

Fast Response Local Equivalence Ratio Measurement in Premixed Turbulent Flame

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Local equivalence ratio at the flame-front of turbulent propane/air premixed flames were measured in time series by spatially and temporally resolved chemiluminescence measurements of OH*, CH* and C2*. Cassegrain optics and high-speed spectrograph were developed to detect these chemiluminescences simultaneously to obtain flame spectroscopic data for a local point. It was found that emission intensity of OH*/CH* was a good marker to measure local equivalence ratio. A new fast response non-intrusive sensor for determination of local turbulent flame structure is proposed and its performance is proven.

1. Introduction

In order to control the turbulent combustion for reducing pollutant, increasing combustion efficiency and obtaining stable flame holding, we have to know more detailed structure at turbulent flame-front. Local flame-front structures have been investigated to determine effects of turbulence - chemistry interaction, vortex interaction with the flame-front, stretch rate, flame curvature, extinction, and equivalence ratio [1-3]. Turbulent flames can be defined by the chemical reaction at the flame-front affected by turbulence, so it is necessary for combustion diagnostics to have a high spatial and temporal resolution.

Laser techniques have greatly been playing a major role to measure flame-front structures and their features under various conditions. Laser-induced fluorescence (LIF) [4] becomes a very powerful tool to visualize the OH/CH/C2 reaction zone and its time evolution [5]. LIF techniques can provide useful 2-dimensional information on flame shape and flame front structure, but time-series analysis of the flame front structure could not be demonstrated because the laser repetition rate.

The chemiluminescent emissions from excited OH, CH and C2 originate from the chemical production of the excited states. Even by LIF, the ground state radical concentration can be measured. Chemiluminescence measurements are needed in reaction modeling to predict excited radical concentrations, but what we can actually measure is not the excited radical concentrations but the intensity of chemiluminescent emissions [6-9].

In order to measure the chemical reaction scale and the flame-front structure with high temporal

and spatial resolutions, Cassegrain optics were developed that are capable of measuring local chemiluminescences (OH^* , CH^* , C_2^*) in a small control volume ($0.1 \times 0.8 \text{ mm}$) [10,11]. The size of the measurement volume was sufficiently small as to detect the flame-front location and reaction intensities profiles.

The purpose of the present study is to develop measurement system to measure the local equivalence at the flame-front of turbulent premixed flames by using the Cassegrain-based with sufficient high enough response to turbulent motion. Here, local equivalence ratio can be an important maker for determination of flame structure and also fuel-air mixing.

2. Experimental apparatus

The experiments were carried out using a turbulent premixed burner of 20 mm inner diameter, Reynolds number of 14,000, mean velocity U of 4.9m/s, RMS velocity u' of 0.43m/s. Propane was used as fuel at an equivalence ratio ϕ of 1.1, where the laminar burning velocity S_L is 0.45 m/s. Turbulence intensity is relatively low as $u'/S_L = 1.08$.

Cassegrain optics was developed [10,11]: the measurement volume dimensions are shown in Fig. 1. A small measurement volume of $\phi 0.1 \times 0.8 \text{ mm}$ was achieved to produce a spatial resolution similar to that of Laser Doppler Velocimetry [12]. The simultaneous measurement system for the local chemiluminescences of OH^* , CH^* and C_2^* is also shown in Fig. 1. Flame emissions from excited species received by the Cassegrain optics was focused onto an optical fiber (quartz, core: $200 \mu\text{m}$ diameter), transmitted to band-pass filtered (BPF) spectroscopy unit and photo-multipliers (PMT). The analog output signals of these PMTs were amplified, filtered, and digitized by a multi-channel A/D converter at a sampling rate of 200 kHz. The large memory capacity of the system permitted continuous measurements for several seconds. As shown in the figure, four color splitters (interference and dichroic filters) for OH^* , CH^* and C_2^* were implemented for each radical emissions. The specifications for each of the optical filters were determined as follows (center wavelength / half-band width / transmitting efficiency):

