OH planar laser-induced fluorescence measurement for H\(_2\)/O\(_2\) jet diffusion flames in rocket combustion condition up to 7.0 MPa

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Abstract

This study focuses on the application of OH planar laser-induced fluorescence (OH-PLIF) in high-pressure rocket combustion conditions, up to 7.0 MPa. The signal to noise ratio of PLIF degrades in high-pressure combustion owing to effects such as line broadening and interference from intense chemiluminescence. The OH(2,0) band excitation method was applied to obtain the OH(2,1) fluorescence emitted near 290 nm and filter out the intense OH(0,0) band chemiluminescence emitted near 308 nm. The gaseous H\(_2\)/O\(_2\) (GH\(_2\)/GO\(_2\)) jet diffusion flame was formed using a recessed coaxial shear injector. The GH\(_2\)/GO\(_2\) injection Reynolds number, \(Re(Re_{H2}/Re_{O2} \approx 2320/22800-4660/45600)\), was varied to examine the variation of the flame structure and reaction zone thickness under each pressure condition \(Pc\), and \(Re\) injection condition. In addition, the variation of the experimentally derived full width at half maximum (FWHM) of the radial OH distribution, \(\delta_{OH}\), with the Damköehler number, \(Da\), was compared with that of the simulated FWHM of the OH mole fraction, \(\delta_{OH-SIM}\). The OH distribution was clearly observed in the instantaneous PLIF image while eliminating the intense OH chemiluminescence even in the highest pressure condition of 7.0 MPa, which is a pressure higher than any of the previous OH-PLIF studies conducted on rocket combustion. The flame structure showed the typical characteristics of a turbulent jet diffusion flame and depended on \(Re\) rather than on the chamber pressure \(Pc\). The variation of \(\delta_{OH}\) with \(Da\) corresponded qualitatively with \(\delta_{OH-SIM}\) and showed the characteristics of flame stretch in the vicinity of the injector.

Keywords: High-pressure combustion, Laser-induced fluorescence, Jet diffusion flame, Chemiluminescence, OH(2,0) band excitation

1. Introduction

Typical bipropellant liquefied hydrogen and liquefied oxygen (LOX) rocket engines feature an extreme combustion environment such as high-flame temperature, high-pressure, and supercritical fluid condition. In addition, combustion instability which involves high-frequency combustion oscillation exceeding 1 kHz, is one of the phenomena representing rocket combustors. Yoshida et al. (2009) and Huynh et al. (2009) reported that self-excited T (tangential) mode combustion oscillation can be generated in a H\(_2\)/O\(_2\)/N\(_2\) coaxial flame under atmospheric conditions. The oscillation occurs in the cases of lifted flame and lifted/attached flame to the injector lip, because the flame base transits a premixed flame and induces intensive fluctuation of heat release. It has been considered that these flame shape transitions may depend on a flame strain rate. These results indicate that the instability factor of the rocket combustor exists in the vicinity of the
injected flame and that obtaining a detailed flame structure will lead to the elucidation of the instability.

Owing to the outstanding improvement in computer performance, high-precision turbulent numerical simulations such as large eddy simulations (LESs) have become a trend of analysis, and many combustion evaluation reports have been published recently (Urbano et al., 2016; Matsuyama et al., 2017). In addition, many experimental studies using direct imaging such as chemiluminescence and the shadowgraph imaging method are available (Smith et al., 2007; Lux and Haiden, 2009). However, image conversion, such as the Abel inversion, must be used to evaluate the cross-section of the flame structure. Therefore, the reaction zone and structure formed by mixing H2 and O2 at the shear surface cannot be acquired directly in such measurements. OH planar laser-induced fluorescence (OH-PLIF) measurement is a commonly used method to visualize a detailed two-dimensional cross section of the flame structure. Singla et al. (2006) conducted an OH-PLIF measurement to obtain the instantaneous two-dimensional OH distribution of the coaxial H2/LO2 jet flame at a pressure of up to 6.3 MPa, which is the highest pressure condition for OH-PLIF measurement up to date, to the best of the authors’ knowledge. They examined the full width at half maximum (FWHM) of the radial OH fluorescence distribution to evaluate the flame thickness. Flame thickness is one of the significant criteria for flame instability (Singla et al., 2007). When the flame is thicker than the O2 post lip thickness, it becomes unstable and sensitive to the high-speed stream.

