Effect of differential diffusion on turbulent lean premixed hydrogen enriched flames through structure analysis

Weijie Zhang, Jinhua Wang*, Wenjun Lin, Runze Mao, Hao Xia, Meng Zhang, Zuohua Huang

State Key Laboratory of Multiphase Flow in Power Engineering, Xi’an Jiaotong University, Xi’an 710049, China

HIGHLIGHTS

• Coupling effects of the differential diffusion and turbulence were conducted.
• Preferential H₂ transport produces bulge-cusp structures similar to the DL instability.
• Turbulence enhances the wrinkling mainly by influencing the positively curved flamelet.
• Differential diffusion effects are even strengthened at higher turbulence intensity.

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* Corresponding author.
E-mail address: jinhua.wang@mail.xjtu.edu.cn (J. Wang).
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ABSTRACT

This study presents the flame structure influenced by the differential diffusion effects and evaluates the structural modifications induced by the turbulence, thus to understand the coupling effects of the diffusively unstable flame fronts and the turbulence distortion. Lean premixed CH₄/H₂/air flames were conducted using a piloted Bunsen burner. Three hydrogen fractions of 0, 30% and 60% were adopted and the laminar flame speed was kept constant. The turbulence was generated with a single-layer perforated plate, which was combined with different bulk velocities to obtain varied turbulence intensities. Quasi-laminar flames without the plate were also performed. Explicit flame morphology was obtained using the OH-PLIF. The curvature, flame surface density and turbulent burning velocity were measured. Results show that the preferential transport of hydrogen produces negatively curved cusps flanked with positively curved bulges, which are featured by skewed curvature pdfs and consistent with the typical structure caused by the Darrieus-Landau instability. Prevalent bulge-cusp like wrinkles remain with relatively weak turbulence. However, stronger turbulence can break the bulges to be finer, and induce random positively curved cusps, therefore to destroy the bulge-cusp structures. Evident positive curvatures are generated in this process modifying the skewed curvature pdfs to be more symmetric, while the negative curvatures are not affected seriously. From low to high turbulence intensities, the hydrogen addition always strengthens the flame wrinkling. The augmentation of flame surface density and turbulent burning velocity with hydrogen is even more obvious at higher turbulence intensity. It is suggested that the differential diffusion can persist and even be strengthened with strong turbulence.

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**Introduction**

The performance of lean premixed fuel-flexible combustor depends on the development of robust flame controlling techniques, which largely relies on a better understanding of the differential diffusion especially when invoking alternative hydrogen-enriched fuels [1–5]. The differential diffusion appears when the molecular transport of the mixture species is not equivalent [6]. For lean premixed and hydrogen contained flames, the flame structure with differential diffusion is featured with prevalent positively curved bulges propagating to the unburned reactants, as was observed experimentally by our previous study of [7], and numerically demonstrated in laminar flames by Altantzis et al. [8], and in turbulent flames by Bell et al. [1], Vreman et al. [9], Day et al. [10] and Hong et al. [11]. This is due to the preferential transport of H₂, which always leads to the enhanced burning intensity at a positively curved flame front, as demonstrated in detail by recent DNS results of Mizobuchi et al. [12]. The mixture around the positive curved part is more stoichiometric as a result of the accumulated deficient reactant H₂. The burning of the negatively curved flame front, however, is diminished or even extinct for a lack of reactants, which causes the uneven burning along the flame front [9,10,12,13].