OH^* :	306nm / 14nm / 61%
CH^* :	431.4nm / 1.5nm / 40%
C_2^* :	516.5nm / 2nm / 58%

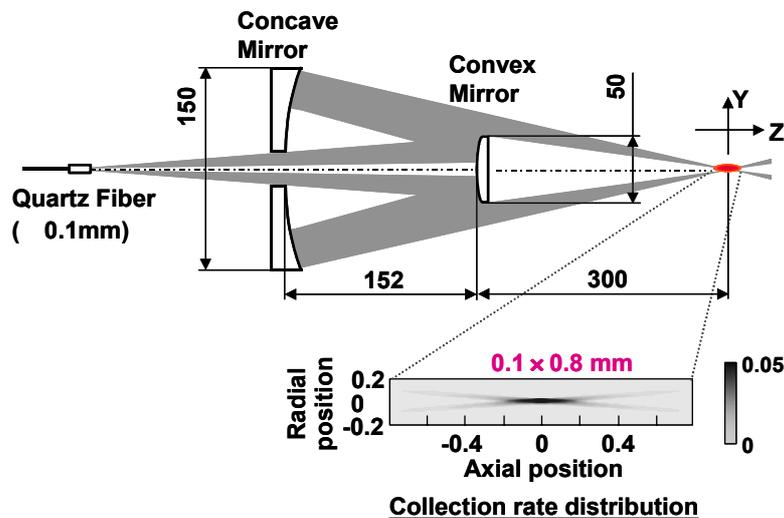


Fig. 1 Developed Cassegrain Optics [10]

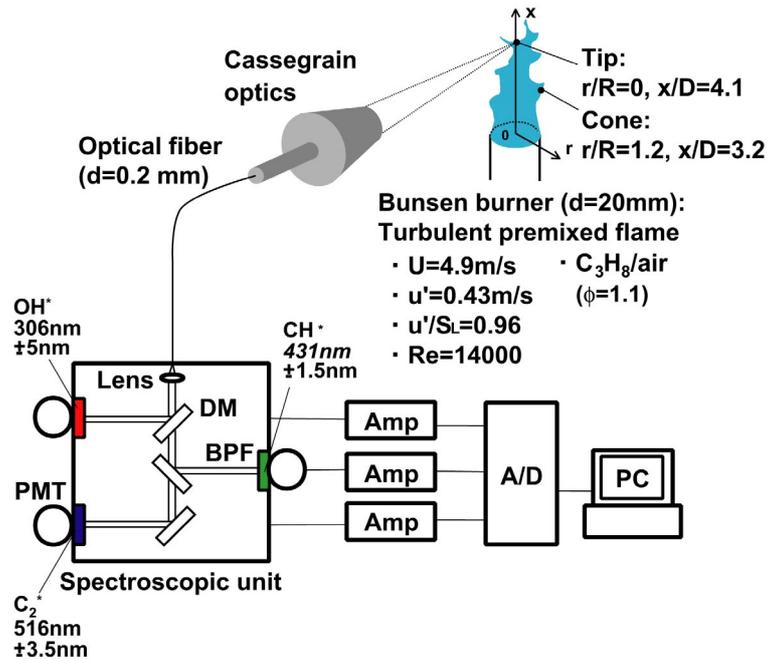


Fig. 2 Experimental apparatus [15]

3. Results and discussions

The detailed local flame spectra measured at different positions ($x = 50\text{mm}$ and $r/R = 0.8, 0.9$ and 1.0) of turbulent flames are shown in Fig. 3 in which a standard monochromator (Mepherson, 2035, 300 lines/mm) was used. The exposure time was 100 ms. The spectra at $r/R = 1.0$ showed OH^* but not significant CH^* and C_2^* . The OH^* spectrum detected at $r/R=1.0$ was produced when the flame front passes with turbulent motion, but the CH^* and C_2^* could not be measured. This OH^* may be produced by residual hot gas and thermal excited radicals. The peak ratio of OH^* , CH^* and C_2^* can be used to understand the equivalence ratio as demonstrated in premixed laminar flame [13,14]. On the other hand, the $\text{C}_2^*(516\text{nm})$ peak is the same level of $\text{CH}^*(431\text{nm})$ at $r/R=0.9$, so the equivalence ratio may be high. At $r/R=1.0$, there are low OH^* peaks but also CH^* and C_2^* peaks, which means that the flame front does not stay at this location and some hot burnt gas remains.

