ARTICLE IN PRESS

INTERNATIONAL JOURNAL OF HYDROGEN ENERGY XXX (2018) 1–12

Available online at www.sciencedirect.com

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Combustion and heat release characteristics of hydrogen/air diffusion flame on a micro-jet array burner

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ARTICLE INFO

Article history:
Received 9 February 2018
Received in revised form
11 April 2018
Accepted 19 April 2018
Available online xxx

Keywords:
Heat release rate
H_2 combustion
Micro-jet burner
OH radical
Diffusion flame

ABSTRACT

Hydrogen (H_2) is considered as a carbon-free alternative fuel. The heat release characteristics of H_2 flame as a key parameter in its combustion process are unclear. In this study, the combustion and heat release characteristics of H_2/air diffusion flame on a micro-jet array burner were experimentally and numerically investigated. It is shown that the OH distribution and flame length based on Bilger mechanism are in good agreement with the experimental results. Furthermore, the intensity and distribution of OH and heat release rate can be adjusted by the thermal power and equivalence ratio. A uniform flame with intensive heat release rate can be achieved at a thermal power of 0.1 kW. R41: $H + O_2 = OH + O$ and R43: $H + O_2 + M = HO_2 + M$ are the main reactions with oxidizer consumption to form reactive radicals. R40: $OH + H_2 = H_2O + H$ and R47: $OH + OH = O + H_2O$ with OH consumption are the main heat release reactions at the upstream and downstream of the flame.

Introduction

In recent decades, alternative and clean fuels have attracted increasing research attentions because of the global concern over energy crisis and pollutant emissions. Numerous candidates, such as biofuels, natural gas, ammonia, and hydrogen (H_2), have been proposed as alternative fuels [1–3]. Among these candidates, H_2 exhibits unique features during combustion, such the absence of CO_2 emission and other pollutants (except NO_x). Furthermore, H_2 is widely produced from various energy sources [4–7], including among others, fossil fuels (i.e., natural gas and brown coal) [4,5] and renewable sources (e.g., hydropower and solar energy) [6,7]. Therefore, H_2 holds great potential to become one of the main alternative fuels for power generation in the near future.

Numerous researches have been conducted on the co-combustion characteristics of H_2 with other hydrocarbon fuels [8–10] and H_2 addition into various internal combustion engines [11–13]. Wu et al. [9] investigated the emission and heat transfer characteristics of methane–hydrogen laminar diffusion flames. They found that the combustion temperature increased with an increase in H_2 addition ratios, leading to low emission of CO and CO_2, low flame length, and high soot-free length fraction. Meanwhile, NO_x increased due to high formation of prompt and thermal NO_x, as well as the

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https://doi.org/10.1016/j.ijhydene.2018.04.195
0360-3199/

NNH pathway, and the total heat flux approximately increased by 20% with 50% H_2 addition. Li et al. [10] simulated the combustion and heat release characteristics of biogas under various H_2-enriched conditions. The enhancement on the formation of free radicals of H, O and OH resulted in a high net heat release rate of biogas flames, which could benefit the application of biogas under H_2-enriched conditions during practical applications. Iorio et al. [12] investigated the spectroscopic characteristics of energy transfer and thermal conditions of the flame kernel in a spark engine fueled with methane and hydrogen. They applied a UV emission spectrum to detect CN and OH formation in a SI engine fueled with CH_4 and H_2-CH_4 blends (20% and 40% of H_2 by volume). The CN emission intensity confirmed only at the initial ignition stages of ignition, for which kernel temperature was high enough. With H_2 blends condition, the OH/CN emission ratios were higher than pure CH_4 condition. Yilmaz et al. [13] carried out a comprehensive investigation into the combustion and heat release of H_2 enrichment on a compression ignition engine. Combustion analysis showed a desirable combustion feature of H_2 diesel dual fuel operation. The maximum cylinder pressure and heat release rate increased, and ignition delay decreased with increasing amount of H_2 in the intake air. A comparative study on the combustion characteristics of methane, propane, and hydrogen fuels in a micro-combustor was conducted by Tang et al. [14]. Their results showed that H_2/air flame exhibited a wide range of stable flames at various equivalence ratios. The temperature gradient of combustor wall was found large because short H_2 micro-jet flames were formed near the inlet, which was different from that of methane and propane flames.

