Response of a lifted turbulent premixed flame to cyclic swirl oscillations

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1 Introduction

Turbulent lifted flames sustained by the low-swirl burner (LSB), which was developed by the group of Cheng^[1,2], have been widely investigated in terms of fundamental aspects of turbulent premixed flames. Plessing et al.^[3] measured the turbulent burning velocity and validated the expression for the velocity with the measured data. Shepherd and Cheng^[4] examined two widely used experimental methods to measure the turbulent burning velocity and showed the two methods gave different velocities. Shepherd et al.^[5] investigated flame structure in intense turbulence and reported the effect of turbulence levels on the structure. Kortschik et al.^[6] confirmed the hypothesis of turbulent transport ahead of the preheat zone for the flame in thin reaction zones regime. In these studies, swirl numbers were fixed at some appropriate values so that the flame contours be perpendicular to the incoming flow of mixture in the central region of the burner. On the other hand, how the flame behaves when changing the swirl number is considered to be another important aspect since it is related to the stability of the flame. For example, the occurrence of low-frequency flame bouncing was briefly reported in the early works^[1,2]. By comparing energy spectra for swirling and non-swirling cases, it was indicated that the bouncing is caused by the interaction between swirl jets and the main flow. Tachibana and Zimmer^[7] investigated the effect of swirl on the flame stability by a parametric study and reported that the flame brush thickness showed a linear growth against the flame lift-off height. In this paper, dynamic response of the LSB flame to cyclic swirl oscillations is investigated. Dynamic response of turbulent premixed flames has a crucial role in the study of combustion instabilities and those controls^[8,9,10]. Bellows et al.^[9] investigated the response of swirl flames to harmonic excitation. Balachandran et al.^[10] reported the response of bluff body flames to imposed inlet velocity oscillations. In this study, the inlet velocity oscillations are generated by oscillating swirl flow. Phase-locked OH-PLIF measurements are conducted and flame surface area analysis^[8,10] is applied to see the dynamic behavior of the flame structure.

2 Experimental Arrangements

Fig.1 shows the schematic of the experimental configuration. A jet-type low-swirl burner (LSB) is used to sustain a lifted turbulent premixed flame. Methane and main air are mixed through a static mixer of 520mm long before entering the burner. The burner is composed of a punching plate of 64% blockage ratio as a turbulence generator, a swirl generator which produces four tangential air jets and a pipe nozzle. The four tangential air jets produce a divergent flow. A lifted flame is sustained at a position of balance between the decaying velocity of reactant and the flame propagating velocity. Detailed configuration of the burner used in this study can be found in the ref.[7].



Fig.1 Configuration of the experimental setup.



Fig.2 Phase-averaged axial velocity measured at the location 5mm after the nozzle on the center line. E.R. = 0.80, Vp-p = 10 V, Frequency = 50Hz.

To produce a perturbation to the inlet flow velocity, the swirl air flow is modulated by a high-speed DDV valve of MOOG. The valve is controlled by a voltage signal from a signal generator. The command signal is a sinusoidal function with a peak-to-peak amplitude of 10V and a frequency of 50Hz. The volume flow rate of the main mixture is 662 *l*/min, which gives a nozzle area velocity of 5m/s. Mean swirl number, which can be calculated from the secondary air flow rate before the plenum chamber is 1.23. Equivalence ratio of the main mixture is 0.80. Fig.2 shows phase-averaged axial velocity measured by a LDV system for the condition described above at the location 5mm after the nozzle on the center line. Both the overall mean velocity and the peak-to-peak variation have a similar magnitude of 2.8 m/s.

Measurement system is also shown in Fig.1. A photo-multiplier system and an ICCD imaging system are used, respectively, for temporally and spatially resolved measurement of OH* chemiluminescence. An OH-PLIF measurement system is used as well to capture the 2-D cut of the flame structure. In this paper, results from the phase-locked OH-PLIF measurement are mainly discussed. For phase-locking measurement, the sinusoidal signal from the signal generator is used as reference signal. Zero-degree phase is defined on the reference signal as the zero-crossing point with positive gradient. For the OH-PLIF, a dye laser (Spectron Laser Systems, Model 4000G (Rhodamine 590)) together with an Nd:YAG laser (Spectron Laser Systems, Model SL 825G-400mJ) is used. The wavelength after a KDP doubling crystal is 283.636 nm with 10mJ pulse energy. This wavelength pumps the Q₁(8) transition of the $A^{2}\Sigma^{+} - X^{2}\Pi$ (1,0) band. An ICCD camera (PI-MAX:1K from Princeton Instruments) with UV-Nikkor 105mm lens is used for image capturing. A set of optical filters (Schott UG-5 and high-pass Schott WG-305) is used so that only fluorescent light around 310nm be measured. The resolution is set as 215*512 pixels with a binning option. Field of view is 28*66 mm², which gives a magnification 0.13 mm/pixel. The camera is operated in gate mode with an exposure of 10nsec, synchronized with the pulse of the dye laser. 1000 images are taken for each phase angle. Phase-locked OH-PLIF measurement was carried out for 16 phase angles (from 0 to 315 degree with a step of 22.5 degree). The acquired PLIF images were postprocessed to see the statistical feature of the flame structure like mean progress variable and flame surface density.

