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Laminar burning velocities and flame instabilities of diluted H_2/CO/air mixtures under different hydrogen fractions

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ABSTRACT

An experimental study was conducted using outwardly propagating flame to evaluate the laminar burning velocity and flame intrinsic instability of diluted H_2/CO/air mixtures. The laminar burning velocity of H_2/CO/air mixtures diluted with CO_2 and N_2 was measured at lean equivalence ratios with different dilution fractions and hydrogen fractions at 0.1 MPa; two fitting formulas are proposed to express the laminar burning velocity in our experimental scope. The flame instability was evaluated for diluted H_2/CO/air mixtures under different hydrogen fractions at 0.3 MPa and room temperature. As the H_2 fraction in H_2/CO mixtures was more than 50%, the flame became more unstable with the decrease in equivalence ratio; however, the flame became more stable with the decrease in equivalence ratio when the hydrogen fraction was low. The flame instability of 70%H_2/30%CO premixed flames hardly changed with increasing dilution fraction. However, the flames became more stable with increasing dilution fraction for 30%H_2/70%CO premixed flames. The variation in cellular instability was analyzed, and the effects of hydrogen fraction, equivalence ratio, and dilution fraction on diffusive-thermal and hydrodynamic instabilities were discussed.

Introduction

Syngas is derived from coal, fossil fuels, biomass, and even organic waste. The combustible components in syngas are mainly H_2 and CO, and the inert gases in syngas are N_2 and CO_2 [1]. Compared with coal and oils, syngas has less corrosive ash elements and particulate emissions [2], and it is recognized as a potential alternative fuel. Syngas can be used in IGCC systems [3], IC engines [4], and industrial burners [5]. The specific formation of syngas depends on the feedstock and gasification. The variation in syngas composition significantly affects the laminar burning velocity, ignition delay, and extinction limit [6]. Fundamental combustion characteristics are significant for the optimization of thermal devices [7]. It is important to better understand the combustion characteristics of syngas for further applications. In addition, lean combustion is favorable for energy saving and low emission [8].

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Laminar burning velocity is the inherent characteristic of a fuel, and it is significant to elucidate chemical reaction mechanisms [9,10]. Recently, the laminar burning velocity of syngas has been extensively studied. Syngas mainly consists of H_2 and CO, including some dilution of CO_2 and N_2. A few previous studies evaluated the laminar burning velocity of H_2/CO mixtures under different H_2 or CO fractions [11–22]. In recent years, some studies evaluated the effect of dilution on H_2/CO/air mixtures [14,23–31]. Burke et al. [14] studied stoichiometric 25%H_2/75%CO mixtures diluted with CO_2; the laminar burning velocity clearly decreased with increasing CO_2 dilution. Serrano et al. [23] studied the laminar burning velocity of 21%H_2/24%CO/55%N_2 at normal pressure; the highest laminar burning velocity in their research scope was 0.67 m/s. Prathap et al. [24] measured the laminar burning velocity of 50%H_2/50%CO mixtures with CO_2 and N_2 dilution; CO_2 decreased the laminar burning velocity more clearly than N_2. Vu et al. [25] studied the effect of different dilutions on the laminar burning velocity of H_2/CO mixtures with the H_2 fraction equal to CO; the dilution with CO_2 decreased the laminar burning velocity more apparently than N_2 and He. Kishore et al. [26] reported that the dilution of CO_2 clearly decreased the laminar burning velocity of H_2/CO mixtures (H_2:CO = 4:1, 1:1, 1:4). Burbano et al. [27] evaluated the effect of dilution on the laminar burning velocity of 50%H_2/50%CO mixtures; the effect of CO_2 was higher than N_2 because of its dissociation effect and higher heat capacity. Xie et al. [28] reported the effect of H_2O and CO_2 addition on the laminar burning velocity of H_2/CO mixtures; H_2O and CO_2 dilution showed different effects. Han et al. [30] reported the laminar burning velocity of H_2/CO mixtures with different CO_2 dilution ratios; the dilution of CO_2 affected the elementary reaction of "$H + O_2 = O + OH$" and "$CO + OH = CO_2 + H$." Zhang et al. [31] reported the effect of CO_2 and N_2 dilution on the propagation of lean H_2/CO/air flames. The decrease in laminar burning velocity was analyzed through thermal and chemical effects; the thermal effect decreased the laminar burning velocity more obviously. In previous studies, most studies focused on the H_2 or CO fraction at a certain value. Moreover, the data for high dilution fraction are absent. Further study is needed about diluted H_2/CO flames over a large scope of H_2 fractions and CO_2 or N_2 dilutions.

