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# Flame stability and $NO_x$ emission characteristics of a high H<sub>2</sub>-content CH<sub>4</sub>/H<sub>2</sub> fueled micro-mixing burner



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#### ABSTRACT

Micro-mixing combustion technology premixes air and fuel in a microscale channel, enabling efficient mixing within a short distance can preventing flame flashback suitable for H<sub>2</sub>-enriched fuels. This approach effectively mitigates the formation of localized high-temperature zones in the flame and shortens the residence time of fuel in the high-temperature zone, thereby significantly minimizing NOx emissions. In this study, a self-designed micro-mixing multi-injector burner was constructed for burning high-hydrogen-content CH<sub>4</sub>/H<sub>2</sub> fuels. The H<sub>2</sub>/ CH<sub>4</sub> volume ratios range from 0:10 to 8:2. The effects of fuel composition and equivalence ratio on flame structure, flame stability, and pollutant emission of the CH<sub>4</sub>/H<sub>2</sub> micro-mixing combustion were investigated experimentally. The results demonstrated that even at an adiabatic flame temperature of 2100 K, the micromixing burner can achieve low NOx emissions (less than 8 ppm@15 %O<sub>2</sub>). Furthermore, compared to pure methane, highly hydrogen-enriched fuel can exhibit lower NOx emissions under stable combustion conditions. Based on the measurement of the distribution of OH radicals using Planar Laser-Induced Fluorescence (PLIF), and the captured OH\* chemiluminescence signals, the impact of H<sub>2</sub> concentration, equivalence ratio and Reynolds number on the flame morphology were investigated. The measurements suggest that hydrogen plays a pivotal role in the formation of OH radicals. For fuels with higher H<sub>2</sub> concentration, the flame height and lift-off height are smaller, and the heat release area is more concentrated. The flame with higher H<sub>2</sub> concentration can be stabilized at a lower equivalence ratio. As the H<sub>2</sub> concentration decreases, the distance between flame jets shortens, leading to gradual coupling and eventual reunion of the jet flames. When the combustion state approaches the lean blowout (LBO) limit, the flame structure of high hydrogen concentration fuel exhibits notable disparities compared to that of pure methane fuel, indicating distinct mechanisms for flame stabilization between these two fuels.

#### 1. Introduction

As a clean and efficient energy carrier, hydrogen serves as a crucial link between traditional fossil fuels and renewable energy, playing an important role in promoting the transition towards green and low-carbon energy systems [1,2]. However, the practical application of hydrogen combustion faces significant challenges due to its high reactivity, large flame propagation velocity, and risk of explosion. Currently, hydrogen-enriched fuel has been applied in industries such as coking, ammonia synthesis, and petroleum refining, etc. [1]. Nevertheless, due to the risk of flashback, these applications mainly run with diffusion combustion mode which leads to high NO<sub>x</sub> emissions, and poor flame stability [3,4]. Although the lean premixed, low swirl combustion mode can effectively suppress  $NO_x$  emissions, it is susceptible to potential

issues such as flame oscillation and flashback [5].

Due to its excellent flashback resistance and low emission performance, micro-mixing combustion technology [6,7] has garnered significant attention as an advanced combustion technique with great potential for H<sub>2</sub>-enriched fuel. The basic principle of micro-mixing combustion is the rapid mixing of air and fuel within many microchannels. Aachen University of Applied Sciences (AcUAS) proposed a micro-mixing combustion burner that integrated multiple microchannels with numerous hydrogen micro-injection holes and the combustion characteristics as well as NO<sub>x</sub> emission were investigated [8]. Zhang et al. designed a micro-mixing fuel injection burner and studied the flame temperature and emission characteristics of syngas combustion by integrating micro-mixing injection and N<sub>2</sub> dilution. The results demonstrate that an increase in N<sub>2</sub> dilution leads to a reduction of NO<sub>x</sub>

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emissions with syngas fuel [9]. Liu et al. developed a micro-mixing model burner based on the air-fuel collision effect to achieve efficient short-distance mixing [10]. Experimental and numerical investigations were conducted under atmospheric pressure conditions to study the combustion and emission characteristics of the micro-mixing model burner [11]. However, the range of hydrogen-blended ratio is limited, and there remains a lack of in-depth investigation into the flame structure, flame stability, and other characteristics associated with hydrogenrich fuel micro-mixed combustion. To achieve a more comprehensive analysis of the combustion and emission characteristics of hydrogen-rich gas fuel micro-mixing combustion, it is necessary to expand the variation range of the hydrogen-blended ratio while employing precise combustion diagnosis technology.

