Effects of hydrogen addition on the stabilization of lean premixed swirl flames

Weijie Zhang[a], Jinhua Wang[a*], Wenjun Lin[a], Bingxuan Lin[b], Yun Wu[b], Meng Zhang[a], Zuohua Huang[a]
[a]State Key Laboratory of Multiphase Flow in Power Engineering, Xi'an Jiaotong University
Xi'an, Shaanxi, China
[b]Science and Technology on Plasma Dynamics Laboratory, Air Force Engineering University
Xi'an, Shaanxi, China

Abstracts

This paper described an experimental study on the effects of hydrogen addition on the stabilization of ultra-lean premixed CH_4/H_2/air flames. The flames were stabilized with a bluff-body and swirl burner. Flame structure and flow characteristics were investigated with simultaneous measurements of OH-PLIF and PIV. It is observed that, the hydrogen addition promotes the flame towards the main flow and the direct distortion from shear layer vortexes is decreased. The flamelet conditioned straining shows different patterns of flow shear forces. Especially, the resistance to the straining near flame attachment with hydrogen addition is probably the vital step for the hydrogen to stabilize the lean flames.

1 Introduction

Lean premixed (LPM) combustion may be one of the most promising ways to attain clean and efficient conversion of fuels to energy [1-4]. The increasingly strict regulations for emission has led to the urgent need for application of LPM in gas turbines. However, even today the LPM combustion has only been partially applied with acceptable cycle efficiency penalties [3]. The lean premixed flames, if applied to real combustor, are generally assisted with a pilot diffusion flames, or only partially operated [3]. This is because the LPM combustion is hindered by the flame stabilization, especially the blowoff behaviors of the fast flowing, lean flames [3, 5, 6]. One solution is by introducing more reactive fuels into the mixtures such as hydrogen (H_2) and the flame will be more stable in respect of the blowoff behaviour [7, 8].

The effects of hydrogen addition on flame stabilization have been revealed by studies before [7-9]. The hydrogen addition has been generally discussed to increase the laminar flame speed, resistance to the strain-induced extinctions and higher adiabatic flame temperature. Strakey et al. [8] invoked non-dimensional parameters such as Damköhler number, Peclet number to model the blowout data. Zhang et al. [7]

investigated the hydrogen added flames on a swirl burner and it was observed that the increase in hydrogen content induced a thin columnar shape flame which was observed to be critical for the flame stabilization. Li et al. [9] investigated the hydrogen addition on precessing vortex core (PVC) instabilities. The combustion suppression impacts on PVC was observed. The recirculated mass flow into center recirculation zone (CRZ) was decreased with hydrogen addition as was observed by Kim et al. [10]. This effect was assumed to increase the temperature in CRZ and thus the hydrogen contained flames can be more stable.

However, detailed interactions between flamelet and flow were not fully characterized in previous studies. The flames were demonstrated roughly with OH* chemiluminescence in Ref. [7]. Li et al. [9] studied only the flow field of the flames. Instead, detailed flame front is capture in present study and the corresponding flow field is obtained simultaneously. So, an investigation on more detailed interactions between hydrogen contained flame and flow can be possible. The results will be helpful for designing more efficient hydrogen-assisted engine system.

2 Experimental methods

Figure 1(a) shows the schematic of the burner. The burner consists of a buffer chamber, a venturi nozzle, a premixing tube and an assembly of the swirler and bluff-body. Compressed air is firstly introduced into the buffer chamber. The air is then accelerated and depressurized during the constricted section of a venturi nozzle. The high speed air (subsonic) blows upwards the fuels introduced through a multi-holed injector at the nozzle throat. The mixture is decelerated at the divergent stage and further premixed in the premixing tube. The premixing tube is 200 mm in length and with a 35 mm inner diameter.

