1. Introduction

Combustion in the rocket chamber is in the extreme conditions of high-temperature and high-pressure (temperature 3000 K, pressure 7 MPa ~). Adaptable measurement technique to such severe conditions was limited, and has been made only to acquisition of qualitative information by chemiluminescence measurement and schlieren method. These measurements are not sufficient to understand the phenomenon of rocket combustion and to validate CFD, so the acquisition of quantitative information of rocket combustion is desired.

In recent years, with the development of laser technology and spectroscopic measurement technique, measurement method using laser is developed. Since laser measurement is non-intrusive and has no physical constraints on the temperature, it is applicable to rocket high temperature environment. Among the many laser spectroscopic measurement techniques, OH-Laser Induced Fluorescence (LIF) is the most promising to the rocket combustion measurement. As the advantage of the OH-LIF, firstly, the tracer addition disturbing the measurement object is not necessary because it is using OH radicals present in abundance in the rocket combustion. Secondly, OH radicals are measured in the combustion field with a variety of fuels, so that the wealth of basic data have been accumulated because it is an important intermediate product of combustion. Temperature measurement techniques based on the OH-LIF, such as Boltzmann plot method (Zizak et al., 1981) and Planer Laser Induced Fluorescence (PLIF) method (Seitzman et al., 1994) have been reported. Problems of these techniques in order to adapt to the rocket combustion are difficulty in acquisition of fluorescence and instantaneous value at high-pressure environment. These LIF temperature measurement techniques studied so far generally use OH(1,0) (A-X) band excitation. With OH(1,0) band excitation, OH(1,1) emission, the most high-intensity fluorescence in the OH-LIF, can be observed, so that it is widely
used in the LIF measurement. However, OH radicals are known to emit chemiluminescence of high intensity OH(0,0) band near about 308 nm, very close to OH(1,1) band. In particular, in PLIF measuring the fluorescence emitted from the OH radicals excited by a laser, a method of acquiring the plane information by ICCD camera through an optical filter, flame chemiluminescence is treated as noise. It is difficult to separate the OH(0,0) band noise from OH(1,1) band LIF signal by optical interference filter for the wavelengths of the signal and the noise, are too close as shown in Figure 1. In reduced-pressure to atmospheric pressure environment, chemiluminescence is not a problem. Under high-pressure environment, such as the rocket combustion, the chemiluminescence intensity increased too much due to very high heat release and temperature to be ignored. To solve this problem, Takeuchi et al. showed that the emission band could be separated from the influence of the OH(0,0) chemiluminescence by using OH(2,0) band excitation (Takeuchi et al., 2015). As shown in Figure 1, in contrast to the OH(1,0) band excitation case, the OH(2,0) band excitation is possible to separate it emission from the effects of chemiluminescence, since fluorescence (OH(2,1) band) is remote from the OH(0,0) band. However, no study has been reported on LIF temperature measurement using the OH(2,0) band excitation. Then, in the present study, possibility of LIF temperature measurement by using the OH(2,0) band excitation was explored. Note that the measurement was adapted to burner flames in atmospheric pressure as the first step toward the measurements in high-pressure rocket combustion.

Figure 1  spectrum of OH fluorescence and chemiluminescence

In this paper, as a result of the research, the OH(2,0) excitation Laser Induced Fluorescence Spectroscopy (LIFS) -2 line method will be described. Usage of the LIFS measurement made it able to separate the fluorescence and chemiluminescence. The LIFS-2 line method make it possible to perform two-line method temperature measurements with one laser by using excitation lines within the half-width of the laser wavelength. Adopting temperature measurement principle for the PLIF-2 line method, it is possible to eliminate the influence of the excitation error and quenching.