For diffusively stable flames, the curvature (κ) probability density functions (pdf) are more likely symmetric [14–16]. The turbulence almost equally influences the positively and negatively curved fronts of the stable flames. This was shown by the simultaneous augmented (reduced) positive and negative pdf with the increased (decreased) turbulence intensity (u’), as obtained by Gashi et al. [15] and Haq et al. [16]. However, it may be not true for diffusively unstable flames. Due to the uneven burning, the quantity and magnitude between the negative and positive curvatures are different, which can lead to asymmetric curvature pdfs [1,7,17]. Previously, the structure statistics and turbulence effects for diffusively unstable flames were not well addressed. Instead, the focus was extensively on how to incorporate the differential diffusion, for example by Vreman et al. [8] and de Swart et al. [18] using the FGM method. The initial stage of vortex-flame interactions with the differential diffusion were demonstrated by de Swart et al. [18] whereas evolution of the unstable flame fronts in the presence of the strong turbulence have not been fully revealed. One inspiring DNS study of Day et al. [10] showed that with higher turbulence intensity, the positively curved bulges possess higher curvatures. Namely, the turbulence can break the large-scale bulges to be finer, which was similarly suggested by Aspden et al. [19] later. Nevertheless, the structural feature of the finer bulges was not explicitly discussed.Comparatively, breaks appear for negatively curved unstable flame front with diminished burning intensity. The breaks are flanked by positively curved bulges of intensified burning intensity. Bell et al. [1] suggested that these breaks participate in merger events, for example from two to one. The merging may be driven by the propagating bulges into the unburned mixture which was regarded as a leading flame kernel [19,20]. Actually, the trailed flame fronts by the leading bulges cause cusps pointing to the burned region. As will be revealed in the present study, these cusps are very similar to those generated by the Darrieus-Landau (DL) instability [21–24]. From the result of Day et al. [10], increased negative curvatures were also noticed with stronger turbulence, indicating that the turbulence may also break the cusps. But this should be verified and inquired further especially with the experimental method.

A common observation of the differential diffusion with hydrogen is its promotion on the turbulent burning velocity (Sₓ), especially at relatively low turbulence intensity [20,25–27]. Despite being broken for the diffusively unstable bulges with strong turbulence, the differential diffusion remains, merely being moderated according to Day et al. [10]. Dunn et al. also indicated that this instability, although can saturate, persists at very high Reynolds number [28]. Meanwhile, the diffusive instability apparently increases the Sₓ, both in thin and distributed reaction regimes, as measured by Daniele et al. [29] and Venkateswaran et al. [30]. On the contrary, Aspden et al. [31] and Lapointe et al. [32] indicated that the molecular diffusion will be overwhelmed by the turbulent mixing with extremely strong turbulence, which was also concluded by Ranga Dinesh et al. [33]. The small-scale turbulent dissipation was observed to influence radical transport by Minamoto et al. [34]. Therefore, how the turbulence acts on the differential diffusion effects remains to be studied with these discrepancies.

The objective of this study is to address this problem by experimentally investigating the structure of the hydrogen contained flames. The uneven burning intensity is highly correlated with the flame structure with differential diffusion effects, as stated above and indicated in Ref. [19]. Therefore, revealing the structural feature and its evolution with the coupling turbulence is expected very helpful. Lean premixed turbulent flames with CH₄/H₂/air mixtures were conducted. Unstretched laminar flame speed (Sₓ,0) was controlled to be constant with different hydrogen fractions to isolate the differential diffusion [2,7]. The flame structure was firstly studied with quasi-laminar flames, thereby to identify structural feature induced by the preferential transport of H₂. Then the turbulent flame structure was studied with increasing turbulence intensity to examine, for instance, whether the bulges broken by the turbulence also appear in the experiment, whether the molecular diffusion can be diminished, and how it affects the flame wrinkling and turbulent burning velocity. The DL instability was also analyzed as to its effects on the quasi-laminar and weak turbulent flames. The burner, mixture, experimental method and image processing are shown in section Experimental apparatus and methods. The morphologies and structure of quasi-laminar flames are displayed in section Structural feature of quasi-laminar flames, and that of the turbulent flames are demonstrated in section Effects of turbulence on the flame structure. The flame surface density and turbulent burning velocity with differential diffusion are discussed in section Flame surface density and turbulent burning velocity.

**Experimental apparatus and methods**

**Burner and experimental conditions**

The piloted Bunsen burner is illustrated in Fig. 1(a). The outlet diameter of the burner is D = 20 mm. An annular co-flame...
with the CH\textsubscript{4}/air mixture at $\phi = 1.0$ was designed to stabilize the main flame. The volumetric flow rate of the co-flame was kept constant about 13 L/min in the experiment. The outer diameter of the multi-holed co-flame holder is 40 mm. Water was recycled to protect the burner from high temperature. The turbulence was generated with a perforated plate as shown in Fig. 1(b). The plate was installed at 40 mm upstream of the outlet.

The bulk velocities ($U_b$) for the turbulence flames were set as 4, 6, 10 and 14 m/s. The bulk flow was controlled with the mass flow controllers (MFC, CS230, Beijing SevenStar Co., China). The uncertainty of the controllers is about $\pm 1.0\%$ of the set point. The turbulence properties were calibrated with a constant-temperature hot-wire anemometer (Dantec, Streamline 90N) using a one-dimensional probe 55P11 (Dantec). The hot-wire anemometer was calibrated with an auto-calibrator. The sampling rate was 10 kHz with 13 s duration.

