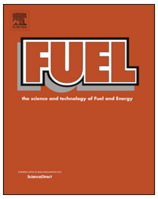
Fuel 233 (2018) 269–282

Contents lists available at ScienceDirect

Fuel

journal homepage: www.elsevier.com/locate/fuel



Full Length Article

Effects of hydrogen and initial pressure on flame characteristics and explosion pressure of methane/hydrogen fuels

Yanchao Li, Mingshu Bi, Bei Li, Yonghao Zhou, Wei Gao*

School of Chemical Machinery and Safety Engineering, Dalian University of Technology, Dalian, Liaoning 116024, PR China

ARTICLE INFO

Keywords:
Energy utilization
Hydrogen addition
Initial pressure
Flame characteristics
Explosion pressure

ABSTRACT

Methane/hydrogen fuels are widely applied in the internal combustion engine and gas turbine due to enhanced laminar burning velocity and extended flammability limits. In order to ensure energy utilization in safety, the flame characteristics and explosion pressure in the lean, stoichiometric and rich mixture are investigated systematically by varying hydrogen addition and initial pressure. In the lean and stoichiometric mixture, effects of the diffusional-thermal and hydrodynamic instability on flame destabilization are enhanced with hydrogen addition. As initial pressure increase, the diffusional-thermal instability has a limited effect on flame destabilization while effects of the hydrodynamic instability continue to enhance. In the rich mixture, effects of the diffusional-thermal instability on the flame stabilization and effects of the hydrodynamic instability on the flame destabilization enhance significantly with hydrogen addition. As initial pressure increase, effects of the diffusional-thermal instability on the flame stabilization are very limited and effects of the hydrodynamic instability on the flame destabilization are enhanced. The variation in maximum explosion pressure could be neglected with hydrogen addition due to decreasing heat loss, and maximum pressure rise rate increases with hydrogen addition. Besides, explosion pressure evolution could be evaluated accurately by considering the flame instabilities. And by varying equivalence ratio, hydrogen addition and initial pressure, the most enhancing and inhibiting reactions to laminar flame velocity are $H + O_2 = O + OH$ and $H + CH_3(+M) = CH_4(+M)$, respectively.

1. Introduction

Among all fossil fuels, methane is one of most promising solutions to the environmental issues due to lowest global warming emissions and is widely applied in internal combustion engine and gas turbine due to high knocking resistance [1–3]. In order to reduce NO_x emissions, lean combustion of premixed methane/air mixture is prerequisite for energy systems, which will decrease the flame stability and result in the extinction phenomena [4–6]. Based on the fact that hydrogen-addition into methane could improve laminar burning velocity, extend flammability limits and increase the flame resistance to strain-induced extinction, thus methane/hydrogen fuel is attracting substantial attentions for energy supply [7–12]. In order to ensure energy utilization, explosion hazard evaluation of methane/hydrogen fuel is indispensable to establish safety precautions.

Laminar burning velocity is one of most fundamental properties for premixed flame which presents the reactivity and exothermicity of combustible mixtures. Laminar burning velocity of methane/hydrogen/air mixture has been investigated in [13–15]. According to their results, laminar burning velocity of methane/hydrogen fuel will increases significantly with increasing hydrogen addition. Hu [16] also found that laminar burning velocity of lean methane/hydrogen/air flame increases with initial temperature and decreases with initial pressure, respectively, the suppression of overall chemical reaction is closely linking to the decrease of H, O and OH mole fractions with increasing initial pressure. Sarli [17] calculated laminar burning velocity of hydrogen-methane-air mixtures using GRI kinetic mechanism and found that three regime are identified depending on the hydrogen mole fraction, which is associated with the amount of H radicals. Li [18] pointed out that the reaction $H + O_2 = OH + O$ could promote laminar burning velocity and the promoting effect is more obviously with hydrogen addition. Besides, due to the fact that Lewis number of hydrogen/air mixture is less than unity on the lean side and the flame thickness is relatively smaller than that of methane/air mixture, the methane/hydrogen/air flame on the lean side tends to be more unstable with increasing hydrogen addition. Especially at the elevated operating pressure, the flame instability of methane/hydrogen/air mixture could be enhanced significantly [19]. Okafor [20] suggested that the propensity

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* Corresponding author.
E-mail address: gaoweidlut@dlut.edu.cn (W. Gao).

https://doi.org/10.1016/j.fuel.2018.06.042
Received 23 December 2017; Received in revised form 9 June 2018; Accepted 11 June 2018

of flame instability varied non-monotonically with hydrogen fraction, the measured Markstein number of $\Phi = 0.8$ and 1.0 varied non-monotonously while Markstein number of $\Phi = 1.2$ increases monotonously with hydrogen addition, and the above results could be attributed to the non-monotonic variation of effective Lewis number. Hu [21] pointed out that the flame instability is insensitive to initial temperature while the critical radius and Markstein length should increase with initial pressure due to enhanced hydrodynamic instability. And Hu also found that Markstein length decrease significantly with increasing hydrogen addition due to the enhancement in both diffusional-thermal and hydrodynamic instability. Recently, the explosion pressure of methane/hydrogen/air mixture has been paid attention in [22–25]. A consensus is reached over the issue that the explosion pressure could be enhanced significantly with increasing hydrogen addition. Faghih [26] found that the deflagration index of methane/hydrogen mixture increases exponentially with hydrogen addition when hydrogen addition is above 70%. Salzano [27] thought that the pressure rise rate is increased with increasing hydrogen content regardless of initial pressure. Besides, Zheng [28] pointed out that the explosion pressure is closely related to the flame propagation speed and they increases obviously with hydrogen addition. In fact, the flame propagation speed could be increased relatively significantly by flame instability, which would enhance the explosion pressure. Based on the assumption of fractal flame, a simple method for predicting explosion pressure evolution is developed by Nishimura [29]. And Li [30] suggested that the fractal dimension in above model must be considered carefully.

