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BURNING RATES AND SURFACE CHARACTERISTICS OF HYDROGEN-ENRICHED TURBULENT LEAN PREMIXED METHANE-AIR FLAMES

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ABSTRACT

The burning rates and surface characteristics of hydrogen-enriched turbulent lean premixed methane-air flames were experimentally studied by laser tomography visualization method using a V-shaped flame configuration. Turbulent burning velocities were measured and the variation of flame surface characteristics due to hydrogen addition was analyzed. The results show that hydrogen addition causes an increase in turbulent burning velocity for lean CH_4-air mixtures when the turbulent level in the unburned mixture is not changed. The increase rate of turbulent burning velocity is higher than that of the corresponding laminar burning velocity, suggesting that the increase in turbulent velocity due to hydrogen addition is caused by not only chemical kinetics effect, but also the variation in flame structure due to turbulence. The further analysis of flame surface characteristics and brush thickness indicate that hydrogen addition slightly decreases local flame surface density, but increases total flame surface area because of the increased flame brush thickness. As a result, turbulent burning velocity is intensified by the increase in total flame surface area and the increased laminar burning velocity, when hydrogen is added.

INTRODUCTION

Lean premixed combustion is a promising concept for substantial reduction in fuel consumption and emissions of greenhouse gases and pollutants. It involves operation at lower equivalence ratios to reduce flame temperatures. At these lower temperatures and equivalence ratios, NO formation from thermal and prompt routes can be effectively suppressed. Emission of soot, the predominant source of particulate matter and a major global warming contributor, can also be essentially eliminated in these flames.

However, lean premixed combustion has some intrinsic weaknesses. These include that at a lower equivalence ratio, the lean flammability limit is approached and flame speed becomes very low. A strategy to overcome the weaknesses of lean premixed combustion is to adopt fuel enrichment, i.e. adding a small amount of other fuel, to extend the flammability limit, increase flame speed and improve flame stability, while maintaining the advantages of lean premixed combustion. It has been shown [1-5] that hydrogen or reformate gas enrichment can extend the flammability limit and reduce emissions of CO and NO in lean premixed flames. Besides, the addition of hydrogen to a hydrocarbon fuel also increases the laminar flame speed [2,6-8]. However, the data of burning velocities of hydrogen-enriched turbulent premixed flames are relatively limited.

Due to its significant importance in application, huge amount of efforts have been attempted on turbulent burning velocity, following the pioneering work of Damköhler [9]. Various expressions have been proposed for turbulent burning velocity base on experimental results. Although these expressions differ, most of them can be written in the form similar to [10]

$$S_T / S_L = 1 + A\left(v' / S_L \right)^n \quad (1)$$

with S_T, S_L and v' being turbulent burning velocity, laminar burning velocity and the root-mean-square velocity fluctuation, respectively, and A being a quantity dependent on the length scale ratio. According to this kind of correlations, S_T/S_L should have decreased when hydrogen is added to a hydrocarbon premixed flame at a similar turbulent level, since S_L increases [6-8] and thus v'/S_L decreases.

About twenty years ago, Liu and Lenze [11] investigated turbulent burning velocities of CH_4-H_2 flames at various turbulent levels. They found that turbulence effect did remain uninfluenced by fuel composition, provided S_L was maintained constant. Therefore, the turbulent velocities could still be expressed by a correlation similar to Eq. 1 for CH_4-H_2 turbulent premixed flames. Mandilas et al. [12] investigated the effect of hydrogen addition on laminar and turbulent burning velocities using spherical expanding flames. They also observed that S_T/S_L did not significantly change with the addition of hydrogen at a similar turbulent condition. However, the study of Goix and Shepherd [13] noted that for the same turbulent flow condition, the turbulent flame front surface area was sensitive to the Lewis number, suggesting that the addition of hydrogen may change the characteristics of turbulent premixed combustion due to the variation in Lewis number. A DNS study by Hawkes and Chen [14] indicated that turbulent burning velocity increased faster than laminar burning velocity due to the addition of hydrogen for a lean CH_4-air mixture at a same turbulent condition, implying that turbulent burning velocity cannot be expressed by a correlation similar to Eq. 1. More recently, the experimental study of Cohé et al. [15] showed that the addition of hydrogen to a CH_4-air premixed flame resulted in an increase in fractal dimension, which also implied that the addition of hydrogen at a similar turbulent level led to an increase in S_T/S_L, based on the fractal theory [16]. These contradictory results in the literature suggest that the current understanding on the effect of hydrogen addition on turbulent premixed combustion is not enough. There is a need to further investigate how the addition of hydrogen affects turbulent premixed combustion characteristics of hydrocarbon fuels.

In this paper, the effect of hydrogen addition on the characteristics of CH_4-air turbulent premixed flames is experimentally investigated by a V-shaped flame configuration. Laser tomography visualization method was employed to measure burning velocities and surface characteristics. The paper starts with the introduction of experimental setup and methodology. Then the results are presented and discussion is provided. Finally concluding remarks are drawn.

EXPERIMENTAL METHODOLOGY

Flame Configuration and Conditions

The studied flame configuration is shown in Fig.1. The premixed CH_4/H_2-air mixture issued from a wind tunnel (11.5 x 11.5 cm^2). The flame was stabilized by a 2 mm diameter rod which is located at the center of the tunnel exit. The turbulent intensity at the exit of the tunnel was controlled by a perforated plate set at 5.0 cm upstream of the tunnel exit. All experiments were conducted at room temperature and atmospheric pressure condition.

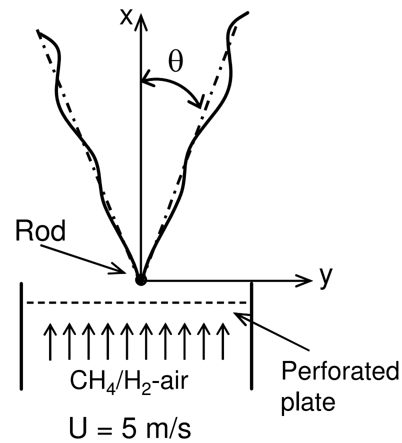


Fig. 1 Flame configuration.

The mean velocity (U) of unburned CH_4/H_2-air mixture at the exit of the tunnel was kept as 5.0 m/s for all flames. Two perforated plates were used to generate different turbulent intensities. A measurement by Laser Doppler Anemometry (LDA) showed that the two perforated plates generated two sets of turbulent levels at the tunnel exit. The turbulent intensity and integral length scale of the first set is 4.0% (v'=20.0 cm/s) and 4.8 mm, respectively, while they are 8.0% (v'= 40.0 cm/s) and 7.3 mm for the second set. These two sets of turbulent parameters generated two sets of turbulent Reynolds numbers (Re_L) around 60.0 and 180.0.

The fraction of added hydrogen is defined as $\alpha_{H2} = V_{H2}/(V_{H2} + V_{CH4})$, with V_{H2} and V_{CH4} being, respectively, the volume flow rates of hydrogen and methane in the unburned mixture. The complete combustion of the fuel mixture goes via the reaction $(1-\alpha_{H2})CH_4 + \alpha_{H2}H_2 + \frac{1}{2}(4-3\alpha_{H2})O_2 = (1-\alpha_{H2})CO_2 + (2-\alpha_{H2})H_2O$. Therefore, the stoichiometric fuel-oxidant volume ratio in a CH_4/H_2-air mixture is:

$$\left(F/O\right)_{st} = 2\big/\left(4-3\alpha_{H2}\right) \qquad (2)$$

Equivalence ratio is defined as the ratio of actual fuel-oxidant ratio to the stoichiometric value, i.e.

$$\phi = \left(F/O\right)\big/\left(F/O\right)_{st} \qquad (3)$$

Two equivalence ratios (0.55 and 0.60) were investigated. The fraction of hydrogen (α_{H2}) varied from 0 to 0.3 in this paper. For these flames, the quantity v'/S_L lies between 1.0 and

2.0. Most flames studied in this paper are in the wrinkle flame regime.

Flame Image Processing

Laser tomography technique was used to study flame structures and to measure turbulent burning velocities. The unburned mixture was seeded with incense particles and illuminated with a laser sheet created by Nd:YAG (120 mJ) laser source. Tomography of the flame front and position were recorded by a CCD camera (1376 x 1024 pixel^2). To avoid the effect of stabilization rod, the image window was located above tunnel exit, starting at x = 40 mm and ending at x = 140 mm.

Three hundred images were taken for each flame. The images were analyzed and binarized by an edge-finding algorithm of Matlab Software to generate the binary images of burned and unburned regions of each flame, with burned region having value unity and unburned region having value zero. The mean progress variable (C) of each flame was obtained by summing and averaging the three hundred instantaneous binary images. This led to a mean progress variable map whose value changes gradually from zero (unburned region) to unity (burned region) for each flame. We define a flame brush thickness at each section above the tunnel exit as the distance between the progress variable values 0.01 and 0.99 along the horizontal (y) direction.

To understand the variation of turbulent characteristics when hydrogen was added, flame surface density was obtained. For each flame, the instantaneous flame front position was fitted by a polynomial curve based on the binary image. Then flame surface density of each flame was calculated as suggested by Veynante et al. [17]:

$$F_{SD} = \frac{1}{n}\sum \frac{dL}{ds} \tag{4}$$

where n is the number of images, dL is the infinitesimal flame front length in the surface element ds that is 10x10 pixel^2 (about 0.8x0.8 mm^2).

For each instantaneous image, flame angle (θ) was calculated based on two positions on the flame front. Then the mean flame angle ($\overline{\theta}$) of each flame was obtained by averaging the angles of all three hundred instantaneous images. The turbulent burning velocity of each flame was then obtained by

$$S_T = U \sin \overline{\theta} \tag{5}$$

RESULTS AND DISCUSSION

The effect of hydrogen addition on turbulent burning velocity is examined first. Figure 2 displays the variation of turbulent burning velocity at two different turbulent intensities (TI) and two equivalence ratios (ϕ), when the fraction of hydrogen (α_{H2}) is gradually increased. It is revealed that the addition of hydrogen results in an increase in turbulent flame speed at a constant equivalence ratio and a similar turbulent level. This is as expected and qualitatively consistent with the variation trend of laminar flame speed [6-8].

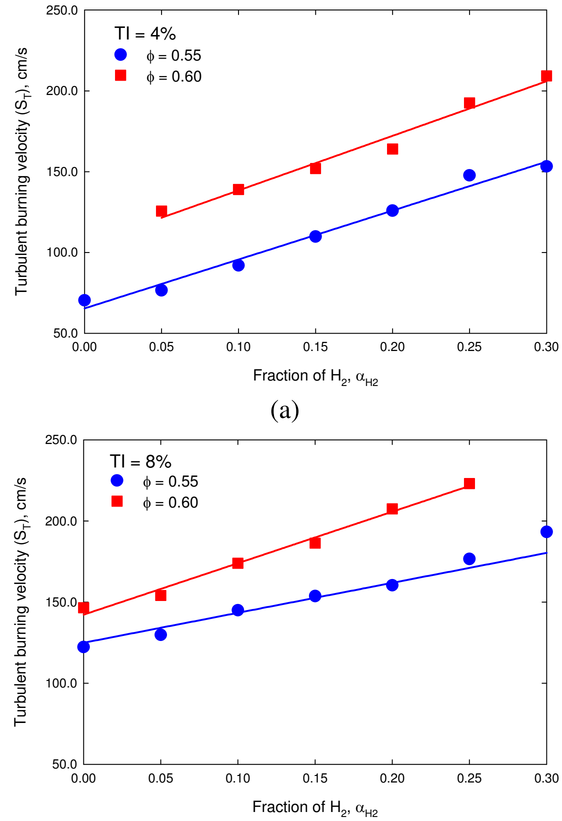


Fig. 2 Variation of turbulent burning velocity with the addition of hydrogen. (a) TI = 4%; (b) TI = 8%.

The increase in turbulent burning velocity with increasing hydrogen fraction could be caused by chemical kinetics, which is usually reflected by the variation in laminar burning velocity, or/and turbulence caused variation in flame structure, such as flame surface density, etc. It has been clear from the early studies [6-8] that the addition of hydrogen causes an increase in laminar burning velocity at a constant equivalence ratio. This is one factor that leads to the increase in turbulent burning velocity.

To figure out the influence of turbulence on burning velocity, Fig. 3 shows the variation in the ratio of turbulent to laminar burning velocities (S_T/S_L), where the laminar burning velocities used are those obtained experimentally by Yu et al. [6]. It is observed that the ratio of turbulent to laminar burning velocities also increases with increasing the fraction of hydrogen at a constant equivalence ratio and similar turbulent level in unburned mixture, although v'/S_L decreases due to the increased S_L. This indicates that turbulent burning velocity increases faster than laminar burning velocity due to the addition of hydrogen, suggesting that kinetic effect is not the sole factor that increases flame velocity when hydrogen is added to a turbulent flame. This result is inconsistent with most previous turbulent premixed flame experimental data, which showed that turbulent burning velocities can be expressed by a correlation like Eq. 1 [10] or other similar forms which suggest that turbulent flame speed decreased with reducing v'/S_L. It is also contradicts the result of Liu and Lenze [11] and Mandilas et al. [12], who indicated that the turbulence effect remained uninfluenced by fuel composition, provided S_L was maintained constant. However, it supports those observed by Haekes and Chen [14] who suggested that turbulent burning velocity increased faster than laminar burning velocity due to hydrogen addition, and Cohé et al. [15] who observed that the addition of hydrogen increased the fractal dimension, which also implied the increase in the ratio of turbulent to laminar burning velocities based on fractal theory [16]. The reason that the current results cannot qualitatively expressed by most previous correlations like Eq. 1 may be that most previous results were obtained by hydrocarbon fuels and focused on the influence of turbulence intensity. It is not clear what causes the difference between the results in this paper and those by Liu and Lenze [11] and Mandilas et al. [12].

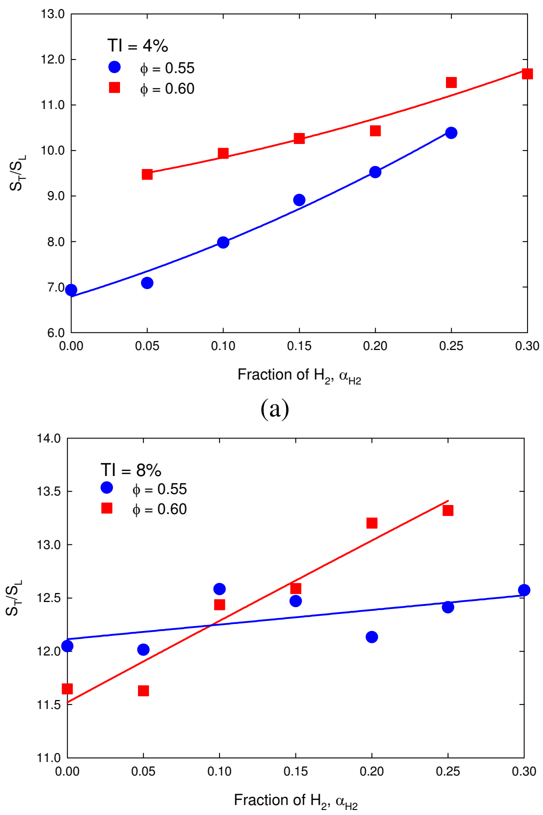


Fig. 3 Ratio of turbulent to laminar burning velocities. (a) TI = 4%; (b) TI = 8%.

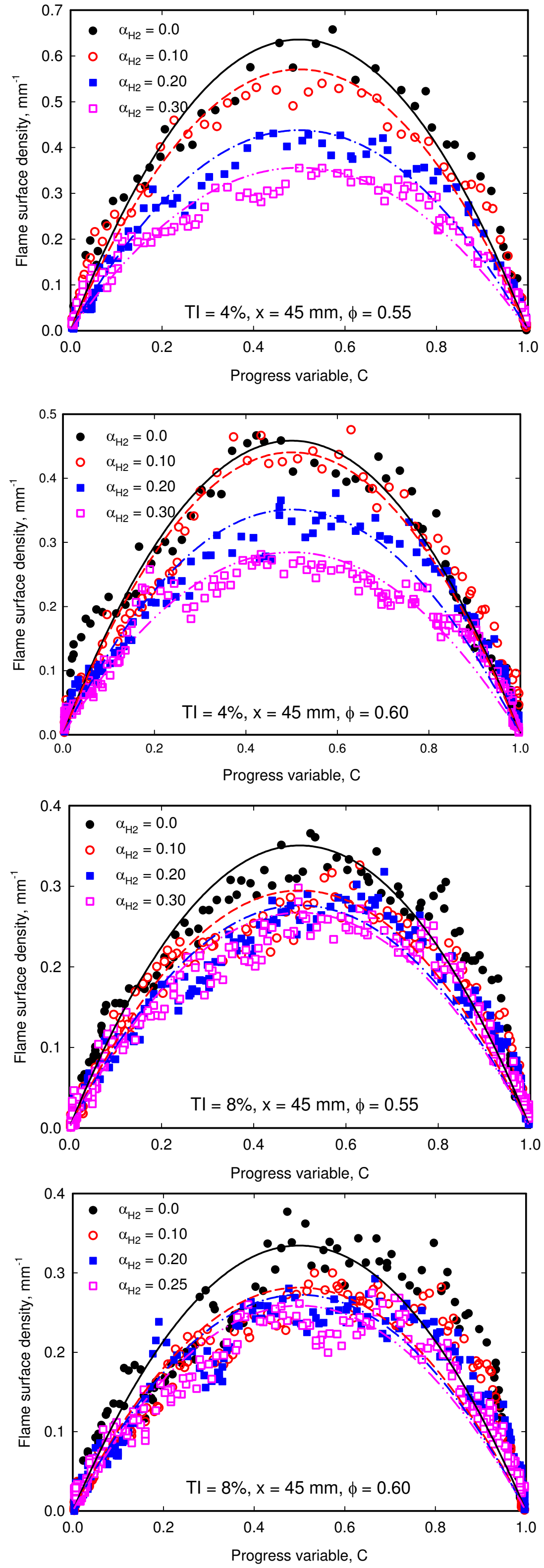


Fig. 4 Flame surface density. The scattered points are measured, and the lines are regression results based on the form $\sum = kC(1.0 - C)$.

According to the flamelet theory [18], a turbulent flame zone is viewed as an ensemble of laminar flamelets whose local burning rates are determined by the local flame stretch. The total burning rate of a turbulent flame is the integration of the local laminar burning rate over the whole flame brush region by [19]

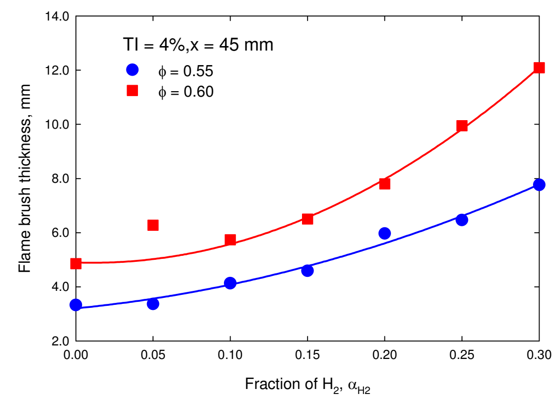
$$\overline{W} = \int_0^{1.0} \rho_u S_L I_0 F_{SD} dC \qquad (6)$$

where C is progress variable, ρ_u the unburned gas density, I_0 the mean modification to S_L due to stretch, and F_{SD} the local flame surface density. Although the debate on flamelet theory is still going on, it can qualitatively explain most turbulent flame phenomena. In this paper, the turbulent burning velocity mentioned above is a reflection of the total burning rate, i.e. $S_T \propto \overline{W}$. Therefore, turbulent burning velocity qualitatively depends on S_L, I_0 and F_{SD}. As mentioned, early studies [6-8] have shown that the addition of hydrogen increases laminar burning velocity (S_L). Therefore, we'll discuss the effects of other factors.

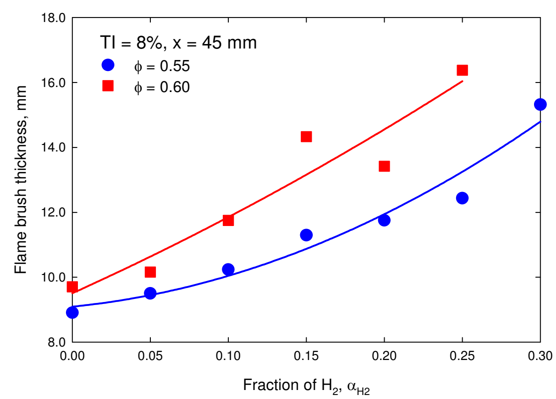
Figure 4 shows the flame surface density (F_{SD}) distribution in the progress variable space at the section x = 45 mm above the tunnel exit. Other sections have similar results. It is observed that local flame surface density decreases with increasing the fraction of hydrogen at a constant equivalence ratio and similar turbulence level. This seems to contradict the phenomena observed in Figs. 2 and 3. However, as mentioned before, turbulent burning velocity is a reflection of the overall burning rate, i.e. an integrated quantity over the whole flame brush region. Therefore, in addition to local flame surface density, we should also examine the flame brush thickness.

Figure 5 displays the variation of flame brush thickness at the section x = 45 mm when hydrogen fraction is gradually increased. Other sections have similar results. It is noted that the addition of hydrogen results in an increase in flame brush thickness at a constant equivalence ratio and similar turbulent level. This is because the addition of hydrogen reduces the fuel Lewis number to a value less than unity. The local burning rate of a lower Lewis number mixture is enhanced by stretch. The enhanced burning rate further intensifies the flame surface wrinkle. Such a process results in the increase in flame brush thickness.

The increase in flame brush thickness may result in the increase in the turbulent burning velocity at a constant equivalence ratio and similar turbulent level, when hydrogen is added. We can indirectly confirm this by integrating the local flame surface density over the flame brush region along the horizontal (y) direction. Figure 6 shows the variation of the integrated flame surface density with increasing the fraction of hydrogen. It is observed that the integrated flame surface density increases with the addition of hydrogen at a constant equivalence ratio and similar turbulent level. This contributes to the increase in the overall burning rate, i.e. the turbulent burning velocity, as indicated by Eq. 6, although the local flame surface density slightly decreases when hydrogen is added. Therefore, the addition of hydrogen increases the overall flame surface area and thus turbulent burning velocity. This supports the observations of Goix and Shepherd [13] and Hawkes and Chen [14].



(a)



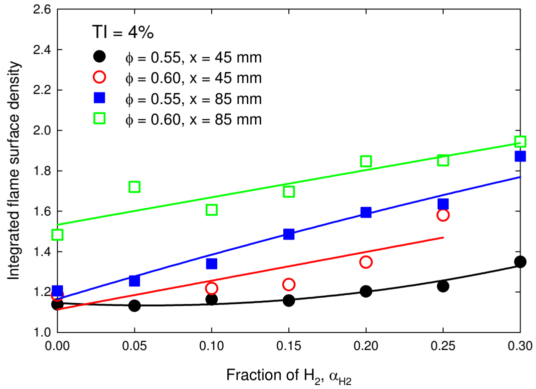
(b)

Fig. 5 Variation of flame brush thickness. (a) TI = 4%; (b) TI = 8%.

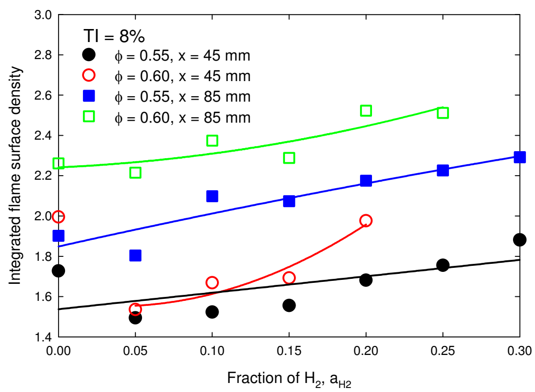
Another factor that causes the increase in turbulent burning velocity is the stretch factor I_0 in Eq. 6. Due to the complexity, this quantity was not measured in this study. Its influence on the turbulent flame speed is mainly due to the change in laminar burning velocity. This is easy to understand. The fuel Lewis number is decreased to a value less than unity with the addition of hydrogen. Therefore, the enhancement of laminar burning velocity due to stretch is intensified at a constant stretch rate, leading to a higher laminar burning velocity. As a result, the turbulent burning velocity is also increased. This has been discussed by Hawkes and Chen [14].

In summary, the investigation of this paper shows that the addition of hydrogen results in an increase in turbulent burning velocity. Further, the ratio of the turbulent to laminar burning velocities also increases with the addition of hydrogen.

Therefore, the addition of hydrogen intensities the overall turbulent burning rate due to not only the enhancement in the corresponding laminar burning velocity caused by chemical kinetics and stretch effect, but also the change in flame structure that is reflected by the increase in flame brush thickness and total flame surface area.



(a)



(b)

Fig. 6 Integrated flame surface density. (a) TI = 4%; (b) TI = 8%.

CONCLUSIONS

The effect of hydrogen addition on CH_4/air turbulent flame characteristics has been experimentally investigated by laser tomography technique using a V-shaped flame configuration. The results show that overall the addition of hydrogen results in an increase in turbulent burning velocity. Further, turbulent burning velocity increases faster than laminar burning velocity due to the addition of hydrogen at a constant equivalence ratio and similar turbulent intensity level, suggesting that the increase in turbulent burning velocity are due to not only the enhancement in laminar burning velocity caused by chemical kinetics and stretch effect, but also the variation in flame structure. The further analysis of flame images and surface density indicate that the addition of hydrogen slightly decreases the local flame surface density, but increases flame brush thickness. It is the increase in the flame brush thickness that increases the total flame surface area and intensifies turbulent burning velocity, in addition to the enhancement in laminar burning rate, when hydrogen is added.

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