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Effect of flame inherent instabilities on the flame geometric structure characteristics based on wavelet transform

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ABSTRACT

To investigate the effect of flame inherent instabilities on the flame structural characteristics of H_2/CO/air mixtures, experiments were conducted in a constant combustion bomb at various hydrogen fraction and equivalence ratio at room pressure and temperature. Wavelet transform was adopted to decompose the disturbances with different scales in the flame front. To study quantitatively the flame geometric structure characteristics, the maximum and minimum fluctuation radius growth rate, fluctuation range growth rate and energy of decomposition component were defined. The results indicated that with the flame development the disturbances at different scales all get greatly promotion. The higher the scale of the decomposition, the greater the amplitude and the energy of the disturbances. The disturbances at lower decomposition scales are the dominant component of the flame geometric structure characteristics; the ones at higher decomposition scales have a significance influence on the flame local geometric structure characteristics. When the flame development approached to a certain degree, the fluctuation range growth rate increased with the flame development. With the decrease of the equivalence ratio or the increase of hydrogen fraction, the thermal-diffusive instability enhances, leading to an increase of the fluctuation range growth rate and the relative energy of the approximate component at decomposition scale nine.

Introduction

Energy is the source of power for the development of human society. Throughout the history of humanity, every innovation in human society is followed by the reform of the energy structure. Especially fossil fuels represent a prominent parameter. However, under the dual pressure of limited fossil fuel reserves and environmental pollution, it is urgent to explore clean alternative energy sources [1–4]. Due to simple preparation method and low production cost, syngas has gradually become a high interest research topic in recent years [5,6]. Additionally, past studies have indicated that syngas is very promising as an alternative fuel for automotive internal combustion engines [7,8].

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The laminar burning velocity and the flame inherent instabilities are the two core topics of the expanding premixed flame [9,10]. The laminar burning velocity is ordinary used to verify and improve the existing chemical kinetic model, and lay a solid foundation for the study of the velocity of turbulent premixed combustion [11,12]. The laminar burning velocity of syngas/air mixtures at different initial pressures, initial temperatures and hydrogen fractions have been extensively studied [13–16]. To simulate the influence of EGR on the laminar burning velocity of syngas, nitrogen and carbon dioxide are used as a dilution gas to study the influence of the dilution gas on the laminar burning velocity of syngas [17,18]. Moreover, the kinetic calculation of chemical reaction is also adopted to reveal the mechanism of the core element reaction and the influence of the core component on the laminar combustion speed [19,20].

Furthermore, the research on the flame inherent instabilities of expanding premixed flame has also attracted more attention. Critical radius and critical Peclet number based on the evolution of the cellular structure are significant parameters for quantifying the influence of flame inherent instabilities on the flame geometric structure characteristics [21,22]. Li et al. [23] experimentally studied the hydrogen fraction and equivalence ratio on the flame inherent instabilities of syngas/air premixed flame at room temperature and elevated pressure, demonstrating that the critical radius decrease and the critical Peclet number decreases first and then increases at equivalence ratio 0.8 and 1.0 by increasing the hydrogen fraction. Askari et al. [24] investigated the critical Peclet number of low hydrogen fraction syngas/air premixed flame at elevated pressure and temperature, showing that at the hydrogen fraction of 5% and 10% the critical Peclet number initially decreases and then increases with the increase of the equivalence ratio. However, the measurement of critical radius is intensively limited by the fuel composition and the size of the quartz window of the constant combustion bomb. Thus, it is impossible to measure the majority of the critical radius within a wide range of equivalence ratio. In addition, according to the definition of critical radius, that is, the flame radius corresponding to the uniform cellular structure of the flame front, the critical radius selected by different scholars may be slightly different for the same set of experimental data.

In addition to observing the evolution of the cell in the flame front and studying the flame inherent instabilities, the flame front also includes intense and significant information. Based on the decomposition of the flame front, the evolution of the disturbances at the microscopic is obtained. This is of great significance for further in-depth studying the effect of flame inherent instabilities on the propagation mechanism of laminar premixed flame and exploring the coupling mechanism of turbulence and flame inherent instabilities on the turbulent premixed flame. Fourier Transform and Wavelet Transform are two important means to realize the decomposition of discrete signals and are widely used in different scientific fields [25–30]. Li et al. [31] obtained the amplitude of different disturbances by using the fast Fourier Transform to decompose the disturbance in the flame front of hydrogen/air laminar premixed flame. Additionally he further studied the effect of equivalence ratio on the amplitude of the flame front disturbance. To obtain the amplitude information of the flame front disturbance and study the phase information of different disturbances at the same time, the wavelet transform was used to decompose the flame front of syngas/air turbulent premixed flame and the disturbance information under different decomposition scales was obtained [32].

The wavelet transform can not only obtain the amplitude information of the disturbance, but also can obtain the phase information of the disturbance. It is able to have a more comprehensive understanding of the evolution of the flame front disturbance. Therefore, the wavelet transform was chosen to study the flame inherent instabilities of syngas/air premixed flame at various equivalence ratios (0.6–1.0) and various hydrogen fractions (50%–90%) at room temperature and pressure.

Experimental setup and procedures

Experimental setup

The constant combustion bomb used in the experiments was installed with two pairs of quartz windows at the horizontal direction to ensure the optical path requirements of Schlieren system. The inner chamber of the constant combustion bomb was spherical with a diameter of 380 mm. The Schlieren system was arranged with Z shape. A FASTCAM SA-X2 high-speed digital camera at a rate of 13500 frames per second and a resolution of 1024*1000 was used to record the images of flame evolution. The volume fraction of each component was calculated according to the Dalton law of mixing and was charged into the chamber through an inlet valve. The ignition signal was provided by a 12 V power supply in the synchronous trigger device. The mixture was ignited by the ignition electrodes installed in a horizontal position, which distance was 1.5 mm. Simultaneously, the high-speed camera was triggered to capture the flame images. Following the complete fresh mixtures burn, the combustion products were pumped out by a vacuum pump, and the high-pressure air was used to wash the chamber three times to eliminate the influence of residual combustion products on the experiments. A schematic illustration of the experimental setup is presented in Fig. 1.

Parameter definition

The hydrogen content in syngas can affect the prefer diffusivity of the flame front, which directly affect the flame thermal-diffusive instability due to the high molecular diffusivity of hydrogen [33]. The hydrogen fraction of the H_2/CO mixture was defined as

$$X_{H2} = V_{H2}/(V_{H2} + V_{CO}) \quad (1)$$

The influence of the flame inherent instabilities on the flame geometric structure characteristics can be reflected in the flame profile. Therefore, it is of great significance to extract the information of the flame front profile. In this paper, the flame front contour information was extracted by using Matlab. Due to the influence of the ignition electrodes and the flame inherent instabilities, the flame front cannot maintain a standard sphere. The flame local radius somewhere in the

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