Measurements of turbulent premixed flames
by simultaneous CH-OH PLIF and stereoscopic PIV

by
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ABSTRACT

Simultaneous CH and OH planar laser induced fluorescence (PLIF) and stereoscopic particle image velocimetry (PIV) measurement have been developed to investigate the local flame structure of turbulent premixed flames. In this system, high-speed CMOS cameras were adopted to capture the clear stereoscopic particle images without contamination by the flame radiation. The developed simultaneous two radical concentrations and three component velocity measurement on a two-dimensional plane was applied for relatively high Reynolds number turbulent premixed flames in a swirl-stabilized combustor. All measurements were conducted for methane-air premixed flames in the corrugated flamelets regime. Detailed analysis of simultaneous CH and OH images reveals that the minimum curvature radius of the flame front coincides with Kolmogorov scale. Figure 1 shows results of simultaneous CH and OH PLIF and stereoscopic PIV for different Reynolds number. Strong three-dimensional velocity fluctuation implies that misunderstanding of the flame/turbulence interactions would be caused by the analysis of two-component velocity distribution in a cross section. Furthermore, comparisons of CH-OH PLIF and three-component velocity field show that the burned gases not always have high-speed velocity in relatively high Reynolds number turbulent premixed flame. The Reynolds number dependence of the flame front was clearly captured by the simultaneous CH-OH PLIF and stereoscopic PIV measurement.

Fig. 1. CH PLIF image (left), OH PLIF image (center) and velocity distribution (right) for different Reynolds number.
(a) Re₈ = 63.1 and (b) Re₈ = 115.0. Visualized domain size is 31mm × 31mm for PLIF images and 16.2mm × 16.2mm for velocity field (white box in CH and OH images).
1. INTRODUCTION

To investigate turbulent flame structures experimentally, planar laser induced fluorescence (PLIF) of OH radicals and CH radicals are commonly used (Dyer and Crosley 1984, Hanson 1986). Since OH radicals show high concentration in the burned gas, OH PLIF measurements are useful to separate the unburned mixture and the burned gas. Although the edges of OH radical distribution may correspond to the flame fronts for low Reynolds number turbulent flames, there is a possibility that the flame fronts do not exist at the edge of OH radicals in high Reynolds number cases in which flame front is significantly distorted and multiply folded. On the other hand, CH PLIF measurements have been used to investigate characteristics of the flame fronts in turbulence because CH radicals are produced at the flame front and have very narrow width enough to represent the reaction zones (Allen et al. 1986, Mansour et al. 1998, Carter et al. 1998). Furthermore, it is well known that distribution of CH radicals agrees with that of the heat release rate (Paul and Najm 1998). However, only from the CH PLIF measurement, it is hard to differentiate the unburned and burned gases. To overcome these defects in single radical PLIF, simultaneous OH and CH PLIF measurements have been developed and applied for turbulent non-premixed flames (Donbar et al. 2000, Watson et al. 2002).

In addition to the PLIF measurements, particle image velocimetry (PIV) have been adopted to measure the turbulence characteristics near the flame (Kalt et al. 1998, Rehm and Clemens 1998, Han and Mungal 2000, Sinibaldi et al. 2003). Recently, simultaneous CH, OH and velocity measurement has been reported in non-premixed flame (Kothnur et al. 2002). However, almost all studies used two-dimensional PIV to measure the velocity field with PLIF. To obtain the detailed information about turbulent velocity field, three component velocity measurement such as the stereoscopic PIV (Arroyo and Greatet 1991, Westerweel and Nieuwstadt 1991, Willert 1997, Prasad 2000) are desirable. In this study, simultaneous CH-OH PLIF and stereoscopic PIV measurement are developed to investigate the local flame structure of turbulent premixed flames. The developed simultaneous two radical concentrations and three component velocity measurement are applied for relatively high Reynolds number turbulent premixed flames in swirl-stabilized combustor, and characteristics of flame geometry and its Reynolds number dependence are discussed.

