Application of OH(2,0) Band Excitation Planar Laser-Induced Fluorescence to High-Pressure H₂/O₂ Jet Flames for Rocket Combustion

Kiyonori TAKEUCHI,† Yoshio NUNOME,² Sadatake TOMIOKA,² Takeo TOMITA,² Taku KUDO,¹
Akihiro HAYAKAWA,³ and Hideaki KOBAYASHI¹

¹Institute of Fluid Science, Tohoku University, Sendai, Miyagi 980–8577, Japan
²Research and Development Directorate, Japan Aerospace Exploration Agency, Kakuda, Miyagi 981–1525, Japan

The purpose of this study was to develop an advanced method to measure the properties of rocket combustion using the OH(2,0) band-excited Planer Laser-induced Fluorescence (OH-PLIF) method. This diagnostic method was applied to capture images of the high-pressure H₂/O₂ jet diffusion flames found in typical liquefied bi-propellant rocket combustion. In addition, axisymmetric numerical simulations of H₂/O₂ jet flames modeling the experimental conditions were conducted to evaluate the consistency of the OH-PLIF imaging results and to predict the OH chemiluminescence intensity and flame temperature at high pressure. Experimental results show that it is possible to detect the OH(2,1) band fluorescence effectively by eliminating the interference of OH(0,0)-band chemiluminescence under high-pressure conditions of up to 2.0 MPa. The OH fluorescence signal distributed near the injector face almost corresponded to the OH molar concentration distributions simulated by numerical simulations. Moreover, the simulated pressure dependence of the local OH⁺ peak mole concentration reasonably corresponded to that of the local peak chemiluminescence intensity of the experimental chemiluminescence images.

Key Words: High Pressure Combustion, Planer Laser Induced Fluorescence, Chemiluminescence

Nomenclature

| Symbol | Definition |
|--------|------------|
| ṁ | mass flow rate |
| P_C | pressure in chamber |
| O/F | mass flow rate = ṁ_O / ṁ_F |
| D.R. | dilution ratio = ṁ_N / (ṁ_O + ṁ_F + ṁ_N) |
| r | radial distance |
| Z | axial distance |
| v | vibrational level |
| N | rotational level |
| f_B | Boltzmann fraction |
| SNR | signal to noise ratio |
| S_LIF | fluorescence counts |
| n | noise counts |
| C | molar concentration |

Suffix

- O: oxidizer (O₂)
- F: fuel (H₂)
- N: inert gas (N₂)
- '': excited state
- '': ground state

1. Introduction

H₂/O₂ combustion has been used for general liquefied bi-propellant rocket engines. H₂/O₂ rocket combustion generates a much higher temperature compared to that of ordinary combustion and it can also easily produce high thrust. Lately, numerical simulation techniques for rocket combustion have progressed remarkably and the research and development (R&D) of rocket engines using combustion simulations have been actively conducted. However, the data for verifying the calculations have been insufficient. This means that an experimental technique for measuring the properties of rocket combustion, i.e., high-pressure H₂/O₂ combustion, has not been established.

Recently, various optical diagnostic methods have been applied to measure rocket engine combustion, with OH-Planer Laser-induced Fluorescence (OH-PLIF) being a technique for flame structure visualization. It is known that the fluorescence of OH(0,0) and OH(1,1) band (A₂Σ⁺ → X²Π) near the 310 nm wavelength is effectively collected after pumping OH(1,0) band (A₂Σ⁺ → X²Π). Table 1 shows findings of typical OH-PLIF studies on high-pressure rocket combustion. OH(1,0)-band excitation methods have been frequently applied in such studies because the quantum yield and the absorbance of those methods are sufficiently high to collect the fluorescence signals. Nevertheless, the OH fluorescence signal intensity decreases as the ambient pressure rises because of line broadening and the increase in quenching rate. On the other hand, the OH(3,0)-band excitation method is capable of reducing the sensitivity of quenching since predissociation due to transitions within the OH(3,0)-band occur frequently. This seems to be as promising as the OH-Planar Laser-induced Pre-dissociative Fluorescence (OH-PLIPF) technique for high-pressure combustion. However, the fluorescence signal obtained using this method is much weaker than that of the OH(1,0) band excitation method because of the lower quantum yield.