Propagation flame has intrinsic instability, inducing flame wrinkles and flame self-turbulization [32]. Flame instability includes diffusive-thermal instability, hydrodynamic instability, and body-force instability [33]. A flame with $Le < 1$ exhibits diffusive-thermal instability a [34,35] (Le is defined as the ratio of heat diffusivity to mass diffusivity); all the flames exhibit hydrodynamic instability [36,37]. A flame with a very low laminar propagation velocity exhibits body-force instability [38,39].

To study the flame intrinsic instability of H_2/CO mixtures diluted with an inert gas [25,27,28,40], Vu et al. [25] evaluated the flame instability of 50%H_2/50%CO mixtures with N_2 and CO_2 dilution; the flame surface instability of 50%H_2/50%CO flames diluted with N_2 and CO_2 was not inhibited. Burbano et al. [27] evaluated the flame instability of H_2/CO mixtures with N_2 and CO_2 dilution under lean conditions; the dilution of 50%H_2/50%CO mixtures with N_2 and CO_2 increased their flame instability. Wang et al. [40] evaluated the flame instability of H_2-CO-CO_2-O_2; the flame cellular instability decreased with increasing CO_2 fraction. Xie et al. [28] evaluated the effect of H_2O and CO_2 dilution on H_2/CO flame instability. The flame instability increased at normal pressure and decreased at higher pressure. Previous studies on the effect of dilution on the flame instability of H_2/CO flames did not provide a consistent conclusion. For syngas, the H_2 fraction is variable, and the flame instability with inert gas dilution is complex. To achieve a deeper insight of the flame intrinsic instability of diluted H_2/CO/air flame, it is essential to evaluate the flame intrinsic instability of diluted H_2/CO/air mixtures with different H_2 fractions. To provide more valuable information to better understand syngas, a systematic investigation was conducted to evaluate the effect of dilution on the laminar burning velocity and flame instability of H_2/CO mixtures.

Experimental facility and data processing

In this study, the spherically expanding flame method was used. As shown in Fig. 1, the experimental setup is mainly composed of a combustion chamber, a gas intake and exhaust system, an ignition system, a schlieren optical system, a high-speed camera system, and a data acquisition and control system. The inner diameter of combustion chamber is 140 mm; two quartz windows of 100 mm are oppositely mounted in the combustion chamber. The hydrogen, CO, and air were passed into the chamber individually. The ignition system consists of an ignition coil and two electrodes. The schlieren system consists of a Xe lamp, two concave mirrors, and two reflectors of 120 mm in diameter. The high-speed camera is FASTCAM X2. The data acquisition and control system consists of a synchronizer trigger, two electrical piezometers, and a piezoelectricity-type pressure sensor. The electrical piezometers are Delta DPA01M-P and DPA10M-P, and the piezoelectricity-type pressure sensor is Kistler 6052C. During the experiment, the combustion chamber was first pumped to vacuum; then, flammable gases were added into the chamber using Dalton's law. The flammable gases were ignited using the centrally located electrodes. The flame propagation images were recorded at 8000 to 10,000 frames per second using a piezoelectricity type high-speed camera and Schlieren technique.

Within the experiment, as shown in Table 1, the initial pressures were 0.1 MPa and 0.3 MPa, and the initial temperature was 298 K. The experiment was conducted in a laminar environment. The H_2 fraction in H_2/CO mixtures changed from 30% to 100% (H_2 fraction is defined as the ratio of volume of H_2 to the total volume of H_2/CO mixture). The diluents were N_2 and CO_2, and the dilution fraction varied from 0% to 60% (dilution fraction is defined as the proportion of dilution volume to the total volume of H_2/CO/dilution mixtures). The equivalence ratio was increased from 0.6 to 1.0.

The flame schlieren picture was recorded by the high-speed camera. The flame radius was obtained from the schlieren pictures. The stretched flame propagation speed (S_b) can be expressed as follows:

$$S_b = \frac{dR}{dt}, \quad (1)$$

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