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Mixing Enhancement of Coaxial Jet with Arrayed Flap Actuators for Active Control of Combustion Field

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A novel coaxial jet nozzle equipped with a row of miniature electromagnetic flap actuators was developed for active mixing and combustion control. The spatio-temporal flow structures of the coaxial jet were studied in terms of the scalar mixing through flow visualization and some quantitative measurements by using PLIF and LDV. Mixing between the inner and outer fluid was enhanced most effectively by the axisymmetric flap motion at $St = 0.9$, which is close to the preferred mode frequency. Preliminary attempt was also made for active combustion control. A lifted flame was stabilized by the axisymmetric flap motion at the optimum flapping frequency for mixing.

Keywords: Coaxial jet, Mixing Control, Combustion Control, Micro Actuators, PLIF

1. INTRODUCTION

Reducing the emission of toxic effluents such as NOx as well as unburned hydrocarbons from combustors is a challenging technological target. In general, lean premixed combustion mode is often adopted, and a swirler and/or a flame holder using a bluff body is employed to hold a flame. However, for small content combustors such as those in micro gas turbines, large load changes are expected, and the mixing should be deteriorated due to the low Reynolds number. Thus, it should be difficult to keep appropriate combustion condition by using these passive devices. Therefore, a more advanced flow and combustion management method is desired. Since the emission of NOx depends on local equivalent ratio and/or temperature distribution, active control of mass, momentum and heat transport in combustors should be one of the promising way for suppressing NOx as well as unburned hydrocarbons. Combustion control has been studied by many researchers (e.g., MacManus *et al.*, 1990; Chao *et al.*, 1996) but most studies employed homogenous control input into the bulk fluid using loud speaker.

Recent development of MEMS (Micro electro-mechanical Systems) technology enables us to fabricate actuators small enough to control primary flow structure directly (e.g., Ho & Tai, 1996; McMichael, 1996; Smith and Glezer, 1997). Suzuki *et al.* (1999) developed a novel axisymmetric nozzle, equipped with a row of miniature flap actuators on its nozzle lip, and realized flexible jet flow control. They found that the axisymmetric jet is effectively controlled by introducing control input directly into the initial shear layer, and the mixing is significantly enhanced in their bifurcating jet. Suzuki *et al.* (2000) extended the control scheme developed by Suzuki *et al.* (1999) to mixing enhancement of an isothermal water coaxial confined jet. They found that the mixing between the inner and annular jets are markedly enhanced through the vigorous pinching of the central fluid by large vortex rings generated by the flaps motion.

The final goals of the present study are to realize flexible mixing control in a coaxial jet with arrayed micro actuators and consequently to realize stable combustion with low toxic effluents at a low Reynolds number expected in micro gas turbine combustors. In the present report, an isothermal air coaxial jet was employed, and the effect of flap motion on the mixing process was investigated through flow visualization and quantitative measurements with the aid of planar laser-induced fluorescence (PLIF). Moreover, preliminary attempt was made for controlling combustion by using these actuators.

2. EXPERIMENTAL SETUP

A coaxial air jet discharging vertically into a test section is employed in the present study. The central jet flow was supplied from a long straight tube (diameter, D_i = 10 mm), in which a fully-developed laminar flow was established. The annular flow was discharged through a 42:1 area ratio nozzle with an exit diameter of D_o = 20 mm. Considering operation condition of lean premixed combustors, the bulk mean velocity of the central and annular parts of the nozzle is respectively set to be $U_{m,i}$ = 0.35 m/s and $U_{m,o}$ = 1.8 m/s with a velocity ratio of r_u=5. An array of miniature electromagnetic flap actuators developed by Suzuki *et al.* (1999) was mounted inside the outer lip of the annular nozzle (Fig. 1), since the vortex structure emerging from the outer shear layer dominates the flow field when the velocity ratio r_u is large (Rehab *et al.*, 1997). Each flap is driven independently by a control signal supplied by a PC, and their maximum displacement of the flap was set to be about 0.4 mm. The Reynolds number defined with D_o and $U_{m,o}$ equals 2.2◊10^3.