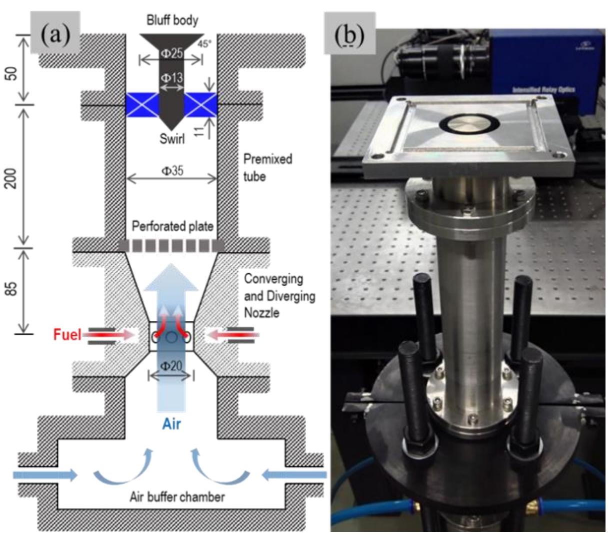

Figure 1. (a) Swirl burner schematic; (b) a direct photo of upper part of the burner

The swirler and the bluff-body are combined with a thread connection. The bluff-body is supported by the swirler and they are concentrically fitted at downstream of the premixing tube. Maximum diameter of the bluff-body is 25 mm. Hub diameter of the bluff-body is 13 mm, and outer diameter of the swirler is slightly above 35mm.The swirler is imparted by eight vanes at with θ = 45°respect to the burner axis. The swirl number can be estimated to be about 0.7.

The experimental setup is shown in Fig. 2. The system is comprised of a LaVision Particle Image Velocimetry (PIV) system and a Planar Laser Induced Fluorescence of hydroxyl (OH-PLIF) system. For the OH-PLIF system, the YAG laser produced a 532 nm laser beam with pulse energy of about 300 mJ. Using a Rhodamine 6G dye solution, the laser beam was then tuned to about 283 nm with pulse energy of 15 mJ by a dye laser for OH excitation. For the PIV system, a dual pulsed YAG laser produced two 532 nm laser beams. The PIV laser beams and OH-PLIF laser beam were transformed to laser sheets, and aligned across the center of the burner from two opposite directions. The two individual systems were externally triggered by a delay generator with a time interval of 10 μs. The systems were operated at 10 Hz. Size of the OH-PLIF snapshots was 600×800 pixels (after a 2x2 binning), with resolution of 0.145mm/pix. The field of PIV was about 1200×1600 pixels, with resolution of about 0.089mm/pix. An interrogation window of 32×32 and an overlap ratio of 50% were adopted for vector processing. This resulted in a velocity field with vector spacing of nearly 1.43 mm. The uncertainty normalized by the bulk velocity was about 4.9 %.

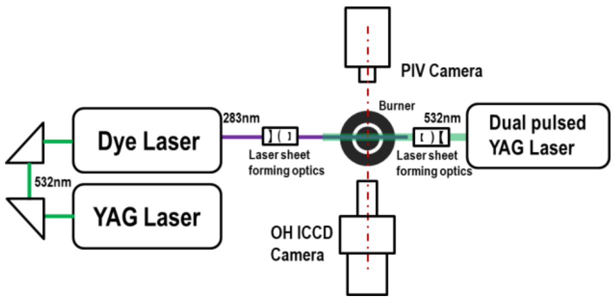

Figure 2. Experimental setup

Hydrogen fractions of the CH_4/H_2/air mixture were 0, 40% and 80% in this study. Three equivalence ratios at lean condition were chosen. Flame A2 and A3 with hydrogen addition were with ϕ=0.55. However, without hydrogen addition, flame A1 was blow off at about ϕ=0.60. So, for the CH_4/air mixture, the equivalence ratio was set at 0.65 which is very prior to blowoff. The bulk velocity of the flow was kept as a constant of U=20m/s. The laminar flame speed ($S_{L,0}$) and Lewis number are shown in Table 1. The laminar flame properties are estimated with CHEMNKIN Pro with GRI 3.0 [11].

Table 1: Mixture properties of present study.