2. Apparatus

Laser used as the OH(2,0) band excitation light source, was composed of a Nd:YAG laser (Spectra-Pysics, PRO-250DP-KE) and a wavelength-tunable dye laser (Sirah, PrecisionScreen). Laser oscillation frequency was 10Hz. Laser power at the outlet of the dye laser was up to about 16 mJ/pulse. Calibration of the center wavelength of the laser was done with WaveMaster (Coherent). This wavelength meter had resolution of 0.001 nm, and measured the wavelength of the double wave crystal just before in the dye laser. Laser beam was introduced through 7 mirrors and one focal lens (f = 4000 mm) to the burner. Laser was shaped to sheet-like by cylindrical lens (concave focal length -100 mm, convex focal length + 100 mm, + 500 mm) and irradiated onto the flame center axis at a height of 10 mm from the burner ejection faceplate. The laser sheet height was 10 mm and the thickness
was about 0.1 mm. Laser intensity before passing through the cylindrical lens, was about maximum 12 mJ/pulse. The spectral measurement was done with Czerny-Turner spectrometer SP3504i (SOL Instruments). The light measurement focus position was at the center height of about 15 mm of the burner. The light passed through a correcting mirror and a fiber optic cable from the light receiving lens, and it was irradiated to the spectrometer. A ICCD camera (Andor Technology, iStar DH-734) was used as detector.

A hydrogen / oxygen coaxial jet burner was used to evaluate the temperature dependence of the OH spectrum. It injected hydrogen gas from the center, and oxidizer gas from the outer periphery. Mixed gas of oxygen and nitrogen was used as the oxidizer, to adjust the mixture ratio O/F (Oxygen/Hydrogen mass flow ratio, O/F = 8 becomes the stoichiometric mixture ratio) in of the flame by adjusting the fraction of nitrogen. Mass flow controllers (MFC, H2: BROOKS INSTRUMENT, 5850E, N2 30SLM F.S. oxygen: BROOKS INSTRUMENT, 5850E CH4 20SLM F.S., N2: KOFLOC, CL-400) were used for flow rate regulation. The MFC used for hydrogen and oxygen are calibrated for different gas, but was calibrated with the actual flow rate on cite. The flow rate of the hydrogen gas and oxidizer gas mixture was set as shown in Table 1. Adiabatic flame temperature in each flow conditions was calculated using the calculation the NASA-CEA code (Gordon and McBride, 1996). Note that conditions listed in Table 1 were to find out whether the available OH spectrum had temperature dependence, so that quantitative information was not necessary to be exact.

Although the final target of our study is to adapt the temperature measurement technique to rocket combustion, it was difficult to attain reference data with the resulting turbulent flame of the co-axial injector. Then, we used so-called McKenna burner in the present study to examine the validity of the temperature measurement technique, as quantitative reference data (Prucker, Meier and Stricker, 1994) were available with the burner. The McKenna burner formed a flat flame, with its ejection faceplate made of sintered metal with embedded cooling pipe. The reference data were function of equivalence ratio and flow rate, the values being shown in Table 2. Gaseous hydrogen and air flow rates we re controlled by mass flow controllers (KOFLOC, 8550MC). Gases are mixed in the burner plenum after passing through check valves and filters (Swagelok, pore size 90 μm) for rectifying and mixing promotion. Circulating cooling water controlled by SMC HRS050-A, protected the ejection faceplate of the burner. Cooling water flow rate was set to 1 L / min and inlet temperature to 16 °C, following the literature (Prucker, Meier and Stricker, 1994). Table 3 summarizes test cases. Note that the McKenna burner could provide lower temperature than rocket combustion, while the lower temperature would result in weaker emission signal and larger measurement errors, so that the burner was thought to be suitable for accuracy evaluation.

| No. | H2 [L/min] | O2 [L/min] | N2 [L/min] | O/F [-] | Adiabatic Temperature [K] |
|-----|------------|------------|------------|--------|---------------------------|
| O100 | 5.0        | 2.50       | 0.00       | 8.0    | 3074                      |
| O90  | 5.0        | 2.25       | 0.25       | 7.2    | 3047                      |
| O80  | 5.0        | 2.00       | 0.50       | 6.4    | 3004                      |
| O70  | 5.0        | 1.75       | 0.75       | 5.6    | 2932                      |
| O60  | 5.0        | 1.50       | 1.00       | 4.8    | 2808                      |
| O50  | 5.0        | 1.25       | 1.25       | 4.0    | 2601                      |
| O40  | 5.0        | 1.00       | 1.50       | 3.2    | 2276                      |