Concentration field of acetone was measured by using planar laser-induced fluorescence (PLIF) in order to access the effect of the present control scheme on the scalar mixing. The experimental setup is shown in Fig. 2. A frequency-doubled dye laser (Lamda Physik, SCANmate) coupled with a Nd:YAG laser was employed as a light source. Coumarin 153 dye was employed and the acetone vapor in the inner jet was excited with a 270 nm UV light pulses of about 4 mJ/pulse. Linear dependence between incident laser energy and fluorescence could be ensured, because the laser power was considered to be too weak to cause absorption saturation (Lozano *et al.*, 1992). The laser beam was formed into a laser sheet having about 0.3 mm in thickness through several cylindrical lens. An image-intensified CCD camera (LaVision, Flamestar2; 576◊384 pixels) was employed to capture the fluorescent images. The whole system was synchronized by a trigger signal generated by a PC. The repetition rate of the image acquisition was about 2.5 flames/sec. The field of view was 60◊40 mm^2, and the spatial resolution was 0.10 mm/pixel. Spatial inhomogeneity of the laser intensity was compensated by using a reference image obtained for uniform acetone vapor in a quartz container. The concentration is normalized by the fluorescence intensity at the potential cone end.

In addition to the PLIF measurement, velocity measurements were made by using a two-component fiber LDV (Dantec; 60X11) with a 4W Ar ion laser.

3. RESULT AND DISCUSSION

3.1. Flow visualization

Figure 3(a) shows a typical instantaneous image of a natural jet. A laminar shear layer separates from the outer nozzle lip and roles up into vortex rings and these vortices pinch off the inner jet at x/D_o ò 2.5. Figure 3(b) shows a typical instantaneous image of the jet controlled by axisymmetric flaps motion (Axisymmetric Mode, hereafter), in which all eighteen flaps are driven in phase by a square-wave signal of f_a = 27 Hz. The Strauhal number based on f_a, D_o, and $U_{m,o}$ is 0.3. It is clearly observed that one large scale vortex ring strengthened by the flaps motion is followed by two small scale vortex rings generated spontaneously by the shear layer instability, since the flapping frequency is almost one third of the preferred mode frequency. On the other hand, when St = 0.9, which is close to the preferred mode Strauhal number (St = 0.7-0.9) measured at x/D_o = 3.0, vortex rings are shed synchronized with the flapping motion. It is observed that a vortex ring produced periodically in the outer shear layer induces another vortex ring in the inner shear layer, and they evolve and grow downstream rapidly into much stronger vortex rings, pinching off the downstream end of the inner potential cone as shown in Fig. 3(c). Thus, the mixing between the inner and the outer fluid is enhanced dramatically by transporting the inner fluid away from the jet axis. When St = 1.7, since the flapping frequency is approximately twice the preferred mode, smaller and weaker vortex rings are generated by the flaps motion and they undergo pairing near the nozzle exit. The boundary of inner and outer fluid is smeared out by the action of these smaller vortices, but mixing is not enhanced as shown in Fig. 3(d). Therefore, the mixing between the inner and the outer fluid is enhanced most effectively at $St = 0.9$.

Suzuki *et al.* (1999) employed almost the same actuators for controlling an axisymmetric free jet. They found that when each half cluster of flaps are driven out of phase (Alternate Mode, hereafter), the jet clearly bifurcates into two branches and the entrainment is significantly enhanced. Figure 3(e) shows a typical instantaneous image of the jet controlled by the Alternate Mode of $St = 0.9$. An asymmetic vortex, which is much larger than that of Axisymmetric Mode, is observed at the end of the inner potential cone.

3.2. Concentration distribution

In total, 1164 instantaneous images are employed to obtain ensemble-averaged statistics of the concentration field. Streamwise distribution of the fluorescence intensity is shown in Fig. 4. Cross-stream location in this figure was chosen in such a way that the inner potential cone takes the maximum value in its length. The length of the inner potential cone for the controlled jets becomes shortened dramatically for Axisymmetric Mode, the inner potential cone length becomes 0.6 - $0.8D_o$ for the Strauhal numbers examined. The potential cone length is relatively insensitive to the Strauhal number, but at $St = 0.9$, the mean concentration is rapidly decreased in the x direction. The jet controlled by Alternate Mode loses its concentration much more rapidly than by Axisymmetric Mode. Figure 5 shows the probability density function of the concentration at $x/D_o = 1.0$ for various Strauhal numbers for Axisymmetric Mode. At $St = 0.3$ and 1.7, the probability density remains to be relatively large in high concentration and there are two distinct peaks. Thus, the inner and the outer fluid is only partially mixed at these Strauhal numbers, although the mean concentration is significantly lower than that of the natural jet. On the other hand, at $St = 0.9$, the probability density is completely shifted toward the lower concentration and the contribution in the low concentration range becomes maximum among various Strauhal numbers examined. Therefore, the mixing is enhanced most effectively at $St = 0.9$, which is close to that of the preferred mode.