Flame	ϕ	Z_{H2}	$S_{L,0}$/cm·s^{-1}	Le
A1	0.65	0	15.1	0.99
A2	0.55	40%	11.7	0.78
A3	0.55	80%	25.3	0.57

3 Results and discussion

3.1 *OH-PLIF results*

Figure 3 shows the raw OH-PLIF snapshots of flame A1 to A3. The flames are seriously disturbed. Without hydrogen, flame A1 seems even cut through by the flow close to blowoff. This is probably a result from the downstream backflow. Flame A1 now resides nearly in the shear layer between CRZ and the main flow.

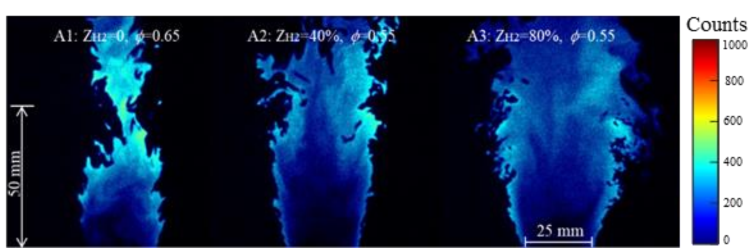

Figure 3. Instantaneous OH-PLIF results

However, the hydrogen contained flames are more outwardly expanded away from CRZ. This indicates that the flames burn more intensively with hydrogen. To gain more insights after the hydrogen contained flames are proceeding away from the CRZ, the simultaneous flow and flame characteristics are necessary. The sharp boundary of the OH-PLIF result has been commonly regarded as the flamelet where reaction exists [12]. As shown in Fig. 4 (a), the raw OH-PLIF image is firstly background subtracted, laser beam corrected. Then it is transformed to a gray-scale image and binarized with the Otsu's method [13]. The binarized image in Fig. 4 (b) is white in burned area (ones) and black in unburned area (zeros). The unburned and burned pockets are eliminated. The flame front (flamelet) is extracted by detecting the edge of the binarized image.

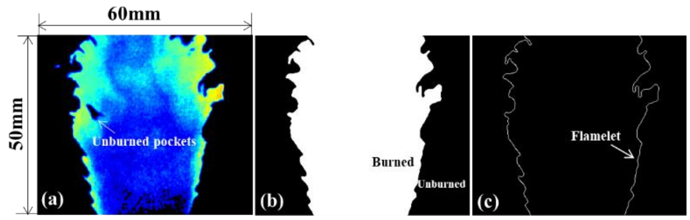

Figure 4. (a) Adjusted raw OH-PLIF; (b) binarized result; (c) flame front extracted

3.2 *Effects of flow straining*

With the flamelet extracted above, the flamelet itself can be conditioned as a coordinate. Then the flamelet conditioned flow characteristics can be obtained [14]. Flamelet conditioned flow straining is derived below to explore the flame-flow interaction mechanism.

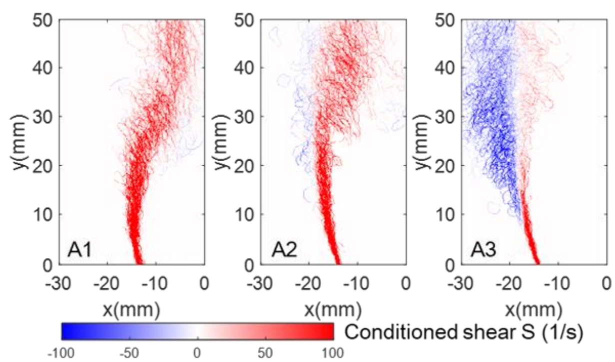

Figure 5. Flamelet conditioned in-plane shear

The straining demonstrated with the in-plane shear is analyzed. This straining highlights the variations in the local shearing dynamics as also adopted in Refs. [14, 15]. The in-plane shear is defined here as:

$$S=-\frac{1}{2}\cdot(\frac{\partial u}{\partial y}+\frac{\partial v}{\partial x}) \tag{1}$$

where u, v are the velocity components along x and y directions. The flamelet conditioned shear is shown in Fig. 5. It can be seen that, for flame A1, the shear force is all positive indicating a prevalent northwest-southeast stretch along the main flow. Such lengthways straining is induced by the fast flowing unburned mixtures. With hydrogen addition, the flames are penetrating outwardly. The negative shear strength is now appeared especially at downstream. The negative sign of shear indicating a directional change in the shearing of fluid elements. The main flow now impinges on the expanded flames which may reinforce the burning intensity at downstream.