However, owing to the difficulty of measuring OH-PLIF in high-pressure combustion conditions, the experimental data required to investigate flame thickness variations with propellant injection and under rocket combustion pressure conditions are still lacking. The signal to noise ratio, S/N, for the OH-PLIF measurement degrades as the absorption line broadening caused by pressure increases. Moreover, the intense OH chemiluminescence becomes a significant interference in the measurement, because the wavelengths of OH(0,0) and OH(1,1) band fluorescence (AΣg+ ← XΠg), which are detected in the OH-PLIF measurements using the conventional OH(1,0) band excitation method, overlap with that of the intensive OH(0,0) band chemiluminescence. Vaidyanathan et al. (2009) also conducted OH-PLIF measurement in a coaxial gaseous H2/O2 rocket combustion condition, with pressures up to 5.3 MPa. However, dissipations of the fluorescence signal distribution were noticed in the region close to the injector face owing to the OH chemiluminescence interference. This result indicates that in the OH-PLIF measurement of rocket combustion, the interference of background light, or chemiluminescence of the flame, cannot be ignored and is a significant factor that lowers the S/N ratio, together with a decrease in the fluorescence intensity. Meanwhile, the authors have reported that the OH(2,0) band excitation (AΣg+ ← XΠg) is a promising method, which can effectively eliminate the intensive OH(0,0) band chemiluminescence, and applied it to H2/O2 jet diffusion flames at a maximum pressure of 2.0 MPa (Takeuchi et al., 2017). However, this method has not yet been applied to higher pressure conditions. Thus, a verification of the applicability of the OH(2,0) band excitation method at higher pressures under actual rocket combustion conditions is still required.

In this study, OH(2,0) band excitation PLIF measurement was conducted to evaluate the flame characteristics and ascertain the availability of the measurement method under high-pressure rocket combustion conditions to measure the instantaneous OH distribution of H2/O2 jet diffusion flames under the maximum pressure of 7.0 MPa, which is a pressure higher than any of the previous OH-PLIF measurements conducted on rocket combustion. Furthermore, the FWHM of the radial OH distributions, δH, is calculated to evaluate the flame thickness variation with H2/O2 propellant injection and pressure conditions.

2. Experimental and numerical method
2.1 OH(2,0) band excitation PLIF method

Figure 1 shows the simulated results of the conventional OH(1,0) excitation fluorescence spectrum, proposed OH(2,0) excitation fluorescence spectrum, and emission spectrum corresponding to OH chemiluminescence under the pressure condition of 7.0 MPa and 3000 K using Lifbase (Luque and Closely, 1999). Lifbase simulates the spectra by incorporating the transition probabilities that are calculated using the Rydberg–Klein–Rees (RKR) method, standard frequencies, Hönl–London factors (line-strengths), radiative life times, and rotationally dependent predissociation in addition with the quenching rate set to zero at default. The simulation was used to roughly check the spectrum position of each emission band and the quenching rate does not have an influence on the spectral wavelength itself. Therefore, the quenching rate was not considered in the simulation in this study. The line shape was fitted with a Voigt profile and the wavelength resolution was set at 0.01 nm. When the OH(1,0) band is excited, the fluorescence emitted at it cannot be obtained because the elastic scattering of the excitation laser interferes at the same wavelength. Therefore, the
fluorescence spectra emitted at the OH(0,0) and OH(1,1) bands are obtained, which have strong peaks at around 308 nm and 315 nm, respectively. However, Fig. 1 clearly shows that the OH(0,0) band chemiluminescence overlaps with the fluorescence wavelength obtained by OH(1,0) band excitation. In other words, it is difficult to separate the fluorescence signal using an optical interference filter when the chemiluminescence is very strong, as in the case of rocket combustion. In contrast, when the OH(2,0) band is excited, fluorescence is emitted at the OH(2,1) band, which has a peak at around 290 nm. As shown in the figure, the difference between the peak wavelength of the OH(0,0) chemiluminescence and the peak wavelength of the OH(2,1) fluorescence is 20 nm or more. Therefore, OH(2,0) band excitation should be able to separate OH(0,0) chemiluminescence from OH(2,1) fluorescence and drastically reduce the interference of intense OH chemiluminescence using an optical interference filter of approximately 10 nm at half-width, denoted as a type-A filter, which is also shown in Fig. 1. The detailed specification of the type-A filter is provided in the following section. However, the fluorescence yield for the OH(2,0) band excitation method is lower than that for the OH(1,0) band excitation method (Takeuchi et al., 2017) because of lower Einstein B coefficient, and A coefficients and increasing number of paths for the vibrational energy transfer (VET) process. Although the VET process was not considered in the simulation shown in Fig. 1, it will cause weak OH(1,0) band and OH(0,0) band fluorescence to be emitted in the OH(2,0) band excitation method. Moreover, the rate of the VET increases as the pressure rises, along with the quenching rate. Therefore, the S/N characteristics of the OH(2,0) band excitation method should be verified in sufficient detail to apply it to the high-pressure rocket combustion condition.

