INTERNATIONAL JOURNAL OF HYDROGEN ENERGY XXX (2017) 1–12

Available online at www.sciencedirect.com

ScienceDirect

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

Effects of hydrogen addition on laminar flame speeds of methane, ethane and propane: Experimental and numerical analysis

Zhongqiu Li, Xiaobei Cheng, Wenming Wei, Liang Qiu, Hui Wu***

State Key Laboratory of Coal Combustion, School of Energy and Power Engineering, Huazhong University of Sci. & Tech, Wuhan, Hubei, China

ARTICLE INFO

Article history:
Received 17 February 2017
Received in revised form
27 June 2017
Accepted 22 July 2017
Available online xxx

Keywords:
Counter-flow flat flame
Hydrogen addition
Laminar flame speed
Sensitivity analysis
Component concentration

ABSTRACT

The main purpose of this study is to investigate the effects of hydrogen addition on the laminar flame speeds of methane, ethane and propane. In this work, a flat flame method was used to measure the laminar flame speed in a counter-flow configuration combined with particle image velocimetry (PIV) system. The results indicate that with the increase of hydrogen amount, the laminar flame speeds of methane, ethane and propane increase linearly approximately. In addition, as hydrogen is increased, the flame speed of methane has the maximum increasing amplitude among them, which indicates that methane is more sensitive to hydrogen addition in flame speed than the other two fuels.

Simulation analysis finds that the reaction R1: $H + O_2 \Leftrightarrow OH + O$ can promote the flame speeds of these three kinds of gaseous fuel obviously, and with the increase of hydrogen amount, the promoting effect is more obviously. Therefore, the main reason why hydrogen addition could increase flame speed is that the increase of H radical prompts reaction R1 to proceed in the forward direction. Comparing the flames of methane, ethane and propane mixed with hydrogen, it was found that the promotion of reaction R1 to the methane/hydrogen mixtures flame speed is strongest, and its free radicals concentration in flame increase more obviously. Therefore, hydrogen addition has a greater effect on the flame speed of methane than on that of ethane and propane.

Introduction

As the energy and environment problems became increasingly prominent, it is imminent to find new engine fuels and reduce emissions [1]. Gaseous fuel is considered to be the most practical alternative fuel for engine and widely studied. In recent years, hydrogen-hydrocarbon blends are receiving attention as alternative fuels in power automotive industries. This is because hydrogen is the most environmental friendly gas which produces only water when it is burnt. Hydrogen has a very high combustibility, high flame speed with wide flammability limits and thus has a great opportunity to improve performance, extend operability ranges and reduce pollutant emissions of lean combustion in both stationary and mobile systems when it is added to hydrocarbon fuel (such as methane diesel and gasoline) [2]. Extensive studies have been conducted on internal combustion engines fueled by

* Corresponding author.
** Corresponding author.
E-mail address: xbcheng@hust.edu.cn (X. Cheng).

http://dx.doi.org/10.1016/j.ijhydene.2017.07.190

hydrogen-natural gas mixtures [3–6]. According to the research results of many scholars, hydrogen addition to gaseous fuel could obviously improve the engine's combustion and emission performances [5,7–9]. The main combustible components of the general gaseous fuels (natural gas, coal-bed gas, biogas and etc.) include methane as well as small amounts of ethane and propane, thus it is of great significance to study the flames of methane, ethane and propane.

In the actual engine combustion process, especially in spark ignition engine, the flame is laminar originally, then turn to turbulent flame, which is essentially highly folded laminar flame. Under the same turbulent intensity and air inlet, the combustion speed in cylinder depends on the chemical and physical properties of different fuels, namely the laminar combustion characteristics. Laminar propagation speed is a key parameter of laminar flame, and embodies the fuel diffusivity, exothermicity and reactivity. Therefore, the study of laminar flame speed contributes to the understanding of the engine combustion process in cylinder. Hydrogen has a high burning velocity that is about six times larger than that of methane at stoichiometric conditions and a lower flammability limit that is lower than those of conventional fossil fuels. Hence, hydrogen addition is one of the practical means of increasing the burning velocity of the fuel in natural gas SI engines [10].