3.3. Preliminary control experiment of combustion field

Preliminary experiments for controlling a combustion field was carried out. The same coaxial nozzle equipped with the flap actuators was used, while methane is introduced into the inner jet. The bulk mean velocities of the central and annular parts of the nozzle are respectively set to be $U_{m,i} = 1.0$ m/s and $U_{m,o} = 1.8$ m/s ($r_u = 1.8$). The velocity ratio is set to be smaller than that of the isothermal mixing experiments in order to keep flame without flame holder. The Reynolds number defined with the D_o and $U_{m,o}$ equals 2.2◊10^3. Figure 6 shows instantaneous images of the lifted flame. Without the flaps motion, the flame is instable and the flame base oscillates violently. On the other hand, the lifted flame and the flame base becomes quite stable when Axisymmetric Mode at $St = 0.9$, which is the optimum Strauhal number for the mixing as shown above, is applied. In addition, it is observed that the controlled flame is held up to the velocity ratio of 4.2 ($U_{m,i} = 0.43$ m/s and $U_{m,o} = 1.8$ m/s) while it blows out without any flap motion.

4. CONCLUSIONS

Active control by using a row of miniature flap actuators is applied to mixing control of a coaxial air jet. Flow visualization and quantitative measurements with LDV and LIF were made in order to evaluate the effect of the flaps motion. The following conclusions can be derived:

1) The length of the inner potential cone is shortened to about $0.8D_o$ and $0.6D_o$ respectively for Axisymmetric and Alternate control modes.
2) The optimum flapping Strauhal number for the mixing of the inner and outer fluid is 0.9, which is close to the preferred mode frequency.
3) The lifted flame controlled by Axisymmetric Mode becomes stable at large velocity ratios.

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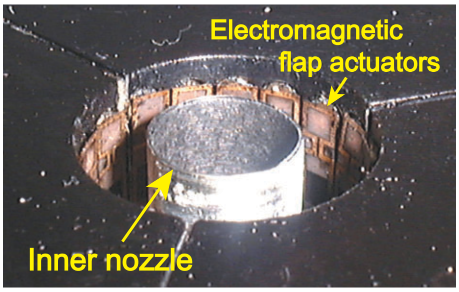

Figure 1. Coaxial nozzle equipped with eighteen electromagnetic flap actuators.

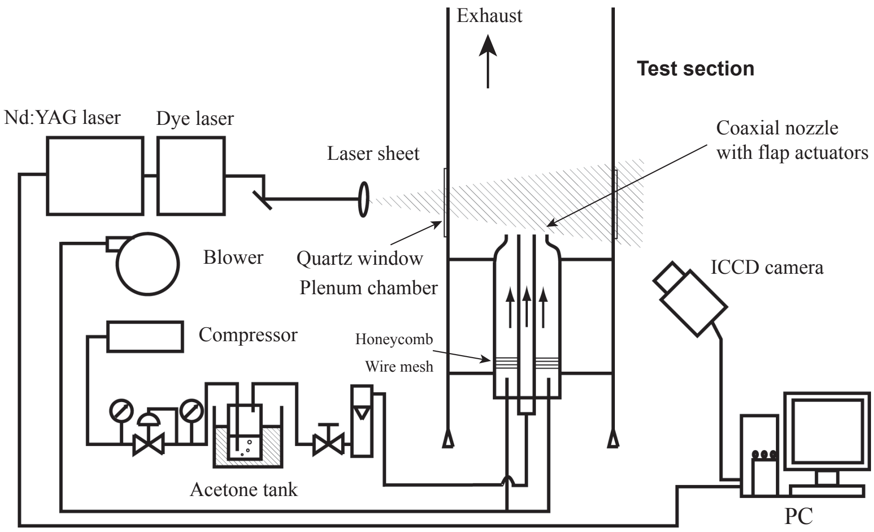

Figure 2. Schematic view of the experimental system.