Following our previous works [20,23], the turbulence was calibrated at 10 mm above the outlet along the burner axis, which is similar to Ref. [35]. Using the transient velocities obtained by the hot-wire anemometer, the turbulence intensity ($u'$) was obtained [35]. The integral scale ($\lambda_z$) measures the large eddies in the turbulence and was calculated by integrating the Eulerian autocorrelation coefficient according to the Taylor’s hypothesis [36]. The results are shown in Table 1, where the nominal Reynolds number ($Re = DU_b/\nu$) and the turbulent Reynolds number ($Re_t = u'/\lambda_z/\nu$) are also displayed. The uncontrolled $Re$ can affect the residence time of the flow through the flame brush [37]. However, the differential diffusion effects are discussed always with the precondition of a constant $Re$ in this study.

Three lean premixed CH\textsubscript{4}/H\textsubscript{2}/air mixtures named H1, H2, and H3 were adopted and the properties are given in Table 2. The hydrogen fractions ($Z_{H2}$) of the mixtures were set as 0, 30 and 60%.

Table 1 – Turbulence properties.

<table>
<thead>
<tr>
<th>$U_b$ (m/s)</th>
<th>$u'$ (m/s)</th>
<th>$u'/S_{L0}$</th>
<th>$\lambda_z$ (mm)</th>
<th>$Re$</th>
<th>$Re_t$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>0.01</td>
<td>0.03</td>
<td>–</td>
<td>2581</td>
<td>–</td>
</tr>
<tr>
<td>4</td>
<td>0.56</td>
<td>1.66</td>
<td>3.01</td>
<td>5161</td>
<td>108.07</td>
</tr>
<tr>
<td>6</td>
<td>0.79</td>
<td>2.37</td>
<td>3.02</td>
<td>7742</td>
<td>154.40</td>
</tr>
<tr>
<td>10</td>
<td>1.33</td>
<td>3.98</td>
<td>3.07</td>
<td>12903</td>
<td>263.93</td>
</tr>
<tr>
<td>14</td>
<td>1.83</td>
<td>5.47</td>
<td>3.21</td>
<td>18065</td>
<td>378.49</td>
</tr>
</tbody>
</table>

Table 2 – Properties of the CH\textsubscript{4}/H\textsubscript{2}/air mixture.

<table>
<thead>
<tr>
<th>Mixture No.</th>
<th>$Z_{H2}$</th>
<th>$\phi$</th>
<th>$S_{L0}$ (cm/s)</th>
<th>$Le$</th>
</tr>
</thead>
<tbody>
<tr>
<td>H1</td>
<td>0</td>
<td>0.91</td>
<td>33.66</td>
<td>0.99</td>
</tr>
<tr>
<td>H2</td>
<td>30%</td>
<td>0.8</td>
<td>33.21</td>
<td>0.86</td>
</tr>
<tr>
<td>H3</td>
<td>60%</td>
<td>0.69</td>
<td>33.52</td>
<td>0.70</td>
</tr>
</tbody>
</table>

Fig. 1 – Turbulent premixed Bunsen burner: (a) schematic of the burner; (b) the perforated plate.
Details of the ring can be found in Ref. [23]. The bulk velocity was decreased to 2 m/s with Reynolds number Re about 2600 and the turbulence intensity was also measured, which is about 0.01 m/s as shown in Table 1. So, quasi-laminar conditions of these flames can be properly assumed. However, the flame perturbations still appear as will be discussed later.