2. EXPERIMENTAL METHOD

2.1 CH and OH Planar Laser Induced Fluorescence

The schematic diagram of the experimental setup for simultaneous CH and OH PLIF and stereoscopic PIV measurement is shown in Fig. 1. For CH-PLIF measurement, the Q_{(7,5)} transition of the B^2Σ-X^2Π(0,0) band at 390.30nm was excited and fluorescence from the A-X(1,1), (0,0) and B-X(0,1) bands between 420 and 440nm was detected (Garland and Crosley 1985, Carter et al. 1998). Many groups have conducted successful CH PLIF measurements using this transition (Han and Mungal 2000, Watson et al. 2000). The laser system consists of a XeCl excimer laser (Lambda Phisik, LPX 110I, 308nm, 200mJ/pulse) and a dye laser (Lambda Phisik, Scanmate 2), and generates laser pulses about 5mJ/pulse with 8-12 ns pulse width. The dye laser with Rhodamine 590 dye in methanol solvent is pumped by the Nd:YAG laser and emits 282.93nm light. The fluorescence from the A-X(1,0) and (0,0) bands (306-320nm) was collected with an UV-Nikkor 105mm/F4.5 lens and imaged onto a second intensified CCD camera (PI-MAX, 512RB-G1, 512×512 pixels). This camera, which is located on the opposite side of the burner from the intensified CCD camera for CH, was fitted with WG305 and UG-11 filters to reject incident light.

For OH PLIF measurement, the laser system consists of a Nd:YAG laser (Spectra-Physics, Quanta Ray PRO-110, 532nm, 350mJ/pulse) and a dye laser (Sirah Precisionscan), and generates laser pulses about 5mJ/pulse with 8-12 ns pulse width. The dye laser with Rhodamine 590 dye in methanol solvent is pumped by the Nd:YAG laser and emits 282.93nm light. The fluorescence from the A-X(1,0) and (0,0) bands (306-320nm) was collected with an UV-Nikkor 105mm/F4.5 lens and imaged onto a second intensified CCD camera (PI-MAX, 512RB-G1, 512×512 pixels). This camera, which is located on the opposite side of the burner from the intensified CCD camera for CH, was fitted with WG305 and UG-11 filters to reject incident light.

For PLAIF, the laser beam is shaped into 200μm vertical sheet with about 30mm height, which is measured value not estimated one. The CH-OH PLIF system afford a view of 31mm × 31mm. Therefore, spatial resolution of PLIF is 31μm × 31μm × 200μm for CH and 61μm × 61μm × 200μm for OH. To optimize signal-to-noise ratio, all
measurements were conducted with an image intensifier gate time of 30ns; this value was determined by preliminary experiments with a different gate time.

2.2 Stereoscopic Digital Particle Image Velocimetry

A schematic of stereoscopic PIV is also shown in Fig. 1. This system consists of a double pulsed Nd:YAG laser (New Wave Research, 532nm, 100mJ/6ns), an optical system and two high speed CMOS cameras (Vision Research, Phantom V5.0) with 105mm/f2.8 lens. CMOS cameras are located at both sides of the intensified CCD camera for OH PLIF with ±18 degree to capture stereoscopic particle images. The double-pulsed beams are expanded by the laser sheet optics. The double-pulsed laser sheets illuminate the measuring region and scattered light by tracer particles is recorded by the high-speed CMOS camera of which resolution is $1024 \times 1024$ pixels at 1000 frames/s and $512 \times 512$ pixels at 3700 frames/s. For the stereoscopic PIV, the measuring region and the interrogation region are set to $16.2mm \times 16.2mm$ and $24 \times 24$ pixels, respectively. Since the thickness of the laser sheet is about 1.0mm, spatial resolution of the PIV becomes $759 \mu m \times 759 \mu m \times 1000 \mu m$. As for the tracer particles, $3\mu m \text{SiO}_2$, $0.4\mu m \text{TiO}_2$ and $0.18\mu m \text{Al}_2\text{O}_3$ were tested because scattering of CH PLIF excitation laser by the particles contaminates the CH fluorescence image. In this study, spectrum of scattered light by each tracer was measured by a spectrograph. As the intensity of the scattered light near CH fluorescence seems to depend on the diameter of the particle, $\text{Al}_2\text{O}_3$ are used for tracer particles in this study.

In this study, a high spatial resolution PIV algorithm developed by our previous study (Tanahashi et al. 2002) is used to calculate two-dimensional velocity field from successive particle images obtained by each CMOS camera. To ensure the accuracy of the PIV measurement, the elimination scheme of the spurious vectors and noises is established by a PIV simulation based on DNS of particle-laden homogeneous isotropic turbulence, and gives high correlation (about 98%) with DNS (Tanahashi et al. 2002). Note that number of the spurious vectors included in the raw data is very few (less than 0.5%) in the present measurements and the elimination scheme is mainly used for cutoff of the high wave number noises which exceed the spatial resolution of PIV. The high wave number noises are introduced by the overlap of the interrogation regions. From two-dimensional velocity fields obtained by each CMOS camera, three component velocity vectors on a two-dimensional plane are calculated by using a geometrical relation (Arroyo and Great 1991, Westerweel and Nieuwstadt 1991, Willert 1997, Prasad 2000).