Yu et al. [11] studied the flame propagation speed of methane and propane mixed with hydrogen, and found that hydrogen addition could increase the flame speed, which was linear to the hydrogen content. Laminar burning velocity and flame stability of LPG (mainly consisted of C_3H_8 and C_4H_{10}) with various percentages of hydrogen were studied recently in a constant volume chamber by Miao et al. [12]. The results indicated that the accelerating effect on laminar burning velocity is substantial when hydrogen fraction is larger than 60% and is insignificant when it is less than 50%.Wu et al. [13] studied the flame of ethane, ethylene, acetylene, and carbon monoxide mixed with hydrogen, and found that the laminar flame speeds of these gaseous fuels were also linear to the hydrogen content. According to the research on the effects of pressure and hydrogen addition on methane-hydrogen-air premixed flame by Halter et al. [14], hydrogen could increase the flame propagation speed and decrease the thickness of flame surface, and when pressure increased, the flame speed and thickness decreased. Tang et al. [15,16] studied the effects of pressure and temperature on the flame speed of propane mixed with hydrogen. The results showed that with the increase of mixing amount of hydrogen, propane flame propagation speed increases, and meanwhile the thickness of flame surface decreases. With the increase of initial temperature, flame propagation speed increased gradually; but with the increase of initial pressure, the flame speed gradually decreases. Hu et al. [17,18] carried on experiment and simulation study on the premixed methane-hydrogen-air flame combustion characteristic. The experiment results showed that the increase of hydrogen content in the gas mixture can enhance the flame stability and increase the laminar flame speed. And the simulation results showed, when hydrogen content is less than 40%, the flame speed increased with the increase of hydrogen content in slow growth; when hydrogen content is higher than 40%, the flame speed increase exponentially with the hydrogen content. Brower et al. [19] conducted laminar flame speed calculations for natural gas/hydrogen blends at elevated pressures. Their calculated results indicated that the effect of hydrogen addition has a greater impact on CH_4 mixtures than on NG_2 mixtures, which is because CH_4 has less impact on the heat balance of the total fuel composition than NG_2. Park et al. [20] investigated the combustion characteristics of mixtures of hydrogen, carbon monoxide, and C_1–C_4 saturated hydrocarbons with air in the counter-flow configuration. It was determined that when hydrocarbons are added to hydrogen flames as additives, flame ignition, propagation, and extinction are affected in a counterintuitive manner. Spherical premixed flames of mixtures of hydrogen, hydrocarbon (methane, ethylene, and propane), and air were studied by Law et al. [21] at NTP condition (298 K and atmospheric pressure) in a constant-pressure combustion chamber. Their results showed substantial reduction of laminar burning velocities of hydrogen with hydrocarbon substitution and support the potential of propane as a suppressant of both diffusion–thermal and hydrodynamic cellular instabilities in hydrogen–air flames, which was not found for methane and ethylene as substituents.

Additionally, Tang et al. [22] noted that hydrogen addition influences the flame speed through increased flame temperature (thermal effect), enhanced reactivity (kinetic effect) and facilitated diffusion (diffusion effect). Furthermore, their sensitivity analysis showed that the kinetic effect is the most prominent, followed by the thermal effect, with the diffusion effect being minimal. In the study of Liu et al. [23], the chemical, thermal and diffusion effects of H_2 and CO addition on the characteristics of methane laminar flame are examined numerically by using the CHEMKIN II code with a modified GRI-Mech 3.0 mechanism. The effect of H_2 addition to flame speed is mainly due to chemical effect at lean and stoichiometric conditions. However, with the addition of CO, thermal effect plays an obvious role for the increase of flame speed. In addition, the content of H + OH radicals in the flame reaction zone has a close relationship with flame speed. Wang et al. [24] reported the chemical kinetics effect of hydrogen addition on the characteristics of methane-air mixtures combustion by using Premix code in CHEMKIN II program. They showed that the promotion of chemical reaction with hydrogen addition is due to the increase of H, O and OH mole fractions in the flame as hydrogen is added. Numerical simulations on the laminar premixed C_1–C_4 n-alkanes with various hydrogen addition fractions were conducted using USC Mech II by Cheng et al. [25]. The results showed that flame parameters, including laminar flame speeds, adiabatic flame temperature, flame thickness, Lewis number, Zeldovich number and Markstein number are all altered with the increase of hydrogen addition.

The various experimental configurations used for flame speed may be classified as follows: (a) conical stationary flames on cylindrical tubes and nozzles; (b) flames in tubes; (c) soap bubble method; (d) constant volume explosion in spherical vessel; (e) flat flame methods [26]. Every approach has certain advantages that attend its usage [27–29]. In this work, a kind of flat flame method was used to measure the laminar flame speed in a counter-flow configuration combined with particle image velocimetry (PIV) system [30–32].

Please cite this article in press as: Li Z, et al., Effects of hydrogen addition on laminar flame speeds of methane, ethane and propane: Experimental and numerical analysis, International Journal of Hydrogen Energy (2017), http://dx.doi.org/10.1016/j.ijhydene.2017.07.190