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Experimental study of premixed syngas/air flame propagation in a half-open duct

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ABSTRACT

The flame propagation characteristics of premixed syngas/air mixtures are investigated in a half-open duct over a wide range of hydrogen fractions at various equivalence ratios. A high-speed camera and a pressure transducer are used to acquire the flame images and overpressure dynamics. The results indicate that the flame shape changes as the hydrogen fraction and equivalence ratio vary. There are two different styles of tulip flame inversion. When the equivalence ratios, Φ, are 2.5 and 3.0 and the hydrogen fraction, φ, is higher than 0.3, the flame inversion is more complicated than the classical tulip flame inversion. Moreover, the distorted tulip flame, which is always obtained in closed duct, is observed in a half-open duct in three cases, i.e., $\Phi = 1.0$ and $\varphi = 0.1$, $\Phi = 1.0$ and $\varphi = 0.3$, and $\Phi = 3.0$ and $\varphi = 0.1$. Both the equivalence ratio and the hydrogen fraction can affect the flame propagation velocity and the pressure dynamics. Dramatic flame reacceleration and pressure oscillation occur after the flame inversion. The hydrogen fraction has a significant influence on the characteristics of premixed syngas/air flame. The influence is significant when hydrogen fraction was small ($\varphi < 0.5$), and the influence is moderate when hydrogen fraction was large ($\varphi \geq 0.5$).

1. Introduction

With increasing concerns regarding environmental protection, the emissions of pollutants are subject to stringent regulations. Synthesis gas (syngas), which primarily consists of hydrogen and carbon monoxide, has recently attracted significant interest around the world [1]. Syngas can be produced through the gasification of coal [2], biomass [3–6], refinery bottom residues (e.g., petroleum coke, asphalt, and visbreaker tar) [7], and municipal wastes [8]. The primary particulates, sulphur, and carbon dioxide can be removed after gasification [7]. Compared with directly combusting the fossil fuels, producing and using syngas is a cleaner and more efficient approach. Therefore, syngas, which currently plays an important role in the integrated gasification combined cycle (IGCC), is considered to be a future alternative fuel [9,10].

In the past decade, the focus has been on the use of syngas for the engineering application of combustion, e.g., laminar flame speed measurements [2,11–15], ignition delay time [16,17] and flame extinction [18,19]. There are, however, great challenges to overcome when handling syngas. On the one hand, the syngas composition, especially the hydrogen concentration, varies depending on the gasification process [7]. Hydrogen is dangerous because of its low ignition energy, wide range of flammability, high diffusivity and reactivity [20]. A small amount of hydrogen can affect the characteristics of syngas combustion significantly [15]. The complex properties of syngas pose a high risk of accidental fires and explosion because of the variation of hydrogen concentration. Currently, numerous experimental and numerical studies have been performed to identify the characteristics of syngas combustion [11–19]; however, the study of syngas explosions and premixed syngas flame propagation is limited. Understanding the explosion characteristics is crucial to ensure safe application of syngas. Basically, there are two experimental methods to examine the explosion characteristics. The first method is performed in a confined vessel [21–24] and is mainly used to investigate the explosion limit; the second method is conducted in a duct/tube. The process of flame propagation in a duct/tube is quite complicated. Flame propagation in a duct/tube can accelerate from a laminar combustion to deflagration and eventually transform into devastating detonation in certain conditions [25,26].

Since Mallard and Le Chatelier first observed the flame propagation in a tube [27], it has attracted significant interest from the combustion community. The tulip flame shape, which is first observed by Ellis [28] and named by Salamandra [29], has puzzled researchers for decades. The premixed flame propagation in a duct can experience a series of

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structural changes. A well-known example of the change of flame structure in the early stage is suggested and investigated by Clanet and Searby [27], who provided an empirical model and divided the flame propagation dynamics into four stages: hemispherical flame, finger-shaped flame, elongate flame with skirt touching the sidewalls and tulip flame. Various mechanisms and hypotheses have been proposed to explain the tulip flame formation. Markstein [30] demonstrates that flame front inversion occurs while the curved flame front meets a planar shock wave, and the flame front inversion is a consequence of the interaction between a flame front and a pressure wave. The results of a numerical simulation performed by Gonzales et al. [31] indicate that the "squish" flow and Darrieus-Landau instability are both crucial to the tulip formation. Moreover, many researchers [32–34] believe that Darrieus-Landau instability can influence the tulip flame formation. The Darrieus–Landau instability exists in all the subsequent inversions of the flame front curvature [35]. Ponizy et al. [36] suggests that the tulip flame is a pure hydrodynamic phenomenon. There are some contrary results regarding the tulip flame formation; for example, Matalon and Metzener [37,38] suggests that the tulip flame is caused by vorticity, whereas Dunn-Rankin et al. [39] prove that the tulip flame can successfully form without vorticity effects. An excessive wall friction precludes the tulip phenomenon and the tulip flame can form in absence of the wall fraction [31,40]. Apparently, several factors may contribute to the tulip flame phenomenon [41].

Recently, Xiao et al. [42] reveals an additional stage of the tulip flame propagation, named the "distorted" tulip flame. They suggest that the distorted tulip shape is an exclusive feature in a premixed hydrogen/air flame [42]. The distorted tulip flame, however, has been successfully obtained in stoichiometric premixed propane/air and acetylene/air flame [43,44]. It seems that the tulip distortion is an intrinsic and universal phenomenon in closed duct. Numerous experiments and numerical studies have been performed to explain the mechanism of the distorted tulip flame [40–43]. All of the evidence indicates that the distorted tulip flame is mainly caused by the interaction of flame and a pressure wave [41,45]. Furthermore, the parameters that affect the distorted tulip flame formation have been fully investigated, e.g., equivalence ratio [42], opening ratio [46] and wall friction [40]. All of the evidence shows that the distorted tulip flame can only form in a closed duct.