If high power and high-repetition-rate pulse lasers for industrial processing are adopted as a light source instead of the double pulsed Nd:YAG laser, temporal resolution of this stereoscopic PIV exceeds several tens of kHz as reported by Tanahashi et al. (2003). However, we focus on the simultaneous CH-OH PLIF and stereoscopic PIV measurement because temporal resolutions of PLIF are of the order of Hz.
2.3 Control of CH-OH PLIF and Stereoscopic PIV

In Fig. 2, the timing diagram of the simultaneous CH-OH PLIF and stereoscopic PIV measurement is shown. As for the stereoscopic PIV, CMOS cameras are operated with 3.2kHz using 512×512 pixels, which results in 302µs exposure time. This high-speed operation was conducted to reject flame radiation and ensure the quality of particle images. The CMOS camera starts to expose 3µs after the negative edge of the trigger. Each laser beam is synchronized to each frame interval. Generally, cameras need the dead time ($T_s$) to store data between camera frames and the time interval of successive images ($Δt$) is limited by this dead time. The theoretical minimum $T_s$ of the CMOS camera used in this study is about 5µs. CH and OH PLIF measurements are synchronized to $Δt/2$ after the first laser pulse for PIV. Timing controls of this system are conducted by two delay generators (SRS, DG535) and two function generators (SONY Tektronix, AFG320). Time difference error between PLIF and PIV is limited to be less than 100ns, and that between
Table 1 Experimental conditions.

<table>
<thead>
<tr>
<th>ID</th>
<th>$Q$ [l/min]</th>
<th>$Re_l$</th>
<th>$Re_{Re}$</th>
<th>$l/\delta_F$</th>
<th>$u'_rms$/S_l</th>
<th>$l$ [mm]</th>
<th>$\lambda$ [mm]</th>
<th>$\eta$ [\mu m]</th>
</tr>
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<tr>
<td>Case 1</td>
<td>200</td>
<td>265.8</td>
<td>63.1</td>
<td>82.9</td>
<td>3.20</td>
<td>3.42</td>
<td>0.812</td>
<td>57.5</td>
</tr>
<tr>
<td>Case 2</td>
<td>250</td>
<td>602.0</td>
<td>95.0</td>
<td>146.0</td>
<td>4.12</td>
<td>6.02</td>
<td>0.950</td>
<td>54.8</td>
</tr>
<tr>
<td>Case 3</td>
<td>300</td>
<td>881.0</td>
<td>115.0</td>
<td>176.6</td>
<td>4.99</td>
<td>7.27</td>
<td>0.949</td>
<td>49.8</td>
</tr>
</tbody>
</table>

Fig. 4. Energy spectrum of streamwise velocity component in the inert flow (a) and turbulent combustion diagram (b).

Fig. 5. Simultaneous fluorescence images of CH radicals (right) and OH radicals (left) for $Re_l = 115.0$ ($Q=300$ l/min). (a) and (b) represents a different realization. Visualized domain size is 31mm × 31mm.

CH PLIF and OH PLIF is controlled to be of the order of 1ns. Based on the characteristics of the turbulent flow field, $\Delta t$ is set to 15\mu s.

2.4 Experimental Apparatus

Figure 3 shows the schematics of the swirl-stabilized burner and a direct photograph of methane-air turbulent premixed flame at stoichiometric condition with a flow rate $Q=300$ l/min. This combustion rig consists of a contraction section, a swirl nozzle section and combustion chamber. The inner diameter of 120mm in the contraction section is reduced to 40mm diameter. The swirl nozzle of 40mm inner diameter was mounted on the contraction section. The inner cross-section of combustion chamber was 120mm × 120mm, and the length of the chamber was 550mm. On each side of combustion chamber, a silica glass plate of 120mm × 170mm and 5mm thickness was installed to allow optical access. The swirl nozzle has swirl vanes of 14mm inner diameter and 40mm outer diameter, inclined 45 degree from the nozzle axis. Although a secondary fuel nozzle was mounted at center of the swirl vanes, this nozzle was not used in the present study. The premixed methane-air mixture pass through the swirl vanes and the flame was stabilized at swirl vanes as shown in the direct photograph.

