Two-Dimensional Observation of Fluctuation in Methane-Air/LPG-Air Premixed Flames by Planar Laser-Induced Fluorescence (PLIF)

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Synopsis

OH-PLIF images were observed sequentially at a rate of 30 frames/s on CH₄-air and liquefied petroleum gas (LPG)–air premixed flames, followed by statistical analysis including Fast Fourier Transformation (FFT) to examine flame fluctuations at inner and outer regions of the premixed flames. Characteristics in the FFT power spectra were different between the inner and outer cases due to a difference in mixing condition of the fuel gas and air between the inner and outer flame regions. Correlation profiles between average value and standard deviation of the consecutively measured OH-PLIF intensity showed that combustion reaction activity was not always a prevailing driving force for the fluctuation. This characteristic was independent of the difference in mixing condition of the fuel gas and air between the inner and outer flame regions.

Key words: flame fluctuation, premixed flames, OH—PLIF distribution, statistical analysis

1. Introduction

Combustion control in all types of hydrocarbon fuel combustion systems must be effective and efficient for clean conversion of chemical energy to thermal energy. Improvements of combustion control techniques require comprehensive understanding of combustion phenomena. An important phenomenon of combustion is a temporal fluctuation in flames. It is useful for an unravelment of the temporal fluctuation to observe temporally resolved distributions of OH radical using planar laser induced fluorescence (PLIF) diagnostics. OH radical plays an important role on one of chain carriers in combustion reactions and appears in high temperature regions. Several investigations have provided temporally resolved information on the OH distribution using PLIF diagnostics. Dyer and Crosley¹ used a double pulse technique to obtain two-frames of two-dimensional (2-D) images of OH sequentially using LIF. These two images were separated by some time of the order of 100 μs. Seitzman et al.² observed the evolution of large-scale structures in high-speed nonpremixed combustion flows using double-pulse OH/acetone PLIF visualization technique. Kychakoff et al.³ measured sequential images of OH and O₂ with a PLIF system having a maximum framing rate capability of 250 Hz and assembled three-dimensional images of a flame. Kaminski et al.⁴ developed a PLIF system that could observe up to eight sequential images of OH at several kHz. They measured the distribution of OH in a turbulent non-premixed flame at a high repetition rate. Dreizler et al.⁵ characterized a spark ignition system and Abu-Gharbieh et al.⁶ tracked the response of flame front to a turbulent flow field using a PLIF system.

In this study, 550 sequential images of OH distributions have been obtained using PLIF diagnostics at a rate of 30 frames/s from CH₄-air and liquefied petroleum gas (LPG)–air premixed flames, followed by statistical analysis including Fast Fourier Transformation (FFT). The acquired sequential images are used to examine important differences in the
flame fluctuation at inner and outer regions of the premixed flames. An examination of two fuels (CH$_4$ and LPG) allows us to determine an influence of molecular weight of the fuel gas on the flame fluctuation.

2. Experimental

Figure 1 shows a schematic diagram of the experimental apparatus assembled for this work. An ultraviolet radiation for excitation of OH radical was produced using a pulsed Nd:YAG laser (Spectron Laser Systems, model SL852G), a dye laser (Spectron Laser Systems, model SL4000) and a DKDP crystal (Spectron Laser Systems, model FD2). A tunable dye laser with Rhodamine 590 was pumped by the second harmonic of the Nd:YAG laser (wavelength of 532 nm, pulse duration of 6 ns and pulse repetition rate of 30 pps), and converted into the ultraviolet radiation through the use of the DKDP crystal. The resulting ultraviolet laser beam (having approximately 8.2 mJ/pulse) was formed into a planar laser sheet of about 0.5 mm thickness and 50 mm height through the use of cylindrical lenses. The laser sheet excited OH radical in a longitudinal cross section including the central axis of a burner. The OH excitation line was the Q$_1(7)$ rotational line at 283.222 nm of the A$^2\Sigma^+$$^\leftrightarrow$X$^2\Pi$ (1,0) transition. The temperature dependency of number density of OH radical in ground state was reported to be within 10% over a range of 1000-2000 K.

