Local Burning Velocity Measurements in Turbulent Jet Premixed Flame by Simultaneous CH DPPLIF/OH PLIF and Stereoscopic PIV

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Abstract
Simultaneous measurement of CH double-pulsed planer laser-induced fluorescence (CH DPPLIF), OH planer laser-induced fluorescence (OH PLIF) and stereoscopic particle image velocimetry (stereoscopic PIV) has been developed and conducted on relatively high Reynolds number methane-air turbulent jet premixed flame to investigate characteristics of local flame element such as local burning velocity. The CH DPPLIF system consists of two independent conventional CH PLIF measurement systems and laser beams from each laser system are led to same optical pass using the difference of polarization. By selecting an appropriate time interval of CH DPPLIF, displacement of the flame front can be measured directly. In this study, interval time and exposure time are decided from preliminary experiments and turbulent characteristics of this jet burner. CH DPPLIF gives flame displacement speed, and OH PLIF is used to discriminate between burnt area and unburnt area, and to evaluate flame normal vectors. Fluid velocity is measured by stereoscopic PIV. By comparing the flame displacement speed with fluid velocity near the flame front, local pseudo-burning velocity is evaluated. Probability density function (pdf) of the pseudo-burning velocity was obtained from several hundred measurements. The peak of the pdf locates at laminar burning velocity, whereas maximum burning velocity reaches to about 10 times laminar one and minimum burning velocity is negative. The result indicates a possibility that dynamics of turbulent flame cannot be explained by flamelet concept. The concept of flame stretch is validated by evaluating mean growth rate of the flame area. Direct numerical simulation (DNS) was also conducted for vortex/flame interaction with detailed kinetic mechanism to verify experimental results. In DNS analysis, local pseudo-burning velocity was evaluated by the same way with experimental analysis. The result from DNS shows same tendency with experimental results. The present experimental and numerical results indicate a possibility of the existence of flame elements which cannot be explained by the flamelet concept and the concept of flame stretch.

1. Introduction

The description of dynamics of flame front has been one of the most important subjects in the turbulent combustion research since that is the basis of turbulent combustion models in the flamelet concept (Clavin 1985; Williams 1985; Pope 1988; Peters 2000; Law and Sung 2000; Williams 2000). In the concept of the flame stretch, increasing rate of the flame area is expressed by flame displacement speed, flame curvature and strain rate at the flame front (Pope 1988; Candel and Poinsoot 1990). The effects of the strain rate have been discussed based on the Markstein number (Peters 2000; Clavin 2000). In previous studies (Poinsoot et al. 1992; Sinibaldi et al. 2003), the curvature and strain rate effects have been investigated in the steady or unsteady laminar flames because the flame elements in turbulent flames are assumed to be laminar flame under weak stretch with small curvature. To confirm the theory of the flame stretch experimentally, measurements of the flame displacement speed are required in turbulent flames. In general, shadowgraph or laser tomography has been adopted to estimate flame displacement (Sinibaldi et al. 2003; Kido et al. 2002). However, in these techniques, flame propagation normal to the flame front is assumed. In turbulent flames, the flame elements do not always move into the flame normal direction due to strong convection effects of turbulence.
In the numerical investigations by direct numerical simulations (DNS) (Haworth and Poinset 1992; Baum et al. 1994; Echekki and Chen 1996; Tanahashi et al. 2000; Nada et al. 2004; van Oijen et al. 2005), consumption speed and local heat release rate are commonly used to represent characteristics of flamelet instead of the flame displacement speed. In experiments, however, measurements of the local consumption speed or heat release rate are quite difficult.

To investigate turbulent flame structures experimentally, PLIF (Dyer and Crosley 1985; Hanson 1986) of molecules and radicals produced in chemical reactions, such as OH (Smooke et al. 1992), CO (Seitzman et al. 1987), CH (Allen et al. 1986; Carter et al. 1998; Mansour et al. 1998) and CH₂O (Bockle et al. 2000), are commonly used. Although the conventional PLIF measurement has been a very powerful tool to obtain instantaneous local flame structures, investigation of dynamics of flame structures in turbulence has been difficult due to the limitation of time resolution. Recently, several time-resolved PLIF measurements have been reported (Kychakoff et al. 1987; Seizman et al. 1994; Schefer et al. 1994; Kaminski et al. 1999; Nygren et al. 2001; Watson et al. 2002; Hult et al. 2005). In our previous study (Tanahashi et al. 2008), CH double-pulsed PLIF (CH DPPLIF) measurement has been developed to estimate local flame displacement speed in turbulent premixed flame. To investigate local burning velocity, however, simultaneous measurement of fluid velocity with CH DPPLIF has been required.