| No. | H2 [L/min] | Air [L/min] | φ [-] | V_{flow} [cm/s] | Temperature [K] |
|-----|------------|-------------|------|-----------------|----------------|
| Mc01| 34.6       | 82.4        | 1.0  | 76.4            | 2100 - 2160    |
| Mc02| 34.6       | 68.7        | 1.2  | 67.5            | 1848 - 1873    |
| Mc03| 34.6       | 63.4        | 1.3  | 64.0            | 1755 - 1775    |
| Mc04| 19.7       | 78.2        | 0.6  | 63.9            | 1751 - 1798    |
| Mc05| 19.7       | 58.6        | 0.8  | 51.1            | 1895 - 1920    |
Table 3 experimental cases

| Case   | McKenna burner conditions | Excitation Wavelength [nm] | Purpose          |
|--------|----------------------------|-----------------------------|------------------|
| Case1  |                            | 262.448 - 262.458           |                  |
| Case2  | Mc01                       | 262.446 - 262.456          | \(L_w\) calculation |
| Case3  |                            | 262.452 - 262.455          |                  |
| Case4  | Mc01 - Mc05                | 262.445                     | Temperature calculation |
| Case5  |                            |                             |                  |

3. Method

3.1. Overlapping excitation line

First, temperature dependence of the LIF spectrum was explored by using a co-axial burner easy to change the flame temperature. \(Q_L(4)\) to \(Q_L(9)\) excitation lines were targeted. Figure 2 shows the \(Q_L(5)\) excitation and \(Q_L(6)\) excitation OH fluorescence spectra. As \(Q_L(5)\) excitation case shown in Fig. 5a, \(Q_L(4), Q_L(5),\) and \(Q_L(7)\) to \(Q_L(9)\) excitation cases showed no temperature dependence. On the other hand, the temperature dependence was observed in the \(Q_L(6)\) excitation case, overlapped excitation being found to be responsible for the temperature dependence. Figure 3 shows the results of the absorption spectrum around \(Q_L(6)\) and \(R_L(12)\) calculated by LIFBASE (Luque and Crosley, 1999). It can be seen that is \(Q_L(6)\) excitation line and \(R_L(12)\) excitation line are adjacent at a distance of about 2 pm. Since the FWHM (full width at half maximum) of the dye laser and the two excitation lines were in the same width, it is considered to be simultaneously excited. This overlapping excitation was utilized in the present study to measure temperature in the present study. Because it can be excited simultaneously two excitation lines with one laser, can simplify the configuration of the apparatus, it can be considered also as a combination that is suitable for temperature measurement.

In general, the overlapping excitation line is not used for the temperature measurement by the PLIF-2 line method (to use two lasers for different excitation lines, and to take ratio of signals from two corresponding emissions), as the temperature dependence in respect to the emission lines, as observed in the present study, would bring measurement errors in processing the signals with two excitations. Thus, selection of two excitation lines should be very careful. Moreover, overlap of the emission also can bring measurement errors. For example, one excitation should result in three emission peaks \((P, Q, \text{and } R \text{ branches})\) as shown in Fig. 2a. However, \(R_L(12) - P\) branch emission was not observed in Fig. 2b, as it was covered by \(Q_L(6) - R\) branch emission, and this coverage should be avoided. Without spectrum measurement, it is difficult to eliminate above-mentioned errors. On the other hand, LIFS measurements allow detailed examination on the status of emission, so that possibility of error can be reduced.