2.2 Experimental facility and configuration

The high-pressure combustion experiments up to 7.0 MPa were conducted at JAXA, Kakuda Space Center. Figure 2 shows the schematic diagram of the high-pressure chamber, which has four windows and a coaxial-type injector installed at the bottom. The diameter of the window was 48 mm. Quartz glass capable of transmitting UV radiation was installed in three of the windows for optical access near the injector, and one window was equipped with an igniter. Gaseous nitrogen (N₂) was used for cooling and pressurizing the chamber as well as for purging the window. Three modifications were made to the chamber from the previous study conducted by the authors (Takeuchi et al., 2017). Firstly, the N₂ coflow injection plate were modified to enhance the rectification of the flow field. Secondly, secondary N₂ injection was introduced to protect the inner wall of the chamber from the burnt gas. Thirdly, the window section was modified to prevent the water droplets from attaching to the windows. A coaxial shear injector was used to inject gaseous H₂ and O₂. The injector geometry parameters of the oxidizer were as follows: inner diameter d₀ = 3.0 mm, outer post diameter =

Fig. 1 Comparison of fluorescence and chemiluminescence spectra. These spectra were simulated by Lifbase (Luque and Closely, 1999), without the involvement of any VET process. The simulated pressure and temperature were 7.0 MPa and 3000 K, respectively. The transmittances for type-A and type-B filters are also shown in this figure.
Coumarin 522B (Exciton) was chosen as the dye for OH(2,0) band excitation. The OH(2,0) band Q (Spectra-Physics, PRO-250DP-KE ) and a wavelength-tunable dye laser with a frequency doubler (Sirah, PrecisionScan).

Figure 3 shows the laser assembly used to excite the OH radical. The assembly was composed of an Nd:YAG laser and three injection conditions at each value of pressure were tested. These are listed in Table 1. The mean injection constant at 4.5 to maintain a constant velocity was pumped with the laser wavelength tuned at 263.586 nm, which was simulated by Lifbase (Luque and Closely, 1999).

Table 1 List of operating conditions.