In addition, it is inferred that high-pressure H₂/O₂ flames...
emit intense chemiluminescence of the OH(0,0)-band.\(^6\)

When the chemiluminescence is much stronger than the fluorescence obtained using the OH(1,0)-band excitation method, it is difficult to collect the fluorescence emitted in the same bands as the chemiluminescence. In other words, the chemiluminescence is also the cause of signal-to-noise ratio (SNR) degradation when studying OH-PLIF measurements of rocket combustion. Therefore, a technique that can detect fluorescence while eliminating intense chemiluminescence should be established to measure high-pressure H\(_2\)/O\(_2\) flames. Steffens et al. showed transition probabilities and the fluorescence spectrum of OH(2,0)-band excitations.\(^5\)

This spectrum shows that the fluorescence of the OH(2,1)-band near 290 nm can possibly be detected. According to this result, there is a possibility of being able to completely separate the fluorescence from intense OH(0,0)-band chemiluminescence and scattered laser light. However, the transition probabilities within OH(2,0)-band excitations are weaker than that of OH(1,0)-band excitations. Moreover, to apply OH(2,0)-band excitation methods to OH-PLIF measurements for rocket combustion investigations is beyond all precedents.

The purpose of this study is to realize OH-PLIF that eliminates the chemiluminescence of the OH(0,0) band. OH-PLIF measurements using OH(2,0)-band excitation were conducted to observe OH fluorescence distributions and to investigate the details of fluorescence intensity for high-pressure H\(_2\)/O\(_2\) jet diffusion flames modeling typical bi-propellant rocket combustion. In addition, numerical simulations of axisymmetric H\(_2\)/O\(_2\) jet diffusion flames that model the experimental conditions were conducted to evaluate the consistency of the OH-PLIF imaging results and predict the flame temperature by simulating the OH\(^+\) mole concentration.

2. Principle of OH(2,0)-Excited PLIF

Figure 1 shows a schematic of OH electron energy transitions after pumping the OH(2,0) band. As mentioned above, the electrons at the \(v'=2\) state excited by OH(2,0) mainly return to the \(v''=1\) or 2 state expressed as OH(2,1) or (2,2) transition after rotational energy transfer. Some electrons return to the ground state non-radiatively (quenching) as with other excitation methods. The predissociative time for \(v'=2\), \(N'=6\) is approximately 60 ns. On the other hand, the times for \(v'=1\) and \(v'=3\) are approximately 767 ns and 0.16 ns, respectively.\(^6\) The fluorescence lifetime is assumed to be approximately 2 ns at atmospheric pressure.\(^7\) Hence, quenching will be the main cause of the degradation of the fluorescence quantum yield in the OH(2,0)-band excitation method. The peak fluorescence wavelengths for OH(2,1) and OH(2,2) transition are near 290 nm and 320 nm, respectively.

Figure 2 shows experimental comparisons of the fluorescence pumped OH(1,0) and OH(2,0)-band and the OH chemiluminescence spectrum measured using a spectrometer. The Q\(_1(6)\) branch was chosen as the excitation line in both band excitation methods. Those spectra were obtained from an H\(_2\)/O\(_2\) jet diffusion flame at atmospheric pressure. The spectrum was normalized by each maximum intensity. As shown in Fig. 2, the fluorescence after pumping by the OH(1,0) band is mainly detected at the OH(0,0) and OH(1,1) bands. The fluorescence intensity of the OH(1,1) band is the strongest on the spectrum. However, it can be clearly seen that the spectrum of the intensive OH(0,0) band chemiluminescence also overlaps that of OH(1,1) fluorescence. In the case of OH(2,0)-band excitation, the intensity of OH(2,1)-band fluorescence is much stronger than that of the OH(2,2) band. Moreover, the wavelength of OH(2,1)-band fluorescence is much shorter than that of the intensive OH(0,0)-band chemiluminescence. This indicates that the fluorescence and chemiluminescence are able to be more easily separated using an optical filter than the case with OH(1,0)-band excitation methods. Therefore, OH(2,1)-band fluorescence was chosen in this study because it is possible to obtain the fluorescence...
signal distribution, resulting in effective elimination of the interference of intense OH(0,0)-band chemiluminescence.

