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Effects of hydrogen addition on propagation characteristics of premixed methane/air flames

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A B S T R A C T

An experimental study has been conducted to investigate the effects of hydrogen addition on the fundamental propagation characteristics of methane/air premixed flames at different equivalence ratios in a venting duct. The hydrogen fraction in the methane–hydrogen mixture was varied from 0 to 1 at equivalence ratios of 0.8, 1.0 and 1.2. The results indicate that the tendency towards flame instability increased with the fraction of hydrogen, and the premixed hydrogen/methane flame underwent a complex shape change with the increasing hydrogen fraction. The tulip flame only formed when the fraction of hydrogen ranged from 0 to 50% at an equivalence ratio of 0.8. It was also found that the flame front speed and the overpressure increased significantly with the hydrogen fraction. For all equivalence ratios, the stoichiometric flame ($\Phi = 1.0$) has the shortest time of flame propagation and the maximum overpressure.

1. Introduction

Methane, the main component of natural gas, is one of the most promising gaseous fuels in the world. It is a form of clean energy, but is also a greenhouse gas that has a far stronger effect on climate change than carbon dioxide (Bermana et al., 2012). As the chief greenhouse gas in the atmosphere, the reduction of CO_2 emissions and the adaption of renewable energy sources with a low environmental impact are urgent objectives for future energy systems for both stationary and mobile applications (Klell et al., 2012). To solve this problem, one effective measure is the addition of hydrogen to fuel.

Hydrogen is an excellent additive to improve the combustion of methane. To use hydrogen/methane mixtures effectively, fundamental investigations were conducted by many researchers to understand their essential combustion properties (Chen et al., 2012; Halter et al., 2007; Hu et al., 2014; Okafor et al., 2014; Pareja et al., 2010; Zhao et al., 2008). The results suggest that hydrogen addition could significantly increase the laminar flame speed, extend the flammability limits, enhance the reactivity and increase burn temperature, which greatly raises the fear of explosions and generally makes hydrogen/methane mixtures more dangerous.

For the safe use of hydrogen/methane mixtures, it is essential to investigate their explosion characteristics. Ma et al. (2014a), (2014b) numerically and experimentally studied the confined and vented explosion characteristics of a hydrogen/methane mixture in a vessel, and both groups showed that the addition of hydrogen induces greater reactivity and raises the explosion pressure and temperature. Porowski and Teodorczyk (2013) experimentally studied the flame propagation, acceleration and transition to detonation of a stoichiometric hydrogen/methane mixture and determined the deflagration and detonation regimes and velocities of flame propagation in the obstructed duct. Salzano et al. (2012) investigated the combined effects of mixture composition and initial pressure on maximum pressure, maximum rate of pressure rise and burning velocity in a closed cylindrical vessel for explosions of a hydrogen/methane mixture. Woolley et al. (2013) described a mathematical model of confined and vented explosions of hydrogen/methane mixtures. The results showed that the addition of hydrogen has an obvious effect on explosion overpressure.

These previous studies were generally limited to the effects of hydrogen addition on the explosion overpressure and temperature, while the premixed flame propagation of a hydrogen/methane mixture in a duct has been rarely reported. Premixed flame

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propagation in a duct is intrinsically unstable and can undergo a series of shape changes (Xiao et al., 2014), and thus a premixed flame may spontaneously accelerate and trigger detonation. Moreover, the earlier studies on premixed flame propagation in a duct focused mainly on the mechanism of flame acceleration in a duct that is smooth or filled with obstacles (Clanet and Searby, 1996; Di Sarli et al., 2009; Ibrahim and Masri, 2001; Wen et al., 2012; Wen et al., 2013a; Wen et al., 2013b; Xiao et al., 2014; Xiao et al., 2011). All of the previous studies have focused on the flame propagation of a single gas, especially methane and hydrogen, but to the best of our knowledge, little attention has been devoted to the flame propagation of a hydrogen/methane mixture; thus, further study is needed.

In the present paper, experiments were conducted to provide a comprehensive investigation on the effects of hydrogen addition to the propagation characteristics of methane/air premixed flames in a venting duct. Experimental data for mixtures of varying fractions of hydrogen from 0 to 1.0 with three different equivalence ratios are presented. The effects of hydrogen addition on the flame front structure, flame speed and overpressure of methane/air were analyzed based on the experiment results.

2. Experimental setup and mixture composition

2.1. Experimental setup

A schematic diagram of the experimental set-up is shown in Fig. 1; the experimental set-up is very similar to that used in previous study (Ibrahim and Masri, 2001; Wen et al., 2013a). The experiments were performed in a 22.5 L duct with a cross-section of 150 × 150 mm^2 and a length of 1000 mm. The duct was placed horizontally, and it was made from 20 mm thick Perspex, which allows optical access permitting high-speed flame visualization. The right side, which is the ignition end of the duct, is closed by steel plate, and the left side, which is referred to as the "venting" end, is completely open and is covered with a thin PVC membrane. The membrane was used to retain the hydrogen/methane mixture in the duct.