<table>
<thead>
<tr>
<th>RUN-Number</th>
<th>( P_c ) [MPa]</th>
<th>( \dot{m}_{H2} ) [g/s]</th>
<th>( \bar{U}_{H2} ) [m/s]</th>
<th>( Re_{H2} )</th>
<th>( \dot{m}_{O2} ) [g/s]</th>
<th>( \bar{U}_{O2} ) [m/s]</th>
<th>( Re_{O2} )</th>
<th>( O/F )</th>
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<tr>
<td>P1-Re1</td>
<td>1.05</td>
<td>0.136</td>
<td>46.4</td>
<td>2310</td>
<td>1.09</td>
<td>11.1</td>
<td>22800</td>
<td>8.01</td>
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<td>P1-Re2</td>
<td>1.08</td>
<td>0.204</td>
<td>67.6</td>
<td>3480</td>
<td>1.63</td>
<td>15.9</td>
<td>34100</td>
<td>7.99</td>
</tr>
<tr>
<td>P1-Re3</td>
<td>0.98</td>
<td>0.274</td>
<td>98.1</td>
<td>4660</td>
<td>2.18</td>
<td>22.8</td>
<td>45500</td>
<td>7.96</td>
</tr>
<tr>
<td>P3-Re1</td>
<td>3.04</td>
<td>0.136</td>
<td>16.7</td>
<td>2330</td>
<td>1.10</td>
<td>3.80</td>
<td>22900</td>
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<td>P3-Re2</td>
<td>3.01</td>
<td>0.205</td>
<td>25.3</td>
<td>3490</td>
<td>1.64</td>
<td>5.70</td>
<td>34300</td>
<td>8.00</td>
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<tr>
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<td>0.273</td>
<td>32.4</td>
<td>4640</td>
<td>2.18</td>
<td>7.30</td>
<td>45700</td>
<td>7.99</td>
</tr>
<tr>
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<td>0.136</td>
<td>10.1</td>
<td>2320</td>
<td>1.08</td>
<td>2.22</td>
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<td>15.2</td>
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<td>3.41</td>
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<tr>
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<td>4.52</td>
<td>45700</td>
<td>7.99</td>
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<tr>
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<td>0.135</td>
<td>7.32</td>
<td>2300</td>
<td>1.09</td>
<td>1.62</td>
<td>22800</td>
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<tr>
<td>P7-Re2</td>
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<td>10.9</td>
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<td>1.64</td>
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<td>34200</td>
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<td>14.8</td>
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<td>2.18</td>
<td>3.12</td>
<td>45600</td>
<td>7.93</td>
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4.0 mm, and the fuel annulus diameter \( d_{H2} = 4.5 \) mm. The oxygen post lip had a 3.0-mm recess against the injector surface. A mass flow controller was used to maintain the mass flow rate of the gaseous \( \text{H}_2/\text{O}_2 \) under all chamber pressure, \( P_c \), conditions. The ratio of the oxidizer and fuel mass flow rates, \( O/F \), was set at 8, which is the stoichiometric \( O/F \) under all \( P_c \) conditions. In this study, the injector geometry was maintained constant. Therefore, the velocity ratio of \( \text{H}_2/\text{O}_2 \) was constant at 4.5 to maintain a constant \( O/F \) in all the conditions. Four pressure conditions, from the range 1.0 to 7.0 MPa, and three injection conditions at each value of pressure were tested. These are listed in Table 1. The mean injection velocity \( \bar{U} \) decreased as the pressure arose because the three cases of injection Reynolds number, \( Re \), of \( \text{H}_2 \) and \( \text{O}_2 \) were maintained the same at each \( P_c \) condition. \( Re \) was defined as follows:

\[
Re = \frac{\rho \bar{U} d e}{\mu},
\]

where \( \rho, de, \) and \( \mu \) are the density, hydraulic diameter, and viscosity at the injection temperature of 293 K, respectively.

Figure 3 shows the laser assembly used to excite the OH radical. The assembly was composed of an Nd:YAG laser (Spectra-Physics, PRO-250DP-KE) and a wavelength-tunable dye laser with a frequency doubler (Sirah, PrecisionScan). Coumarin 522B (Exciton) was chosen as the dye for OH(2,0) band excitation. The OH(2,0) band Q(\( J'' = 9.5 \)) transition was pumped with the laser wavelength tuned at 263.586 nm, which was simulated by Lifbase (Luque and Closely, 1999).

Fig. 2 Schematic diagrams of the high-pressure test chamber with windows and coaxial shear injector.
At high pressures, the $R_2(13.5)$ and $P_{21}(9.5)$ transitions partially overlap with the $Q_1(9.5)$ transition owing to line broadening and shift. These transitions were selected because the $Q_1(9.5)$ transition becomes almost independent of temperature in the range 3300 K–3700 K. The flame temperature range was calculated using equilibrium calculation (Gordon and McBride, 1996). The temperature dependence of each excitation line is expressed as $f_b/T$ when the collisional quenching rate is assumed as $cP$, where $f_b$ is the Boltzmann fraction, $T$ is the temperature, $c$ is a constant and $P$ is the pressure. The $f_b$ for diatomic molecules such as OH, which has linear molecular geometry, is defined in the existing literature (Bechtel, 1979, GuoBiao et al., 2016). The variation of $f_b/T$ for the $Q_1(9.5)$ transition in the given temperature range is approximately 17% at maximum. The energy of the laser beam measured before the experiment at the dye laser exit was approximately 16 mJ/pulse. The incident laser beam was steered by two mirrors and then formed into a sheet with dimensions of approximately 18 mm by 30 $\mu$m using cylindrical lenses, to be vertically introduced into the injector center. The intensity profiles of the laser sheet were evaluated using alignment papers. There were no experimental apparatus to measure the spatial resolution and the temporal fluctuation of the laser pulse energy during the measurement so they are not corrected for the PLIF results. However, the laser sheet profiles were almost uniform in the alignment paper profiles. The main source of laser energy fluctuation is the Nd:YAG laser which has an energy stability error range of ±4% which will account for the uncertainty of fluorescence intensity detected in the PLIF images. The OH-PLIF image was acquired using an intensified CCD camera (Andor Technology, USB iStar-DH334T) equipped with a UV lens (Nikkon, UV-105 mm, F4.5) placed perpendicular to the laser sheet. The ICCD camera was set to collect fluorescence for 20 ns at a rate of 5 Hz. The image resolution was approximately 45 $\mu$m/pixel. The type-A filter, composed of a UG11 filter (SCHOTT, centered at a wavelength of 330 nm), and an LX0290 filter (Asahi Spectra, centered at a wavelength of 290 nm, FWHM = 10 nm) were mounted in front of the UV lens to obtain only the OH(2,1) band fluorescence. In addition, the type-B filter, also composed of a UG11 filter, and an LX0310 filter (Asahi Spectra, centered at a wavelength of 310 nm, FWHM = 10 nm) were used to compare the interference of the OH(0,0) band chemiluminescence with the type-A filter. The transmittance efficiencies of these filters are shown in Fig. 1.