3. Experimental Setup and Procedure

High pressure combustion experiments were conducted using a chamber with four windows and an injector. The windows were 48 mm in diameter and there was one window on each side. One window was equipped with an igniter, and the other three windows were quartz glass to allow optical access. Gaseous nitrogen (N2) was used to purge and cool the inner side of the window. Gaseous hydrogen (H2) and oxygen (O2), which are typical liquid rocket elements, were injected from the coaxial shear injector. The fuel annulus diameter, the oxidizer outer post diameter and the inner diameter of the window. Gaseous hydrogen (H2) and oxygen (O2) were set to approximately 8, which is denoted as stoichiometric O2/H2, and the dilution ratio of burning gas in the chamber (D.R.) was 97–99% for all chamber pressure conditions. The mass flow rates of all the gases were regulated at each ori

The schematic of the optical setup is shown in Fig. 3. The laser assembly, which was used to conduct OH-PLIF measurements, was composed of a Nd:YAG laser (Spectra-Physics, PRO-250DP-KE) and a wavelength tunable dye laser with a frequency doubler (Sirah, PrecisionScan). Coumarin522B (Exciton) was chosen as the dye for the OH(2,0)-band excitation. The laser wavelength was tuned at 262.455 nm, which excites Q1(6) transition within the OH(2,0)-band excitation. The laser wavelength was tuned by an intensifier injection tube had 3-mm recess against the injector surface. The ratio of the O2 and H2 mass flow rates (O2/H2) was set to approximately 8, which is denoted as stoichiometric O2/H2, and the dilution ratio of burning gas in the chamber (D.R.) was 97–99% for all chamber pressure conditions. The mass flow rates of all the gases were regulated at each ori

4. Method of Numerical Simulation

Numerical simulations to model the experimental flow and combustion field were performed using FLUENT. In this study, two-dimensional (2-D) compressive Reynolds Averaged Navier-Stokes (RANS) equations were used as governing equations, where the experimental phenomenon was assumed to be axisymmetric and interference of the window section in the chamber were not considered in the simulations. These equations were solved using the finite volume method. The k-ε model was used as the turbulence model. In order to fit the actual experimental conditions, mass flow rate, injection gas pressure and temperature were set as shown in Table 2. The calculation domain was set as shown in Fig. 4. It was identical to the experimental setup used in this study, although the window sections were negligible as mentioned above. Isothermal walls at 300 K were used as the boundary conditions for all simulations. As for the chemical reaction kinetics, the extended H2/O2 reactions, and the OH+ reactions, which are shown in Table 3, were employed.

