Simultaneous CH DPPLIF/OH PLIF and Stereoscopic PIV in Turbulent Premixed Flames

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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 [1, 2, 3]. 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 [2, 4]. In previous studies [5, 6], 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. 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) [7, 8], consumption speed and local heat release rate are commonly used to represent characteristics of flamelets 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 of molecules and radicals produced in chemical reactions, such as OH, CO and CH, 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 measurement have been reported [9, 10, 11]. In our previous study [12], 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 and fluid velocity near the flame front, has been developed and applied to relatively high Reynolds number turbulent jet premixed flames. By comparing the flame displacement speed with fluids velocity, characteristics of local flame element such as local burning velocity are discussed.

2 Experimental Setup and Apparatus

The schematic diagram of the experimental setup for CH DPPLIF/OH PLIF and stereoscopic PIV measurement is shown in Fig. 1. By combining two independent CH PLIF systems, the time-resolved PLIF system is comprised [12]. CH radical is excited by two laser systems. First dye laser is pumped by a

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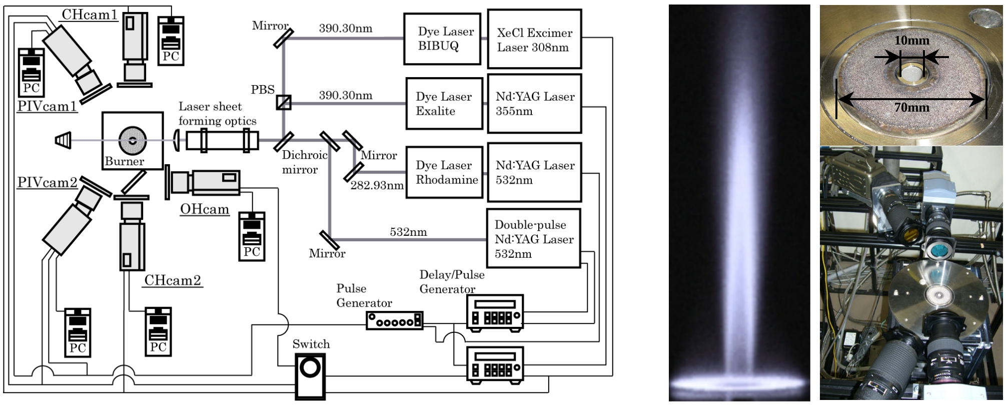

Figure 1: Schematic diagram of the CH DPPLIF/OH PLIF and stereoscopic PIV measurement(left) and the turbulent jet burner(right).

Table 1: Experimental conditions.

$u_0[m/\text{s}]$	x/D	Re_D	Re_λ	$u_m[m/\text{s}]$	u'_{rms}[m/s]	l[mm]	λ[mm]	η[mm]	l/δ_F	u'_{rms}/S_L
10	5	6667	93.4	11.40	1.15	6.21	0.998	0.0580	150.8	5.96
15	7	10001	173.7	14.47	2.12	11.65	1.006	0.0429	282.8	10.98
20	10	13333	256.8	14.49	2.87	18.83	1.100	0.0386	457.1	14.87

XeCl excimer laser with BiBuQ dye and second dye laser is pumped by a Nd:YAG laser with Exalite389 dye. These laser systems generate laser pulses of about 18-20 mJ/pulse and about 20-22 mJ/pulse, respectively. Laser beams from each laser systems are polarized in vertical and horizontal direction and are lead to same optical pass by a polarizing beam splitter. The combined beams are expanded into laser sheets by laser sheet forming optics. Fluorescence from excited CH radicals is detected by two intensified CCD cameras (1024×1024 pixels) fitted with 105 mm f2.8 lens and optical filters. These cameras are located on the opposite side of the burner, and optical axes are set to be perpendicular to the laser sheet. For OH PLIF measurement, the laser system consists of a Nd:YAG laser and a dye laser with Rhodamine 590 dye, generates laser pulses about 5mJ/pulse. The fluorescence, which is reflected by a dichroic mirror, was collected with UV-lens and imaged onto the third intensified CCD camera (512×512 pixels). The laser beam is shaped into about 200 μm thickness vertical sheet with 30 mm height. To optimize signal-to-noise ratio, image intensifier gate time is set to 30 ns. Time interval Δt of successive PLIF is set to the range of 10 to 30μs; this value is given from preliminary experiments of different time interval [12].

Stereoscopic PIV system consists of a double-pulsed Nd:YAG laser, an optical system and two high-speed CMOS cameras (800×600 pixels) with 200mm/f4 lens. CMOS cameras are located at the each side of the intensified CCD cameras with about 20 degree to capture stereoscopic particle images. The double-pulsed laser sheets illuminate the measuring region and scattered light by tracer particles is recorded by the high-speed CMOS camera. For the stereoscopic PIV, the measuring region and the interrogation region are set to 13mm $\times$ 10mm and 48×48 pixels, respectively. Since the thickness of the laser sheet is about 1.0mm, spatial resolution of the PIV becomes 960μm $\times$960μm $\times$ 1000μm. Al_2O_3 with 0.18μm diameter are used for tracer particles in this study. From the turbulence characteristics in measurement region, time interval Δt of PIV is set to 8μs.