An ICCD camera (PCO, model DiCAM-PRO) was set perpendicular to the laser sheet to observe OH-PLIF distributions. The central wavelength and full width half maximum (FWHM) of a bandpass filter (OMEGA OPTICAL) were 310 nm and 20 nm, respectively. OH—LIF spectra were measured using a multi-spectrometer (Acton Research Corporation, model SpectraPro 500) equipped with an ICCD detector (ANDOR TECHNOLOGY, model DH734) to confirm that the bandpass filter was appropriate for the OH measurement in PLIF diagnostics. A digital delay and pulse generator system (Stanford Research Systems, MODEL DG535) controlled operational timings of the pulsed Nd:YAG laser, the ICCD camera and the multi-spectrometer. The gate widths of the ICCD camera and the ICCD detector attached to the multi-spectrometer were 60 ns, respectively.

A CH$_4$-air or LPG-air premixed flame was formed on a cylindrical fused-silica burner having an inside diameter of 8.2 mm and a wall thickness of 1.1 mm. The LPG was composed of propane (97.7%), isobutene (1.0%) n-butane (0.4%), and ethane + ethylene (0.9%). Three equivalence ratios, $\phi$, of 0.9, 1.1 and 1.3 were employed here to examine the differences in the flame characteristics under fuel-lean and fuel-rich conditions. The CH$_4$-air and LPG-air premixed gases had flow velocities of 1.3 m/s and Reynolds numbers of 660 and 690 at the burner exit under cold flow condition, respectively. For each flame, 550 images of OH distributions in 2-D were obtained successively at a frame rate of 30 Hz using the PLIF diagnostics. For analytical convenience, 2-D cylindrical coordinate system $(r, z)$ was defined as shown in Fig. 1. The origin of $r$ and $z$-axes was fixed at the center of the burner exit. The region of interest (ROI) was from $r= -15$ to 15 mm and from $z= 0$ to 47.5 mm, which corresponded to 241 x 381 pixels.

3. Results and Discussion

Figures 2 and 3 show a part of the sequentially measured OH-PLIF profiles in the CH$_4$-air and LPG-air premixed flames at a sampling rate of 30 frames/s, respectively. In these figures, the profiles sequentially measured at an interval of 1/30 s are numbered in order of measurement. (a), (b) and (c) correspond to the results in cases of equivalence ratios, $\phi$, of 0.9, 1.1 and 1.3, respectively. The results show that the area of stronger OH—PLIF intensity shifts from the inner flame region to outer one with an increase in equivalence ratio. This is because the unburned fuel increases with equivalence ratio and the diffusion combustion with ambient air is promoted in the outer flame region under fuel-rich mixture condition. Note that this enhanced diffusion combustion is more remarkable in case of the CH$_4$ flame. This is attributed to higher diffusivity of CH$_4$ as compared to LPG due to lower molecular weight of CH$_4$.

Figures 2 and 3 show that fluctuations are encountered both at the inner and outer regions of the premixed flames. In order to figure out the fluctuations more quantitatively, FFT analysis of the consecutively measured OH-PLIF intensity was applied to a typical point in the inner and outer flame regions (Figs. 4 and 5). Since the sampling rate of the PLIF system was 30 Hz, the FFT power spectra were obtained for the frequency region under the Nyquist frequency of 15 Hz. The FFT power spectra for the outer flame point show that the fluctuation has a
characteristic peak of 9–15 Hz. It is expected that this fluctuation is chiefly caused by low-frequency instability that may be influenced by buoyancy forces. It is noted that this peak becomes stronger and shifts to the higher frequency side with the increase in equivalence ratio. This is because a heat discharge is increased in the outer flame region with the increase in equivalence ratio. This situation causes an expansion of the burnt gas frequently and widens the differences in velocity and density between combustion gas and ambient air. The widened differences enhance the instability of the outer flame region. It is also noted that this peak appears in the inner flame region as compared to the outer one since the mixing of the premixed gas in the inner one is sufficient in comparison to that of the fuel gas and ambient air.