![Figure 2](image-url)
3.2. Investigation of excitation line

Combination of the most appropriate overlapping excitation lines to this method was investigated. Combination of the excitation lines was so selected that the distance between the excitation lines was less than the FWHM of the laser, evaluated by LIFBASE database. Results of the investigation, Q2(1)-Q2(2), Q1(13)-R1(18) ass the excitation line pair were combination overlapping as well in addition to the Q1(6)-R1(12) pair. Figure 4 shows the results of simulation showing temperature dependence of the absorption intensity for these excitation lines. As can be seen from Fig. 4, the excitation lines of Q1(6) had the highest strength. Also with respect to the Q1(6) excitation, emission abruptly increased with temperature up to about 1500 K, and after that gradually decreased. In contrast, emission from the R1(12) excitation increased with temperature from around 1000 K at relatively monotonically strength. The 2-line method, obtains the temperature from the change in the intensity ratio of the two fluorescence for two excitation lines. Therefore, the combination of excitation lines having such temperature dependency should be suitable for temperature measurement. For the other two pairs, absorption intensity was low, and they showed similar temperature dependence to the Q1(6)-R1(12) pair. Thus, Q1(6)-R1(12) was found to be optimum in this aspect. Figure 5 shows the predicted spectrums with these excitation line pairs, with ‘total’ line as integration of overlapping emissions. For LIFS measurement, as will be described later, it was necessary to identify individual the emission peaks. In the Fig. 5a and 5b cases, some peaks could be identified, while in the Fig. 5c case, no individual peak could be identified. Though peak identification seemed easier in the Fig. 5b case, emission signal level was sizably lower than those in Fig. 5a case in experiment, so that Q1(6) - R1(12) pair was selected in the present study.
3.3. LIFS-2 line method temperature measurement theory

3.3.1. Application of PLIF-2 line method

The current LIFS temperature measurement applied the theory of PLIF-2 line method for data processing. Actual expression of the temperature measurement by the PLIF-2 line method is expressed with following equation (Saiki. et al., 2007-8).

\[ T = A_s \frac{\Delta E}{k} \left[ \ln \left( \frac{S_{FL1} I_2 J_2 + 1}{S_{FL2} I_1 J_1 + 1} \right) \right]^{-1} \]  \hspace{1cm} (1)

where

- \( T \) \hspace{0.5cm} Temperature by LIF measurement
- \( A_s \) \hspace{0.5cm} Correction term of the measurement system
- \( \Delta E \) \hspace{0.5cm} The difference between the energy levels in the ground state of the excitation line
- \( k \) \hspace{0.5cm} Boltzmann’s constant
- \( S_{FL1}, S_{FL2} \) \hspace{0.5cm} Fluorescence intensity
- \( I_1, I_2 \) \hspace{0.5cm} Laser strength
- \( B_1, B_2 \) \hspace{0.5cm} Einstein’s B coefficients (Einstein’s transition probability)
- \( J_1', J_2' \) \hspace{0.5cm} Rotational quantum number

Figure 5 Simulated Fluorescence spectrum at overlapping line excitation.
(a) Q1(6) - R1(12) excitation \hspace{0.5cm} (b) Q1(13) - R1(18) excitation \hspace{0.5cm} (c) Q2(1) - Q2(2) excitation
The PLIF-2 line method is to measure the temperature distribution by the ratio of the fluorescence intensity from the two excitation lines. On the other hand, the LIFS-2 line method was to deduce temperature at the spectroscopic measurement points by the ratio of fluorescence peak intensities from two excitation lines. As shown in Fig. 2b, two fluorescence signals overlapped somehow, made it difficult to integrate the signal to attain intensity. Thus, some technique to deduce intensity ratio from peak intensity (detectable) should be introduced. Another problem was uneven laser intensities at two excitation wavelengths, can be expected from Fig. 3, requiring another technique to deduce the intensity ratio. To eliminate the influence of difference in fluorescence intensity and the laser intensity on the temperature measurement, conversion to data reduction was adapted in the present LIFS measurement.