Motivated by the abovementioned reason, a multi-element micromixing injector burner was designed for studying the flame structure and emissions characteristics. The effects of fuel composition, equivalence ratio, and other variables on the flame structure, flame stability, and CO/NO<sub>x</sub> emissions of hydrogen-enriched methane fuels under atmospheric pressure were experimentally investigated. The instantaneous structure of the multi-jet flames was captured using a 10 Hz OH Planar Laser-Induced Fluorescence (OH-PLIF) technique, and the interaction between jets was examined.

#### 2. Experimental setup

In this paper, a novel micro-mixing burner is designed, which aims to achieve low  $NO_x$  emissions when burning hydrogen-enriched fuels or pure hydrogen. The structure diagram of the micro-mixing burner is illustrated in Fig. 1. The fuel enters from the bottom of the burner, evenly distributes through a porous plate into the capillary, and finally forms a radial high-speed jet. The inner diameter (d) of each fuel microhole is 0.5 mm, and the quenching effect of the small hole makes the

burner prevent the risk of flashback. The air enters through the inlet of the side wall of the burner, and the plenum formed between the porous plate and the bottom plate exhibits a favorable steady flow effect, ensuring uniform air distribution into the micro-mixing nozzle. In the upstream of the nozzle, fuel and air are rapidly mixed in the form of a cross-jet collision to form a mixture of fuel and oxidizer through axial flow, ultimately forming a high-speed jet at the burner outlet. The nozzle assembly comprises a central injector and six surrounding array injectors arranged hexagonally. Each injector has an inner diameter (D) of 8 mm, with adjacent injectors having a center distance (S) of 20 mm. There is a cylindrical quartz glass tube with a diameter of 100 mm and height of 300 mm placed on top of the burner to prevent the influence of environmental air. The structural dimensions of the burners are detailed in supplementary materials.

The arrangement of the optical diagnostics system is shown in the right half of Fig. 1. The OH distribution was measured using a Planar Laser Induced Fluorescence (PLIF) system. A 10 Hz Nd:YAG laser (Continuum, Powerlite 8100) was employed to pump a dye laser (Continuum, Vista), with Rhodamine 590 as a dye, after frequency doubling generating a 283.049 nm UV laser with an energy of approximately 15 mJ/pulse. The laser beam was shaped into vertical sheet through a series of lenses. The laser sheet passes through the center of the flame and excites the OH radical Q1(8) line in the flame. The OH fluorescence was captured by an ICCD camera (Princeton Instrument, PI-MAX 4, 1024 imes1024 pixels) equipped with a 105 mm, f/4.5 Nikon UV lens. To filter out laser scattering, appropriate filters (WG305 and UG11) were utilized, allowing for the acquisition of fluorescence around 308 nm wavelength. The gate width of the ICCD camera was set to 50 ns, and the delay time was adjusted to ensure of the measurement within the pulse width of each laser pulse capturing the fluorescence signal and minimizing clutter interference. The basic principle and data processing of the OH-PLIF method can be found in our previous publications [12,13].



Fig. 1. Experimental setup for micro-mixing model burner with OH PLIF diagnostic and emissions monitor.

The OH\* chemiluminescence can also independently characterize flame characteristics, including flame structure, heat release rate and so on [14–16]. For OH\* chemiluminescence measurements, an ICCD camera equipped with an OH \* bandpass filter centered at 310 nm (10 nm FWHM, peak transmittance of ~ 60 %, Alluxa) was positioned at  $60^{\circ}$  concerning the flow direction (see Fig. 1), recording the OH\* signal in the reaction zone under both stable and unstable conditions.