Figure 6 shows 2-D profiles of average value and standard deviation of the acquired OH–PLIF intensity which were calculated from the 550 consecutively measured distributions of OH–PLIF intensity. The upper and lower profiles are for the CH₄ and LPG flames, respectively, while the left and right profiles represent the average value and standard deviation, respectively. It is noted that a double layer structure
Fig. 6 2-D profiles of the average value and standard deviation of the consecutively acquired OH-PLIF distributions measured in the CH$_4$ and LPG-air premixed flames.

Fig. 7 Correlation profile between the average value and standard deviation of OH-PLIF intensity at the inner and outer flame regions. (a), (b), (c) and (d) are the profiles for $\phi = 0.9$ at the inner flame and for $\phi = 1.3$ at the outer flame in CH$_4$ and LPG cases, respectively. The ROI is between (a) $r = 2.5$ to $2.5$ mm and $z = 5$ to $12.5$ mm, (b) $r = -12.5$ to $-7.5$ mm and $z = 25$ to $47.5$ mm, (c) $r = 2.5$ to $2.5$ mm and $z = 5$ to $12.5$ mm, (d) $r = -12.5$ to $-7.5$ mm and $z = 20$ to $47.5$ mm, respectively.

appears in the standard deviation profiles of the outer flame region (especially under fuel-rich cases), while only a single layer structure appears at the inner one. This is because the buoyancy effect, which is predominant for the fluctuation at the outer flame region, gives rise to a larger fluctuation in the traverse direction.

Figure 7 is correlation profiles between the average value and standard deviation of the acquired OH-PLIF intensity at the inner and outer flame regions. Since OH radical is one of major intermediate species produced from combustion reactions, it can be interpreted that combustion reactions are more active at a position with the higher OH average value and that a flame fluctuation is more significant at a position with the higher OH standard deviation. In Fig. 7, (a), (b), (c) and (d) are the correlation profiles for $\phi = 0.9$ in the inner flame region and for $\phi = 1.3$ in the outer one in CH$_4$ and LPG flames, respectively. In the correlation profiles, a positive correlation appears on the side of smaller OH average value, while a negative correlation appears on the side of higher OH average value. That is, the OH standard deviation is not directly proportional to the OH average value. This suggests that combustion reaction activity is not always a prevailing driving force for the flame fluctuation and that the fluctuation is significantly raised at a circumference of reaction zone. The contribution of combustion reaction activity to the fluctuation is probably less significant than that in the gas stream. This characteristic is independent of the difference in mixing condition of the fuel gas and air between the inner and outer flame regions.

4. Conclusions

Flame fluctuations at inner and outer flame regions under fuel-lean and fuel-rich conditions were investigated from statistical analysis including FFT of OH-PLIF distributions consecutively measured at 30 frames/s in CH$_4$-air and liquefied petroleum gas LPG-air premixed flames.

In result, the FFT power spectra for the outer flame region showed that the fluctuation had a characteristic peak of 9–15 Hz, which was mainly caused by low-frequency instability due to buoyancy forces. In contrast, the FFT power spectra for the inner one showed that the fluctuation had no characteristic peak below 15 Hz and that was not directly excited by the instability of the outer one. This difference in the inner and outer cases depended on a difference in mixing condition of the fuel gas and air between the inner and outer flame regions.

The average value and standard deviation of the consecutively measured OH-PLIF intensity were not directly proportional to each other. This indicated that combustion reaction activity was not always a prevailing driving force for the flame fluctuation. The contribution of combustion reaction activity to the fluctuation was probably less significant than that of the gas stream. This characteristic was independent of the difference in mixing condition of the fuel gas and air between the inner and outer flame regions.

References