Effect of Swirl on the Stability of a Lifted Flame Sustained by a Low-Swirl Burner

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1. Introduction

Lean premixed combustion is one of the most promising technologies to reduce NOx emission from gas-turbine combustors. However it is well known that lean premixed combustors tend to be unstable due to its susceptibility to flow perturbations. Hence many works have been carried out to investigate the flame stabilities and explore stabilizing method. The purpose of this work is to investigate the effect of swirl on global flame motions of a lifted premixed flame sustained by a low-swirl burner (LSB). The LSB was originally developed for fundamental research on turbulent premixed flames and has been investigated for basic aspects[1-7]. In recent years, it has also attracted attention for the possibility as practical applications because of the robust stability over wide range of operating conditions [8-11]. One important aspect of the LSB flame is its global flame motion in the lean operating range. In the early work of the jet-type LSB flames[1,2], the occurrence of low-frequency flame bouncing was briefly reported. 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. A recent study[12] reported also the bouncing motion of the order of 10 Hz from time-series data taken by time-resolved PIV measurements. However, detailed characteristics of the phenomenon, for instance, the effect of swirl intensity, equivalence ratio, nozzle length, etc., have not been investigated yet. Since the global flame bouncing can be considered to affect the flame stability, like lean blow-out, and swirl strength plays a key role on the flame motion, the effects of swirl on flame properties were investigated in this study.

2. Experimental Arrangements

2.1. LSB Configuration and Experimental Conditions

Fig.1 (a) and (b) show the configuration of the LSB. Fuel (CH4) and main air are completely mixed through a static mixer of 520mm long before entering the inlet of the nozzle. The burner is composed of three parts. Those are a punching plate, four tangential air jets and a pipe nozzle. The role of the punching plate is to generate turbulence. In the present case, a plate of 64% blockage ratio was used. The four tangential air jets produce a divergent flow of reactant from the exit of the burner. A lifted flame is sustained at the position of balance

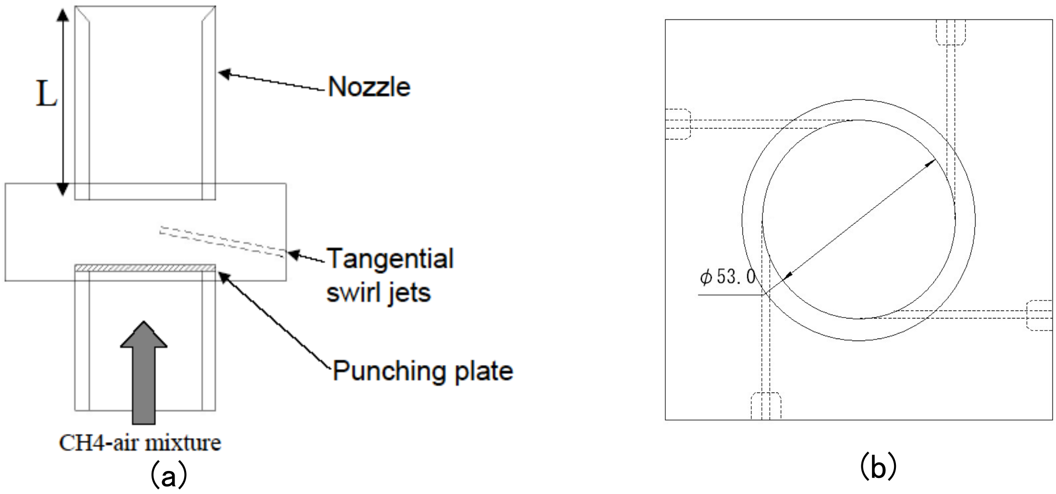


Fig.1 Configuration of the LSB. (a) Vertical view of the burner (b) Horizontal view of the part of tangential swirl jets

between the decaying velocity of reactant and the flame propagating velocity. Swirl number for the jet-type LSB is given by the following expression [13]:

$$S = \frac{\pi R^2 Q_j^2 \cos\alpha}{4\pi R_j^2 (Q_m + Q_j)^2} \quad . \qquad (1)$$

Here, α is the inclined angle of the air jets, R and Rj are the radii of the main nozzle and the air jets respectively. Q_m and Q_j are the total flow rate of the mixture and the swirl air jets respectively. Actual values in this work are as follows:

α=20deg, R=26.5mm, R_j =1mm and Q_m =662NLM.

Q_m =662NLM is corresponding to the bulk mean velocity of 5m/s. Q_j is a variable to change the swirl number.