In this study, simultaneous CH DPPLIF, OH PLIF and stereoscopic PIV measurement, which is a simultaneous measurement of local flame displacement speed, flame-normal direction and fluid velocity near the flame front, has been developed and applied to relatively high Reynolds number methane-air turbulent jet premixed flames to investigate characteristics of local flame element such as local burning velocity. DNS of flame-vortex interaction was also conducted to validate experimental results. Local pseudo-burning velocity was evaluated from DNS results by the same way with experimental analysis. By comparing experimental and DNS results, characteristics of local flame element are discussed.

2. Experimental setup and apparatus

The schematic diagram of the experimental setup for simultaneous CH DPPLIF, OH PLIF and stereoscopic PIV measurement is shown in Fig. 1.

2.1 CH double-pulsed PLIF (CH DPPLIF) measurement system

By combining two independent CH PLIF systems, the time-resolved PLIF system is comprised (Tanahashi et al. 2008). For CH PLIF measurement, the Q₁(7,5) transition of the B²Σ−X²Π(0,0) band at 390.0 nm is excited and fluorescence from the A−X(1,1), (0,0) and B−X(0,1) bands between 420 and 440 nm is detected. CH radical is excited by two laser systems. First dye laser (Lambda Physik, Scanmate2) is pumped by a XeCL excimer laser (Lambda Physik, LPX 110I, 308 nm, 200 mJ/pulse) with BiBuQ dye in p-dioxane solvent and second dye laser (Sirah Precisionscan) is pumped by a Nd:YAG laser (Spectra-Physics, Quanta Ray PRO-190, 355 nm, 300 mJ/pulse) with Exalite389 dye in p-dioxane solvent. These laser systems generate laser pulses of about 18-20 and about 20-22 mJ/pulse, respectively.

Laser beams from each laser systems are polarized in vertical and horizontal directions and are led to same optical path by a polarizing beam splitter (PBS). The combined beams are expanded into laser sheets by laser sheet forming optics. Fluorescence from excited CH radicals are detected by two intensified CCD cameras (Andor Technology, iStar DH734-25U-03, 1024×1024 pixels) fitted with 105 mm f2.8 lens (Nikon, Micro-nikkor) and an optical filter (SCHOTT, KV418). These cameras are located on the opposite side of the burner, and optical axes are set to be perpendicular.
to the laser sheet. The laser beam is shaped into about 200 µm thickness vertical sheet with 30 mm height. The pixel resolution is set to 28 µm/pixel.

2.2 OH PLIF measurement system

For OH PLIF measurement, the $Q_1$ (7) transition of the $A^2\Sigma^+ - X^2\Pi(1,0)$ band at 283.0 nm is excited and fluorescence from the $A-X(1,1), (0,0)$ bands between 306 and 320 nm is detected. The laser system consists of a Nd:YAG laser (Continuum, Powerlite 9030, 532nm, 200mJ/pulse) and a dye laser (Lambda Physik, Scanmate2) with Rhodamine 590 dye, which generates laser pulses about 5 mJ/pulse. The fluorescence, which is reflected by a dichroic mirror located at the front of 2nd ICCD camera for CH DPPLIF, was collected with UV-lens (Nikon, UV-Nikkor, 105 mm, f4.5) and imaged onto the third intensified CCD camera (Roper Scientific, PI-MAX 512RB-G1, 512×512 pixels). The laser beam is shaped into about 200 µm thickness vertical sheet with 30 mm height. The pixel resolution is set to 46 µm/pixel.

2.3 Stereoscopic PIV measurement system

Stereoscopic PIV system consists of a double pulsed Nd:YAG laser (New Wave Research, MiniLase III, 532nm, 50mJ/pulse), an optical system and two high-speed CMOS cameras (Vision Research, Phamtom V7.1, 800×600 pixels) with 200mm/f4 lens (Nikon, Micro-Nikkor). CMOS cameras are located at the each side of the intensified CCD cameras with about 20 degrees to capture stereoscopic particle images. To focus clearly on all over the measurement region, the Scheimpflug condition was applied. The double-pulsed laser sheets illuminate the measuring region and scattered light by tracer particles is recorded by the high-speed CMOS cameras. The pixel resolution and the measuring region are set to 20 µm/pixel and 13 mm×10 mm, respectively. The interrogation region is set to 48 pixels×48 pixels. Al$_2$O$_3$ with 0.18 µm diameter are used for tracer particles in this study.
2.4 Experimental apparatus