5. Results and Discussion

5.1. OH-PLIF images

Figure 5 shows single-shot OH-PLIF images acquired using the OH(2,0)-band excitation method at high pressure. At each pressure in the chamber, PC, an image was chosen randomly from all 20 images. The OH fluorescence signals were successfully obtained and it was possible to sufficiently ob-
serve the instantaneous flame structures in terms of OH profiles at a $P_C$ up to 2.0 MPa. The flames were stabilized on the injector outlet at all $P_C$, and transition to turbulent flame was observed in the downstream region. These images also indicated the necessity of the single shot imaging for flame observation. Although the quantum yield and absorbance for OH(2,0)-band excitation are much weaker than those for OH(1,0)-band excitation, the intensity of the OH(2,1)-band fluorescence signals was sufficiently strong. This is because the OH mole concentration in H$_2$/O$_2$ flames is much higher compared to that in ordinary fuel/air flames. However, the intensity of the fluorescence signals at $P_C = 2.0$ MPa was less than half the value of that at $P_C = 0.65$ MPa. It is presumed that quenching and line broadening are the main reasons for SNR degradation of the OH-PLIF images, and the influence of the increasing quenching rate cannot be negligible, as with the typical OH(1,0)-band excitation methods mentioned in Section 2. However, interference from the intense OH chemiluminescence was not observed in any of the OH-PLIF images, as shown in the back-ground images of Fig. 5(e) and (f).

In order to evaluate the consistency of the OH-PLIF imaging results, averaged OH-PLIF images obtained after processing 20 single-shot images taken at $P_C = 0.65$ and 2.0 MPa were compared with the results of axisymmetric numerical simulation, as shown in Fig. 6. According to the averaged PLIF images, it was observed that the flame near the injector seems to be almost steady because the fluorescence signals are uniformly distributed in the region from $Z = 0$ to 6 under all $P_C$ conditions. On the other hand, those signals fluctuated widely in the region from $Z = 6$ mm to the downstream region due to the transition to turbulent flame, as shown in Fig. 5. In contrast to the PLIF images, the numerical simulations showed that the OH molar concentration was distributed almost uniformly along $Z$. This indicates that the flames were not disturbed from $Z = 6$ mm to the downstream region and that these distributions were different from the experimental results under all $P_C$ conditions. One of the reasons for the difference is the influence of the window sections in the high pressure chamber where the N$_2$ jet was injected. As mentioned in section 4, the window sections were not considered in the calculation domain in order to perform axisymmetric numerical simulation. The N$_2$ gas flows not only from the bottom as co-flow but also from the window.

![Fig. 4. Schematic of calculation domain.](image)

![Table 3. Reaction kinetics for OH.](image)

| Reaction | Reference |
|----------|-----------|
| H + O + M = OH$^+$ + M | 11) |
| OH$^+$ + N$_2$ = OH + N$_2$ | 12) |
| OH$^+$ + O$_2$ = OH + O$_2$ | 11) |
| OH$^+$ + H$_2$O = OH + H$_2$O | 11) |
| OH$^+$ + O = OH + O | 11) |
| OH$^+$ + H = OH + H | 11) |
| OH$^+$ + H$_2$ = OH + H$_2$ | 11) |
| OH$^+$ + OH = OH + OH | 11) |
| OH$^+$ = OH + hv | 11) |

![Fig. 5. Single-shot OH-PLIF and background images of H$_2$/O$_2$ jet diffusion flames under high pressure conditions.](image)

(a) $P_c=0.65$ MPa (PLIF-01)  
(b) $P_c=1.03$ MPa (PLIF-02)  
(c) $P_c=1.49$ MPa (PLIF-03)  
(d) $P_c=2.00$ MPa (PLIF-04)  
(e) $P_c=2.01$ MPa, $O/F=8.43$  
(f) $P_c=2.53$ MPa, $O/F=7.77$
section. These sections are close to the injector and may cause flame disturbances.

The averaged PLIF signals intensity distribution was higher in the region close to injector outlet in contrast to the numerical simulation. The density of OH fluorescence signals close to the injector was higher than that of downstream region. Moreover, the temperature dependence of the OH absorption line is also considered to be another reason for the difference. In this study, the Q1(6) branch was selected as the absorption line because it is strong and because the rotational levels $N_00 = 6$ and 7 are the most populated state at the flame temperature. However, the corresponding absorption coefficients are temperature dependent. It is known that the Boltzmann population fraction, $f_B(T)$, rises initially and then decreases as the temperature rises. Figure 7 shows the peak temperature at a given $Z$ in the axial direction obtained by numerical simulation of the jet flame. In both $P_C$, the peak temperature at $Z = 0$ mm was more than 200 K lower than that at $Z = 3$ mm due to the heat loss at the injector face. This indicates that the quantitative observations on distribution of temperature and OH molar concentration should not be conducted using the Q1(6) branch, and that it is necessary to select a branch corresponding to a higher $N''$ level in order to obtain a constant $f_B(T)$ at high-pressure $H_2/O_2$ flame temperatures.

