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Detonation limits in binary fuel blends of methane/hydrogen mixtures

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ABSTRACT

Binary fuel blends of methane and hydrogen have a wide application in the internal combustion engines due to their promising combustion performance, although substantial studies have been carried out to investigate the combustion characteristics, very limited study focused on its detonation limits for propagation in tubes or pipes. In this study, near detonation limits behavior, which includes velocity deficit and cellular structure, of binary fuel blends of methane and hydrogen mixtures with different compositions (i.e., CH_4–$2H_2$–$3O_2$, CH_4–H_2–$2.5O_2$ and CH_4–$4H_2$–$4O_2$) are experimentally studied, experiments are carried out in a 36 mm inner diameter round tube and annular channels with three gaps ($w = 2$ mm, 4.5 mm and 7 mm). The results show the maximum detonation velocity deficit is 7% of CJ (Chapman–Jouguet) velocity for three mixtures in the 36 mm inner diameter round tube, and this velocity deficit is universal in the mixtures with different compositions. As detonations transmit into the annular channels, the velocity deficits in CH_4–$2H_2$–$3O_2$ and CH_4–$4H_2$–$4O_2$ mixtures are very close, i.e., within 10–20% V_{CJ} in the different scale of channels. For CH_4–H_2–$2.5O_2$ mixtures, velocity deficit varies from 15.0% to 34.1% V_{CJ} as the annular channel gap reduces from 7 mm to 2 mm, which is due to it has a higher degree of instability and hence more robust than other mixtures, a critical value of stability parameter χ is determined as 15–20, below which the instability has no significant effect on the velocity deficit. The cellular pattern from the smoked foils indicates single-headed spinning detonation in CH_4–H_2–$2.5O_2$ mixture appears at lower initial pressure than other two mixtures, and the detonation cell size for this mixture is larger at the same initial condition, which is verified by the evidence from ZND induction zone length analysis.

1. Introduction

Natural gas (NG) has been widely used in the automobile engines due to the combustion of NG generates relatively low levels of unwanted pollutants, e.g., nitric oxide (NO_x), polycyclic aromatic hydrocarbons (PAHs) and soot particles. Meanwhile, the higher octane number of NG also makes it applicable in spark-ignition engines for automotive transportation [1]. Nevertheless, the usage of NG in spark-ignition engine still has some drawbacks, e.g., low thermal efficiency, large cycle-by-cycle variation, and poor lean-burn capability, those negative properties of NG would decrease the efficiency of engine power output and increase the fuel consumption [2]. Therefore, seeking solutions to improve the combustion performance of NG is being a challenging and formidable task for researchers.

By using more reactive fuel additives (e.g., hydrogen), the ignition and combustion performance of NG (major component is methane CH_4) could be greatly enhanced in combustion engines [3], which is due to hydrogen has the fastest flame speed among practical fuels, binary fuel blends (e.g., NG and H_2) used in the combustion engine can improve the lean-burn characteristics as well as the fraction of exhaust gas recirculation and decrease the emissions [4,5].

Substantial fundamental studies of binary fuel blends of methane–hydrogen mixtures have been performed on its combustion characteristics. Halter et al. [6], Di Sarli et al. [7] and Hu et al. [2,4,5] studied the laminar burning velocities of methane–hydrogen mixtures, Hu et al. [4,5] also conducted experimental investigation on the influence of different hydrogen fractions and exhaust gas recirculation (EGR) rates on the performance and emissions of a spark-ignition engine fuelled with natural gas–hydrogen blends. Numerical study of the effect of hydrogen addition on methane-air mixtures combustion was carried out by Wang et al. [8]. Chen et al. [9] conducted a theoretical

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analysis for a planar premixed flame of binary fuel blends and developed a model for the laminar flame speed, good agreement was found between the model and experimental results of methane/hydrogen mixtures. Chaumeix et al. [10] validated a detailed kinetic mechanism for the oxidation of hydrogen–methane–air mixtures in detonation waves, the auto-ignition delay times were also measured from experiment. Gersen et al. [11] investigated the ignition properties of methane–hydrogen mixtures in a rapid compression machine (RCM), the auto ignition behavior of methane–hydrogen mixtures in a RCM was characterized, ignition delay times were also compared with simulation using various chemical mechanism. Porowski and Teodorczyk [12] performed an experimental study on flame propagation, acceleration and transition to detonation in stoichiometric hydrogen–methane–air mixtures using 6 m long tube filled with obstacles located at different configurations, the deflagration and detonation regimes and velocities of flame propagation in the obstructed tube were determined.

