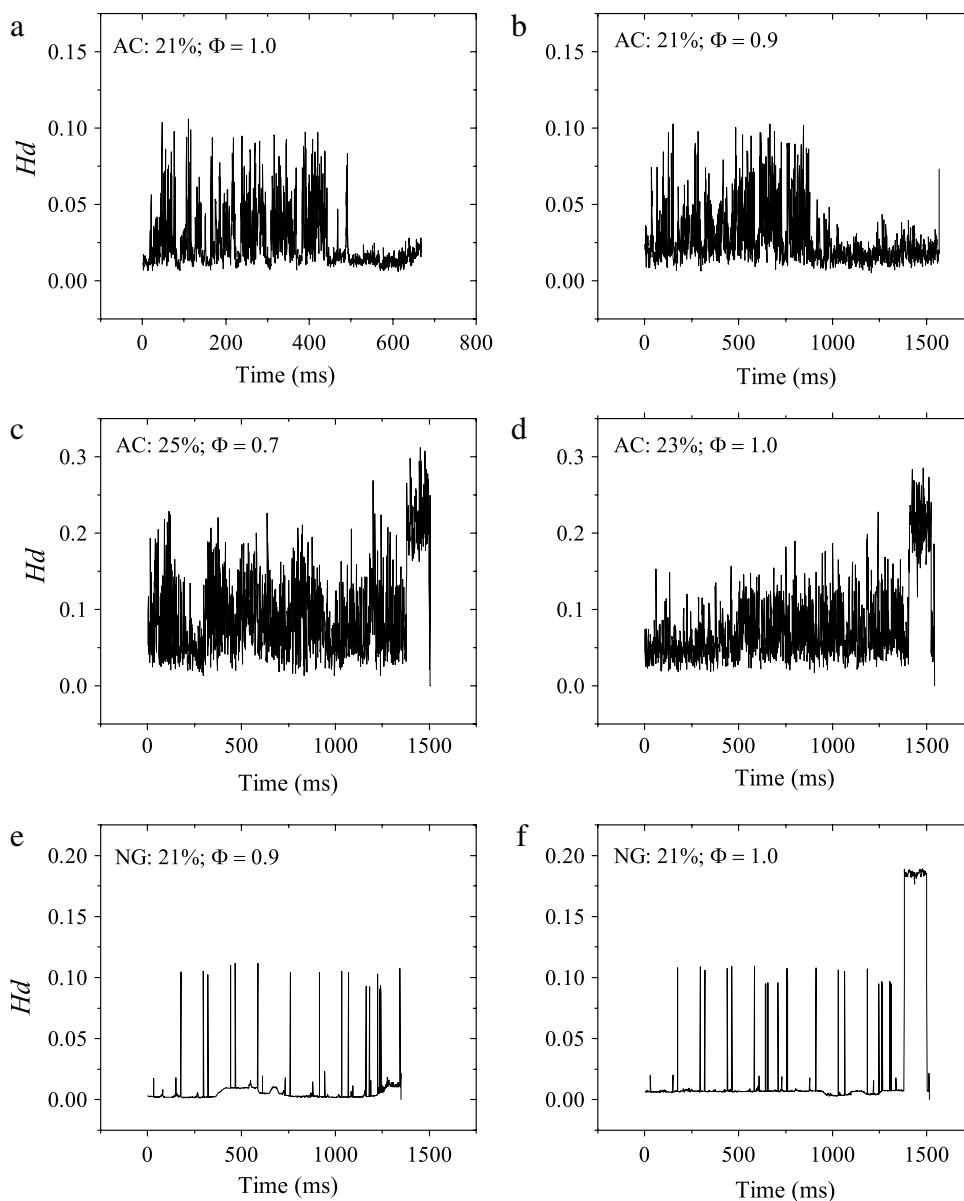


Fig. 3. Frequency of the Hd values using the combustibles AC and NG.

No Hd pattern was observed for AC with 23% and 25% oxygen concentrations. We can conclude that Hd, by remaining unstable, indicates increased soot formation, i.e., an increase in oxygen concentration within the flame makes the system sensitive to initial conditions and thus chaotic.

At oxygen concentrations of 21%, 23%, and 25%, for NG, Hd oscillates within a small interval with some localized pulses. In this context, the behavior of Hd indicates that this combustion process undergoes a radiation emission decrease and consequently an increase in flame temperature independently of the oxygen concentration, thus increasing soot formation during combustion. In addition, there was no indication that Hd was influenced by the flame's degree of equivalence. We recall that given the large amount of data, all the equality hypotheses applied to the series (same gas) were rejected with extremely low p values (less than 10^{-12}). In addition, the equality hypothesis between AC and NG is rejected with p value exactly equal to zero ($p = 0$).

Acknowledgments

This work received financial support from CNPq (grant no. 308785/2011-8) (Brazilian federal grant agency) and *Fundação de Amparo à Pesquisa do Estado da Bahia - FAPESB* (grant no. BOL01662012) (Bahia state grant agency).

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