3 Results and discussion

Typical distributions of the mean progress variable (PV) and mean flame surface density (FSD) are shown in Fig.3. The post-processing procedures for deriving PV and FSD are similar to those in refs. [10] and [11]. Window size for the FSD analysis is about 1.7*1.7mm². By assuming axisymmetric, only left half of the core region, -15mm < x < 0mm, is analyzed. Distribution of the PV is shown in the left hand side, and the distribution of the FSD is inverted around y-axis and is shown in the right hand side, 0mm < x < 15mm, for convenience. It can be seen that the flame structure varies strongly depending on the phase angles. Flame brush thickness at 180 degrees (Fig.3(c) left) is two times or more thicker than that of 0 degree angle (Fig.3(a) left). While flame fronts densely gather along the <c>=0.50 contour at 0 degree (Fig.3(a) right), those are distributed over a wider range at 180 degrees (Fig.3(c) right). The flame brush thicknesses of 90 and 270 degrees seem to be similar, but the flame lift-off heights are different(Fig.3(b) and (d)).

Revolving the FSD around y-axis provides an estimate of 3D surface area. This calculation was performed for every phase as in ref.[10]. In Fig.4, the relative surface area variations, A'/<A>, are shown in two ways. In Fig.4(a), the variations are plotted against phase angle. For comparison, OH* chemiluminescense variations, OH*'/<OH*>, are shown in the same figure. Even though A'/<A> shifts several tens of degrees in phase from OH*'/<OH*>, amplitudes of those variations show good agreement. This indicates, as reported in the previous studies^[8-10], that flame surface area variations contributes to the global OH* variations, which can be considered as the global heat-release variations. The 0 and 180 degrees (Fig.3(a) and (c)) are corresponding to the minimum and near-maximum points, respectively. It should be noted that the analyzed region of the PLIF data is restricted in the core region (0mm <x < 15mm), while the field of view of the OH* chemiluminescense measurements covered overall flame region (-25mm < x < 25mm). This difference may be one reason for the discrepancy in the distributions versus phase. In Fig.4(b), A'/<A> is plotted against flame lift-off height, which is defined as the position of $\langle c \rangle_{1D} = 0.50$ in y-direction. The $\langle c \rangle_{1D}$ is the 1D distribution of the mean progress variable which is calculated by integrating the 2D distribution in horizontal direction. It is obvious that the surface area is strongly dependent on the direction of the flame movement. The surface area shows a minimum value when the flame goes upward and maximum when it goes downward. This point is completely different from the steady swirl cases^[7], which show a one-to-one relationship between the flame lift-off height and brush thickness.



Fig.3 Mean progress variable and mean flame surface density distributions for phase angles of (a) 0, (b) 90, (c) 180 and (d) 270 degrees. Left and right in each figure show the mean progress variable and the mean flame surface density, respectively. E.R. = 0.80, Vp-p = 10 V, Frequency = 50Hz.

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Fig.4 Flame surface variations plotted against (a) phase angle and (b) flame lift-off height. E.R. = 0.80, Vp-p = 10 V, Frequency = 50Hz. In figure (a), OH* chemiluminescense variations measured by a photomultiplier and an ICCD are shown for comparison.

4 Conclusions

Dynamic features of a lifted turbulent premixed flame sustained by a low-swirl burner under a cyclic modulation of swirl were investigated by a series of OH-PLIF measurements. From 2D distributions of the mean progress variable and flame surface density, it was found that the flame structure varied strongly depending on the phase angles. Flame brush thickness at 180 degrees was two times or more thicker than that of 0 degree angle. While flame fronts densely gathered along the $\langle c \rangle = 0.50$ contour at 0 degree, those were distributed over a wider range at 180 degrees. The flame brush thicknesses of 90 and 270 degrees seemed similar, but the flame lift-off heights were different.

Revolving the FSD around y-axis provided an estimate of 3D surface area. From the estimation of the flame surface area, it was indicated that the flame surface area variations contributed to the global OH* variations, which can be considered as the global heat-release variations. It was found also that the surface area is strongly dependent on the direction of the flame movement. The surface area showed a minimum value when the flame went upward and maximum when it went downward. This point was completely different from the steady swirl cases, and was considered to be due to dynamic nature of the flame.

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