**OH-PLIF system**

The Planar Laser-Induced Fluorescence (PLIF) of OH was adopted to capture the flame structure. The OH-PLIF system was introduced before [14,23] and the setup is shown in Fig. 2. Firstly, a second harmonic pumped Nd: YAG laser (QuantaRay Pro-190) produced a 532 nm laser beam. The pulse energy was about 300 mJ. The beam then entered into a tunable dye laser (SirahPRSC-G-3000), where it was tuned to about 566 nm using a Rhodamine 6G dye solution. Then the beam was further turned to about 283 nm by a frequency doubler, with the pulse energy about 15 mJ. After the dye laser, the 283 nm laser beam passed through a sheet optics component to form a laser sheet. The beam was expanded to about 80 mm in height and 0.5 mm in thickness. The laser sheet then crossed the centerline of the burner, where it excited the Q(6) line of the A\(^1\Sigma^-\rightarrow X^1\Sigma^+\)(1,0) bands of OH excitation. OH fluorescence of about 308 nm was then captured by the CCD camera (LaVision Image Prox). The camera was equipped with the Intensified Relay Optics (LaVision VC08-0094) and mounted with a UV lens (Nikon Rayfact PF 10545 MF-UV), as well as an OH bandpass filter (LaVision VC08-0222). Gate and delay of the intensifier was 200 ns and 100 ns, respectively. The system was operated with a frequency of 100 Hz. For each flame, \( N = 400 \) instantaneous OH snapshots were detected and background of these OH-PLIF images was subtracted. The size of the OH-PLIF snapshots was 600 × 800 pixels (after a 2 × 2 binning), with a resolution of about 0.192 mm/pixel.

**Image processing**

OH radicals are mainly distributed in the reaction zone and the burned region [42]. The front of the OH fluorescence with a sharp signal gradient has been widely used to extract the flame front [42,43]. The procedures are shown in Fig. 3 with one snapshot of the flame with mixture H1 and \( U_b = 14 \) m/s. The original OH-PLIF image of Fig. 3(a) was firstly translated from the format of RGB to a gray image with 256 intensity levels. The gray image was processed with a 3 × 3 median filter to smooth the noises and was next binarized. Previously, we adopted a global gray threshold to binarize the flames [14], which was obtained with the Otsu’s method [44]. In the present study, the global threshold was further self-adapted for each row according to the local mean signal level. This was used to deal with the signal differences from the flame root to the cone resulting from the laser non-uniformity, as shown by Fig. 3(a). The binarized result is Fig. 3(b), where the unburned region was assigned with zeros (black) and the burned region with ones (white). The flame pockets both in unburned and burned regions were all removed.

The flame front of Fig. 3(c) was extracted with the edge of Fig. 3(b). To derive the curvature (\( \kappa \)), the raw flame front was discretized with a proper arc-length step as introduced before [23,45,46] and was rebuilt with a cubic spline to eliminate the noises. Then the curvature was calculated with [7,47]:

\[
\kappa = \frac{x(s)y'(s)^2 - y(s)x'(s)^2}{(x(s)^2 + y(s)^2)^{3/2}}
\]

where \( s \) is the accumulated arc length along the flame front. \( x \) and \( y \) is the coordinate column and row of the image pixel matrix. The normal vector of the flame front is in the direction towards the burned region. The curvature for the flame front bulge convex to the burned side is negative while to the unburned side is positive. The curvature was determined based on a 2D cross section of the 3D flame similar to Refs. [21,22]. However, this approximation is acceptable because the attention is not on quantifying the value of the curvature, but on the statistical results. Considering the limit of the resolution, the curvature was restricted to ±6/1 mm).

A sample flame brush of 10 flame fronts is displayed in Fig. 3(d) and the mean progress variable contours (\(<c>\) of the flame brush are shown in Fig. 3(e). The contour of \(<c> ≥ 0.1\) delineates the unburned and burned side, respectively. According to Kobayashi et al. [43], the binarized result of Fig. 3(b) also represents the reaction progress variable (\( c \)) field, if a step function of \( c \) is assumed across the flame front. Thus to derive the mean \(<c>\) contours, the \( N = 400 \) binarized images were firstly overlapped. Then the pixels of \(<c> ≥ 0.2\)%*N were identified as the \(<c>\) contour. Due to the ±2% deviation, the \(<c>\) contours are quite thick in Fig. 3(e). This is a proper method to find the course contour which will be fitted with a cubic spline interpolation. The fitted \(<c> ≥ 0.1\) contour is shown in Fig. 3(e). For the flame brush, the flame surface density (FSD, \( \Sigma \)) and turbulent burning velocity (\( S_v \)) were computed. The FSD was calculated with [14,48]:

\[
\Sigma = \lim_{\Delta x \to 0} \frac{\Sigma_f}{\Delta x^2}
\]

