Study on OH Structure in Turbulent Premixed Flames by PLIF

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Abstract

Instantaneous two-dimensional OH structure in turbulent methane-air premixed flame measured by PLIF (Planer Laser Induced Fluorescence) is studied. Turbulence is generated by a perforated-plate. A lean mixture (equivalence ratio: ϕ = 0.65~0.95, Lewis number: Le~0.94) of 175cm/s averaged flow rate is selected for the experimental condition. Turbulent intensity is about 17cm/s, indicating these categorized laminar flamelet regime according to the combustion diagram [1]. Instantaneous 2-D OH image is visualized by PLIF system with $Q_1(7)$ line of the (1, 0) band of the $A^2\Sigma^+$-$X^2\Pi$ transition. The flame front and OH structure are extracted from the image. Regarding as the experimental results the well-known “cusp” is observed, and the cusp formation is enhanced as the mixture gets closer to the stoichiometric condition. Data analyses reveal that the produced OH structure has certain dependency on the turbulent structure (e.g. curvature of the flame) even in Le~1 condition. This dependency is pronounced as the mixture gets closer to the stoichiometric condition. The results given here show experimentally that Lewis number cannot completely describe the local flame structure depending on the turbulent structure.

Keywords; Curvature, Flame Structure, OH-PLIF, Premixed Flame, Turbulent Flame

Introduction

Precise flame structure study is one of the basic turbulent flame research topics, since the interaction between turbulence and combustion characteristics must be understood in the first place. Most basic approach for the flame diagnostics study is chemi-luminescence [ex.2]. Although recently the new method of chemi-luminescence diagnostics with high resolution is developed [3], it only gives the point-source information. LIF (Laser Induced Fluorescence) is, therefore, very powerful measurement tool for the flame diagnostics because 1) it could be expanded to two-dimensional measurement, known as PLIF (Planer LIF), and 2) relatively stronger signals from the selected radicals can be tracked. Since PLIF could give the flame front information extracted from the visualized image, an interaction between turbulence and local flame structure can be investigated. Indeed, there are many review articles and researches [ex.4-7] by using PLIF for the flame diagnostics, and show their usefulness.

According to Lee et al. [6], with lean methane-air mixture (equivalence ratio; ϕ=0.71~0.75), it was reported that the flame curvature hardly affects the OH structures, (e.g. distributions, normalized peak intensity). They explained that this was because that the lean methane-air mixture has nearly unity Lewis number (Le~0.94). As for this explanation, the tendency described above must be consistent as long as lean methane-air mixture is used. However, recently we have

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experienced that OH signal has certain curvature dependency, suggesting the turbulent characteristics may affect the local flamelet structure. Other researches also imply that the flame structure might be affected by the turbulence [7-9].

In the present study, we have conducted the experiment to visualize the produced 2-D OH image of lean methane-air premixed flame by PLIF, and extracted its turbulent structure (i.e. the flame front curvature) as well as the local flame structure (i.e. OH structure) to understand the interaction between turbulence and combustion structures.

Experiment

A schematically illustration of PLIF system is shown in Fig.1. A Nd:YAG (Spectra Physics GCR-230; 5ns pulse with 10Hz) pumped dye laser (Lumonics HD-300) with a frequency doubled 283.222nm is tuned to the $Q_1(7)$ OH line of the (1, 0) band of the $A^2\Sigma^+\text{-}X^2\Pi$ transition. This line is selected because it has small temperature dependency on fluorescence signal. The laser beam is expanded to the sheet with two cylindrical lenses. Thickness of the sheet is about 0.4mm. The laser sheet passes the premixed turbulent flame generated by the Bunsen-type burner mounted perforated plate. Fluorescence is selected in the wavelength range from 301nm to 312nm via narrow band pass filter and collected by a UV Nikkor lens (f/4.5, 105mm focal length). OH image is detected by CCD camera with Image Intensifier (Hamamatsu Photonics C3077-50 & C4274). Gate in the camera system and the laser pulse is synchronized by the pulse generator (Stanford Research; DG535). Observed domain is 26.0x24.5mm^2 (256x256 pixels) at 20mm over the burner exit surface. Each image is corrected by the averaged laser (sheet) profile; the profile is obtained from 50 fluorescence images of uniformly distributed test sample.

Experiments are performed in various ϕ (0.65~0.95) with constant flow rate (1000cm^3/s). The perforated plate mounted in the burner generates 175cm/s average velocity uniformly formed at burner exit with 17cm/s turbulent intensity, indicating these categorized laminar flamelet regime according to the combustion diagram [1]. To prevent the blow-off in quite lean condition, flame is stabilized by pilot flame formed around the burner exit. Results discussed here are analyzed by using at least 1000 data, supporting they reveal the trend (if any) correctly.