In this study, the simultaneous CH-OH PLIF and stereoscopic PIV measurements are conducted for three different flow rate: $Q=200$, 250 and 300 l/min for equivalence ratio $\Phi=1.0$ as shown in Table 1. To investigate the turbulent characteristics of the unburned mixture, a hot-wire measurements are conducted in inert flows. The simultaneous CH-OH PLIF and stereoscopic PIV measurements were conducted in a cross-section with the maximum $u'_rms$, where $u'_rms$ indicates r. m. s. velocity fluctuation. The white box in the direct photograph denotes the measurement region of CH.
Fig. 6. Simultaneous CH and OH PLIF for different Reynolds number. (a) Reₐ = 63.1, (b) Reₐ = 95.0 and (c) Reₐ = 115.0. For each case, two different realizations are shown. Visualized domain size is 31 mm × 31 mm.

and OH PLIF, and a box with broken lines represents the measurement region of PIV.

Figure 4(a) shows energy spectrums of the streamwise velocity at the maximum u’ₘₚ point. The energy spectrum is non-dimensionalized by the Kolmogorov micro scale (η) and kinematic viscosity (ν). The energy spectrum shows -5/3 power law in the inertial subrange and turbulence is fully developed. The turbulence characteristics obtained by the hot-wire measurement were shown in Table 1, where l is integral length scale, Reₐ is Reynolds number based on integral length scale and u’ₘₚ, Reₐ is Reynolds number based on Taylor micro scale (λ) and u’ₘₚ, δ is a laminar flame thickness and Sₕ is laminar burning velocity. With the increase of the flow rate, Reₐ changes from 63.1 to 115.0. In Fig. 4(b), experimental conditions are plotted in the turbulent combustion diagram proposed by Peters (Peters 1999). All conditions are classified into the corrugated flamelets.

3. FINE SCALE STRUCTURE OF TURBULENT PREMIXED FLAMES

Figure 5 shows CH and OH PLIF images obtained by two different realizations for Reₐ=115.0 (Q=300 l/min). In this figure, red color denotes high concentration and white line represent integral length scale of turbulence. CH and OH radicals show very complicated distributions. The edge of OH radical concentration coincides with CH layer very well. Flame fronts have large scale wrinkling of the order of the integral length scale and small scale wrinkling less than Taylor micro scale. From comparisons of CH and OH radical distributions, isolated burned gas in the unburned mixture (see circle A) and isolated unburned mixture in the burned side (see circle B) can be observed even in the corrugated flamelet regime. Appearance of the isolated unburned mixture has been shown by Chen et al. (1998), Tanahashi et al. (2001) and Saito et al. (2002) from two-dimensional DNS. Three-dimensional DNS by Nada et al. (2004) showed that the isolated unburned mixture reflects one feature of three-dimensional flame structure, which is called as the handgrip structure. The isolated burned gas in the unburned side is also predicted by DNS of hydrogen-air and methane-air turbulent premixed flame (Tanahashi et al. 2001, Saito et al. 2002). These results suggest that the simultaneous CH and OH PLIF is important in
high Reynolds number turbulence because these flame structures cannot be recognized by

![Images of flame front detection from simultaneous CH and OH PLIF (Re$_{\text{l}}$ = 95.0, Q=250 l/min).](image)

(a) CH image, (b) Flame front and (c) OH image with unit vectors normal to the flame front. Visualized domain size is 31mm × 31mm.

**Fig. 7. Flame front detection from simultaneous CH and OH PLIF (Re$_{\text{l}}$ = 95.0, Q=250 l/min).**

To show effects of Reynolds number on the local flame structure, CH and OH PLIF images obtained for different Reynolds number are shown in Fig. 6. Two different realizations are shown for each Reynolds number case. These images clearly demonstrate Reynolds number effects on flame wrinkling. For all Reynolds number cases, flame wrinkling and flame front cusps were observed, whereas local flame structure becomes more complicated for high Reynolds number case. To investigate statistical characteristics of the flame front, flame front are identified from CH and OH images. Figure 7 shows the procedure of flame front detection from simultaneous CH and OH PLIF. Flame front was determined from CH PLIF image (Fig. 7 (a) and (b)) and a unit vector normal to the flame front was estimated from the gradients of OH at the flame front (Fig. 7 (c)). Figure 8 shows probability density functions (pdf) of the curvature of the flame front. The curvature is defined to be positive value for the flame element convex toward the burned side and is non-dimensionalized by $h$. The pdf was constructed from 150-170 sets of CH and OH images for each case. The curvature is ranging in $|k| < 1/\eta$ and the minimum curvature radius of the flame front is Kolmogorov scale for all different Reynolds number cases, which coincides with our previous DNS results (Tanahashi et al. 2000, Tanahashi et al. 2002, Nada et al. 2004).