where \( \Sigma_f \) is the averaged flame surface length \( \Sigma_f = L_f/N \). Within the flame brush, the length of \( L_f \) was measured by counting the flame front pixels within a local pixel box of \( \Delta x^2 = 11 \times 11 \), as shown in Fig. 3(d). The box size has negligible effects on the \( \Sigma \) [37]. The mean surface density \( \Sigma \) was ultimately obtained along each fitted \(<c>\) with a step of 0.1. The turbulent burning velocity is defined according to the turbulent consumption speed: \( S_t = m_s/\rho_u A_f \) [23,49]. Here \( m_s \) is the total mass flow rate, \( \rho_u \) is the unburned mixture density. \( A_f \) is the rotated surface area of the fitted leading edge \( <c> ≥ 0.1 \) [20,23]. Firstly, the left and right half of the leading edge was averaged. Then the contour was rotated around the flame central axis to derive the \( A_f \).

![Fig. 2 – The system of OH-PLIF technique.](image-url)
Results and discussions

Structural feature of quasi-laminar flames

Typical OH-PLIF snapshots of the three quasi-laminar flames are shown in Fig. 4. From mixture H1 to H3, the flame front in Fig. 4 transforms from smoother to obvious corrugated morphology. For mixture H1, although with neutral differential diffusion, the flame front of Fig. 4(a) is still wrinkled. This is due to the omnipresent Darrieus-Landau (DL) instability as was demonstrated before [8,23]. The initial wrinkles, however, can be enhanced by the differential diffusion with hydrogen addition. Namely, the preferential transport of hydrogen increases the burning velocity of the positively curved bulges due to the H₂ accumulation as aforementioned. The bulges can be seen from the flames of H2 and H3 labeled with red “x”.

Although the bulges are increased in number with more hydrogen, their scale is decreased and the flame front wrinkling is intensified as shown in Fig. 4(b) and (c). While these positively curved bulges propagate fast towards the reactants, the trailed negatively curved parts are forming highly curved cusps pointing to the burned region, see the flame front between the two red “x” in Fig. 4(c).

Actually, previous studies revealed that the cusps flanked with smooth positive bulges in Fig. 4(c) are also an important manifestation of the DL instability [21–24]. However, DL-type cusps are generated by the thermal expansion, not the trailing effects from the propagating bulges [24]. Note that such a bulge-cusp structure is not present in the laminar flame of Fig. 4(a). Most probably, this is because of the limited perturbation wavenumbers for a positive DL-instability growth rate [23]. In the turbulent flames, as will be shown later, the instability will be easily triggered to display similar bulge-cusp features [23,50].

The feature of cusps can be demonstrated with the curvature statistics. With the evident sharp cusps from Fig. 4(a)–(c), the negative curvatures will appear more and their magnitude increases. Comparatively, the positively curved bulges possess much smaller curvatures since they are generally smoother. Then the negative curvature accumulation furnished by the cusps leads to the skewed pdf of the curvature, which was similarly observed for DL-unstable flames [21–23]. The curvature pdfs.

Of the three quasi-laminar flames are shown in Fig. 5. Note that the y-axis of the pdf was plotted in a log-scale similar to Refs. [21–23]. This is important for revealing the large curvatures of the cusps because they are in minor quantity compared to the curvatures near $k = 0$. For the flame with mixture H1, although perturbed in Fig. 4(a), the DL instability was not evidently induced according to its near symmetric pdf [23]. Note that, large negative curvatures at the tip can be obtained as a result of the tapered shape of the quasi-laminar Bunsen flames, see Fig. 4(a). These curvatures were removed by simply eliminating the highest negative curvature in each flame sample, which was also applied to the hydrogen contained flames. Curvature pdfs of the flames with H2 and H3 are skewed obviously as expected. The cusps are intensified with hydrogen thus the negative pdf increases from H1 to H3. The positive pdf also increases but slower. The increased positive curvatures are coincided with the deeply propagating but finer bulges, see Fig. 4(b) and (c).