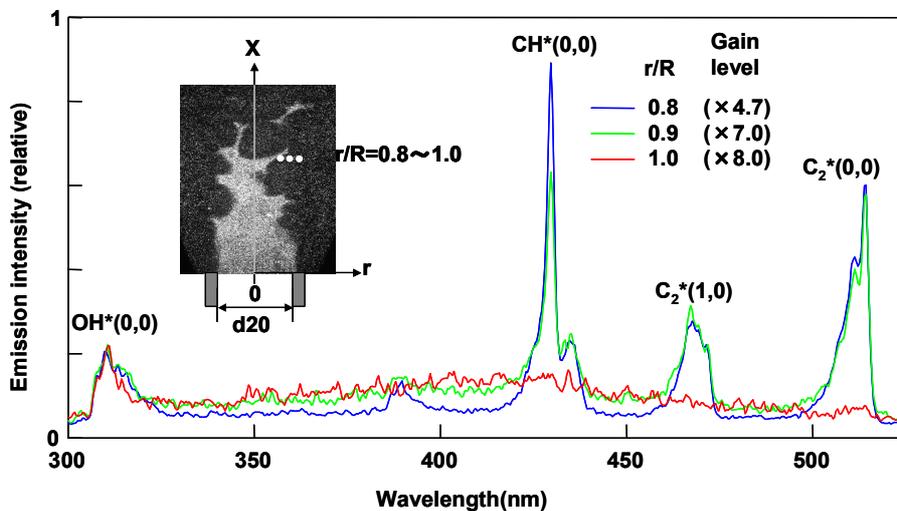


Fig. 3 Local flame spectra at different positions

Time-series signals of OH*, CH* and C2* chemiluminescences at the Tip ($r/R=0$, $x/D=4.1$) and Cone ($r/R=1.2$, $x/D=3.2$) of flame are measured by this system, at 200 kHz sampling rate as shown in Fig. 4. Each intensity of chemiluminescence was normalized by each maximum peak value. These three time traces of chemiluminescence intensity peak and its location synchronized each other very well. The usefulness of Cassegrain optics for understanding local combustion intensity and flame movement is proven in this measurement. Here, each peak intensity of these three radicals, is varying in time and position, this is mainly because the variation of local equivalence ratio.

Here, it is found that the time depending flame front structure can be defined by this measured system in terms of local equivalence ratio and flame passing internal. There are some un-known factors remained, such as effects of flame stretch, curvature, strain rate, temperature, pressure, and so on, which are current research subjects going on.