3.3.2. Obtain the fluorescence intensity

In this method $S_{FL}$ adopts the peak intensity of the fluorescence branch. The fluorescent intensity was estimated by assuming the following relationship from peak intensity the establishment of the transition probability (Einstein’s $A$ coefficients, Einstein’s transition probability).

$$S_{FL} = S'_{FL} \cdot \frac{\Sigma A}{A}$$

\(\Sigma A\) is the sum of the Einstein’s $A$ coefficients for the entire OH(2,1) fluorescence band. $A$ is the Einstein’s $A$ coefficients of measured peak lines. By this relationship, the total fluorescence intensity was estimated from the intensity of one of the branches by calculation. Einstein’s $A$ coefficients of the OH(2,1) fluorescence by Q1(6)-R1(12) excitation are shown in Table 4.

| Emission line | P1(7) | P2(7) | Q1(6) | Q2(6) | R1(5) | R2(5) | O12(8) | Q12(6) | P12(7) | R21(5) | Q21(6) | S21(4) |
|---------------|-------|-------|-------|-------|-------|-------|--------|--------|-------|-------|--------|--------|
| $A$           | 0.2198 | 0.2035 | 0.3544 | 0.3458 | 0.1332 | 0.1408 | 0.0101 | 0.0272 | 0.0361 | 0.0452 | 0.0343 | 0.0133 |

| Emission line | P1(13) | P2(13) | Q1(12) | Q2(12) | R1(11) | R2(11) | O12(14) | Q12(12) | P12(13) | R21(11) | Q21(12) | S21(10) |
|---------------|--------|--------|--------|--------|--------|--------|---------|---------|--------|---------|---------|---------|
| $A$           | 0.1899 | 0.1850 | 0.3592 | 0.3564 | 0.1660 | 0.1686 | 0.0035  | 0.0094  | 0.0121 | 0.0153  | 0.0104  | 0.0052  |

3.3.3. Laser intensity at overlapping line excitation

The PLIF-2 line method uses two lasers for two excitation-line. In the present method two-excitation-lines were excited by one of the laser simultaneously. The laser intensity $I$ of the laser in each of the excitation line was not uniform, while the interval of laser wave lengths was too close for direct measurement of intensity at each wavelength. Therefore, the laser intensity ratio could not be obtained in the same manner as PLIF-2 line method. Then, we substituted the laser intensity ratio to $L_w$ as an experimental constant that depends on the center wavelength of the laser. The $L_w$ value, was calculated with Eq. (3), by giving a known temperature value and resulting emission data. Figure 6 shown the results of the measurement of the peak intensity of the branches by scanning the laser wavelength at three times in same temperature. It was confirmed that the intensity had different peak wavelength, and the laser intensity was different at each wavelength. The wavelength for the peak intensity deviated from the calculation shown in Fig. 3, possibly due to errors in the spectrometer. Figure 7 shows the $L_w$ which was calculated from the known temperature and measured values. Flame one condition (Mc01) of McKenna burner was used. Though the laser intensity was different in three experiments, good reproducibility in the $L_w$ deduction was confirmed. As one can see in Fig. 7, fairly constant $L_w$ was attained at region (a), averaged $L_w$ being 0.766. To attain this high and constant $L_w$ value, we chose a laser wavelength at 262.454 nm in the present study. For this fixed laser wavelength, $L_w$ calibrated at a reference temperature was considered to be valid for other temperature conditions.

Constant for the calculation are shown in Table 5.
\[ T = A \Delta E \frac{k}{k} \left[ \ln \left( \frac{S_{\text{FL1}}}{S_{\text{FL2}}} \cdot \frac{2A_1}{A_1} \cdot \frac{A_2}{A_2} \cdot L_1^W \cdot \frac{B_2}{B_1} \cdot \frac{2J_2+1}{2J_1+1} \right) \right]^{-1} \]  

Figure 6  Q1(6) -Q branch and R1(12) -R branch peak intensity relative to the laser wavelength; solid symbols show intensity at emission peak for Q1(6) excitation (Fig. 2b point ii) and open symbols show that for R1(12) excitation (Fig. 2b, point v)

Figure 7  \( L_w \) of calculated with respect to the laser wavelength where (a) appropriate, (b) too sensitive to laser wavelength, (c) signal too weak