The overpressure was measured using a piezoresistive pressure transducer made by Mingkong Sensor Technology Co. Ltd. in China that has a measurement range of −1.0–1.0 bar and a total error of <0.25%. The pressure transducer was located 20 mm from the center of the steel plate mounted on the ignition end. A photodiode sensor (RL-1) was positioned outside the explosion duct pointing ignition source, as shown in Fig. 1. The photodiode signal is used to capture the time of ignition, which ensures the synchronization of the overpressure signal, high-speed camera, and ignition. In the experiment, signals from the pressure transducer and the photodiode sensor were recorded at a rate of 15 kHz. The images of the premixed flame were captured by a "Lavision" high-speed camera, which can achieve acquisition at a speed of 5000 frames/s with an array of 1024 × 1024 pixels.

The methane/hydrogen/air mixtures were obtained by using mass flow controllers. The volume flow rates of the mixture were controlled to an accuracy of 2.5% of full-scale. The mixture gas enters the duct through an orifice mounted on right plate and may be vented through a valve positioned at the duct wall. The valve is closed to the "vent" end. The flow-rate of the methane/hydrogen/air mixtures is approximately 9 L/min and this process continues for 10 min, supplying a total of 90 L of methane/hydrogen/air mixtures, which is 4 times the volume of the vessel for purging the duct and ensuring that the mixture in the duct is homogeneous (Ibrahim and Masri, 2001; Wen et al., 2013a). After this process, the valve was closed. The mixtures were allowed to settle for 30 s and then ignited by a spark activated by a small electrically (6 V) mounted at the center of the right closed end.

2.2. Mixture composition

The hydrogen/methane/air mixtures used in experiment as shows in Table 1. Three global equivalence ratios ($\Phi = 0.8, 1.0, 1.2$) and five hydrogen fractions (0% H_2, 25% H_2, 50% H_2, 75% H_2 and 100% H_2) were tested in the experiment, respectively. The global equivalence ratio, Φ, is defined as follows (Halter et al., 2007),

Table 1
Compositions of hydrogen/methane/air mixtures.

φ/%	$\Phi = 0.8$			$\Phi = 1.0$			$\Phi = 1.2$		
	H_2/%	CH_4/%	Air/%	H_2/%	CH_4/%	Air/%	H_2/%	CH_4/%	Air/%
0	0	7.75	92.25	0	9.5	90.5	0	11.19	88.81
25	2.34	7.03	90.63	2.86	8.59	88.55	3.36	10.07	86.57
50	5.93	5.93	88.14	7.19	7.19	85.62	8.39	8.39	83.22
75	12.08	4.03	83.89	14.52	4.84	80.64	16.78	5.59	77.63
100	25.16	0	74.84	29.58	0	70.42	33.52	0	66.48

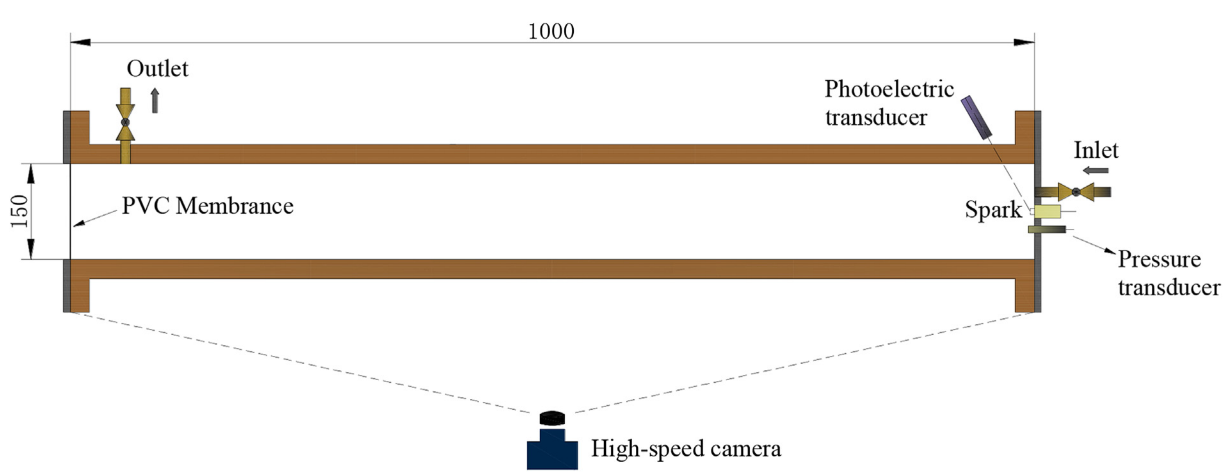

Fig. 1. Scheme diagram of experiment set-up (all dimensions are in mm).