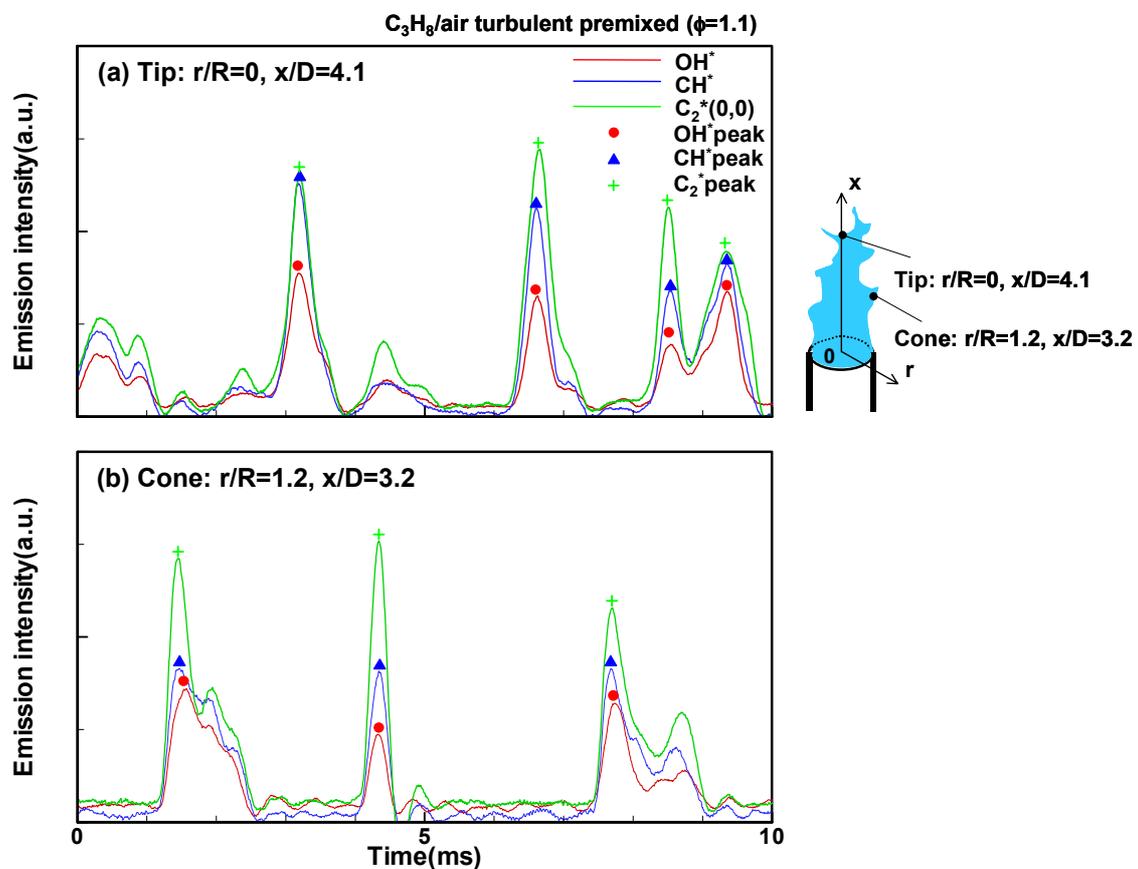


Fig. 4 Time-series signals of chemiluminescence intensities at the flame fronts of turbulent premixed flame

In our previous study [13], the ratio of the C2*/CH* and the OH*/CH* versus equivalence ratio for the local flame front of a laminar premixed flame was investigated and found a strong correlation. That results showed that the relationships between these curves and the equivalence ratio were nearly linear when the equivalence ratio was less than 1.4 as shown in Fig. 5. This high degree of correlation indicated that the local equivalence ratio at the flame front can be determined by spatially resolved chemiluminescence measurements. In the same matter, equations for prediction of local equivalence ratio could be given experimentally as shown in Fig. 5.

In the present study, we applied this technique to analyze turbulent premixed flames in order to

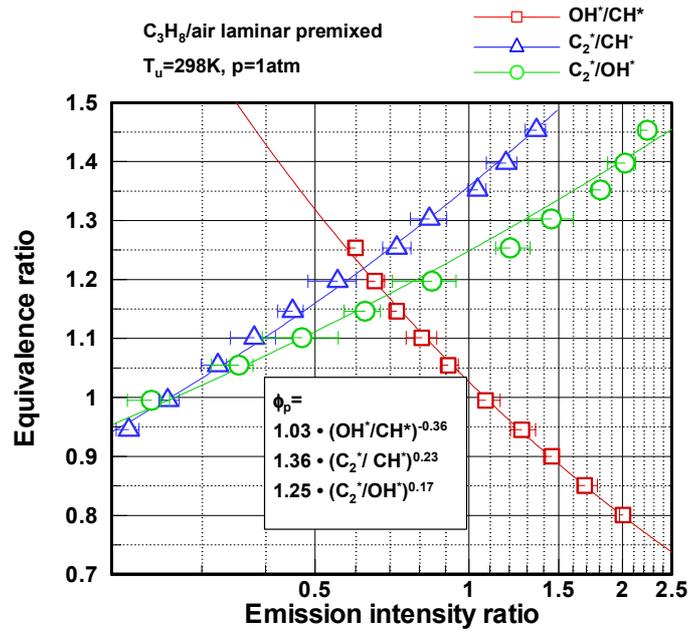


Fig. 5 Correlation of chemiluminescence intensity ratios to equivalence ratio

detect the local equivalence ratio at the flame front in time series. We confirmed that the same correlations between local equivalence ratio and local emission intensity ratio were obtained with the error of 5% in previous studies [13-16].