Effects of turbulence on the flame structure

As observed above, the differential diffusion with hydrogen produces evident bulges and cusps similar to the DL-induced structure. In this section, these features are discussed in the presence of turbulence. The turbulent flame cases stand from the corrugated to the thin reaction zone in Peters-Borghli's

Fig. 3 – The image processing procedures: (a) the original OH-PLIF image of the flame; (b) the binarized result; (c) extracted raw flame front; (d) flame brush obtained by overlaying 10 instantaneous flame fronts and the pixel box for flame surface density; (e) mean progress variable contours of the flame brush.
diagram [51,52], see Fig. 6. Additionally, a $\beta$ threshold is delineated to show the influence of DL instability on the turbulent flames. The $\beta$ criterion, which was proposed by Chaudhuri et al. [53] and modified in our previous study of [23], estimates where the DL instability is overpowered by the turbulence. In the DL-stable region above the threshold, the DL-induced bulge-cusp structure can be theoretically overwhelmed by the turbulence, and therefore the DL instability can be neglected. However, considering that the cases studied in the present study are very near the threshold, and the large theoretical error from the physics simplification [23,53], the DL instability can still exist. This can be observed in Fig. 7(a), where the curvature pdf of the turbulent flame with H1 at the lowest $w'$ of this study, is skewed similarly to that in Fig. 5 of the hydrogen-enriched laminar flames. So, the DL-type bulge-cusp structure is expected to appear. Moreover, the hydrogen addition enhances the cusps and bulges according to the higher pdf both in the negative and positive sides.

The three strongest turbulent flames obtained with mixture H1, H2 and H3 are given in Fig. 7(b). For these flames, the hydrogen still promotes the wrinkling. Importantly, the pdfs in Fig. 7(b) are more symmetric compared to Fig. 7(a). The

![Fig. 4 - OH-PLIF images of quasi-laminar flames.](image)

![Fig. 5 - Curvature pdfs of the quasi-laminar flames.](image)

![Fig. 6 - Peters-Borghi's diagram with the threshold of DL-stable and unstable regions.](image)
The evolution of the curvature pdfs with the increasing turbulence intensity is further demonstrated in Fig. 8. With higher turbulence intensity, the pdfs’ peak (corresponding to $k = 0$) is decreased and the negative curvature pdf is increased slightly. Meanwhile, the positive curvature pdfs are augmented intensively which mitigates the skewness. The results suggest that more planar flame fronts (around $k = 0$) are curved by the strong turbulence, and most of them should be positively curved. Meanwhile, the propagating bulges are finer and highly curved with the stronger turbulence, as indicated by the increase of large positive curvatures.

Fig. 9 demonstrates the typical OH-PLIF snapshots of the flames at the lowest/highest turbulence intensities conducted. The DL-type cusps flanked by smoother bulges can be
identified in Fig. 9(a), as expected from Fig. 7(a). With hydrogen addition, the cusps are more evident and deeper, which are strengthened by the hydrogen addition. Importantly, the turbulence also starts to produce some random cusps pointing into the reactants, as indicated by the red circulars in Fig. 9. The random positive cusps appear in stronger turbulent flames of Fig. 9(d-f) as well. It can be inferred that the DL instability begins to be overpowered in Fig. 9(a) since the DL-induced smooth-bulge, sharp-cusp feature is destroyed. These highly curved cusps should augment the positive curvature in Fig. 8(a) with the increase of $u'$. For flames of H2 and H3 with differential diffusion, the positive cusps are even sharper and appear more frequently, which also increases the positive curvatures intensively.

Furthermore, the disturbance on the positively curved bulges may be seen from the parts labeled with red “x” for

![OH-PLIF Images of Turbulent Flames](image)

Fig. 9 — OH-PLIF images of turbulent flames. Upper row: $U_b = 4$ m/s with $u' = 0.56$ m/s; Bottom row: $U_b = 14$ m/s with $u' = 1.83$ m/s.
flames of H1 and H2. For the flame of H3 in Fig. 9(c), the positively curved cusps are intensified by the differential diffusion, therefore not influenced by the turbulence evidently. However, for the strong turbulent flames in Fig. 9(d-f), the positively curved bulges can not be identified, which possess random shapes. Especially in Fig. 9(f), finer flame fronts are prevalent. The turbulence can break the propagating bulges fertilized by the differential diffusion into smaller scales, as observed by Day et al. [10] and Aspden et al. [13]. The fine structure also contributes to the high positive curvatures displayed in Fig. 8. The flame front seems to have larger scales without hydrogen in Fig. 9(d). Even though, finer flame fronts can still be observed.

The negative curvatures are only slightly increased by the turbulence, similar to the result of [10]. For the flames with lower turbulence intensity in Fig. 9(a-c), negative curvatures are largely generated by the DL-induced cusps or the cusps furnished by the differential diffusion. Some cusps seem to be flattened by the turbulence as shown in Fig. 9(a). In the strong turbulent flames, this effect should also occur. But simultaneously, random negatively curved cusps induced by the turbulence may be present, since some positively curved cusps have been observed above. The negatively curved flame fronts can also be finer with strong turbulence to replenish the large negative curvatures. Most probably the reduction and production of negative curvatures are nearly balanced.

