

Measurement of NO Rotational Temperature using Monochromatic Fluorescence

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Introduction

Laser-induced fluorescence (LIF) is widely applied on diagnostics of high temperature reactive systems such as IC engines, supersonic combustors, and plasma jet facilities. In the LIF thermometry, temperature had been typically obtained by performing an excitation scan [1] and a two-line technique [2]. In these techniques, the temperature was estimated from a rotational population distribution in an electronic ground state of a molecule in burnt gas. In order to measure a rotational population distribution in the ground state, a continuously tunable laser source or two sources tunable to specific wavelengths of target molecule were needed. And the two or several laser lights with different wavelengths were required for exciting the different rotational energy levels in the ground state. So, the application of excitation scan and two-line technique to unsteady high-speed phenomena was difficult.

A monochromatic fluorescence thermometry [3] was developed for the temperature measurement. Use of a thermally assisted fluorescence was one of the typical techniques of monochromatic fluorescence thermometry [4, 5]. In this technique, rotational or vibrational population distribution in an electronic excited state was presumed to be collisionally equilibrated or quasi-equilibrated, so that rotational or vibrational temperature could be extracted from the resulting LIF spectrum. This technique had great advantage, because the rotational temperature could be measured without the scanning of the laser wavelength. If a LIF signal has enough intensity to analysis, the temperature measurement can be performed only by using a single shot of a pulsed laser. Therefore, the monochromatic fluorescence technique has a high possibility for the measurement of temperature profile in an unsteady flow.

In the previous works [4, 5], OH molecule was mainly used as a tracer for the thermally assisted fluorescence. As a tracer for LIF thermometry, although NO had been often used in the excitation scan and two-line technique, it had not been used in the thermally assisted fluorescence. Because the energy difference between adjacent rotational levels of NO was very small, analysis of rotationally resolved fluorescence spectrum was difficult. So, the direct measurement of population distribution in the excited state of NO could not be performed. Furthermore, since many of O₂ transitions overlapped on NO transitions [6], the separation of NO-LIF from O₂-LIF was required for the utilization of NO-LIF spectrum. However, NO has some advantage as the LIF tracer, because the NO is relatively stable and easily seeded into the reacting flow [7].

A spectral matching method, which was one of a plasma thermometry, was developed for a rotational temperature measurement in high-temperature plasma [8]. In this technique, the rotational temperature was estimated by a similarity between numerically calculated spectrum and experimentally obtained emission spectrum. In the previous work [9], we introduced the spectral matching method for the measurement of NO rotational temperature in a flame. In this previous work, a profile matching between NO-LIF spectrum obtained from the experiment and the synthetic spectrum, which was

calculated based on the Boltzmann distribution, was carried out. However, the profile of NO-LIF spectrum did not completely coincide with the profile of synthetic spectrum. And its profile depended strongly on an excited rotational level. It was considered that the spectral matching method should be improved to obtain a reasonable result. In this report, we discussed about the suitable band selection of the excited rotational energy level for an improvement of the spectral matching method.

Experimental setup

A schematic of the experimental apparatus is shown in Fig. 1. A laser diagnostic system consisted of an excimer laser (Lambda Physic, LPX-150), a spectrograph (Chromex, 250IS) and an ICCD camera (La-Vision, FlameStar). A tunable, narrowband ArF excimer laser was used to excite the $D^2 + X^2(0,1)$ band system of NO molecule. Wavelength of this laser was tunable in 193.0-193.9 nm. A laser light was focused with a spherical lens ($f = 1000$ mm) and was introduced into a flame. A laser-induced fluorescence was analyzed by the spectrograph with the ICCD camera. The grating of this spectrograph had 1200 grooves/mm (blazed for 250 nm) which led to a linear dispersion of 2.5 nm/mm. Hence, a spectral bandpass of 36 nm could be captured with the ICCD camera which had 384×288 (horizontal \times vertical) pixels. The spectrum within the 36 nm wide was spread over the 384 rows of the ICCD camera, it resulted in a spectral resolution of 0.2 nm using an entrance slit width of 20 μ m.