A quartz-glass sampling probe is installed near the glass tube outlet for collecting the flue gas samples. The sampling probe consists of an inner channel serving as a flue gas sampling and an outer channel that is connected to a circulating water pump for cooling down the probe, quenching the reaction, and minimizing potential errors during the measurements. After drying, the collected flue gas was introduced into the Testo 350 gas analyzer to analyze the flue gas species concentration i.e. O<sub>2</sub>, CO, NO, and NO<sub>2</sub>. The measurements were conducted under steady-state conditions, and a minimum of 60 data points were collected for each case at an acquisition frequency of 0.5 Hz. The emission data of pollutants measured were corrected to standard 15 % oxygen concentration (dry basis) to ensure comparability under different cases.

The experimental conditions are presented in Table 1. The micromixing burner employs mixed fuels of  $H_2/CH_4$  and operates at atmospheric pressure. The air was supplied by an air compressor, dried, and filtered to eliminate impurities, while the fuel was sourced from highpressure gas cylinders (Jingong Gas) with purities higher than 99.99 %. All gas flows were precisely regulated using mass flow controllers (MFC, Alicat) individually.

Researches have demonstrated that the analysis of OH\* chemiluminescence distribution can effectively determine flame profile structure and predict flame height [17,18]. The methodology for predicting flame height and lift-off height using OH\* chemiluminescence is illustrated in Fig. 2. A signal threshold is carefully selected, and the boundary of the reaction region with OH\* signal intensity close to this threshold is defined as the flame contour, enabling extraction from the OH\* chemiluminescence image. Typically, a general threshold within 8 %-25 % range of maximum OH\* signal strength is employed [19,20]. In this study, a threshold equivalent to 20 % of maximum OH\* signal strength was chosen after comparison, which proved effective in eliminating noise interference from background signals. Flame lift-off height refers to the distance between the nozzle exit plane and the bottom of acquired flame profile, while flame height represents the distance from bottom to peak of the flame profile. To validate reliability in extracting flame profiles through OH\* chemiluminescence method, OH-PLIF images for locating flame front and subsequently comparing obtained flame height were also compared.

The location of the flame front is determined by a single transient, time-average, and statistical OH-PLIF image, as shown in Fig. 3. Firstly, the change in intensity gradient of the OH signal within the reaction region is determined, and the contour of the flame front in each instantaneous image is drawn. The capture of contour lines is achieved through a threshold value of signal intensity. The specific process is to

	Operating	conditions	for the I	H <sub>2</sub> enriched	CH <sub>4</sub> /H <sub>2</sub>	micro-mixed burner
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Unburnt Temperature (K)	Mixing ratio $\chi_{H_2}$	Equivalence ratio $\phi$	Bulk velocity $\nu$ (m/s)
298	0	0.65, 0.7, 0.75, 0.8	18
	0.2	0.6, 0.65, 0.7, 0.75, 0.8	18
	0.4	0.55, 0.6, 0.65, 0.75, 0.8	18
		0.7	14, 18, 22, 26
	0.6	0.45, 0.5, 0.55, 0.6, 0.65,	18
		0.75, 0.8	18, 22, 26
		0.7	
	0.8	0.35, 0.4, 0.45, 0.5, 0.55,	18
		0.6, 0.65, 0.75, 0.8	18, 22
		0.7	

\* The total energy input of the flame ranges from 10 kW to 24 kW.

use the threshold value to perform binary processing on each instantaneous OH-PLIF image, obtain the binary diagram of the OH-PLIF signal, and then extract the flame front contour from the binary diagram. The flame front profile of the instantaneous OH-PLIF image can be accumulated and superimposed to obtain the two-dimensional distribution of the flame front. The intensity of the OH signal on the axial center line is extracted from the two-dimensional distribution image of the flame front, and the intensity distribution curve of OH radical along the axis can be obtained by polynomial fitting. The position corresponding to the maximum signal intensity is the position of the flame front with maximum probability, and the distance between the position and the burner outlet is defined as the flame height extracted by OH-PLIF.