2.3 One-dimensional flame simulation

The reaction analysis software CHEMKIN-Pro (2017) was used to simulate a one-dimensional flame to evaluate the FWHM variations of the OH distribution with the flame stretch rate and pressure. To model the $\text{H}_2/\text{O}_2$ jet diffusion flames, the opposed-flow flame model was used. For the chemical reaction kinetics, the $\text{H}_2/\text{CO}$ reaction scheme (Keromnes et al., 2013) was used, which includes the OH* reaction kinetics. The flame stretch rate in the opposed-flow geometry, $\alpha$, is given as follows:

$$\alpha = \frac{2\bar{U}}{L}.\quad (2)$$

Here, $\bar{U}$ is the mean inlet gas velocity, and $L$ is the nozzle distance. In addition, CHEMKIN-Pro was used to conduct a premixed laminar burning velocity calculation, which includes the preheating zone and reacting zone thicknesses at each
pressure condition, to acquire the laminar burning velocity, $S_L$, and the flame thickness, $\delta_f$. The first Damköehler number, $Da$, was defined as the ratio of the characteristic flow time, $\tau_{flow}$, to the characteristic chemical time, $\tau_{chem}$, which is given as follows:

$$Da = \frac{\tau_{flow}}{\tau_{chem}} = \frac{1/\alpha}{\delta_F/S_L}.$$

(3)

Here, the characteristic chemical time was defined as the ratio of $\delta_F$ to $S_L$.

3. Results and discussion

3.1 Instantaneous two-dimensional OH distributions

The single-shot OH-PLIF images acquired at each $P_c$ and $Re_{H2}/Re_{O2}$ are shown in Fig. 4. One image was selected randomly from the 100 images acquired under each condition. Figures 4 (a) and (b) show the OH-PLIF images acquired at the lowest and highest injection Reynolds number conditions, respectively. The instantaneous two-dimensional OH distribution can be observed in all the experimental conditions with fine $S/N$: the variation of the $S/N$ with pressure will be discussed later. The gain of the ICCD camera was constant for all conditions. Therefore, the highest count range of the color bar decreases owing to the line broadening at higher pressure conditions. Because the OH fluorescence signal was fixed on the injector face, it can be considered that the flame was stabilized on the injector under all the conditions. The OH distribution in the region close to the injector face was almost uniform. In this region, the molecular diffusion is fixed on the injector face, it can be considered that the flame was stabilized on the injector under all the conditions. In contrast, based on the Kelvin-Helmholtz instability, the OH distributions were seen to fluctuate in the downstream region because of the large vortex structures. There was no significant difference in the fluctuations of the OH distribution with respect to variation in $P_c$. In contrast, from a comparison of Figs. 4 (a) and (b), the fluctuations seem to depend on the $Re$. The average OH-PLIF images acquired at each $P_c$ and $Re_{H2}/Re_{O2}$ are shown in Fig. 5. The test conditions depicted

(a) $P_c = 1.05$ MPa
(b) $P_c = 0.98$ MPa

(a) The lowest $Re$ number condition, $Re_{H2}/Re_{O2} \approx 2320/22800$

(b) $P_c = 3.04$ MPa
(b) $P_c = 3.13$ MPa

Fig. 4 Single-shot OH-PLIF images acquired at each $P_c$ and injection $Re$ number. Parts (a) show the results of P1-Re1, P3-Re1, P5-Re1, and P7-Re1, and Parts (b) show the results of P1-Re3, P3-Re3, P5-Re3, and P7-Re3.
in Figs. 5 (a) and (b) correspond to those shown in Figs. 4 (a) and (b), respectively. As the pressurized chamber gradually became fogged owing to the water vapor produced by combustion, the average image was calculated using 20 single-

Fig. 5  Average OH-PLIF images acquired at each $P_c$ and injection Re number. These were processed using 20 single-shot OH-PLIF images. The test conditions correspond to those of Fig. 4.