Additionally, the experimental radial distributions caused by fluorescence intensity at $Z = 3$ mm were compared with simulated OH molar concentration distributions, as shown in Fig. 8. The error bars show the standard deviation calculated from all 20 single-shot images. The distributions of fluorescence intensity corresponded well to that of the simulated OH molar concentrations for all $P_C$ conditions. The maximum difference of those peak positions was approximatively 80 $\mu$m, and smaller than the PLIF image resolution of 90 $\mu$m/pixel in this study. The local SNR of the experimental fluorescence signal at $Z = 3$ mm was higher than 9.9 dB at $P_C = 2.00$ MPa. This was obtained by Eq. (1), where $(S_{PLIF})_{\max}$ is the maximum fluorescence signal count.
The chemiluminescence intensity increases as pressure rises, of OH(0,0)-band chemiluminescence, as shown in Fig. 5. However, the noise value was also low because the chemiluminescence interference was eliminated. Figure 9 shows the pressure dependence of the SNR for averaged PLIF images at \( Z = 3 \) mm. It declines gently with rising pressure, and the curve is approximated by Eq. (2).

\[
\text{SNR} = -6.469 \cdot \ln P_C + 14.517
\]  

(2)

When the OH(2,0)-band excitation PLIF method is applied to \( P_C = 7.0 \) MPa, which is the pressure condition beyond all precedent PLIF, the SNR is estimated to be 1.9 dB. Although this value is obviously low, with the method established in this study, it is possible to eliminate the interference of chemiluminescence at 7.0 MPa. According to these results, it is possible to obtain the local OH profiles with high reliability up to 2.0 MPa using the OH(2,0) band excitation method. These results also show the feasibility of using the OH(2,0)-band excitation method for high-pressure rocket combustion measurement.

### 5.2. Chemiluminescence

In order to clarify the interference between the OH(0,0) band chemiluminescence and the OH-PLIF images, averaged chemiluminescence images, shown in Fig. 10, were acquired using the Type-B filter. These averaged images were also obtained by image processing 20 single-shot images, as shown in Fig. 6. These images show that the signals are not distributed asymmetrically due to the influence of the window sections in the high pressure chamber. The signal intensity of these images is also indicated as the strength of noise in the OH-PLIF images when a typical OH(1,0)-band excitation method is employed. In contrast to the PLIF images, intense chemiluminescence appeared due to the transmission of OH(0,0)-band chemiluminescence, as shown in Fig. 5. The chemiluminescence intensity increases as pressure rises, and the experimental results showed only that the intensity increases monotonously within \( P_C = 2.12 \) MPa. In the cases of lower pressure or flame temperature condition, the OH(1,0)-band excitation method is feasible. However, it is shown that the interference resulting from the OH(0,0)-band chemiluminescence will certainly cause the degradation of SNR for PLIF measurements, and should be eliminated when PLIF measurement is applied to the rocket combustion measurement.

On the other hand, the local peak intensity of chemiluminescence was also considered to clarify the relationship between chemiluminescence intensity and OH* molar concentration at high pressure. Figure 11 shows variations of peak chemiluminescence intensity and OH* molar concentration along the Z axis. It is shown that those dependences correspond well qualitatively with each \( P_C \). The pressure dependence of those peak values will be mentioned in detail later. The intensities increase toward the downstream region. Temperature also increases along Z near the injector outlet, as mentioned in section 5.1. Hence, it is considered that the peak chemiluminescence intensity also corresponds qualitatively to the flame temperature.