Test flame used in this study was methane-air premixed flame. A flat flame burner (McKenna) which had a porous plate (60 mm diameter) with water cooling system was used as a test burner. The flame front was stably formed on 0.5 mm above the porous plate. The laser beam was irradiated at 10 mm above the porous plate. Equivalence ratio of the mixture was chosen at $\phi = 1.2$.

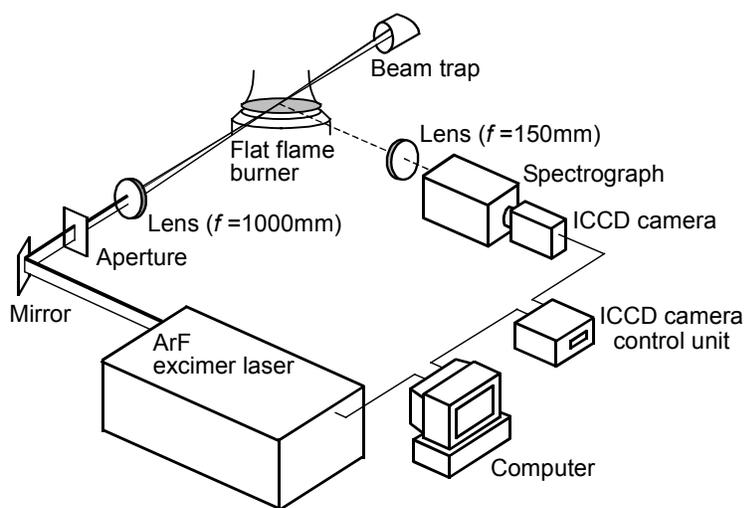


Fig. 1 Experimental setup

Results and Discussion

The examples of NO and O₂-LIF spectra are shown in Fig. 2. The strong peak around 193nm is the Rayleigh scattering. From these spectra, it was confirmed that even if the O₂ and NO molecules existed in a measuring point, the (0,3) band of NO-LIF was nonintrusive to O₂-LIF. Therefore, the spectral matching method could be performed by using the profile of NO (0,3) band.

The synthetic spectra of the NO (0,3) band are shown in Fig. 3. These spectra were calculated theoretically with reliable molecular constants and detailed equations, and they were modulated by a slit function of the real measurement system. Here, it was assumed that the population distribution of excited rotational level was described as the Boltzmann distribution. From Fig. 3, it was confirmed that

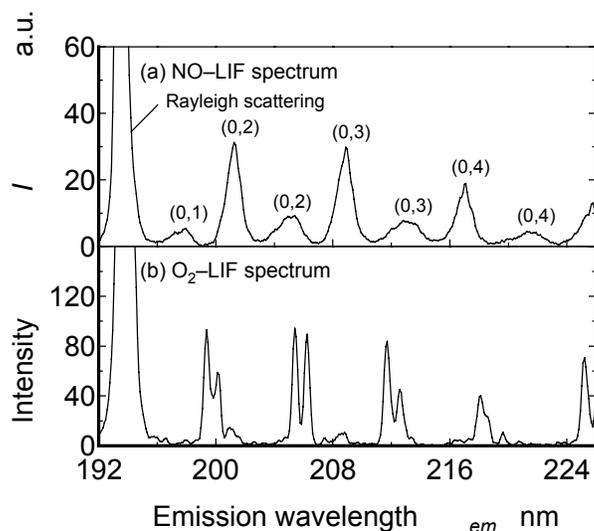


Fig. 2 Examples of NO and O₂-LIF spectrum

the profile of band spectrum depends on the rotational temperature T_R . Especially, the significant difference of spectrum profile due to the difference in rotational temperature was observed at the shorter wavelength side. Therefore, the rotational temperature was estimated from the matching of the profiles at the shorter wavelength side.

The profiles of experimental (0,3) band spectrum obtained from the methane-air premixed flame is shown in Fig. 4. Excited rotational levels used here were $F_1(32.5)$, $F_1(34.5)$, $F_1(35.5)$ and $F_1(36.5)$ in the $v'=0$ vibrational level, respectively. $F_1(32.5)$ level was the lowest F_1 level which could be excited by the ArF excimer laser. In this figure, dashed line indicates the synthetic spectrum at $T_R=1660\text{K}$ which was equal to flame temperature obtained by a thermocouple. This figure shows that the profile of the experimental spectrum approached to the Boltzmann distribution when the rotational level J became lower. In the case of OH molecule, it was known that the rotational energy transfer (RET) rate increases with decreasing rotational level [10]. The result of Fig. 4 indicates that the RET of NO molecule also increases with decreasing the rotational level. As for the short wavelength side of the $F_1(32.5)$, the profile of experimental spectrum well fitted to the profile of the synthetic spectrum. Therefore, the flame temperature could be obtained by using the profile of the (0,3) band with the excitation of the $F_1(32.5)$ level.