Fig. 6  Standard deviation distributions for OH signal at each $P_c$ and injection Re number. These were processed using 20 single-shot OH-PLIF images. The test conditions correspond to those of Fig. 4.
Figure 7 Instantaneous background chemiluminescence images. The condition is $P_r \approx 7.0$ MPa and $Re_{H_2/ReO_2} \approx 4660/45600$. Type-A and type-B filters were used to obtain the results shown in (a) and (b), respectively. The same chemiluminescence detection configurations, other than the filter, were used in both methods.

Shot OH-PLIF images obtained at the beginning of the measurement. It can be observed that the OH intensity in the near field is relatively high for all of the $Re$ conditions. In contrast, the OH intensity in the far field tends to be lower and the flame is more corrugated in the higher $Re$ conditions. In the experiment, $O/f$, which is one of the main causes for development of shear layers was kept the same.

The two-dimensional standard deviation of the OH-PLIF image under each test condition was obtained to evaluate the fluctuations of the OH distribution, which are shown in Fig. 6. The test conditions depicted in Figs. 6 (a) and (b) correspond to those shown in Figs. 4 (a) and (b), respectively. In the region near the injector face, the standard deviation was relatively low compared with that in the region downstream under all conditions. The transition location of the fluctuation appeared to be constant around the axial distance $Z = 3.0$ mm. As $Re_{H_2/ReO_2}$ increased, the standard deviation in the downstream region spread radially. However, because in the present OH-PLIF measurement the turbulence cycle in the region was shorter than the frame rate, detailed investigations of the turbulence required more single-shot images or the use of time-resolved measurement. By comparing the average and the standard deviation images, it can be confirmed that the OH distribution is uniform in the region of $Z \leq 3$ and the corrugation of flame in the far field is dependent on the $Re$ condition and independent of $P_r$. The constancy of the transition location with respect to the Reynolds number means that all the $H_2/O_2$ injection conditions used in this study are conditions of typical turbulent jet diffusion flames, which are defined as free jet diffusion flames at atmospheric pressure. In other words, the characteristics of the turbulent transition are common with the characteristics observed in free jet diffusion flames at atmospheric pressure even under the highest pressure condition of 7.0 MPa.

On the other hand, as shown in Fig. 4, the chemiluminescence interferences were almost eliminated, although the chemiluminescence intensity increases with pressure. Figure 7 compares the background chemiluminescence intensity of the OH(2,0) band excitation method and the conventional OH(1,0) band excitation method at 7.0 MPa when there is no laser insertion. As shown in Fig. 7 (a), the chemiluminescence interference was almost eliminated in the setup for the OH(2,0) band excitation method, where the minimum threshold is 1000. In contrast, as shown in Fig. 7 (b), intense chemiluminescence interference was observed in the OH(1,0) band excitation method setup, even though the intensity count range was set the same in both the cases. These results prove that the elimination of the chemiluminescence interference is a crucial task and the OH(2,0) band excitation method is an effective OH-PLIF measurement for high-pressure rocket combustion.

### 3.2 Evaluation of experimentally derived FWHM of radial OH distribution and $S/N$

To evaluate the reaction zone thickness of the flame, the FWHM of the radial OH distribution, $\delta_{OH}$, was calculated. Figure 8 depicts the evaluation method of $\delta_{OH}$. In this study, the highest and lowest levels were determined from the peak signal intensity of the OH distribution at the laser insertion side and the average noise count at radial distance $r = -0.5$–0.5 mm to take into account the partial chemiluminescence disturbance at high pressures, respectively. The $S/N$ ratio was also defined by the highest and the lowest levels at each intensity. The ensemble average of $\delta_{OH}$ was calculated using 20 samples selected from the 100 single-shot images acquired under each $P_r$ and $Re$ condition. In addition, the $S/N$ ratio
threshold for the selection of samples was determined to be 4, and the results that did not satisfy the threshold were excluded from the evaluation of $\delta_{OH}$.