#### 3. Results and discussions

# 3.1. Influence of fuel composition and equivalence ratio on the flame structure

The flame structure was analyzed using the OH\* chemiluminescence images and the OH-PLIF data. Fig. 4a and Fig. 4b present the OH-PLIF and OH\* signal distribution of lean CH<sub>4</sub>/H<sub>2</sub>/air flame under different fuel composition and equivalence ratios. The upper half exhibits the time-averaged OH\* chemiluminescence images, while the lower half displays the instantaneous OH-PLIF images for the  $58 \times 94 \text{ mm}^2$  region of interest marked in the upper half. According to the signal intensity of OH-PLIF and OH\*, the addition of hydrogen significantly increased the concentration of OH and OH\* in the flame, indicating enhancement of OH radical formation by H2 addition. The distribution analysis of OH and OH\* reveals that an increased hydrogen concentration in the mixture leads to a more concentrated heat release region, which is manifested as the flame height and width decrease. The instantaneous OH PLIF images show that in comparison to pure methane, fuels with higher hydrogen concentration exhibit intensified distortion and stretching of the flame front, and smaller vortex scales in the turbulent structure. For both fuel mixtures containing 20 %  $CH_4+80$  %  $H_2$  and 40 %  $CH_4 + 60$  %  $H_2$ , each flame jet exhibits independent behavior, with a distinct flame front observable. As the hydrogen concentration decreases, the distance between the three independent reaction zones gradually decreases. When the hydrogen concentration in the mixture is reduced to 20 %, the boundary between the micro-mixing flames is no longer clear, multiple interconnecting channels appear between each other, and the flames begin to couple with each other. If the hydrogen concentration in the mixtures is further reduced to pure methane, the micro-mixing combustion mode will change. In this case, the distinct characteristics of independent flame jets disappear, and instead, micromixing flames merge and blend, exhibiting an obvious dispersion state. According to the OH distribution, there is only a single region for pure methane at an equivalence ratio of 0.7.

The impact of varying the equivalence ratio on the flame structure of  $CH_4/H_2$  micro-mixing flame is mainly reflected in the change of heat release rate and length of the heat release region within the reaction zone. With the decrease in equivalence ratio, there is a corresponding reduction in the adiabatic flame temperature (as shown in Fig. S1) and a gradual decline in the flame heat release rate. The attenuation of OH PLIF and OH\* signal intensity can be observed, while the overall flame shape remains relatively unchanged. Furthermore, at a low equivalence ratio, the outermost flame tends to be affected by the entrainment of surrounding cold air, resulting in de-firing phenomena at the root of the outermost flame. This part will be further discussed in section 3.5.

# 3.2. Statistical analysis of the distribution of OH and OH\* in micromixing $CH_4/H_2$ flames

By detecting the distribution of OH and OH\*in the flame, the location of the chemical reaction zone can be determined, and then the flame structure can be characterized [21]. In statistical analysis of the OH and



Fig. 2. Extraction of maximum OH\* signal intensity and flame height from OH\* chemiluminescence images.



Fig. 3. Extraction of maximum OH fluorescence intensity and flame height from OH-PLIF images.

OH\* distribution of  $CH_4/H_2$  flame, the axial centerline of the central nozzle was employed as the reference line. Fig. 5a shows the variation of the maximum OH and OH\* intensity in the axial reference line of the center nozzle with the increase of equivalence ratio at different hydrogen concentrations. It can be found that with the increase of equivalence ratio, the peak OH PLIF and OH\* intensity continuously increases, but with a different trend. The difference can be elucidated from two perspectives.

Firstly, OH\*chemiluminescence is a spontaneous emission by excited

OH radicals in the flame. It is not solely determined by the concentration of OH radicals but is also affected by a variety of factors including flame temperature and chemical reaction rate. The basic principle of OH-PLIF is to use a laser with a specific wavelength to deexcite OH free radicals, thus generating OH fluorescence. The intensity of OH fluorescence mainly reflects the concentration of OH free radicals at a corresponding position on the OH PLIF measurement plane. In this work, the OH radical by the Q1 (8) line of  $A^2 \sum^+ \leftarrow X^2 \prod (1,0)$  was excited, which exhibits insensitivity to temperature variation. With an increase in the equivalence ratio, the concentration of OH radicals in the reaction zone enhances both the OH\* signal and OH fluorescence signal. However, the flame temperature and heat release rate increase at the same time, leading to a more pronounced growth trend observed in the OH\* chemiluminescence signal intensity.

