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Investigation on dilution effect on laminar burning velocity of syngas premixed flames

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ABSTRACT

To provide more insight into the laminar burning velocity reduction of diluted syngas premixed flames, the laminar burning velocities of diluted syngas premixed (H_2/CO/N_2/air and H_2/CO/CO_2/air) laminar spherical flames were systematically and thoroughly investigated experimentally via Schlieren technology. In the present investigation, the volume fraction of H_2 was varied from 30% to 70%, the volume fraction of CO was varied from 30% to 70%, the volume fraction of CO_2 was varied from 0% to 60%, and the equivalence ratio was varied from 0.7 to 1.0. In the present investigation, the effects of equivalence ratio, hydrogen fraction, and dilution fraction on the laminar burning velocities were studied. Compared to N_2 dilution, the laminar burning velocity reduction with CO_2 dilution was analysed through the thermal, transport, and chemical effects. In addition, the contributions of third-body and direction effects were also studied.

1. Introduction

During the energy crisis, the sustainability of human society has been a concern, especially as the current energy system remains; therefore, research on and development of alternative fuels has been highly valued throughout the world in the past decade [1]. Owing to the rich reserves of coal and the demands to use coal in a much cleaner manner, syngas has been gradually regarded as a promising alternative fuel in an increasing number of countries. Because of the complex and changeable compositions of syngas [2], the fundamental combustion characteristics of syngas with various compositions have been considered necessary and important for the further development of syngas-fuelled thermal devices. Additionally, combustion devices favour lean combustible mixtures for low emissions and high fuel economy [3,4].

Laminar burning velocity is an intrinsic property of fuel, it is fundamentally important in developing and justifying chemical kinetic mechanisms [5–7]. Therefore, it is important to conduct experimental measurements on the laminar burning velocities of syngas premixed flames to obtain the understanding of the fundamental combustion characteristics of syngas. The spherically expanding flames have been used extensively to determine unstretched laminar burning velocities (S_u^0) [8].

The investigations on laminar burning velocity of syngas have attracted increasing attention in the scientific fields. Syngas is a mixture mainly composed of H_2 and CO including some diluent gases such as CO_2 and N_2. Some investigations are focused on the measurements of the laminar burning velocities of mono-component syngas-air premixed flames such as H_2/air [9–18] and CO/air [19], and some investigations are conducted on bi-component syngas-air premixed flames, namely H_2/CO/air [20–23] and H_2/inert gas/air [24]. However, based upon reports on H_2/inert gas/air premixed laminar flames, it is known that the inert gas also plays an important role in influencing the fundamental combustion characteristics; hence, for further and deeper understanding of syngas combustion, the effects of the inert gas must be taken into account. Some scholars have begun to study the fundamental combustion characteristics of diluted syngas premixed flames [25–27]. Prathap et al. [25,26] studied the laminar burning velocity of H_2/CO syngas premixed spherical flames diluted with CO_2 and N_2; the CO_2 has a more obvious effect on reducing the value of laminar burning velocity than N2. Vu et al. [27] also studied the laminar burning velocity of H_2/CO/CO_2 syngas premixed spherical flames. Ai et al. [28] studied the laminar flame speeds and Markstein lengths of typical syngas mixtures. Han et al. [29] investigated the laminar burning velocities and Markstein lengths of H_2/CO with different CO_2 dilution ratios at elevated pressures and temperatures. Natarajan et al. [30] studied the laminar flame

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speeds of lean H_2/CO/CO_2 fuel mixtures with different dilution fractions. Zhang et al. [31] studied the effect of CO_2 on the propagation and extinction of lean premixed H_2/CO/air flames; they compared the thermal effect and chemical effect on the reduction of laminar burning velocity under different CO_2 dilution fractions. For H_2/CO premixed flames, the laminar burning velocity decreases with increasing dilution fraction. Compared to N_2 dilution, the effect of CO_2 dilution will be different; CO_2 dilution of a H_2/CO/air mixture will change the transport and thermal properties, chemical effect [32]. However, quantitative contribution analysis of the different effects on laminar burning velocity between N_2 and CO_2 dilution is sparse.

To provide more beneficial information for the understanding of the dilution effect of syngas, a systematic investigation was conducted on diluted syngas premixed laminar spherical flames with various compositions. In the present investigation, the volume fraction of H_2 was varied from 30% to 70%, the volume fraction of CO was varied from 30% to 70%, the volume fraction of N_2 or CO_2 was varied from 0% to 50%, and the equivalence ratio was varied from 0.7 to 1.0.

