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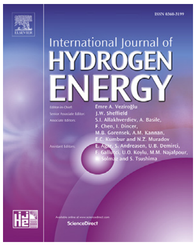

Experimental study of premixed syngas/air flame deflagration in a closed duct

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ABSTRACT

The propagation behaviour of a deflagration premixed syngas/air flame over a wide range of equivalence ratios is investigated experimentally in a closed rectangular duct using a high-speed camera and pressure transducer. The syngas hydrogen volume fraction, φ, ranges from 0.1 to 0.9. The flame propagation parameters such as flame structure, propagation time, velocity and overpressure are obtained from the experiment. The effects of the equivalence ratio and hydrogen fraction on flame propagation behaviour are examined. The results indicate that the hydrogen fraction in a syngas mixture greatly influences the flame propagation behaviour. When φ, the hydrogen fraction, is $\geq$0.5, the prominently distorted tulip flame can be formed in all equivalence ratios, and the minimum propagation time can be obtained at an equivalence ratio of 2.0. When $\varphi < 0.5$, the tulip flame distortion only occurs in a hydrogen fraction of $\varphi = 0.3$ with an equivalence ratio of 1.5 and above. The minimum flame propagation time can be acquired at an equivalence ratio of 1.5. The distortion occurs when the maximum flame propagation velocity is larger than 31.27 m s^{-1}. The observable oscillation and stepped rise in the overpressure trajectory indicate that the pressure wave plays an important role in the syngas/air deflagration. The initial tulip distortion time and the plane flame formation time share the same tendency in all equivalence ratios, and the time interval between them is nearly constant, 4.03 ms. This parameter is important for exploring the quantitative theory or models of distorted tulip flames.

Introduction

Synthesis gas, also known as syngas, primarily consists of hydrogen and carbon monoxide as well as a small amount of methane, carbon dioxide, nitrogen and water, and it can be produced from various sources, such as coal, biomass, refinery bottom residues, and municipal waste [1–6]. Syngas combustion can result in a significant reduction of pollutant emissions such as SO_x, NO_x, particulates, and heavy metals, and a potential reduction in carbon dioxide using carbon

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capture and sequestration (CCS) technology. Syngas is attracting increasing interest as an environmentally friendly renewable energy that is currently used in the integrated gasification combined cycle (IGCC) power plant [7]. However, the changeable hydrogen and carbon monoxide content, which may be caused by various gasification methodologies and source quality [8], is one of the largest barriers to the extensive use of syngas. The variability of syngas composition has a significant influence on the combustion and explosion characteristics, making the prevention of syngas explosions more difficult [9–11]. Important and basic flame parameters are essential to the safe utilization of syngas.

The premixed combustion of syngas has been widely investigated in past decades [12–22], but experiments on premixed syngas/air flames in a closed duct are quite limited. The premixed flame in a closed duct is one of the important aspects of syngas premixed combustion to explore. During flame propagation in a closed duct, many factors can affect the flame such as body force, boundary layers and intrinsic instabilities (Rayleigh-Taylor, Richtmyer-Meshkov and Darrieus-Landau) [23,24], making the flame structure and shape more complicated. Flame structure is a crucial parameter for characterizing flame behaviour, and it explains the flame propagation mechanism. Flame propagation in a closed duct can undergo a series of structural and shape changes under the appropriate conditions. Among all the flame shapes, the most attractive and interesting one is the tulip shape. A tulip flame was first observed by Ellis in 1928 [25] and subsequently named by Salamandra in 1959 [26]. The tulip phenomenon has been described in numerous experimental and numerical studies [27–29]. The four essential phases of a tulip flame are the following: (a) a hemispherical flame; (b) a finger-shaped flame; (c) an elongated flame with flame skirts touching the sidewalls; and (d) a tulip flame.