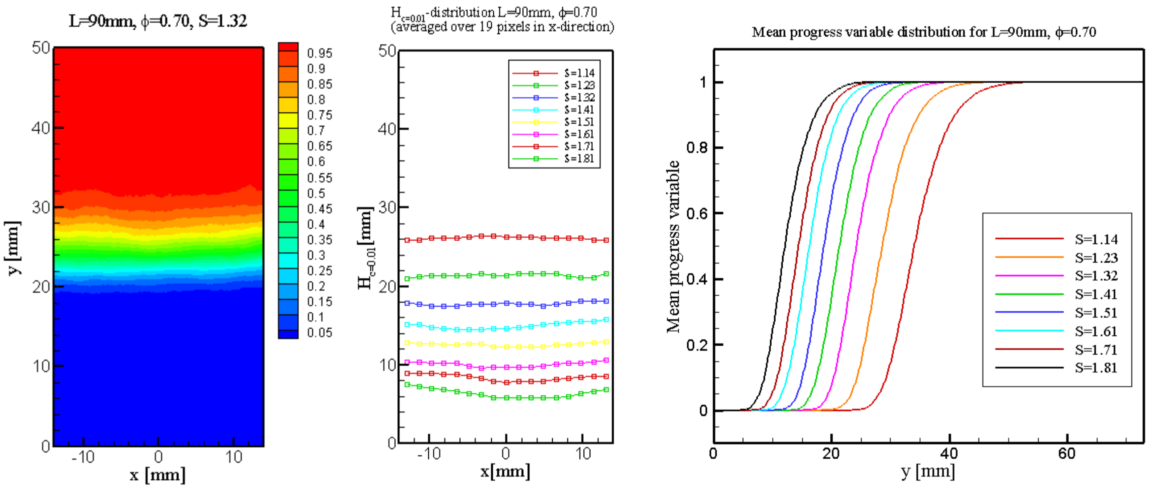
2.2. Measurement System Configuration

The PLIF system is composed of a Spectron Laser Systems model SL 825G-400 mJ together with a dye laser Spectron Laser Systems – 4000G (Rhodamine 590) which output wavelength was set to 283.6386 nm with an energy of 10mJ/pulse after the KDP to excite OH transition. An ICCD camera (PI-MAX:1K from Princeton Instruments) with UV-Nikkor 105mm lens is used for image capturing. A set of band pass filters is placed in front of the camera lens so that only fluorescent light is measured (combination of band pass Schott UG-5 and high-pass Schott WG-305 to remove Mie scattering from seeding particles). Its resolution is 512*512 pixels and typical measured area was 80*80 mm^2, which gives a magnification 0.16 mm/pixel. It is operated in gate mode with an exposure of 10nsec, synchronized with the pulse of the dye laser to minimize natural chemiluminescent emission. 1000 images were taken for each condition.

3. Results and Discussion

The OH-PLIF images were binarized into unburnt or burnt state by a thresholding method as described in ref.[7,12,14]. By taking average over 1000 binary images, the mean progress variable, <*c*>, was calculated. A typical 2-D distribution of <*c*> is shown in Fig.2(a). Horizontally parallel contours can be found. In previous works[7,12,14], similar distribution was observed in the core region. It was also reported that velocity vectors were perpendicular to the flame contours. Fig.2(b) shows the contour of <*c*>=0.01 for various swirl numbers. It indicates that the flat distribution of <*c*> sustains for various swirl numbers. 1-D distributions of <*c*> were calculated by averaging the 2-D distributions over the horizontal range of 30mm and shown in Fig.2(c). It can be seen clearly that the distributions show change in shape and shift in position due to modification of swirl.