Secondly, the OH\* signal captured by the ICCD camera originates from the whole flame, and its intensity represents the line-of-sight integrated OH\* chemiluminescence. In contrast, OH PLIF only comes from the measurement plane where the laser sheet is located. Therefore, the OH intensity captured by the camera is the fluorescence intensity after attenuation of self-absorption attenuation of the OH radical in each cross-section of the plane facing the fluorescence propagation direction to the ICCD camera [22]. With the increase of the equivalence ratio, the concentration of OH radical in the flame increases, and the selfabsorption effect of OH radical on fluorescence is enhanced, which makes the attenuation of the fluorescence signal emitted from the OH PLIF measurement plane to the ICCD camera more significant, and finally results in the growth trend of OH signal intensity slowing down. The peak OH and OH\* intensity increases with an increase in hydrogen concentration at the same equivalence ratio, primarily due to the enhanced heat release rate and altered distribution of the free radical pool resulting from hydrogen addition.

The variation of flame height and lift-off height with equivalence ratio is shown in Fig. 5b and Fig. 5c. Due to the higher flame propagation speed of hydrogen and the increased chain-carrying radicals such as H, O, and OH resulting from hydrogen addition, the flame height of the fuel with high hydrogen concentration is lower. Except for pure methane, the flame height extracted by the OH\* chemiluminescence image is close to that extracted by the OH-PLIF image, indicating that both methods can accurately predict flame height. For methane fuel, the flame root cannot be anchored at the nozzle outlet, causing the flame to lift off. In the method utilizing OH-PLIF images for extracting flame height, it is



Fig. 4. Structures of  $H_2/CH_4/air$  flames with (a) different fuel compositions at  $\phi = 0.7$ , and (b) different equivalence ratios at a hydrogen mixing ratio of 0.8.

defined as the distance from the top of the flame front to the nozzle outlet; hence resulting in higher values compared to those obtained using OH\* chemiluminescence image. The flame lift-off height is a crucial parameter for characterizing flame stability.

As shown in Fig. 5c, with the increase of hydrogen concentration in the fuel, the flame lift-off height significantly decreases, indicating that the addition of hydrogen makes the flame more easily anchored at the nozzle outlet and enhances its stability. This trend becomes even more pronounced when the hydrogen concentration exceeds 20 %. Research has shown that the role of hydrogen in combustion reaction transitions from that of an intermediate substance to a reactant when the hydrogen concentration exceeds 20 % [23]. At this time, the addition of hydrogen promotes the reaction  $OH + H_2 = H + H_2O$ , and the generated H radical accelerates the chain reaction  $H + O_2 = O + OH$ , making the radical group in the reaction zone rapidly increase, and strengthening the combustion of fuel. The area marked by red dashed lines represents the transition from unstable combustion condition to stable combustion condition. It can be observed that during this process, the change in flame lift-off height is particularly evident, and there is even an increase in lift-off height (in the case of 60 % hydrogen blending).

#### 3.3. Influence of Reynolds number on the flame structure

The turbulence intensity at the outlet of the burner nozzle determines the extent of heat and mass transfer in the downstream reaction zone, thereby significantly influencing turbulent combustion characteristics. The instantaneous and time-average OH-PLIF images of  $CH_4/H_2/air$  flame at different bulk velocities are depicted in Fig. 6, along with the relationship between bulk velocity and Reynolds number. The Reynolds number is defined as follows,

 $\operatorname{Re} = \frac{\rho v d}{\mu}$ 

where  $\rho$  refers to the density of mixture,  $\nu$  refers to the bulk velocity, d refers to the hydraulic diameter of the nozzle and  $\mu$  refers to the viscosity of mixture. As the exit velocity increases, the Reynolds number exhibits a nearly linear increase, indicating that the turbulence level of the downstream unburned mixture becomes severe. Due to the

interaction between turbulent flow and flame, the flame front appears highly wrinkled. The instantaneous OH-PLIF images reveal that as the Reynolds number increases, the flame front displays a greater degree of flame wrinkling and smaller-scale vortex structures.