The tulip flame phenomenon puzzles many researchers in the domain of premixed combustion because it can be affected by many factors. Various hypotheses have been proposed to explain the tulip flame formation process, e.g., quenching and viscosity effects [25,30], vortex motion effects [31–33], pressure wave effects [34], Darrieus-Landau (DL) instability effects [35–38] and the Taylor instability effect [39], but none is certain. Xiao et al. [40] suggest that the formation of a tulip flame is a multi-factor interaction. Moreover, external conditions can affect the tulip flame formation. The tulip phenomenon is very sensitive to the aspect ratio. The tulip flame is obtained only in a closed duct with an aspect ratio of >2.0 [25], and it will form only in a half-open duct with an aspect ratio of >6.7 [41]. In addition, the combustible gas has significant influence on flame structure and shape. The flame will undergo a more drastic structure change in highly reactive gas such as hydrogen. Recently, a remarkable tulip flame distortion phenomenon in a premixed hydrogen/air flame was revealed by Xiao et al. who suggests the distorted tulip flame is an additional stage on the premixed flame [42,43]. The pressure wave triggered by the flame touching the sidewall is responsible for the periodic shape change. Rayleigh-Taylor instability plays an important role in distorted tulip flame formation [40,44,45]. The distorted tulip flame is not a unique phenomenon in premixed hydrogen/air flames, and it can also be obtained in premixed acetylene/air, propane/air and methane/hydrogen/air flames [46–49]. However, there are still insufficient data to make the distorted tulip flame formation explanation more convincing.

Although a large number of studies have been conducted to qualitatively reveal the mechanism of the tulip flame and distorted tulip flame formation, additional information is still required regarding a quantitative theory or model to predict the tulip flame and distorted tulip flame. Several analytical theories have been explored to quantitatively predict tulip flame formation [28,50], but these theories only work well in specific conditions. At the distorted tulip flame stage, a quantitative model is missing. Thus, more premixed flame data should be obtained for full consideration. Additionally, there is a lack of studies characterizing syngas explosion flame propagation and pressure dynamics in different scenarios. To address the safety issues of syngas combustion, it is of the utmost importance to study the flame characteristics of premixed syngas/air mixtures over wide range of mixture compositions.

In this study, a systematic investigation of premixed syngas/air mixture flame characteristics is conducted in a closed rectangular duct over a wide range of equivalence ratios and mixture compositions. Through high-speed camera image processing, the syngas explosion flame structure and velocity are obtained. Meanwhile, the pressure dynamics are acquired by a pressure transducer. The flame characteristics of premixed syngas/air mixtures are specially scrutinized. This work can provide more knowledge for premixed flame dynamics and contribute to safe industrial designs.

Experimental setup

The experimental setup is schematically shown in Fig. 1. The system consists of a combustion chamber, a gas distribution system, an ignition system and a data acquisition system. A high-transparency rectangular Plexiglas duct with an inner cross-section of 100 × 100 mm is employed as the combustion chamber. The length of the duct is 1000 mm to ensure the full formation of the remarkable curved tulip flame [24]. Both ends of the duct are closed with TP304 stainless steel plates. There is a round discharge vent near the right end of the duct with the inner diameter of 30.293 mm. The discharge vent is closed by the PVC membrane, and it breaks up easily for safety's sake. The premixed syngas/air mixture is prepared by the partial pressure method. The flow rate of each gas is precisely monitored with three scientific mass flow controllers (Alicat M) to provide the desired mixture composition. When the inlet gas is four times the volume of the rectangular duct, the syngas/air is fully mixed [41].

The mixture is ignited by a pair of spark electrodes with a 2 mm gap perpendicular to the duct axis. The spark electrodes are located in the left stainless steel plate at the centre of the cross-section. For collecting the dynamic pressure details in the duct, the pressure is measured by an MD-HF piezoelectric gauge pressure transducer from Shanghai Mingkong Sensor Technology Co., Ltd. The pressure transducer is located in the stainless plate 20 mm away from the spark electrode. In addition, an FS-N18 N photoelectric transducer is used to record the ignition time. The data acquisition frequency of the

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