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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.

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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.

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).

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

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: