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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 velocity was 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 premixed CH₄–air mixtures when turbulent level in unburned mixture is not changed. Moreover, the increase of turbulent burning velocity is faster than that of the corresponding laminar burning velocity at constant equivalence ratio, suggesting that the kinetics effect is not the sole factor that results in the increase in turbulent burning velocity when hydrogen is added. The further analysis of flame surface characteristics and brush thickness indicates that hydrogen addition slightly decreases local flame surface density, but increases total flame surface area because of the increased flame brush thickness. The increase in flame brush thickness that results in the increase in total surface area may contribute to the faster increase in turbulent burning velocity, when hydrogen is added. Besides, the stretched local laminar burning velocity may be enhanced with the addition of hydrogen, which may also contribute to the faster increase rate of turbulent burning velocity. Both the variation in flame brush thickness and the enhancement in stretched local laminar burning velocity are due to the decreased fuel Lewis number when hydrogen is added. Therefore, the effects of fuel Lewis number and stretch should be taken into account in correlating burning velocity of turbulent premixed flames.

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1. Introduction

Lean premixed combustion technology has attracted more and more attention recently due to its potential to reduce consumption of fuel and emissions of greenhouse gases and pollutants. At a lean premixed operating condition, NO_x emission can be effectively suppressed owing to lower flame temperature. The emission of soot, the predominant source of particulate matter and a major global warming contributor, can also be essentially eliminated in lean premixed flames.

However, some intrinsic drawbacks exist for lean premixed combustion. One of these drawbacks is that the lean flammability limit is approached and flame speed becomes very low at a lean operating condition. This may result in local misfire and combustion instability inside a combustor. A strategy to overcome the problems of lean premixed combustion is to adopt fuel enrichment, i.e. adding a small amount of other more reactive component to the parent fuel. Fuel enrichment can help to overcome the drawbacks, while still maintain the advantages of lean premixed combustion. It has been shown [1–5] that

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hydrogen or reformat gas can be used as such an effective enrichment component that helps extend the lean flammability limits and reduce pollutant emissions in lean premixed flames. Besides, the addition of hydrogen to a hydrocarbon fuel also increases the laminar burning velocity [2,6–8]. The application of hydrogen enrichment to internal combustion engines has been investigated by many researchers [9,10]. However, it seems that relatively not enough attention has been paid to the effect of hydrogen enrichment on burning characteristics of turbulent premixed flames, although many researchers have investigated turbulent premixed hydrocarbon and hydrogen flames.

Due to the significant importance in application, huge amount of efforts have been attempted on turbulent burning velocity, following the pioneering work of Damköhler [11]. Various expressions have been proposed for turbulent burning velocity based on experimental results. Although these expressions differ, most of them can be written in the form similar to the following correlation [12].

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

with S_T , S_L and v' being the 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, the ratio of turbulent to laminar burning velocities 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. However, contradictory results exist in literature for the variation of the ratio of turbulent to laminar burning velocities when hydrogen is added to turbulent premixed hydrocarbon flames.

Liu and Lenze [13] investigated turbulent burning velocities of methane–hydrogen 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 methane–hydrogen turbulent premixed flames. Mandilas et al. [14] investigated the effect of hydrogen addition on laminar and turbulent burning velocities using spherical expanding flames. They also observed that the ratio of turbulent to laminar burning velocities did not significantly change with the addition of hydrogen at a similar turbulent condition. On the other side, the study of Goix and Shepherd [15] 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 might change the characteristics of turbulent premixed combustion due to the variation in Lewis number. A direct numerical simulation study by Hawkes and Chen [16] indicated that turbulent burning velocity increased faster than laminar burning velocity due to the addition of hydrogen for a lean premixed methane–air mixture at the same turbulent condition, implying that turbulent burning velocity cannot be expressed by a correlation similar to Eq. (1). The experimental study of Cohé et al. [17] showed that the addition of hydrogen to a methane–air premixed flame resulted in an increase in fractal dimension, which also

suggested that the addition of hydrogen at a similar turbulent level led to an increase in the ratio of turbulent to laminar burning velocities, based on the fractal theory [18]. A recent study by Shy et al. [19] found that the rising rate of the ratio of turbulent to laminar burning velocities increased with the addition of hydrogen, while it remained almost unchanged with the addition of carbon dioxide or nitrogen, when v'/S_L increased for methane–air premixed flames. Similarly, this also implied that the addition of hydrogen might modify the variation characteristics of S_T/S_L with increasing v'/S_L . These contradictory results in literature suggest that the current understanding on the effect of hydrogen addition on turbulent premixed combustion is not enough. Moreover, in spite of the great importance of flame surface characteristics, few studies have investigated the variation in flame surface characteristics for hydrogen-enriched turbulent premixed flames except for [17] that studied the variation in fractal dimension when hydrogen was added to methane–air turbulent premixed flames. Therefore, there is a need to further investigate how the addition of hydrogen affects burning velocity and surface characteristics of turbulent hydrocarbon premixed flames.

In this paper, the effect of hydrogen (H_2) addition on the characteristics of methane–air (CH_4 –air) turbulent premixed flames is experimentally investigated by a V-shaped flame configuration. Turbulent burning velocity and flame surface density are measured by laser tomography visualization method for hydrogen-enriched CH_4 –air turbulent premixed flames. The paper starts with the description of experimental setup and methodology. Then the results are presented and discussion is provided. Finally concluding remarks are drawn.

2. Experimental methodology

2.1. Flame configuration and condition

The studied flame configuration is shown in Fig. 1. The premixed CH_4/H_2 –air mixture issued from a wind tunnel ($11.5 \times 11.5 \text{ cm}^2$). 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.

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 are 4.0% ($v' = 20.0 \text{ cm/s}$) and 4.8 mm, respectively, while they are 8.0% ($v' = 40.0 \text{ cm/s}$) and 7.3 mm for the second set. These two sets of turbulent parameters generated two sets of turbulent Reynolds numbers (Re_t) around 60.0 and 180.0. The measurement volume of LDA is about 0.01 mm^3 . The estimated LDA measurement uncertainty is about 1.0%.

Fig. 1 – Flame configuration.

The fraction of added hydrogen is defined as $\alpha_{H_2} = V_{H_2} / (V_{H_2} + V_{CH_4})$, with V_{H_2} and V_{CH_4} being the volume flow rates of hydrogen and methane, respectively, in the unburned mixture. The complete combustion of the fuel mixture goes via the reaction

Note that nitrogen contained in air does not explicitly appear in R1, since it does not affect the calculation of fuel-oxidant ratio. The stoichiometric fuel-oxidant volume ratio in a CH_4/H_2 -air mixture is:

$$\left(\frac{F}{O_2}\right)_{st} = \frac{2}{(4 - 3\alpha_{H_2})} \quad (2)$$

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

$$\phi = \left(\frac{F}{O_2}\right) / \left(\frac{F}{O_2}\right)_{st} \quad (3)$$

Two equivalence ratios (0.55 and 0.60) were investigated. The fraction of hydrogen (α_{H_2}) varied from 0 to 0.3 in this paper. For these flames, the quantity v'/S_L lies between 1.0 and 2.0. Therefore, most flames studied in this paper are in the wrinkle flame regime.

2.2. Flame image processing

Laser tomography visualization technique was used to study flame topology and to measure turbulent burning velocity. The unburned mixture was seeded with incense aerosol particles with size between 100 and 500 nm. The flame was illuminated with a laser sheet created by Nd:YAG (120 mJ) laser source. The flame front and position were recorded by a CCD camera (1376×1024 pixel²). 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 measured. 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. [20]:

$$F_{SD} = \frac{1}{n} \sum \frac{dL}{ds} \quad (4)$$

where n is the number of images, dL is the infinitesimal flame front length in the surface element ds that is 10×10 pixel². The spatial resolution of the laser tomography is about 0.08 mm/pixel. The estimated uncertainty of flame tomography measurement is about 4–5%.

For each instantaneous image, flame angle (θ) was calculated based on two positions on the flame front. Then the mean flame angle ($\bar{\theta}$) 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

$$S_T = U \sin \bar{\theta} \quad (5)$$

3. Results and discussion

The effect of hydrogen addition on turbulent burning velocity is examined first. Fig. 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_{H_2}) is gradually increased. It is revealed that the addition of hydrogen results in an increase in turbulent burning velocity at a constant equivalence ratio and a similar turbulent level. This is as expected and qualitatively consistent with the variation trend of laminar burning velocity [6–8].

The increase in turbulent burning velocity with increasing hydrogen fraction could be caused by the variation in chemical kinetics, which is usually reflected by the variation in laminar burning velocity, or/and the turbulence caused variation in flame topology, such as flame surface area, 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 should be one factor that leads to the increase in turbulent burning velocity.

To figure out if turbulent burning velocity increases faster or slower than laminar burning velocity when hydrogen is added, the variation in the ratio of turbulent to laminar burning velocities (S_T/S_L) is plotted in Fig. 3. The laminar burning velocities used to calculate S_T/S_L in Fig. 3 are those obtained experimentally by Yu et al. [6]. It is observed that when the fraction of hydrogen increases at a constant

Fig. 2 – Variation of turbulent burning velocity when hydrogen is added. (a) TI = 4%; (b) TI = 8%.

equivalence ratio and similar turbulent level, the ratio of turbulent to laminar burning velocities also increases, although v'/S_L decreases due to the increased S_L . This indicates that when hydrogen is added, turbulent burning velocity increases faster than laminar burning velocity. It also suggests that kinetic effect may not be the sole factor that increases burning velocity when hydrogen is added to a turbulent premixed flame. This result is inconsistent with the predictions by most previous turbulent burning velocity correlations similar to Eq. (1) [12], since this kind of correlations predicts that the ratio of turbulent to laminar burning velocities decreases with increasing S_L and reducing v'/S_L . It also contradicts the result of Liu and Lenze [13] and Mandilas et al. [14], who indicated that the turbulence effect remained uninfluenced by fuel composition. However, it supports the direct numerical simulation result obtained by Haekes and Chen [16] who showed that turbulent burning velocity increased faster than laminar burning velocity due to hydrogen addition and the experimental result obtained by Shy et al. [19] who found that the rising rate of the ratio of turbulent to laminar burning velocities with increasing v'/S_L increased with the addition of hydrogen. It is also qualitatively consistent with the result of Cohé et al. [17] 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 [18]. The

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

reason that the current results cannot be qualitatively expressed by most previous correlations like Eq. (1) may be that most previous results were obtained by hydrocarbon or hydrogen 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 [13] and Mandilas et al. [14].

The reason that turbulent burning velocity increases faster than laminar burning velocity could be that the addition of hydrogen causes not only the variation in kinetics but also the variation in flame structure, such as surface area. Besides, the addition of hydrogen may also increase the stretched local laminar burning velocity due to the variation in fuel Lewis number, which may contribute to the faster increase in turbulent burning velocity too. It has been suggested by the flamelet theory [21] that a turbulent flame zone can be viewed as an ensemble of laminar flamelets. The total burning rate of a turbulent flame is the integration of the local laminar burning rate over the whole flame brush region by Ref. [22].

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

where C is the 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. $S_T \propto \bar{W}$. Therefore, turbulent burning velocity qualitatively depends on not only S_L but also 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.

Fig. 4 shows the flame surface density (F_{SD}) distribution in the progress variable space at the section of $x = 45$ 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.

Fig. 5 displays the variation of flame brush thickness at the section of $x = 45$ mm when hydrogen fraction is gradually increased. Other sections have qualitatively 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. The increase in flame brush thickness should be a result of the variation in preferential diffusion, since the addition of hydrogen reduces the fuel Lewis number that is defined as the ratio of mixture thermal diffusivity to fuel mass diffusivity. The reduction in fuel Lewis number increases the local flame instability and results in the increase in flame brush thickness.

The increase in flame brush thickness might result in the increase in 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. Fig. 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 should contribute to the increase in the overall burning rate, i.e. the turbulent burning velocity, 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 due to the increased flame brush thickness. This supports the observation from a direct numerical simulation by Hawkes and Chen [16].

We should point out that the variation in the stretch factor I_0 in Eq. (6) might also contribute to the increase in turbulent burning velocity when hydrogen is added, although this quantity was not measured in this study due to the complexity. Its influence on the turbulent flame speed is mainly due to the change in stretched local laminar burning velocity. This is also due to the variation in fuel Lewis number. The fuel Lewis number is decreased 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 stretched local laminar burning velocity

Fig. 4 – Flame surface density. The scattered points are measured, and the lines are regression results based on the form $F_{SD} = kC(1.0 - C)$. Black, red, blue and pink colors represent four different hydrogen fractions, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

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

and thus the higher turbulent burning velocity. This has been discussed by Hawkes and Chen [16].

Above results and discussion show that the addition of hydrogen increases turbulent burning velocity due to not only the effect of kinetics but also the variation in flame topology (brush thickness) and the enhancement in stretched local burning velocity. The variation in flame structure and stretched local burning velocity is caused by the variation in fuel Lewis number. Therefore, the effects of fuel Lewis number and stretch should be taken into account in correlating turbulent burning velocity. According to the suggestion of Bradely et al. [23], Fig. 7 plots S_T/v' as a function of $(KaLe)$, with Ka and Le being Karlovitz number and fuel Lewis number, respectively. Karlovitz number is defined as [23]

$$Ka = 0.157(v'/S_L)^2 Re_L^{-0.5} \quad (7)$$

with Re_L being turbulent Reynolds number ($v'L/\nu$). Quantities L and ν are the turbulence integral length scale and kinematic viscosity, respectively. Please note that Le is the mass fraction based average Lewis number of hydrogen and methane, since both methane and hydrogen are deficient reactants in lean premixed flames. It is found by the least-squares regression that all the measured turbulent burning velocities in this study can be reasonably described by following correlation:

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

$$\frac{S_T}{v'} = 1.00554(KaLe)^{-0.5953} \quad (8)$$

This further confirms the importance of Lewis number and stretch factor in correlating turbulent burning velocity.

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 intensifies the overall turbulent burning velocity due to not only the enhancement in the corresponding laminar burning velocity

Fig. 7 – S_T/v' as a function of $(KaLe)$.

caused by chemical kinetics and stretch effect, but also the change in flame topology that is reflected by the increase in flame brush thickness and total flame surface area.

4. Conclusions

The effect of hydrogen addition on the characteristics of CH₄–air turbulent premixed flames has been experimentally investigated by laser tomography technique using a V-shaped flame configuration. The results show that the addition of hydrogen results in an increase in turbulent burning velocity. Further, turbulent burning velocity increases faster than laminar burning velocity at a constant equivalence ratio and similar turbulent intensity level when hydrogen is added, suggesting that the increase in turbulent burning velocity are due to not only the enhancement in laminar burning velocity caused by chemical kinetics, but also some other factors. The decrease in fuel Lewis number is the primary reason that results in the faster increase of turbulent burning velocity than that of laminar burning velocity with the addition of hydrogen. Firstly, when hydrogen is added, although the local flame surface density slightly decreases, the total flame surface area increases due to the increased flame brush thickness because of the decrease in fuel Lewis number. Secondly, the decrease in fuel Lewis number may causes an enhancement in stretched local laminar burning velocity. The increase in total surface area and enhancement in stretched local laminar burning velocity lead to the faster increase in turbulent burning velocity than that in laminar burning velocity, when hydrogen is added. Therefore, the effects of fuel Lewis number should be taken into account in correlating turbulent burning velocity. The correlation $S_T/v' = 1.00554(KaLe)^{-0.5953}$ can reasonably describe all measured turbulent burning velocity data.

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