The axial profiles of $\delta_{OH}$ acquired for each condition are shown in Figs. 9 (a)–(d). The error bar represents the standard error calculated from 20 samples. Only the $\delta_{OH}$ in the near field were evaluated by considering the two-dimensional or three-dimensional disturbances observed in the downstream region in Figs. 4, 5 and 6. In the region of $Z \leq 3.0$ mm, $\delta_{OH}$ became smaller as the $Re$ increased. In this region, the flame can be regarded as an edge flame because the molecular diffusion accounts for the mixing of the gas rather than the vortex structure of the jet. In such a region, the flame thickness $\delta_{OH}$ may be evaluated using the flame stretch by simply using the opposed-flow flame model. The opposed-flow flame model is considered to be suitable for comparing the differential diffusion effects of the jet diffusion flame with various strain rate simulations and is often carried out in the previous studies (Smith et al., 1994; Noda and 

Fig. 8 Evaluation method for FWHM of radial OH distribution $\delta_{OH}$.

Fig. 9 Axial profiles of ensemble average $\delta_{OH}$ for each $P_c$ and injection $Re$ condition. Error bar represents the standard error derived from 20 samples.
Kimura, 2004). As the velocity ratio is constant in this study, the velocity difference between H\textsubscript{2} and O\textsubscript{2} becomes larger at higher Reynolds number. Thus, the flame thickness in the near field varies owing to the flame stretch caused by the velocity difference. One may notice that the standard error is relatively large because only 20 samples were used to calculate the ensemble average. To discuss the average data with higher accuracy, 20 sample number maybe lacking. Although, the samples were selected in sequence from the early stages of the measurement to insure that the adhesion of water droplets to the chamber window did not occur. Judging from the video recorded during the experiment, 20 samples are quite conservative but the PLIF image quality was prioritized rather than the sample number in this study.

The axial profiles of the \( S/N \) acquired for \( Re_{H2}/Re_{O2} \approx 2320/22800 \) and each \( P_c \) condition are shown in Fig. 10. Only one injection \( Re \) condition is shown because the other injection \( Re \) conditions also produced the same trend. In the figure, the \( S/N \) decreased with increase in pressure owing to the degradation of the fluorescence intensity. Meanwhile, the \( S/N \) decreased sharply after \( Z = 3.0 \) mm in the \( P_c = 1.05 \) MPa condition. This location is the transition point, where the vorticity of the jet develops enough to become the dominant influence in the flow field. In such a field, the OH signal intensity decreases owing to the stretch and the two- or three-dimensional effect caused by the vortex of the jet. In addition, the co-flow N\textsubscript{2} is drawn into the reaction zone by the vortex of the jet, which decreases the flame temperature and lowers the OH signal intensity in this experimental condition. The degradation of the \( S/N \) may account for the source of uncertainties in the \( \delta_{OH} \) evaluation. The \( S/N \) should be improved to investigate the \( \delta_{OH} \) in the downstream region and under high-pressure conditions.

### 3.3. Comparison between experimentally derived local \( \delta_{OH} \) and simulated FWHM of OH mole fraction

The variation of the experimentally derived local \( \delta_{OH} \) with the first Damköhler number \( Da \) was compared with that of the simulated FWHM of the OH mole fraction, \( \delta_{OH-SIM} \). The Damköhler number was defined as follows:

\[
Da = \frac{L_{char}/V_{char}}{\delta_F/S_L} = \frac{1/\alpha}{\delta_F/S_L},
\]

where \( L_{char} \) is the characteristic distance and \( V_{char} \) is the characteristic velocity. The characteristic flow time in the Damköhler number was defined as the ratio of \( L_{char} \) to \( V_{char} \), which is the term proportional to \( \alpha^{-1} \). \( V_{char} \) was defined as the following hydraulic-diameter-weighted average velocity in this study:
\[ V_{\text{char}} = \frac{d e_{\text{H}_2} V_{\text{H}_2} + d e_{\text{O}_2} V_{\text{O}_2}}{d e_{\text{H}_2} + d e_{\text{O}_2}} , \]  
\[ L_{\text{char}} = Z_{\text{recess}} + Z, \]

where the hydraulic diameter of $\text{H}_2$, $d e_{\text{H}_2}$, is 0.5 mm and that of $\text{O}_2$, $d e_{\text{O}_2}$, is 3.0 mm. Assuming that the flame is completely anchored on the injector lip, the characteristic distance can be written as follows:

\[ L_{\text{char}} = Z_{\text{recess}} + Z, \]

where $Z_{\text{recess}} = 3.0$ mm is the depth of the recess and the axial distance of $Z = 1.0$ mm was used as the position of $\delta_{\text{OH}}$ because the vortex from the jet grows along the axial direction.