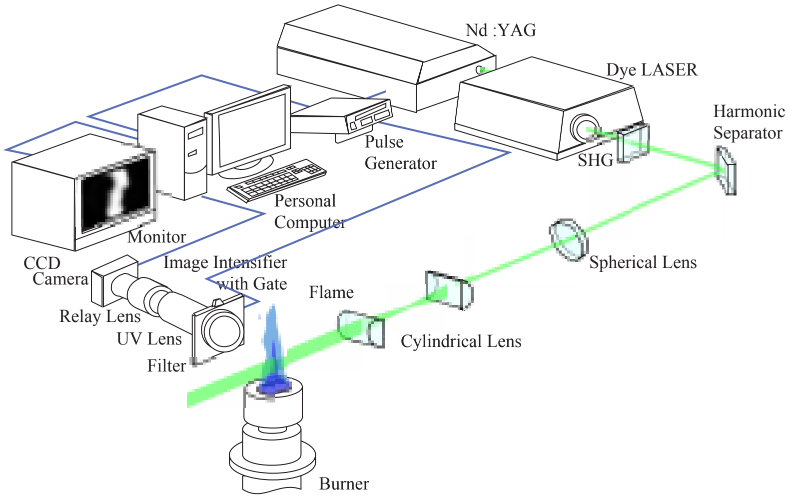

Figure 1 Schematic Illustration of PLIF Systems

Definition of “Flame Front” and “Peak Distance”

The flame front and the OH structure are extracted from the OH fluorescence image. Since the CH peak is known as reliable location of flame front, we attempted to search the corresponding location by using OH. Numerical calculations of 1-D configuration with GRI-Mech.2.11 kinetics model by the generic numerical code [10] were conducted for that purpose. According to the results (not shown), CH peak stays always around the location where 50% of OH maximum in upstream (unburned side). Thus we took the location where 50% OH maximum in upstream as the flame front for all ϕ considered in the present study. Additionally the peak distance is defined as the normal distance from the flame front to the location of the OH peak. Normalized OH peak value (by its average) is also introduced for the further discussion.

Results and Discussion

Fig.2 shows that the typical 2-D instantaneous OH fluorescence image of ϕ=0.65~0.95. In the figure, the left and right hand sides are the burned and unburned regions, respectively. White region corresponds to the OH fluorescence signal. As seen in the figure, well-known “cusp” can be found and it becomes obvious as the equivalence ratio is increased. This is due to the burning velocity is increased when the mixture gets closer to the stoichiometiric condition.

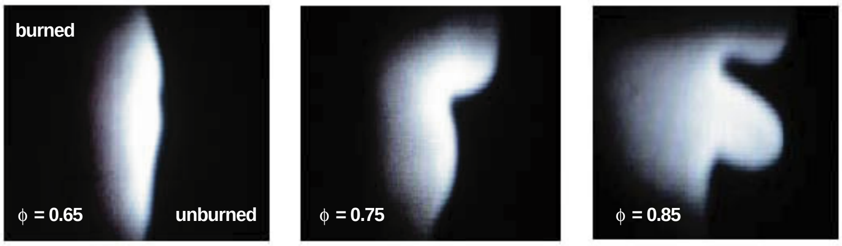

Figure 2 Typical 2-D OH Image by PLIF in ϕ=0.65, 0.75, and 0.85

The curvature of the flame front is calculated at 20.0mm above the burner. Curvature has sign and its positive/negative means that the flame is convex toward the unburned/burned zone. Fig.3 shows the PDFs of the curvature with the various equivalence ratios. As the equivalence ratio is increased (gets closer to the stoichiometric condition), PDFs’ shape becomes smooth and the peak shifts to the positive. This change decreases the number of negative curvature. These PDFs’ trend support the visually observed flame image in the previous section; the cusp is formed and sharpened as the equivalence ratio is increased.