Finally, the local equivalence ratio at a local flame-front was directly measured in turbulent methane/air premixed flames using the correlation formula of OH^*/CH^* based on laminar flame results. Figure 6 shows the time evolution of instantaneous local equivalence ratio of flame front at the Tip and Cone of turbulent premixed flames. Probability density functions (PDF) of instantaneous local

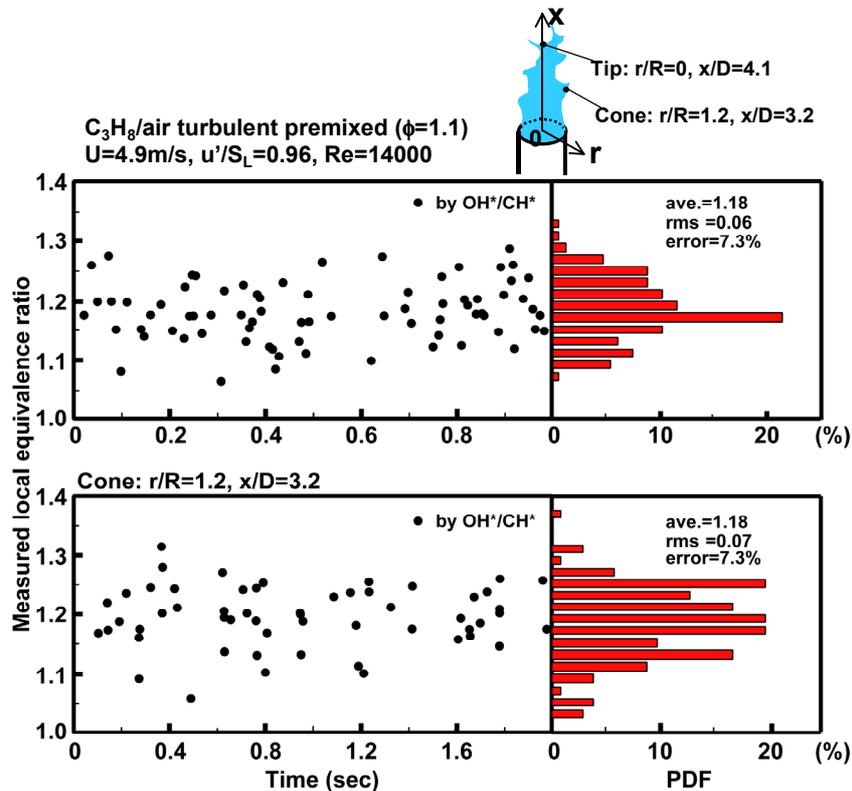


Fig. 6 Time series data of local equivalence ratio of turbulent flame front

equivalence ratio are also shown. Mean measured local equivalence ratios were 1.18 for the pre-set equivalence ratio of 1.1 in both case of Tip and Cone. RMS of time variation of local equivalence ratio was about 0.06.

The accuracy of detection of local equivalence ratio at the present study was about 7 %. In the next study, un-known factors such as effects of strain rate and temperature will be investigated.

4. Conclusion

Fast response local equivalence ratio measurement was demonstrated by local chemiluminescent emissions (OH^* , CH^* and C_2^*) to study the local flame front structure of turbulent premixed flames. The findings are summarized as follows:

1. The usefulness of local flame spectra measurement for understanding local flame structure is proven.
2. Local equivalence ratio was measured in time-series by emission intensity ratio of OH^*/CH^* at the turbulent premixed flame-front.
3. The accuracy of detection of local equivalence ratio at the present study was about 7 %.

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