Kathrotia et al. showed that the temperature dependence of the peak OH* mole concentration corresponded closely to the intensity of OH(0,0)-band emission.\(^{13}\) In addition, verification of OH* at lower pressures has been conducted.\(^{12,14}\) However, there are few verification data of pressure dependence because of the difficulty to conduct high-pressure combustion examinations. The pressure dependency of peak chemiluminescence intensity and OH* molar concentration at \( Z = 3 \) mm in this study is shown in Fig. 12. The one-dimensional (1-D) counter-flow simulations were conducted in a previous study.\(^{15}\) However, the heat loss, ambient flow

---

1. Trans. Japan Soc. Aero. Space Sci., Vol. 60, No. 2, 2017
2. ©2017 JSASS
Fig. 11. Comparisons of axial profiles between OH peak chemiluminescence intensity by experiment and OH* molar concentration by numerical simulation.

Fig. 12. Comparison of pressure dependences of peak chemiluminescence intensity and relative peak OH* mole concentration.

Fig. 13. Comparison of pressure dependence of simulated peak temperature.

In the present 2-D simulations, the heat loss was not considered in the previous 1-D simulations. Since the peak OH* molar concentration increases nonlinearly as temperature rises, the pressure dependence is also different. According to these results, it is assumed that the consistency of simulated OH* molar concentration in this study was higher than that in the previous study, and that the peak OH* molar concentration corresponds qualitatively to the experimental peak chemiluminescence intensity. As mentioned previously, the spatial and time resolutions of the chemiluminescence images were lower than those of the PLIF images. However, the chemiluminescence measurement data can also be used as one of reference data of the details in order to verify the PLIF for high-pressure rocket combustion. These results also show that the OH(2,0) excitation PLIF method, with which it is possible to eliminate the intensive interference of chemiluminescence, is feasible as an advanced diagnostic method for studies of rocket combustion.

6. Conclusion

In this study, OH(2,0)-band excitation PLIF measurement was applied to high-pressure H2/O2 flames modeling rocket combustion. In addition, numerical simulations for an axisymmetric jet diffusion flame were conducted to evaluate the consistency of the OH-PLIF imaging results and to predict flame temperature using the simulated OH* molar concentration. The following results were obtained.

1) Single-shot OH(2,0)-band excitation PLIF measurements are able to detect OH(2,1)-band fluorescence by effectively eliminating the intensive interference of OH(0,0) band chemiluminescence up to the 2.0 MPa pressure condition; actually, the filter used for the OH(1,0)-band excitation method collected intense chemiluminescence.

2) The local radial distributions of OH-PLIF corresponded well to those of the simulated OH molar concentration for each pressure condition, although the SNR of the PLIF image declined as pressure rose due to quenching and line broadening. It is possible to obtain the local OH positions with high reliability up to 2.0 MPa using the OH(2,0)-band
excitation method for H2/O2 flames.

3) The pressure dependence of peak chemiluminescence intensity corresponds qualitatively to the relative peak OH\textsuperscript{*} molar concentration, which was obtained from the numerical simulations conducted in this study.

4) OH chemiluminescence intensity increases as pressure rises, which indicates the necessity of eliminating the interference caused by intense chemiluminescence. Thus, the OH(2,0)-band excitation PLIF method is feasible as an advanced diagnostic method for studying of rocket combustion.

Acknowledgments

The experiments shown in this paper were conducted using test facilities at the Kakuda Space Center, and the authors would like to thankfully acknowledge the contributions of Mr. Yohei Kino, Tohoku University, for conducting the experiments. This work was supported by the JSPS Grant-in-Aid for Challenging Exploratory Research Grant Number 15K14244 and the Division for Interdisciplinary Advanced Research and Education, Tohoku University.