**Fig. 8. Probability density functions of the curvature of flame front.**

To show effects of Reynolds number on the local flame structure, CH and OH PLIF images obtained for different Reynolds number are shown in Fig. 6. Two different realizations are shown for each Reynolds number case. These images clearly demonstrate Reynolds number effects on flame wrinkling. For all Reynolds number cases, flame wrinkling and flame front cusps were observed, whereas local flame structure becomes more complicated for high Reynolds number case. To investigate statistical characteristics of the flame front, flame front are identified from CH and OH images. Figure 7 shows the procedure of flame front detection from simultaneous CH and OH PLIF. Flame front was determined from CH PLIF image (Fig. 7 (a) and (b)) and a unit vector normal to the flame front was estimated from the gradients of OH at the flame front (Fig. 7 (c)). Figure 8 shows probability density functions (pdf) of the curvature of the flame front. The curvature is defined to be positive value for the flame element convex toward the burned side and is non-dimensionalized by $\eta$. The pdf was constructed from 150-170 sets of CH and OH images for each case. The curvature is ranging in $|k| < 1/\eta$ and the minimum curvature radius of the flame front is Kolmogorov scale for all different Reynolds number cases, which coincides with our previous DNS results (Tanahashi et al. 2000, Tanahashi et al. 2002, Nada et al. 2004).

Figure 9 shows CH and OH PLIF images and three component velocities for different Reynolds number. White boxes in CH and OH PLIF images represent the stereoscopic PIV measurement region displayed in the right hand side. Velocity magnitude across the measurement plane is shaded and shown with velocity vector in the measurement plane. The velocity from behind the sheet to the front has positive value and is denoted by red. Since the velocity field includes strong three-dimensional fluctuation, it is hard to discuss the characteristics of the flame fronts only from two-component velocity field that is shown in Fig. 9 by arrows. Comparisons of CH-OH PLIF and three-component velocity field imply that the burned gases not always shows high speed in relatively high Reynolds number turbulent premixed flame, which may caused by multiply folded flame structure and the large scale recirculation zone behind the swirler. Since negative velocity across the measurement plane is scarcely observed in the inert flow with the same flow rate, the velocity field is significantly affected by the presence of the flames. With the increase of Reynolds number, number of wrinkles of flame front increases significantly and flame front show very complicated geometry. Three-dimensional DNS (Tanahashi et al. 2000, Tanahashi et al. 2002, Nada et al. 2004) and fractal analysis of OH PLIF results conducted in high
pressure turbulent premixed flames (Kobayashi et al. 2002) showed that the smallest curvature radius of the

![Fig. 9. CH PLIF image (left), OH PLIF image (center) and velocity distribution (right) for different Reynolds number. (a) Reₐ = 63.1, (b) Reₐ = 95.0 and (c) Reₐ = 115.0. Visualized domain size is 31mm×31mm for PLIF images and 16.2mm×16.2mm for velocity field.](image)

flame front is the Kolmogorov micro scale of the unburned mixture, which is confirmed by the present study in Fig. 8. As the Kolmogorov micro scale in the present study does not change so far as listed in Table 1, the observation in Figs. 6 and 9 are considered as the increase of flame surface density.

4. SUMMARY

In this study, the simultaneous CH-OH PLIF and stereoscopic PIV measurement have been developed to investigate the local flame structure of turbulent premixed flames. In this system, high-speed CMOS cameras were adopted to capture the clear stereoscopic particle images without contamination by the flame radiation. The effects of scattering of CH PLIF laser by tracer particles are investigated carefully to improve signal-to-noise ratio in CH fluorescence images.

The developed simultaneous two radical concentrations and three component velocity measurement on a two-
dimensional plane was applied for relatively high Reynolds number turbulent premixed flames in a swirl-stabilized combustor. All measurements were conducted for methane-air premixed flames in the corrugate flamelets regime. Simultaneous CH and OH images suggest that the presence of the isolated burned gas in the unburned mixture and the isolated unburned mixture in the burned side which have been predicted by DNS. Detailed analysis of simultaneous CH and OH images reveals that the minimum curvature radius of the flame front coincides with Kolmogorov scale. Strong three-dimensional velocity fluctuation, which are measured by the stereoscopic PIV, implies that misunderstanding of the flame/turbulence interactions would be caused by the analysis of two-component velocity distribution in a cross section. Furthermore, comparisons of CH-OH PLIF and three-component velocity field show that the burned gases not always have high-speed velocity in relatively high Reynolds number turbulent premixed flame. The Reynolds number dependence of flame front geometry was clearly captured by the simultaneous CH-OH PLIF and stereoscopic PIV measurement.

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