Figure 2 shows a turbulent jet burner used in this study. This burner has a main jet nozzle and a surrounding nozzle for flame holding. The inner diameter of the main and a surrounding nozzle is 10 mm and 70 mm, respectively. Table 1 shows experimental conditions and turbulence characteristics of inert flow at center of the jet nozzle. Here, \( x \) is distance from the jet exit, \( Re_D \) is Reynolds number based on the nozzle diameter (\( D \)) and mean axial velocity at the jet exit, \( Re_\lambda \) is Reynolds number based on Taylor microscale (\( \lambda \)) and r.m.s. of velocity fluctuation (\( u'_{rms} \)), \( u_m \) is mean velocity, \( l \) is integral length scale and \( \eta \) is Kolmogorov length. Laminar flame thickness and laminar burning velocity are denoted by \( \delta_F \) and \( S_L \), respectively. The characteristics were measured by a hotwire constant temperature anemometer with x-probe (Kanomax Japan, Model0250R, tungsten, \( 5\mu m \)) in preliminary experiments. These conditions are classified into the thin reaction zones in the turbulent combustion diagram by Peters (Peters 1999). In this study, simultaneous measurement of CH DPPLIF/OH PLIF and stereoscopic PIV is conducted for \( u_0 = 10 \) m/s. Equivalence ratio is fixed to 1.0 for the main flame and 0.86 for the surrounding flame. PLIF and PIV were measured at axial distance of \( x/D = 5 \).
2.5 Timing control for simultaneous CH DPPLIF, OH PLIF and stereoscopic PIV

Figure 3 shows the timing diagram of the simultaneous CH DPPLIF, OH PLIF and stereoscopic PIV measurements. The interval time of CH DPPLIF and stereoscopic PIV measurement systems can be decided arbitrarily. In this study, 1st laser pulse for CH DPPLIF, laser pulse for OH PLIF and 1st pulse for stereoscopic PIV are completely synchronized. Time interval of CH DPPLIF ($\Delta t_{CH}$) of successive PLIF is set to 30 $\mu$s; this value is given from preliminary experiments of different time interval (Tanahashi et al. 2008). From the turbulence characteristics in measurement region, time interval of PIV ($\Delta t_{PIV}$) is set to 8 $\mu$s. To optimize signal-to-noise ratio, image intensifier gate time for CH DPPLIF and OH PLIF are set to 30 ns (Tanahashi et al. 2005). Timing control of this system is conducted by two pulse generators (Stanford Research Systems, DG535 and LabSmith, LC880) and delay generators inside of cameras.

3. Direct measurement of local burning velocity

Figure 4 shows the first and second CH fluorescence images and OH fluorescence image for a typical realization. In this study, from successive CH fluorescence images, flame displacement speed is evaluated by the method developed in our previous study (Tanahashi et al. 2008) with several modifications, because fluid velocity is measured by stereoscopic PIV in the present study. In general, direction of flame propagation has three-dimensionality. However, in this study, flame displacement speed was measured in two-dimensional cross section. Therefore, the local burning velocity evaluated in this study is denoted by pseudo-burning velocity. The evaluation scheme consists of following procedures:

(a) Search the flame front from the 1st CH fluorescence image.
(b) Evaluate the fluid velocity at the flame front from the result of stereoscopic PIV.
(c) Set interrogation regions just like an analysis technique for the conventional PIV with offset for the 2nd CH image based on the fluid velocity at the flame front.
(d) Evaluate flame displacement speed using the cross-correlation method.
(e) Estimate local pseudo-burning velocity by subtracting local fluid velocity from flame displacement speed.
Fig. 4 First CH (left), second CH (center), and OH (right) fluorescence images for a typical realization.

Fig. 5 Distribution of CH radical and temperature in one-dimensional methane-air premixed flame.

Here, to evaluate local pseudo-burning velocity, appropriate estimation of fluid velocity is important. In this study, flame front is identified by using CH radicals. However, at the position of highest CH radical fluorescence intensity, the fluid temperature already rises and the fluid velocity is already accelerated by dilatation. Figure 5 shows distribution of CH radical molar fraction and temperature of one-dimensional steady methane-air premixed flame which is preliminary calculated by PREMIX of Chemkin II. This figure shows that the distance between a peak location of CH radicals and a position of maximum temperature gradient is 170 µm. In this study, the flame front position is defined as the position where temperature gradient is maximum value in each flame element. Therefore, the flame front is defined as 170 µm inside from CH fluorescence peak toward unburnt side.