In the case of high hydrogen-content fuels, an increase in Reynolds number induces fragmentation and distortion of the flame front, and the broken flame elements form isolated burned regions. The time-averaged OH-PLIF images reveal that increasing the bulk velocity lead to increase the flame height to some extent. For low hydrogen- concentration fuel, when the bulk velocity rises from 14 m/s to 26 m/s, there is an observable widening of the flame width, gradual convergence of adjacent jet flames, and fusion of downstream flame edges. This phenomenon can be attributed to an increasing in bulk velocity increases the turbulence intensity, which makes the mass and heat exchange between jet flames more intense, and the flame boundary is not clearly distinguishable.

#### 3.4. $CO/NO_x$ emission characteristics

The combustion characteristics, including flame temperature, flame structure, and stability, exert a significant influence on the pollutant emission performance of the burner. On the other hand, CO/NOx emissions can serve as indicators of flame characteristics for evaluating the combustion state. Fig. 7 illustrates the measurement results of CO and NOx emissions of the micro-mixing burner with adiabatic flame temperature for different fuel compositions. With the increase of the equivalence ratio, the adiabatic flame temperature increases (as calculated by CHEMKIN, refer to supplementary materials for detailed process). Except for pure methane (which exhibits a monotonically decreasing trend), the concentration of CO emissions initially experiences a rapid decline before gradually rising again. There is an inflection point when the emission concentration changes with the adiabatic flame temperature, and the higher the hydrogen concentration in the fuel, the lower the adiabatic flame temperature corresponding to the inflection point. At the same adiabatic flame temperature, increasing hydrogen concentration can effectively mitigate CO emissions. For each fuel, when the combustion condition approaches the lean blowout (LBO) limit, the flame tends to become unstable, and the CO concentration in the flue gas



**Fig. 5.** Extraction of (a) maximum OH/OH\* intensity, (b) flame height and (c) lifted-off height from OH\* chemiluminescence and OH-PLIF images. Solid line: from OH\* chemiluminescence images, dash line: from OH-PLIF images.

increases rapidly. In this work, a threshold of 100 ppm for CO emissions was defined as an indicator of combustion instability (red dashed line in Fig. 7a). If the CO emission concentration is higher than this threshold, the combustion is considered to be in an unstable state at this time.

The concentration of  $NO_x$  emissions increases with the rise in adiabatic flame temperature, as depicted in Fig. 7b. When fitting the experimental data using an exponential function, a strong correlation is observed, indicating that thermal  $NO_x$  primarily contributes to combustion-generated  $NO_x$  and the adiabatic flame temperature emerges as a key physical variable governing total  $NO_x$  emissions. The emission data marked by the red circle in Fig. 7b exhibits a significant deviation from the fitting curve, precisely corresponding to the observed unstable combustion conditions depicted in Fig. 7a. In addition, at the same adiabatic flame temperature,  $NO_x$  emission concentration increases with the increase of hydrogen concentration.

In practical industrial applications, hydrogen addition can elevate flame temperature and promote thermal-NOx formation. However, increasing the hydrogen concentration also enhances flame stability, enabling the lean blowout limit to move towards a lower equivalence ratio and expanding the stable combustion range of the micro-mixing burner. Compared to pure methane, hydrogen-enriched fuel allows for stable burning at lower equivalence ratios, effectively suppressing NO<sub>x</sub> generation due to reduced flame temperature. From this perspective, hydrogen-enriched fuel is more conducive to achieving low NOx emissions in micro-mixing burners. Therefore, the optimal approach for micro-mixing combustion lies in minimizing flame temperature while ensuring combustion stability. In general, the micro-mixing burner designed in this study demonstrates the capability to achieve low NOx emissions across a wide range of equivalence ratios and hydrogenblended ratios. Even under operating conditions with a hydrogen concentration of 80 % and an equivalence ratio of 0.8 (corresponding to an adiabatic temperature of approximately 2100 K), the concentration of NO<sub>x</sub> emissions remains below 8 ppm@15 %O<sub>2</sub>.