Figure 1 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 the surrounding nozzle is 10mm and 70mm, respectively. In this study, simultaneous CH DPPLIF/OH PLIF and stereoscopic PIV is conducted for three different jet velocity conditions: $U_0 = 10$, 15 and 20m/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 $x/D = 5$, 7 and 10 for each conditions.

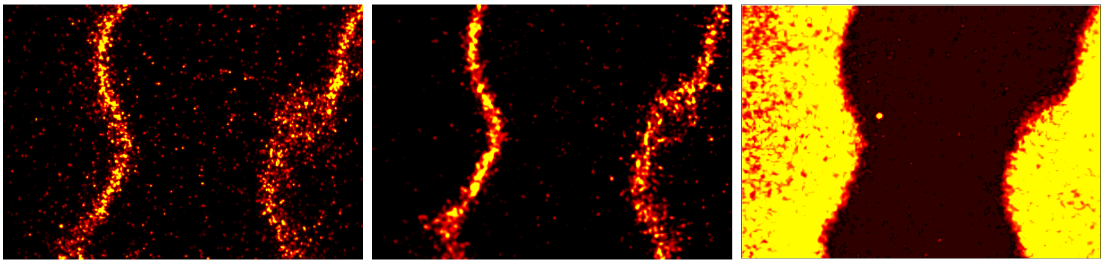

Figure 2: First CH (left), second CH (center) and OH (right) fluorescence images for $Re_\lambda = 93.4$.

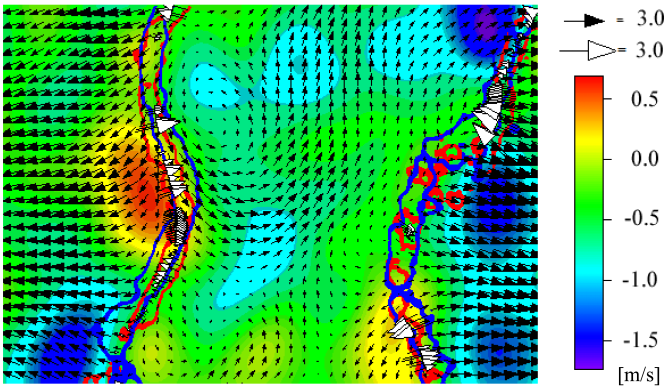

Figure 3: Successive CH fluorescence images (red: 1st, blue: 2nd) and vector map of local pseudo-burning velocity (white arrows) and three-component fluid velocity (black arrows: u and v, color: w) for $Re_\lambda = 93.4$.

From the results of preliminary hot-wire measurements conducted in inert flows, turbulence characteristics are obtained as shown in Table 1. Here, l is integral length scale, Re_l is Reynolds number based on integral length scale and $\boldsymbol{u}'_{rms}$, Re_λ is Reynolds number based on Taylor micro scale (λ) and $\boldsymbol{u}'_{rms}$, δ_F is a laminar flame thickness and S_L is laminar burning velocity. With the increase of the flow rate, Re_λ changes from 93.4 to 256.8. These conditions are classified into the thin reaction zones in the turbulent combustion diagram by Peters [3].

3 Experimental Results

Figure 2 shows the first and second CH fluorescence images and OH fluorescence image for a typical realization for $Re_\lambda = 93.4$. In this study, from successive CH fluorescence images, flame displacement speed is evaluated by the method developed in our previous study [12] with several modifications, because fluid velocity is measured by stereoscopic PIV in the present study. The evaluation scheme consists of following procedures:

- Search the flame front from the 1st CH fluorescence image.
- Evaluate the fluid velocity at the flame front from the result of stereoscopic PIV.
- Set interrogation regions just like an analysis technique for the conventional PIV with offset for the 2nd CH image based on the fluid velocity.
- Evaluate flame displacement speed using the cross-correlation method.

Figure 3 shows the successive CH fluorescence images with vector maps of the local pseudo-burning velocity and three-component fluid velocity. Blue and red 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 this figure, 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.

The pseudo-burning velocity includes effects of out-of-plane velocity component and is different from actual local burning velocity. To discuss relation between turbulent structure and local burning velocity, we have to pay attention to the three dimensionality of fluid velocity. By using the results of stereoscopic PIV, detection of the location where three dimensionality of the fluid velocity is very weak is possible. Therefore, flame front in nearly two-dimensional flow field can be identified. The strain rate at flame front is also estimated from PIV result. As shown in Fig. 2, since OH fluorescence image is obtained simultaneously, curvature of the flame front can be estimated from the flame normal direction which is calculated from gradient of OH radical distribution [13]. The analyses of these flame front reveal the effects of flame curvature and strain rate on the local burning velocity.

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