To evaluate flame displacement speed and fluid velocity, interrogation region is set in the images of CH DPPLIF and stereoscopic PIV. Therefore, spatial resolution is determined by the size of interrogation region. In this study, spatial resolution of CH DPPLIF and stereoscopic PIV is set to 600 µm and 960 µm, respectively.

Figure 6 shows the successive CH fluorescence images with vector maps of the local pseudo-burning velocity and three-component fluid velocity. Red and blue contour lines correspond to high CH fluorescence region of 1st and 2nd image, respectively. White arrows represent the local pseudo-burning velocity vector and black arrows do in-plane component of fluid velocity vector. Out-of-plane component of fluid velocity is denoted by colors. In these figures, mean streamwise velocity in the measurement region is subtracted from the velocity field. Directions of the pseudo-burning velocity do not coincide with the displacement of flame front which is observed from successive CH images, because the pseudo-burning velocity is obtained from the difference between flame displacement speed and fluid velocity at the flame front in two-dimensional cross section. In laminar flamelet, pseudo-burning velocity vector should face toward unburnt side. In Fig.
6, most of the pseudo-burning velocity vectors align its direction to the unburnt side. However, several vectors face to the burnt side.

Figure 7 shows probability density function (pdf) of the pseudo-burning velocity. The pdf is obtained from several hundred measurements. In flamelet concept, local burning velocity is not so far from laminar burning velocity. The peak of the pdf locates at laminar burning velocity, whereas variance of the pseudo-burning velocity is relatively large. The maximum burning velocity reaches to about 10 times laminar burning velocity and minimum one is negative velocity. Note that the negative velocity is observed because steady flamelet concept was assumed in the evaluating process. Negative local pseudo-burning velocity which means flame propagation toward unburnt side might be caused by following reasons. In enormously strong turbulent field, the time scale of fluid is very short compared to the laminar flame time scale. In the present case, the inflow velocity is more than 20 times laminar burning velocity ($S_L$). In such strong turbulent field, fluid flow often changes before fluid velocity is reflected to dynamics of flame front (or combustion chemistry). Therefore, there is a possibility that the dynamics of turbulent flame cannot be explained by flamelet concept. These expectations will be confirmed by DNS in next section.

In the concept of flame stretch, growth rate of the flame area ($A_t$) is written as
where $S_d$, $k$ and $a_t$ denote flame displacement speed, flame curvature and tangential strain rate, respectively. It should be noted that $S_d$ in Eq. (1) is local burning velocity of each flame element. In this study, since the measured local burning velocity has large variance, each flame element is assumed to have laminar burning velocity.

In this study, from several hundred measurements, two terms in the right hand side of Eq. (1) are evaluated. As shown in Fig. 6, since OH fluorescence image is obtained simultaneously, curvature of the flame front can be estimated from the flame normal vector which is calculated from gradient of OH radical distribution (Tanahashi et al. 2005). Tangential strain rate at the flame front is evaluated from in-plane velocity components obtained by SPIV. Figure 8 shows a correlation diagram between two-dimensional tangential strain rate ($a_t$) and $kS_d$. Ensemble averages of the two values are denoted by red lines. Since flame front should stay in a certain area statistically, ensemble average of the right hand side of Eq. (1) should be zero. Figure 8 shows that ensemble average of $kS_d$ is zero, whereas the time average of tangential strain rate is around 200. This fact suggests that flame does not exist as statistically steady state. Therefore, conventional description for the growth rate of flame area (Eq. (1)) might be modified. It should be noted that the assumption of $S_d = S_l$ does not change this result significantly because the curvature is instantaneous property. However, both of the curvature and the tangential strain rate might be modified by the two-dimensional effects. To investigate these effects, further complicated simultaneous measurements such as dual-plane stereoscopic PIV and dual-plane CH PLIF will be required in future works.

4. DNS of vortex pair and flame front interactions

To confirm results obtained from the present experiment, two-dimensional DNS has been conducted on hydrogen-air premixed flame interfered with a vortex pair (Poinsot et al. 1991). The DNS code has been developed in our previous studies (Tanahashi et al. 2000; Tanahashi et al. 2002; Nada et al. 2004). Schematic of the flow geometry is shown in Fig. 9. For discretization methods, forth-order central finite difference method is applied for $x$ direction and Fourier spectral method is applied for $y$ direction. Third-order Runge-Kutta method is used for time integration. A detailed kinetic mechanism (Miller et al. 1989; Smooke and Giovangigli 1991; Kee et al. 1996) which includes 27 elementary reactions and 12 reactive species ($H_2, O_2, H_2O, O, H, OH, HO_2, H_2O_2, N_2$,
NO\textsubscript{2}, N and NO) is used to represent hydrogen-air reaction in turbulence. The temperature dependence of the viscosity the thermal conductivity and the diffusion coefficients are considered by linking CHEMKIN packages (Kee et al. 1986; Kee et al. 1989) with modifications for vector/parallel computations. As shown in Fig. 9, a vortex pair is added in unburned side of planar laminar flame. The inflow speed $u_0$ is equal to $S_L$ and the initial velocity field is given using the stream function $\psi$ as follows:

$$
\begin{pmatrix}
u \\
\eta 
\end{pmatrix} = \begin{pmatrix} S_L \\
0
\end{pmatrix} + \frac{1}{\rho} \begin{pmatrix} \frac{\partial \psi}{\partial y} \\
-\frac{\partial \psi}{\partial x}
\end{pmatrix}, \quad \psi = C \exp \left( -\frac{x^2 + y^2}{2R_c^2} \right),
$$

(2)

where $C$ determines the vortex strength and $R_c$ is the vortex radius (Rutland and Ferziger 1989). Boundary conditions are specified using the Navier-Stokes characteristic boundary condition (NSCBC) (Poinsot et al. 1992; Baum et al. 1994) in the $x$ direction and periodic condition in the $y$ direction (Fig. 9). Numerical parameters of DNS are shown in Table 2. A hydrogen-air mixture in the unburnt side is set to $\phi = 1.0$ at 0.1MPa and 700K. As described in above, as the ratio of the time scale of fluid and the laminar flame time scale may cause negative local pseudo-burning velocity, maximum azimuthal velocity of the initial vortex is changed to 2.1$S_L$, 5.4$S_L$ and 10.7$S_L$.

The local pseudo-burning velocity was evaluated using DNS results by the same way with experimental analysis. Since DNS are conducted in two-dimensional flow field, the local pseudo-burning velocity is exact local burning velocity in DNS analysis.

With the increase of the maximum azimuthal velocity of the vortex, probability of negative local burning velocity increases (not shown here). Figure 10 shows a typical local burning velocity vector map for the maximum azimuthal velocity of 10.7$S_L$. White arrows represent the local burning velocity vectors and black arrows do fluid velocity vectors. Red lines represent flame front and vorticity is denoted by colors. This figure shows the same tendency as experimental results in previous section. As denoted by a box in Fig. 10, local burning velocity vectors change their directions gradually along the flame front from toward the unburnt side to toward the burnt side. These results may confirm the expectation based on the experimental results described in the previous section.

**Table 2** Numerical parameters of DNS.

<table>
<thead>
<tr>
<th>Equivalent ratio $\phi$</th>
<th>1.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max azimuthal velocity</td>
<td>2.1$S_L$, 5.4$S_L$, 10.7$S_L$</td>
</tr>
<tr>
<td>Pressure $P$[MPa]</td>
<td>0.1</td>
</tr>
<tr>
<td>Preheat temperature $T_{pre}$[K]</td>
<td>700</td>
</tr>
<tr>
<td>Computational domain [mm]</td>
<td>10×5</td>
</tr>
<tr>
<td>Grid point</td>
<td>385×192</td>
</tr>
</tbody>
</table>

![Fig. 10 Local pseudo-burning velocity vector map (white arrows), fluid velocity (black arrows) and vorticity (colors).](image)
5. Conclusion

In this study, simultaneous measurement of CH DPPLIF, OH PLIF and stereoscopic PIV has been developed to investigate local burning velocity of turbulent premixed flame. The developed measurement system was applied for relatively high Reynolds number turbulent jet premixed flame. From successive images of CH PLIF, OH PLIF and stereoscopic PIV, local pseudo-burning velocity, flame curvature and tangential strain rate were evaluated. Probability density function of local pseudo-burning velocity was obtained from several hundred measurements. The peak of the pdf locates at laminar burning velocity, whereas variance of the pseudo-burning velocity is relatively large. Maximum burning velocity reaches to about 10 times laminar burning velocity and minimum one is negative. The concept of flame stretch was also validated by evaluating mean growth rate of the flame area. It was shown that steady flamelet concept cannot explain the experimental results.

Two-dimensional DNS was conducted for flame/vortex interactions to confirm experimental results by changing time scale ratio of the vortex and flame. The local burning velocity was evaluated in the same way with experimental method. Detailed analysis of DNS data shows that local burning velocity becomes negative value even in two-dimensional field, and confirms the present experimental results.

The present experimental and numerical results indicate a possibility of the existence of flame elements which cannot be explained by the flamelet concept and the concept of the flame stretch and imply that further improvements in these concepts will be required.

6. References

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