# 3.5. Flame instability analysis of $H_2$ enriched micro-mixing $H_2/CH_4$ flame

As a byproduct of incomplete combustion of hydrocarbon fuel, the concentration of CO can be used to assess the extent of methane combustion in hydrocarbon fuel. In Section 3.4, the concentration of CO in the flue gas was employed as an indicator to define the occurrence of combustion instability. However, the situation becomes different when dealing with high hydrogen-content fuels, and flame stability needs to be analyzed in conjunction with other flame information such as flame structure. The flame image of H<sub>2</sub>/CH<sub>4</sub>/air flame at an equivalence ratio of 0.45 at $X_{H2} = 0.8$  is depicted in Fig. 8. From the OH\*chemiluminescence image presented in Fig. 8a, it can be observed that the flame edge of the outermost flame warps due to the cooling effect caused by the surrounding air. Fig. 8b shows the time-averaged image of the flamewarping area marked by the yellow dotted line. Blow-off has occurred at the outer edge of the nozzle on the right side, indicating that part of the fuel is not burned here and entrainment of unburned fuel by the airflow in this region. In the downstream region of the flame, there is a gradual decrease in the distance between flames, leading to a convergence trend. This intensifies flame-flame interaction and accelerates heat and active component transfer between jet flames. The unburned fuel is reignited by both the central and surrounding flames. According to the instantaneous flame structure depicted in Fig. 8c, it is evident that the region marked by the yellow dashed lines exhibits an obvious reflux of OH fluorescence signal accompanied by the elongated OH fluorescence distribution. This observation signifies that a substantial number of flame-flame interactions significantly enhance the maintenance and stability of multi-jet combustion. Therefore, part of the fuel is not ignited at the nozzle, the intense interaction of multiple flames downstream of the reaction zone leads to ignition and stable combustion of previously unreacted fuel through heat transfer and diffusion of active species in both central and surrounding regions, resulting in a low CO emission.

#### 3.6. Blow-out curves and near-lean blow-off limit flame structure

Investigating the relationship between fuel composition and blow-off limit is of significant importance in the design of lean combustion burners. In this experiment, the lean blow-off limit of  $CH_4/H_2/air$  flames were measured by maintaining a constant bulk velocity while gradually reducing the equivalence ratio until flame blowout occurs. Fig. 9 illustrates the variation trend of the blowout equivalence ratio for micromixing burners with varying hydrogen concentration. It can be seen that an increase in hydrogen concentration leads to an obvious decrease in the blowout equivalence ratio. Interestingly, the relationship between the lean burn limit and hydrogen concentration can be approximated using a piecewise linear function, with a breakpoint at the hydrogen



Fig. 6. Instantaneous and time-average OH-PLIF images of CH<sub>4</sub>/H<sub>2</sub>/air flame under different bulk velocities.



Fig. 7. Variation of measured CO and  $NO_x$  emissions with adiabatic flame temperature at different hydrogen concentrations.

concentration of 30 %, suggesting that high hydrogen-content fuels may exhibit different blow-off behavior compared to low hydrogen-content fuels. Furthermore, Fig. 9 demonstrates that there is no significant change in the lean blow-off limit within a bulk velocity range of 18–26 m/s.