However, it is noted that at the flame root, the positive shear strength remains. This indicates that the flame stabilization near the attachment is probably still periled just as the flame A1 due to the lengthways positive shear forces induced by the fast flow. The flames of A2 and A3 show increased burning velocities according to their expanded flame brush wings. This can be primarily explained with their increased $S_{L,0}$ and decreased Lewis numbers in Table 1. The reinforced burning provides resistance to the local extinction at flame roots, which may be very vital for hydrogen addition to stabilize the flames.

3.3 *Effects of the vortexes*

The vortexes are identified with the Q -criterion. According to Chen et al. [16], the vorticity Q can be defined as:

$$Q = \frac{1}{2}(\|\Omega\|^2 - \|S\|^2) \tag{2}$$

where Ω is the rate-of-rotation tensor and S is the strain tensor. The simplified formula (2) based on a 2D velocity gradient tensor is:

$$Q = \frac{\partial u}{\partial x}\frac{\partial v}{\partial y} - \frac{\partial u}{\partial y}\frac{\partial v}{\partial x} - \frac{1}{2}\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}\right)^2 \tag{3}$$

Figure 6 shows the instantaneous flame front and the corresponding vortexes distinguished. For flame A1 without hydrogen, the flamelet is pushed into the shear layer. There the flames are subjected to stronger flow-induced corrugation from Kelvin–Helmholtz vortices. The flamlet is obviously distorted by the vortexes. Though the distortion may increase the flame wrinkling thus increase the local buring velocity [17], the risk of local extinction also increases probably due to excess stretch. With addition of hydrogen, the distortion of vortex on flame A2 is reduced. For flame A3, the flamelet nearly resides in the main flow between the inner and outer shear layers.

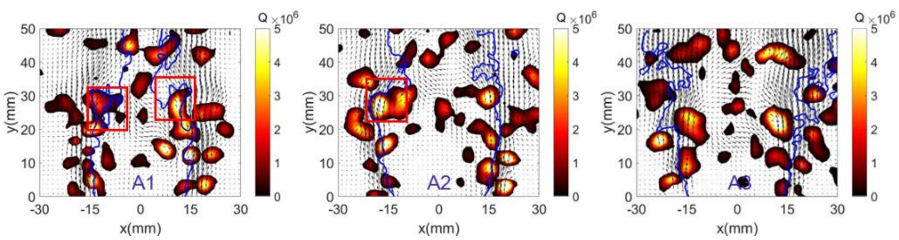

Figure 6. Instantaneous flame front and the corresponding vorticity field

It can be expected that due to the vortexes shed off from the shear layer, the cold reactants will be more easy to be carried into the flame kernel in CRZ if the flamelet is locally extinct. Such a process may decrease the temperature in CRZ and is unfavourable for flame stabilization. However, with hydrogen addition, the vortexes shed off from the shear layer is less dominating.

4 Conclusions

The results show the extraordinary stabilization effects of hydrogen addition on the ultra lean swirl flames as were also observed in literature. Hydrogen fraction of the hydrogen contained flames investigated was up to 80%. The flame front, the corresponding flow straing and vortex field were studied. It was observed that the hydrogen contained flames proceed more outwardly to resiede in the main flow. The hydrogn contained flames thus reduce the distortion and cooling effects from shear layer vortexes. Moreover, the increased resistance to the strong shear forces at flame roots is also vital for flame stabilization.

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