Flame surface density and turbulent burning velocity

The turbulence seems to promote the wrinkling mainly by modifications on the positively curved flame fronts. But the hydrogen addition always enhances both negative and positive curvatures from low to high turbulence intensity as shown in Fig. 7. Fig. 10 shows the mean flame surface density averaged on the mean progress variables. Profiles of the mean FSD are symmetric with the maximum value at around $<c/\gamma>0.5$ [48,54]. It is clear that from low to high turbulence intensity, the hydrogen addition always increases the mean FSD, similar to Ref. [48]. Importantly, the augmentation of mean FSD is even more obvious with higher turbulence intensity.

The turbulent burning velocities obtained in this study are displayed in Fig. 11. The leading edge turbulent burning velocities measured by Tamadonfar and Gülder [54], with similar
CH$_4$/air flames at $\phi = 0.90$ are also shown for comparison. Our previous results of Zhang et al. [20] also obtained the $S_T$ at $\phi = 0.89$. Compared to the present results at $\phi = 0.91$, the turbulent burning velocities generally coincide well. The uncertainty of $S_T$ was estimated based on [1] the asymmetrical error (from 6 to 24%) of the $<c/C_2^-0.1$ contour relative to the flame axis while deriving the $Af$ [2]; the error from the flow controlling (about 1.4$\pm$1.7% depending on the MFCs used). The hydrogen contained flames possess higher asymmetrical errors, which results from their fast and unstable burning. Nevertheless, the pure methane flames are more stable especially at higher bulk velocities.

The turbulent burning velocities are increased with turbulence intensity. With hydrogen addition, the $S_T$ is also increased. Similarly, the augmentation of $S_T$ with hydrogen addition is more evident at higher turbulence intensity. The turbulent burning velocities were fitted with the formula below as was used in Refs. [20,25,43,55]:

$$\frac{S_T}{S_{L,0}} = a\left(\frac{u}{S_{L,0}}\right)^n$$

(3)

For the flames with mixture H1, H2 and H3, the components of $a$ are 2.98, 4.19, 5.65 and $n$ are 0.36, 0.39, 0.45, respectively. Coefficients $a$ and $n$ are both increased with hydrogen fraction. These results reinforce that the differential diffusion with hydrogen may not be overwhelmed. The experiment was not extended to conditions with extremely high turbulence intensity. The flame front was captured with the OH-PLIF. The main objective is to experimentally examine the structural feature influenced by the preferential transport of hydrogen, and its evolution with the turbulence. Quasi-laminar flames were conducted and turbulent flames were performed with increasing turbulence intensity. Main conclusions are summarized as follows:

(1) With hydrogen addition, the differential diffusion promotes the formation of flame bulges propagating towards the reactants, and highly curved cusps pointing towards the burned region. It was found that the bulge-cusp feature manifests itself with a skewed curvature pdf and coincides with the DL-induced structure.

(2) The turbulence was observed to enhance the wrinkling mainly by promoting the positive curvatures, thereby to destroy the bulge-cusp feature and modify the curvature pdf to be more symmetric. This is accomplished partly by disturbing the bulges to be disordered and finer. Meanwhile, some random positively curved cusps are likely to be induced by the turbulence. The positive cusp is intensified by the preferential diffusion of H$_2$.

(3) The negative curvature pdfs were not found to be influenced seriously by the turbulence. Most probably, this is due to a balance between the elimination and production of the negative curvatures.

(4) The enhancement of flame surface density and turbulent burning velocity by hydrogen addition is even more evident at higher turbulence intensity. Therefore, it is expected that the molecular diffusion cannot be overwhelmed by the turbulence easily.

Conclusions

In this study, the differential diffusion effects were studied with the structure of lean premixed CH$_4$/H$_2$/air flames stabilized on a piloted turbulent Bunsen burner. The flame front was captured with the OH-PLIF. The main objective is to experimentally examine the structural feature influenced by the preferential transport of hydrogen, and its evolution with the turbulence. Quasi-laminar flames were conducted and turbulent flames were performed with increasing turbulence intensity. Main conclusions are summarized as follows:

Acknowledgments

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