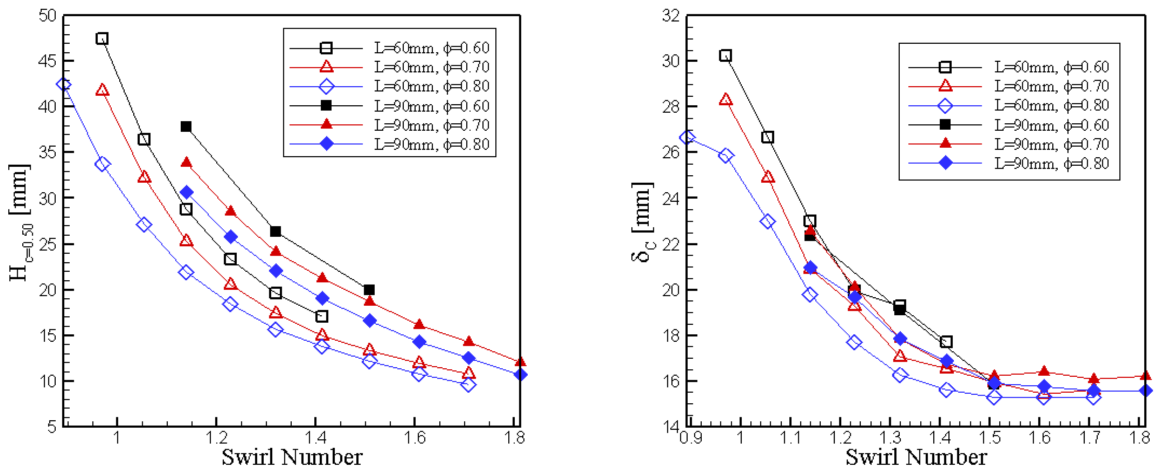
One can define a flame lift-off height by specifying a value to the 1-D <*c*>-distribution. In this case, the value of <*c*>=0.50 was chosen. This value is considered as the most probable position for the existence of flame fronts. The lift-off heights for various conditions are shown in Fig.3(a). It can be seen clearly that the higher the swirl number, the lower the height. This trend is explained by the rapid decay of axial velocity due to higher divergent rate when the swirl is increased. The decayed velocity brings the balancing position of flame holding close to the nozzle exit. One can notice also that the longer the nozzle, the higher the lifted height. Higher axial core velocity and lower turbulent intensity were observed for the longer nozzle in previous PIV results[15]. Both of the properties are contributing to the trend.



(a) (b) (c)

Fig.2 (a) 2-D distribution of progress variable <c> (L=90mm, ϕ=0.70, S=1.32)
(b) Contours of <c>=0.01 for various swirl numbers (L=90mm, ϕ=0.70)
(c) 1-D distribution of <c> (L=90mm, ϕ=0.70)

In the similar way, turbulent flame brush thickness, δ_c, was plotted against swirl number in Fig.3(b). The thickness is defined as the distance between <*c*>=0.01 and 0.99. The effect of global flame bouncing will appear as a thickening of the flame brush thickness. One can find the trend that the lower the swirl, the larger the thickness. The trend is similar to that of the lift-off height. However no clear dependency on equivalence ratio or nozzle length can be found. Fig.4 shows the flame brush thickness plotted against the flame lift-off height. In this figure, there can be seen a linear dependency on the lift-off height for each nozzle length beyond a level, around $H_{c=0.50}$=15mm for L=60mm and $H_{c=0.50}$=17mm for L=90mm. This indicates that the amplitude of global flame bouncing is getting larger as the lift-off height



(a) (b)

Fig.3 (a) Flame lift-off height vs swirl number (b) Flame brush thickness vs swirl number

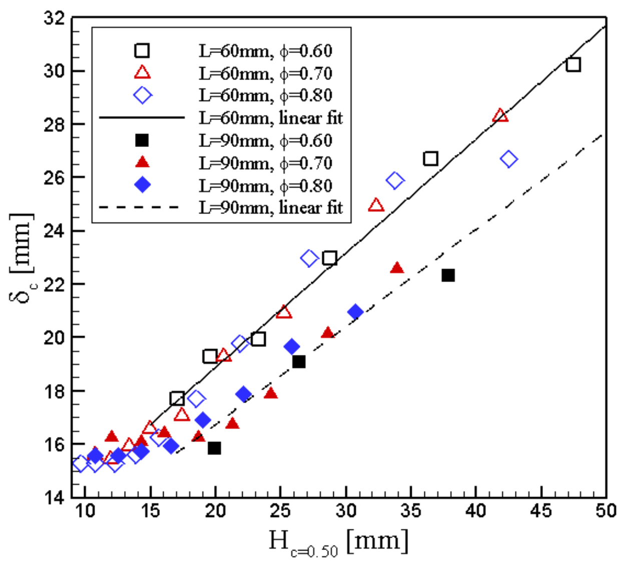


Fig.4 Flame brush thickness vs flame lift-off height

increase. The bouncing can be considered to be driven by purely fluid dynamical effect since there seem to be little dependence on equivalence ratio.

5. Conclusions

From a series of OH-PLIF measurements on a lifted premixed flame sustained by a jet-type LSB, the effects of swirl on several flame properties were investigated. From the analysis of flame brush thickness, a linear growth of the thickness against lift-off height was found. It indicates that the amplitude of global flame bouncing is getting larger as the lift-off height increase. The bouncing seems to be driven by purely fluid dynamical effect since the data shows little dependence on equivalence ratio.

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