Table 5  Constants for the calculation

| Excitation line | Excitation Wavelength (LIFBASE) nm | \( J'' \) | \( B \) | \( E \) \times 10^{-20} \text{ J} | \( L_w \) |
|------------------|-----------------------------------|---------|-------|----------------|------|
| Q1(6)            | 262.444                           | 6.5     | 6.05  | 1.53           | 0.766|
| R1(12)           | 262.442                           | 12.5    | 3.82  | 5.66           |      |
4. Measurement results

4.1. Validity of the technique

The resulting fluorescence spectra are shown in Figs. 8. Here, an average of 1,000 pulses were accumulated for validation approach. Signal level in Fig. 8 (b) was low, so that the low signal to noise ratio should have an effect in poor measurement accuracy. Note that the signal level was minimum for data deduction in the Fig. 8 (b) case because of rather low temperature level, so that better accuracy was expected for the cases with higher temperature conditions. To calculate the temperature from the low intensity signal like Figure 8 (b) (Mc03 φ1.3), Fast Fourier Transform (FFT) low pass filtering was adapted for noise reduction, as shown Figure 9. With the FFT filtering, deviation from the reference temperature was reduced from 751 K to 198 K for the Case 4 with Mc03 condition, and from 238 K to 126 K for the Case 5 with Mc01 condition. Though deviation increased from 40 K to 90 K in Case 5 with Mc01 condition, the filtering worked favourable to decrease deviation as a whole. Figure 10 summarizes the measured temperature in comparison to the reference temperature. As a result, precision of ± 150 K to literature values for McKenna burner (Prucker, Meier and Stricker, 1994) was attained, showing the possibly of temperature measurement by LIFS with OH (2,0) band excitation. For better precision, it is necessary to omit the obvious error data by performing conditional sampling, for example.

Figure 8  LIFS Measurement result spectrum  
(a)Mc01 φ1.0 (b) Mc03 φ1.3

Figure 9  FFT low pass filtered signal (to be compared to Fig 8b before filtering)
4.2. Time resolution and Accuracy

The presented technique allows temperature measurement using spectroscopy. Here, we discuss the accuracy of the measurement value in relation to the measurement time, as time-revolving data are also quite valuable. Figure 11 shows the histograms of deduced temperature from the spectral distribution for each measurement point, based on (a) 1 shot data and (b) accumulation of 5 shots data. Measuring time dependent on the exposure time of the ICCD for 1 shot measurement, and by the oscillation period of the laser for the 5 shots measurement. The median from each result substantially coincides with those with 1,000 shots (in 4.1 section) and the literature values described above. Looking at the measurement accuracy of each case, the dispersion value was 1100 K of 1 shot measurement, and 531 K for 5 shots measurement. Thus, for the deduced value with limited number of data, it is hard to say that accuracy was good. The reasons of the measured value dispersion could be instantaneous flame temperature variation, however, the influence of the variation of the incident laser wavelength, variation of the measuring apparatus, random noise, and the quantum-mechanical probability were also expected. Therefore, in the current stage, it is impossible to discuss the measurement accuracy with single shot for time revolving measurement. Further study and refinements in measurement technique are needed to attain such measurement capability.

![Figure 10](image)

**Figure 10** Summary of LIFS temperature measurement results

**Figure 11** Instantaneous value histogram by LIFS-2 line method
(a) 1 shot  (b) 5 shots

Median: 2138 K  
σ: 1100 K

Median: 2247 K  
σ: 531 K
5. Conclusion

In this study, we investigated the temperature measurement technique using the OH(2,0) band excitation which is promising for high pressure LIF measurement. By applying the theory of data reduction method for PLIF-2 line method LIFS temperature measurement became possible by using overlapping excitation lines. The resulting measurement precision was ± 150 K for the flat flame burner with temperature range of 1700-2200 K at atmospheric pressure. The higher temperature level within the rocket chamber would result in better precision due to higher signal level. For better precision, it is necessary to omit the obvious error data by performing conditional sampling, for example. As instantaneous measurement, there still remained challenges in measurement accuracy. Further efforts are also required to adapt this technique for high pressure environment.

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