The variations of $\delta_{\text{OH}}$ and $\delta_{\text{OH, SIM}}$ with $Da$ are shown in Fig. 11. In the figure, it can be observed that both $\delta_{\text{OH}}$ and $\delta_{\text{OH, SIM}}$ decrease with the decrease in $Da$. This confirms the experimental relationship of $\delta_{\text{OH}}$ with the flame stretch. The stretch rate is inversely proportional to $Da$. Thus, when $Da$ decreases, the stretch rate increases, resulting in a thinner reaction zone. Further, $Da$ shifted to the right with increase in pressure. This was because of the decrease in the injection velocity as well as the characteristic chemical time at higher pressures.

However, the relationship of $\delta_{\text{OH}}$ with $Da$ did not correspond quantitatively to $\delta_{\text{OH, SIM}}$ at each pressure. The $Da$ for the simulation was higher than the $Da$ for the experiment because the simulated $\delta_{\text{OH, SIM}}$ was approximately 0.2 mm thinner than the experimentally derived $\delta_{\text{OH}}$ in each $P_c$ and $Da$ condition. This may be because of the insufficient definition of the characteristic flow time $L_{\text{char}}/V_{\text{char}}$. The characteristic flow time is affected by the recirculation zone developed on the injector lip. In addition, only one injector geometry was used in this experiment, so the injection velocity decreases with the increase in pressure at a constant $Re$ condition. Owing to the decrease in injection velocity, the scale of the recirculation zone formed of the nozzle lip increases with the increase in pressure (Kumagami et al., 2012). As the characteristic flow time increases with the presence of a recirculation zone, the $Da$ for the experiments may be underestimated. The scale for the recirculation zone and the turbulences formed on the injector lip should be investigated to obtain the actual characteristic flow time in the experiments. Furthermore, discussions using the turbulent Damköehler...
number can be conducted when the turbulence scale is obtained. However, this region is unknown in the OH-PLIF measurements because the recess was installed in the injector. Thus, further investigation on the flow field near the lip should be conducted to define the actual flow time in further detail. Although the relationship of $\delta_{OH}$ with the $Da$ did not correspond quantitatively to $\delta_{OH-SIM}$ at each pressure, the variation of $\delta_{OH}$ with $Da$ had an acceptable correlation to the variation of $\delta_{OH-SIM}$ at each pressure. Therefore, in the current study, it was verified that $\delta_{OH}$ varies with the $Da$ number, and the flame has a characteristic of flame stretch in the region close to the injector face within test conditions up to 7.0 MPa.

4. Conclusion

In this study, the OH(2,0) band excitation PLIF measurement was conducted to verify the availability of the measurement method and to investigate the near-field flame structures of the H$_2$/O$_2$ jet diffusion flames under the highest pressure condition of 7.0 MPa. The variations of the FWHM of the radial OH distributions, $\delta_{OH}$, with the pressure $P_c$, injection Reynolds number $Re$, and axial distance $Z$ were evaluated to examine the variations in the reaction zone thickness under each condition.

The OH(2,0) band excitation PLIF measurement was able to obtain the two-dimensional single-shot OH fluorescence distributions of the flames and eliminate the interference of OH chemiluminescence up to 7.0 MPa. In the PLIF image, the typical characteristics of turbulent jet diffusion flames were observed under all the $P_c$ and $Re$ conditions. The OH distributions were almost steady and uniform in the vicinity of the injector but fluctuated in the downstream region.

The variations in the experimentally derived local $\delta_{OH}$ at $Z = 1.0$ mm with the Damköehler number $Da$ qualitatively corresponded to the FWHM of the simulated mole fraction, $\delta_{OH-SIM}$, under each $P_c$ condition. The $\delta_{OH}$ in the vicinity of the injector face depended on the Damköehler number and had the characteristics of the flame stretch.

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