Anyway, the flame characteristics and explosion pressure of methane/hydrogen/air mixture have not been well reveal yet, and the dependence between explosion pressure evolution and laminar burning velocity need to be further illustrated. The objective of this paper is aimed at systematically explore the effect of initial pressure and hydrogen addition on flame instabilities and explosion pressure evolution in the lean, stoichiometric and rich mixture, and an improved method of explosion pressure evaluation is established considering flame instabilities. Finally, based on the relationship between explosion pressure evolution and laminar burning velocity, sensitivity analysis is conducted to reveal the dominant elementary reaction of enhancing or suppressing explosion pressure.

2. Experimental apparatus

Fig. 1 shows the schematic of experimental apparatus, which has been described in detail in the previous work [30]. The experimental apparatus is mainly composed of a 14L spherical combustion chamber, a high-speed schlieren photography system, a gas supplying system, a transient pressure measurement system, a data acquisition system, a high-voltage ignition system, and a time controller system. The flame characteristics are captured by a FASTCAM SA4 high-speed camera with operating speed 10000frame/s. The transient pressure dynamics in the chamber is measured using a PCB piezoelectric pressure transducer (model 113B24) and is recorded using data acquisition YOKOGAWA DL850E of sampling rate 100kS/s. The mixture composition is calculated using partial pressure and the model of pressure gage is Omega DPG4000-100A. It should be noted that the experimental uncertainty is strongly dependent on the resolution of pressure gage and pressure transducer, which least count is 10 Pa and 35 Pa, respectively. Table 1 summarizes the experimental condition.

Table 1
Experimental condition.

Φ	Initial pressure/kPa	Hydrogen addition
0.8	50/100/150/200	0.1/0.3/0.5/0.7/0.9
1.0	50/100/150/200	0.1/0.3/0.5/0.7/0.9
1.4	50/100/150/200	0.1/0.3/0.5/0.7/0.9

The hydrogen addition (volume fraction of hydrogen) in the experiment is defined as:

$$x_{H_2} = \frac{V_{H_2}}{V_{H_2} + V_{CH_4}} \tag{1}$$

where x_{H2} is volume fraction of hydrogen, V_{H2} is hydrogen volume, V_{CH4} is methane volume.

The wrinkling ratio is a quantifiable parameter to characterize wrinkling level of the unstable flame. In this work, the wrinkling ratio could be calculated as follows [31,32]:

$$\Xi_\Delta = \frac{R_p^2}{R_S^2} \tag{2}$$

$$R_p = \frac{p_f}{2\pi} \tag{3}$$

$$R_s = \left(\frac{A_f}{\pi}\right)^{1/2} \tag{4}$$

where Ξ_Δ is wrinkling ratio, R_p is flame radius corresponding to equivalent perimeter, R_s is flame radius corresponding to equivalent

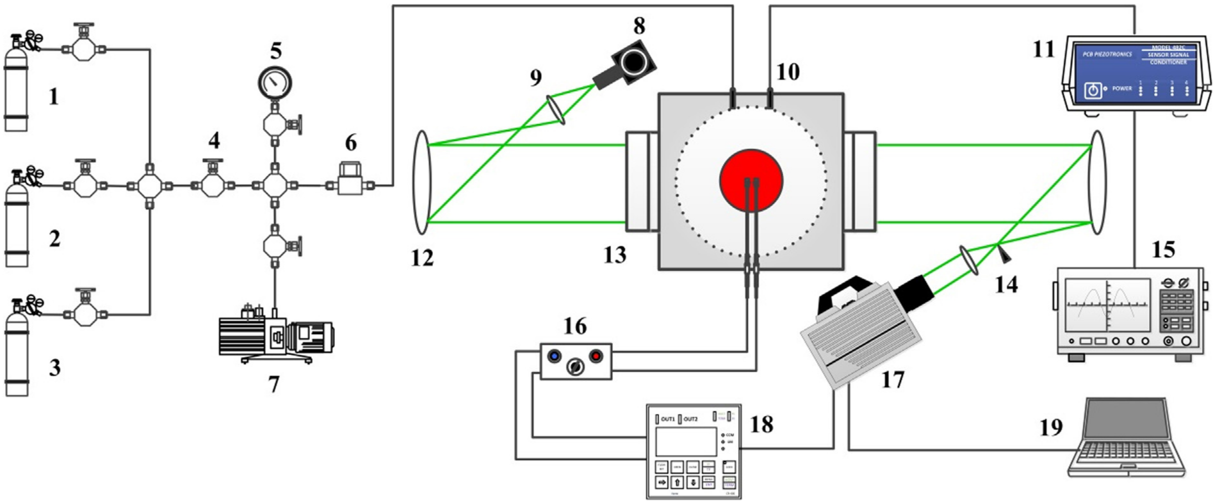

Fig. 1. Schematic of experimental apparatus: (1) hydrogen; (2) methane; (3) air; (4) needle valve; (5) pressure gage; (6) flame arrester; (7) vacuum pump; (8) point light source; (9) focusing lens; (10) pressure transducer; (11) signal conditioner; (12) schlieren mirror; (13) optical window; (14) knife edge; (15) data recorder; (16) high-voltage igniter; (17) high-speed camera; (18) programmable logic controller; (19) computer.