In spite of numerous investigations on the combustion characteristics of the mixtures containing the binary fuel blends of methane–hydrogen have been carried out, very limited study focused on its detonation limits for propagation in tubes or pipes. In fact, the detonation limit is an important property for the deflagration or detonation hazard assessment [13–18]. In this study, the detonation limits in methane–hydrogen–oxygen mixtures with three different compositions are investigated in a round tube with 36 mm inner diameter and thin annular channels with different scales (*w* = 2 mm, 4.5 mm and 7 mm). Velocity deficits are measured in different channels for those mixtures, the effect of detonation instability on the velocity deficit is also explored. Smoked foils are used to record the cellular structure of detonation, the structure of the detonation near the limits is also analyzed, ZND induction zone length is introduced to explain the difference of the cell size for three mixtures.

2. Experimental details

2.1. Experimental setup

Experiments were performed in a 1.2 m long, 68 mm inner diameter steel driver section followed by a test section of tube with 2.5 m in length and an inner diameter of 36 mm, which are shown in Fig. 1(a). Three annular channel gaps (*w* = 2 mm, 4.5 mm and 7 mm) are created by inserting smaller diameter tubes into the test section (Fig. 1b), the outer diameters of smaller tubes are: 32 mm, 27 mm, 22 mm, respectively, detailed information of the experimental setup can be found in our previous study [19].

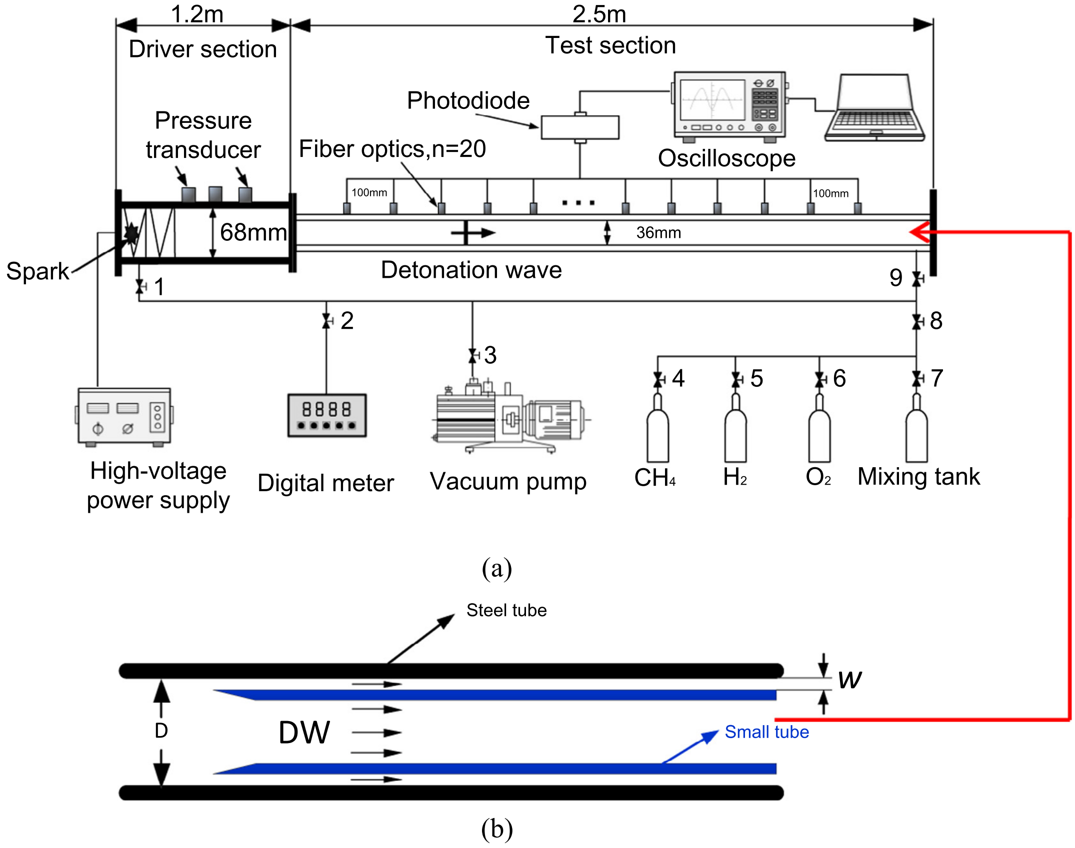

Fig. 1. Sketch of experimental apparatus.

Table 1
CH_4–H_2–O_2 mixtures with different fuel compositions used in the experiment.

Mixture	Molecular formula	Methane vol.%	Hydrogen vol.%	Oxygen vol.%	Equivalence ratio, φ	Note
#1	CH_4–$2H_2$–$3O_2$	16.67	33.33	50.00	1	Stoichiometry
#2	CH_4–H_2–$2.5O_2$	22.22	22.22	55.56	1	Higher content of methane
#3	CH_4–$4H_2$–$4O_2$	11.11	44.44	44.44	1	Higher content of hydrogen