2. Experimental and computational specifications

2.1. Experimental set-ups and procedure

Since it has the better definition of stretch (the major factor in determining the accuracy of measurement of laminar burning velocity), the spherical flame method has been widely employed in the field of fundamental combustion science, and was taken as the experimental method in the present investigation.

The experimental set-up employed for the present study was mainly composed of six parts: a high-speed camera, closed combustion vessel, discharge system, ignition system, optical access system, and data acquisition and control system, as shown in Fig. 1.

The closed combustion vessel was made of stainless steel and had a cubic inner chamber with a length of 140 mm. The discharge system featured six individual passages, namely a hydrogen bottle, carbon dioxide bottle, methane bottle, air bottle, vacuum pump, and the environment. The high-speed camera was an Integrated Device Technology (IDT) Motion Pro-Y4 operating at 8000 frames per second with a resolution of 352 × 352 pixels. The vessel was pumped to vacuum firstly, and the mixture was prepared by adding hydrogen, carbon monoxide, nitrogen, carbon dioxide and air according to Dalton's law. Once the desired mixture was prepared, a 15 min wait was required to ensure the homogeneity and quiescence of the mixture. In this study, the hydrogen had a purity of 99.995%, the carbon monoxide had a purity of 99.995%, the nitrogen and carbon dioxide had a purity of 99.999%, and the air was compressed dry air with an oxygen-to-nitrogen volume ratio of 21:79. In this study, at least three measurements were performed for each condition and the average value was obtained.

2.2. Computational specifications

Within the closed combustion vessel, the premixed flame propagated outward and spherically. The stretched flame propagation speed (***S*~b~**) can be derived from the data of flame radius versus time using equation (1):

$$S_b = \frac{dR}{dt}, \tag{1}$$

where ***R*** is the instantaneous flame radius and ***t*** is the elapsed time after the spark ignition. The flame propagation was affected by the electrodes when the flame was small, such as during the initial propagation period, and by the wall when the flame was sufficiently large, such as when constant pressure was absent in the spatial environment wherein the flame propagated. Thus, only flame radii between 6 [27,33] and 20 mm (approximately 0.3 times the radius of the wall [17]) were employed in order to eliminate the aforementioned effects.

K is the temporal rate of the change of a flame surface element of area ***A*** and is expressed as equation (2):

$$K = \frac{d(\ln A)}{dt} = \frac{1}{A}\frac{dA}{dt}. \tag{2}$$

K is defined as follows in the case of a spherically expanding laminar flame:

$$K = \frac{1}{A}\frac{dA}{dt} = \frac{1}{4\pi R^2}\frac{d(4\pi R^2)}{dt} = \frac{2}{R}\frac{dR}{dt} = \frac{2}{R}S_b. \tag{3}$$

In order to provide more accurate results, the non-linear methodology proposed by Kelly and Law [34] was used to deduce the unstretched flame propagation speed as follows [35,36]:

$$\left(\frac{S_b}{S_b^0}\right)^2 \ln\left(\frac{S_b}{S_b^0}\right) = -\frac{L_b K}{S_b^0}. \tag{4}$$

$\boldsymbol{L_b}$ is the Markstein length of burned mixtures and can be

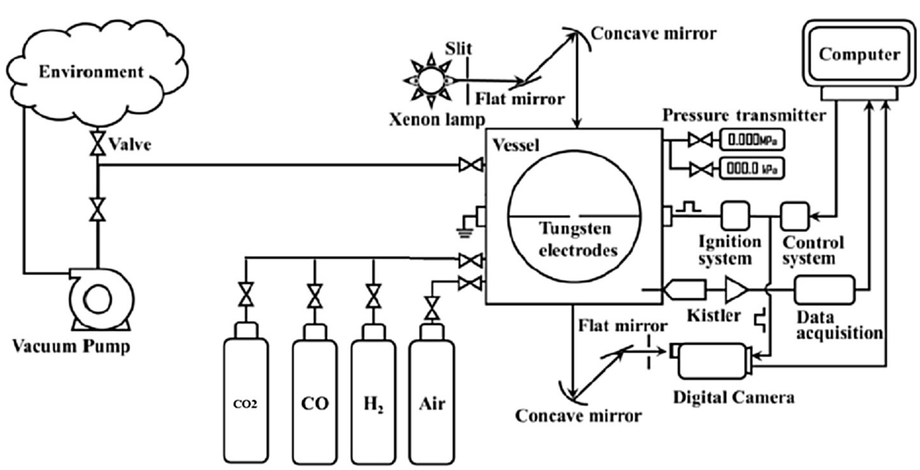

Fig. 1. Schematic diagram of the experimental system employed in the present investigation.