References

1) Singla, G., Scoulaire, P., Rolon, C., and Canuel, S.: Planar Laser-Induced-Fluorescence of OH in High-pressure Cryogenic LOx/GH2 Jet Flames, Combust. Flame, 144 (2006), pp. 151–169.

2) Salguers, D., Mous, A. G., Lee, S. Y., Kalitan, D., Pal, S., and Santoro, R.: Shear and Swirl Coaxial Injector Studies of LOx/GCH4 Rocket Combustion Using Non-Intrusive Laser Diagnostics, Proc. 44th AIAA Aerospace Science Meeting and Exhibit, 2006, 2006-757.

3) Brummund, U., Cessou, A., and Vogel, A.: PLIF Imaging Measurements of a Co-axial Rocket Injector Spray at Elevated Pressure, Proc. Combust. Inst., 26 (1996), pp. 1687–1695.

4) Smith, J. J., Schneider, G., Suslov, D., Oschwald, M., and Haidn, O.: Steady-state High Pressure LOx/H2 Rocket Engine Combustion, Aerospace Sci. Technol., 11 (2007), pp. 39–47.

5) Steffens, K. L., Luque, J., Jeffries, J. B., and Crosley, D. R.: Transition Probability in OH A'\Sigma^+-X'\Pi_G Bands with $\nu=2$ and 3, J. Chem. Phys., 106 (1997), pp. 6262–6267.

6) Luque, J. and Crosley, D. R.: Lifbase, SRI Report No. MP 99-009, 1999.

7) Bergano, N. S., Jaamimagi, P. A., Salour, M. M., and Bechtel, J. H.: Picosecond Laser-spectroscopy Measurement of Hydroxyl Fluorescence Lifetime in Flames, Opt. Lett., 8 (1983), pp. 443–445.

8) ANSYS: http://www.ansys.com (accessed Feb. 1, 2016).

9) Shih, T. H., Liou, W. W., Shabbir, A., Yang, Z., and Zhu, J.: A New k-\varepsilon Eddy Viscosity Model for High Reynolds Number Turbulent Flows, Comput. Fluids, 24 (1995), pp. 227–238.

10) Burke, M. P., Cho, M., Ju, Y., Dryer, F. L., and Klippenstein, S. J.: Comprehensive H2/O2 Kinetic Model for High-pressure Combustion, Int. J. Chem. Kinet., 44 (2012), pp. 444–474.

11) Petersen, E. L. and Kalitan, D. M.: Calibration and Chemical Kinetics Modeling of an OH Chemiluminescence Diagnostic, Proc. 39th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, 2003, 2003-4493.

12) Walsh, K. T., Long, M. B., Tanoff, M. A., and Smooke, M. D.: Experimental and Computational Study of CH, CH+ and OH+ in an Axisymmetric Laminar Diffusion Flame, Proc. Combust. Inst., 27 (1998), pp. 615–623.

13) Kathrotia, T., Fikri, M., Bozkurt, M., Hartmann, M., Riedel, U., and Schulz, C.: Study of the H+O+M Reaction Forming OH+: Kinetics of OH+ Chemiluminescence in Hydrogen Combustion System, Combust. Flame, 157 (2010), pp. 1261–1273.

14) Kojima, J., Ikeda, Y., and Nakajima, T.: Basic Aspects of OH(A), CH(A), and C2(d) Chemiluminescence in the Reaction Zone of Laminar Methane-Air Premixed Flames, Combust. Flame, 140 (2005), pp. 34–45.

15) Takeuchi, K., Nomura, Y., Tomita, T., Kudo, T., Hayakawa, A., and Kobayashi, H.: Application of OH-PLIF Measurements Using OH(2,0) Band Excitations to High Pressure H2/O2 Jet Diffusion Flames, Proc. 10th Asia-Pacific Conference on Combustion, 2015, p. 285.

I.-S. Jeung

Associate Editor