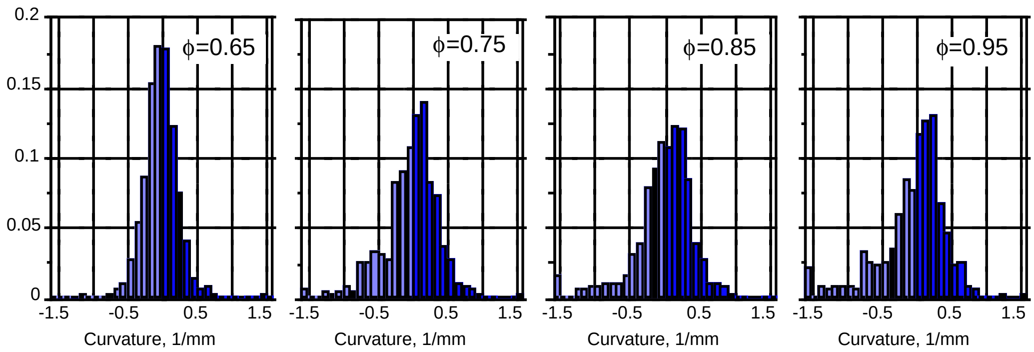

Figure 3 PDFs of Curvature in ϕ=0.65, 0.75, 0.85, and 0.95

Fig.4 shows the normalized OH peak intensity as a function of the curvature with various equivalence ratios. Note that the OH peak is searched along the normal to the flame front and OH peak value is normalized by its average. As seen in the figure an interesting trend can be found; in all equivalence ratios the normalized OH peak intensities and the curvature show linear relationship, however, its gradients are varied depending on the equivalence ratio. When ϕ<0.75, the gradients are slightly positive and approached to zero as the equivalence ratio is increased, then finally turn into negative when ϕ>0.85. The ‘slightly positive gradient’ shown in ϕ<0.75 condition is consistent with the results given by Lee et al., which used ϕ=0.71~0.75 methane-air mixture. On the other hand, the trend in ϕ>0.85 is consistent with the numerically simulated trend of ϕ=1.0, or seems more like Le>1 premixed flame. According to Echekki et al. [8], the stronger heat release is expected in negative curvature regime; therefore it is also expected to produce more OH there.

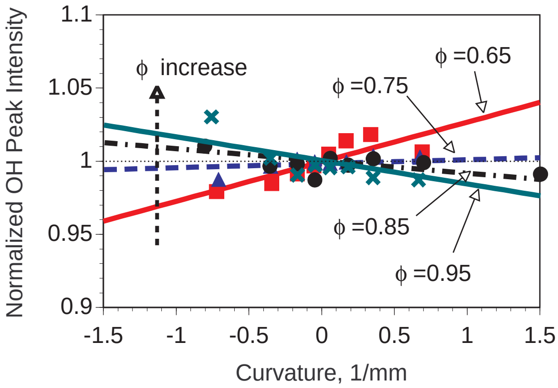

Figure 4 Normalized OH Peak Intensity vs. Curvature

Fig.5 shows the OH peak distance as a function of the curvature with the various equivalence ratios. Note that the peak distance is defined as the length from the flame front to the OH peak. The figure clearly shows that OH peak distance dependency on the curvature is weak when ϕ<0.75, however, it turns apparent as the equivalence ratio is increased. The dependency is consistent with the all equivalence ratio; the positive curvature gives longer peak distance, while the zero curvature gives the minimum. It is implied that the existence of the interaction between turbulence and local flame structure. Regarding as the results derived by numerical simulation with detailed chemistry model, the radical behaviors could modify the flame structure although the mixture's Lewis number is close to unity (i.e. lean methane-air mixture) [8,9]. Present experimental statistic data may support the prediction. Further analyses and discussions are required to explain completely what observed in this study.

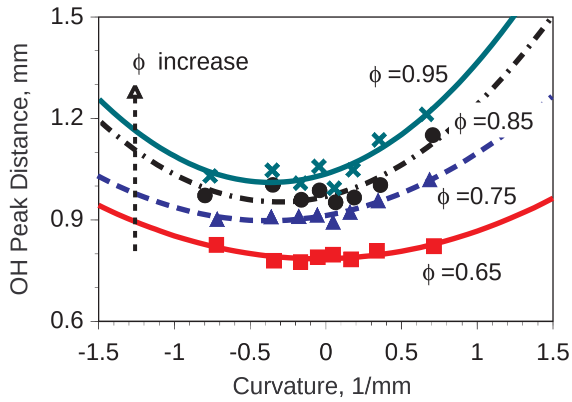

Figure 5 OH Peak Distance vs. Curvature

Concluding Remarks

The relation/interaction between the turbulence and the local flame structure with lean methane-air premixed flames (equivalence ratio; ϕ =0.65~0.95, Lewis number; Le~0.94) has been studied by using OH image given by PLIF system. Curvature of the flame front and the corresponding OH structure are extracted to discuss about the relationship. Overall, it is understood that the local flame structure (e.g. OH peak/distributions) may vary depending on the local turbulence structure. Moreover, the dependency would be the function of the equivalence ratio, which decides the combustion strength. The results provided here also imply that Lewis number cannot completely describe the local flame structure.

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