By examining the flame structure of CH<sub>4</sub>/H<sub>2</sub>/air mixtures near lean blow-off limits, the addition of hydrogen may have a potential effect on the blow-off behavior of fuel. As depicted in Fig. 10, for pure methane, when the combustion condition approached the lean blowout limit, a continuous and complete flame front can be observed based on the distribution of OH fluorescence. Upon adding hydrogen with a volume fraction of 40 % into the methane, at the near lean blowout limit, a complete flame front still exists. However, it exhibits less continuity compared to that observed during pure methane combustion with more tips and wrinkles on the flame front. Furthermore, discrete irregular regions (islands) are observed in the unburned region. This special flame structure may be related to the local blowout and reignition of the flame surface [24]. As the hydrogen concentration continues to increase to 80 % by volume, an interesting phenomenon can be found although the flame does not blow out, there is no specific flame front structure, instead with a large number of discrete irregular reaction zones (islands). This distributed combustion condition is similar to MILD combustion, and its specific flame stabilization mechanism needs to be further explored. From the perspective of the distribution region, these isolated burned regions are mainly located between two jet flames, specifically within the inner recirculation region. This phenomenon has been reported in ultra-lean swirling CH<sub>4</sub>/H<sub>2</sub>/air flames, that is, when the equivalence ratio is reduced to the near-lean blow-off limit, hydrogenenriched flames would break into isolated flame elements and move to the inner recirculation region and stabilize there [25]. Flames with high hydrogen concentration are prone to occur local extinction under nearlean blowout limit conditions. Due to the high diffusivity, the unburned reactant moves to the inner recirculation region and accumulates there, leading to an increase in the local equivalence ratio within this region, which promotes the formation of the isolated burned region in the inner recirculation region. Although it is in an unstable combustion state at this time, if increase the fuel flow rate, the unstable combustion state can be quickly transformed into a stable combustion state. Therefore, the indepth study and analysis of the near blowout limit flame structure of hydrogen-rich fuel has far-reaching significance for the development of efficient combustion organization methods in the future.



Fig. 8. Flame stability analysis of H<sub>2</sub>/CH<sub>4</sub>/air flame at equivalence ratio of 0.45 at hydrogen mixing ratio of 0.8.



Fig. 9. Lean Blow-off limits of  $\rm CH_4/H_2/air$  micro-mixing flames as a function of hydrogen concentration.

#### 4. Conclusion

A new type of micro-mixing multi-injector burner is developed for the combustion of hydrogen-rich fuels. Through the measurement of CO/NOx concentration in flue gas, combining OH-PLIF technology and OH\* chemiluminescence images captured by ICCD camera, a comprehensive experimental investigation is conducted on the influence mechanism of fuel composition and equivalence ratio on flame structure, flame stability, and pollutant emission characteristics of microblended  $CH_4/H_2$ . The main conclusions are presented below.

 Micro-mixing multi-injector burner can achieve low NOx emissions, even when the hydrogen blending ratio is 80 % and the equivalence ratio is 0.8; the concentration of NOx emissions remains below 8 ppm@15 %O<sub>2</sub>. Increasing the hydrogen concentration in the fuel significantly reduces CO emissions, promoting complete combustion of  $CH_4/H_2$  fuel. However, it should be noted that this increase in hydrogen concentration also leads to an elevation in NOx emissions. In terms of both stable combustion and NOx emission control, high hydrogen-content fuel exhibits superior advantages over pure methane fuel.

- (2) The increase in hydrogen concentration in the fuel promotes the generation of OH free radicals within the flame, reduces the flame height and flame lifting height, and makes the flame heat release zone more concentrated. Under lean combustion conditions, the increase of equivalence ratio can accelerate the combustion speed and elevate OH radical concentrations within the flame, thereby facilitating thorough fuel oxidation.
- (3) Fuels with varying hydrogen concentration exhibit distinct flame structures near the lean blowout limit. Pure methane and methane/hydrogen fuel with a 40 % hydrogen ratio display a complete flame front, whereas methane/hydrogen fuel containing 80 % hydrogen lacks a flame front but instead exhibits numerous discrete irregular reaction zones (islands).

#### CRediT authorship contribution statement

Runfan Zhu: Writing – original draft, Methodology, Data curation, Conceptualization. Wubin Weng: Writing – review & editing, Validation, Methodology, Investigation. Siyu Liu: Writing – review & editing, Validation, Methodology, Formal analysis, Data curation. Wenyu Wang: Writing – review & editing, Validation, Methodology, Data curation. Yong He: Writing – review & editing, Validation, Methodology, Conceptualization. Zhihua Wang: Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization.

#### Declaration of competing interest

The authors declare that they have no known competing financial



Fig. 10. Instantaneous flame structure of H<sub>2</sub>/CH<sub>4</sub>/air flame at near lean blowout limit by OH-PLIF.

interests or personal relationships that could have appeared to influence the work reported in this paper.

#### Data availability

Data will be made available on request.

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#### Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.fuel.2024.132506.

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