Although there are a large number of research studies regarding premixed flame propagation in a duct, most of them are conducted in a single gas-fuel condition (e.g., methane, propane and hydrogen). Premixed syngas/air may exhibit different flame behaviours and pressure dynamics because of its complicated compositions compared with single fuel/air. Thus, a systematic investigation on the flame behaviours and pressure dynamics of premixed syngas/air mixtures is conducted in a half-open duct using a high-speed camera and a pressure transducer. A wide range of composition syngas mixtures are examined. The flame structure and overpressure dynamic are obtained to explore the premixed syngas-air flame dynamics.

2. Experimental apparatus

Fig. 1 shows a schematic of the experimental set-up. The system consists of a rectangular combustion duct, an ignition system, a data acquisition system and a gas distribution system. The combustion duct, which is made of the high-transparency Plexiglas, is a horizontal straight rectangular duct with the inner size of 100 mm × 100 mm × 1000 mm. The left side of the duct is closed by a TP304 stainless plate, and the right side of the duct is covered by PVC membrane, which is regarded as a venting end. A very small overpressure in the duct can cause the PVC membrane to rupture. The effect of membrane is negligible on flame propagation [47]; thus, it can be treated as a half-open duct. The ignition system consists of a pair of ignition electrodes, a 6-V power source and an ignition controller. The ignition electrode is located in the centre of the stainless plate to ensure that it is located in the centre of the duct. The data acquisition system includes a pressure transducer and a high-speed camera. The overpressure can be successfully captured by a Meokon MD-HF piezoelectric gauge pressure transducer made by Shanghai Mingkong Sensor Technology CO., Ltd., which is located in the steel plate and is 20 mm away from the ignition electrode point. A "phantom" (Miro M310) high-speed camera by U.S. Vision Research is used to record the details of the flame evolution. The FS-N18N photoelectric sensor is installed at the outside of the duct and points towards the ignition electrode to calibrate the ignition time. Three Alicat M scientific mass flow controllers make up the gas distribution system. The gas inlet is located on the stainless plate at the ignition end, and the gas outlet is near the vent site. In the experiment, the sampling frequency for the pressure transducer is 15 kHz, and the image acquisition rate of the high-speed camera is 3200 frames/s.

The laminar flame speed in the rich-fuel side covers a wide range according to different research methods [48]. The laminar flame speed indicates that the syngas flame characteristic at rich conditions is more complicated. In this study, experiments are conducted with premixed syngas-air at the equivalence ratio range $1.0 \le \Phi \le 3.0$ and hydrogen fraction range from 0.1 to 0.9. The equivalence ratio Φ is defined as Eq. (1), and the hydrogen fraction is defined as Eq. (2), as follows:

$$\Phi = \frac{(F/A)}{(F/A)_{Stioch}} \tag{1}$$

$$\varphi = \frac{V_{H_2}}{V_{H_2} + V_{CO}} \tag{2}$$

where (F/A) and $(F/A)_{Stioch}$ are the actual fuel/air ratio and the stoichiometric fuel/air ratio, respectively; and V_{H2} and V_{CO} represent the volumes of hydrogen and carbon monoxide, respectively. The premixed syngas-air mixture is prepared by the partial pressure method using three scientific mass flow controllers. According to the literature [47], the syngas-air is fully mixed when the inlet gas is four times the volume of rectangular duct. The purities of hydrogen and carbon monoxide, which are provided by Jining Xieli Special Gas Co., Ltd., are 99.995% and 99.99%, respectively. The initial temperature and pressure in the experiment are 298 K and 101,325 Pa, respectively. Tests under each condition are repeated at least three times to ensure the reliability of the results.

3. Results and discussion

3.1. Flame structure changes

Fig. 2 presents a sequence of high-speed camera images of premixed flame propagation for syngas-air mixture under various hydrogen fractions and equivalence ratios, illustrating a typical flame shape change. The contrast and luminosity of the flame pictures are treated to make the flame more unambiguous in some certain Conditions (see Fig. 2(c) $\varphi = 0.9$; Fig. 2(d) $\varphi = 0.9$; and Fig. 2(e) $\varphi = 0.7$ and $\varphi = 0.9$). The pictures show that both the equivalence ratio and the hydrogen fraction have a significant influence on the flame structure evolution. The flame propagation in a duct can be divided into four stages, as proposed by Clanet and Searby [27]. As shown in Fig. 2, the phases of the hemispherical flame, finger shaped flame and the elongated flame with flame skirt touching the sidewalls are observed at all the equivalence ratios and hydrogen fractions, but the tulip shape flame is not observed in some cases. For the case of $\Phi = 1.0$, as shown in Fig. 2(a), the classical tulip flame appears within the hydrogen fraction range from 0.1 to 0.5. Thereafter, with increasing hydrogen fraction in the syngas mixture, the tulip flame shape cannot be obtained in the experiment anymore. For equivalence ratio of 1.5, as shown in Fig. 2(b), only when the hydrogen fraction is between 0.1 and 0.3 can the classical tulip flame forms. When the hydrogen fraction is 0.5, the plane flame forms that is very close to the vent side at t = 13.64 ms. The