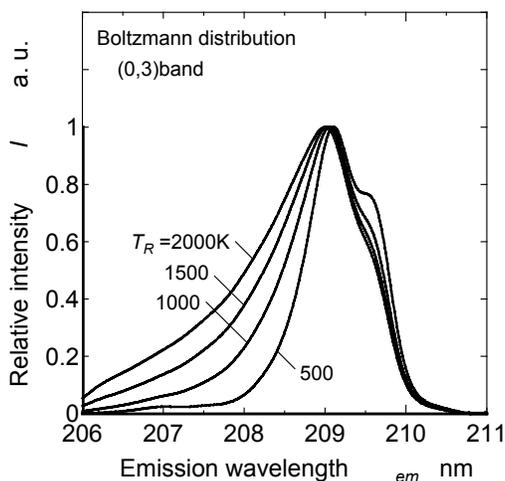


Fig. 3 Synthetic spectrum of (0,3) band

On the other hand, when NO was excited to the F_2 levels, although the rotational level J' was smaller than 32.5, each profile differed from the synthetic spectrum greatly (Fig. 5). This result suggested that the RET rate of F_2 level was slower than that of F_1 level. From these discussion, it was found that the excitation of $F_1(32.5)$ level was suitable for the spectral matching method in a flame thermometry.

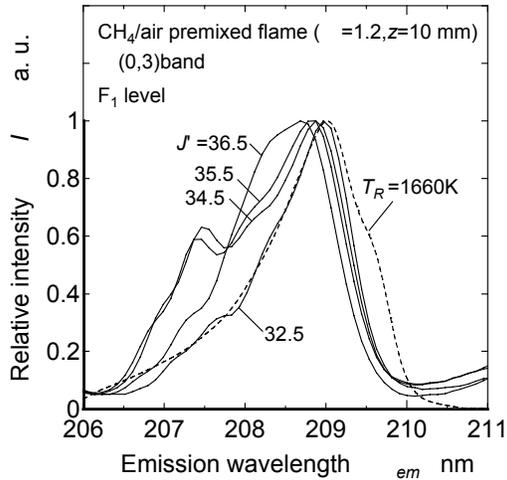


Fig. 4 Experimental spectra of the (0,3) band obtained by exciting to the F_1 levels

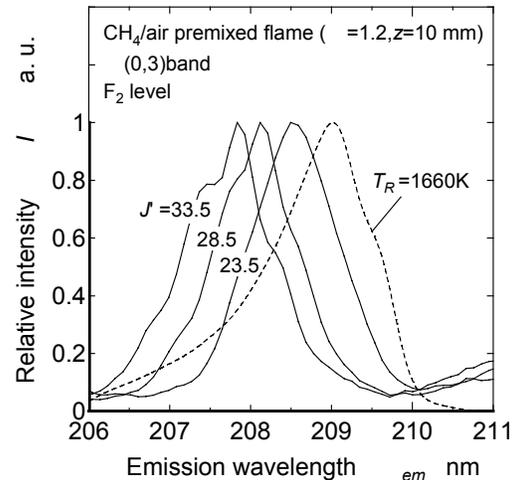


Fig. 5 Experimental spectra of the (0,3) band obtained by exciting to the F_2 levels

Conclusions

In order to measure the rotational temperature of NO using monochromatic fluorescence technique, suitable excitation rotational level was investigated.

- (1) (0,3) band of NO-LIF was not overlapped with the O_2 -LIF.
- (2) The profile with the excitation of the $F_1(32.5)$ level well fitted to the profile of the synthetic spectrum at the short wavelength side of the NO-LIF band spectrum.
- (3) RET rate of F_2 level was slower than that of F_1 level.

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