The combustion development at a micro scale has attracted significant attention due to its high energy densities [15,16]. The convection diffusion controlled laminar micro flames of ethane (C_2H_6), ethylene (C_2H_4), and acetylene (C_2H_2) were firstly investigated by Ban et al. [17]. They found that the buoyancy effects of these micro flames disappeared when the flame size decreased, and the diffusion transport was comparable to the convective transport of these fuels. To improve the combustion performance and flame stability of the micro combustor, considerable researches have been conducted to establish stable combustion in various micro and mesoscale devices, such as small jet burners [18–21], micro combustors [14,22–24], and other micro and mesoscale combustors [25–28]. Yan et al. [18] numerically simulated the effect of hydrogen addition fraction on catalytic micro-combustion characteristics of methane-air. In order to understand the micro-scale combustion mechanism for the development of micro-power devices, they developed a two-dimensional model for methane-hydrogen-air in a micro-combustion. The results showed that H_2 addition could greatly lower CH_4 ignition temperate and shorten ignition time. Furthermore, the improving effect of H_2 on the ignition temperature of the fuel was particularly evident at relatively low H_2 fraction. Li et al. [19] experimentally and numerically investigated the combustion and thermal characteristics of non-premixed H_2 flames on a micro jet burner. They found that H_2 flames varied from lifted jet, attached, hemisphere, and umbrella flames at various fuel flow velocities. The flame structure and heat release distribution on micro jet burner were affected by flame shapes, which was adjusted by fuel and air inlet velocity. Zhang et al. [21] studied the combustion characteristics of non-premixed H_2 micro-jet flames on a solid micro tube. The flame shape and height were altered at various fuel input velocities. The micro-jet tube exerted a positive effect on H_2 micro-jet flames at high H_2 input velocity. However, the effect of solid micro tube on H_2 micro-jet flames was negative at low H_2 input velocity, deviating from that on CH_4 flames. Therefore, the uniformity of fuel/air velocity distribution has a great influence on the combustion performance of micro jet combustor. In this work, we have proposed and fabricated a micro-jet array burner with high accuracy in order to obtain a uniform velocity distribution therein.

The above results have shown that H_2 has intrinsic properties such as high flame speed, high diffusion ability, low molecular weight and high burning rates etc., which is different from hydrocarbon fuels. Furthermore, the heat release characteristics of H_2 micro-jet flame are still unclear. In this study, we aim to evaluate the combustion and heat release characteristics of H_2/air diffusion flame on a proposed micro-jet array burner. To obtain a uniform fuel/air velocity distribution, a micro-jet array burner with high accuracy for H_2 combustion was fabricated. A 2D numerical simulation for a single micro-jet burner was developed. The effect of major parameters, such as thermal power, equivalence ratios on combustion and heat release characteristics was experimentally and numerically investigated, which can provide a fundamental database for H_2 combustion as a thermal supply source in the industrial process.

Experimental and numerically setup

Experimental apparatus

H_2/air diffusion flames on a designated micro-jet array burner were constructed in this study. The experimental apparatus used in this study is shown in Fig. 1. H_2/air diffusion flames were generated from a 3×3 micro-jet array burner with a fuel inner diameter of 1.00 mm and a thickness of 1.00 mm surrounded by the air inlet with an inner diameter of 3.87 mm. The pitches of each fuel and air inlet were 10.0 mm. The designated micro-jet array burner was manufactured by Ito Racing Service Co. Ltd, which presented a high accuracy of 0.01 mm. Fuel and air passed through a slanting fuel and air box before entering the fuel and air inlet. A quartz chamber with a diameter of 36.5 mm and a length of 100 mm was inserted above the burner as the combustion chamber for imaging measurement. H_2 with a purity of 99.999% (Taiyo Nippon Sanao, The Gas Professionals) and compressed dry air (21.0% O_2 and 79.0% N_2) were supplied from the respective gas pressure tanks. H_2 and air flows were regulated by mass flow controllers (Azbil, CMS0050) with an accuracy of ±1.0% full scale. OH radicals in flames were low and should capture light with UV ranges. A CCD (iStar, Andor Technology Ltd) camera with a specialized 105 mm focal length lens (F-stop = F/4.5) that can capture UV light from 250 nm to 900 nm was applied to capture OH radicals. OH distributions of H_2/air diffusion flames were detected with a filter band of 325 ± 50 nm by using a CCD camera. The flame spectrum was captured by a flame

Please cite this article in press as: Li J, et al., Combustion and heat release characteristics of hydrogen/air diffusion flame on a micro-jet array burner, International Journal of Hydrogen Energy (2018), https://doi.org/10.1016/j.ijhydene.2018.04.195