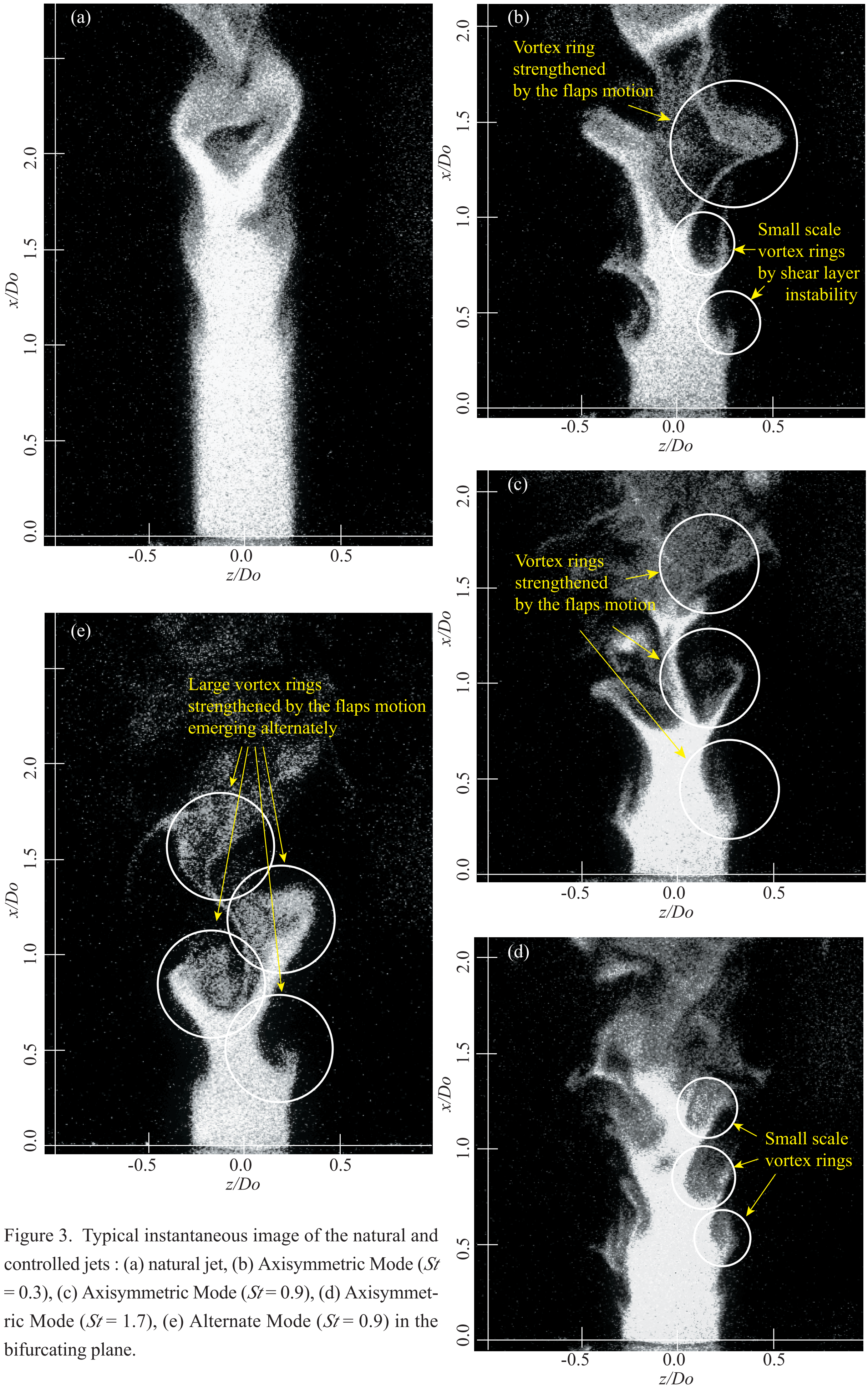

Figure 3. Typical instantaneous image of the natural and controlled jets : (a) natural jet, (b) Axisymmetric Mode (*St* = 0.3), (c) Axisymmetric Mode (*St* = 0.9), (d) Axisymmetric Mode (*St* = 1.7), (e) Alternate Mode (*St* = 0.9) in the bifurcating plane.

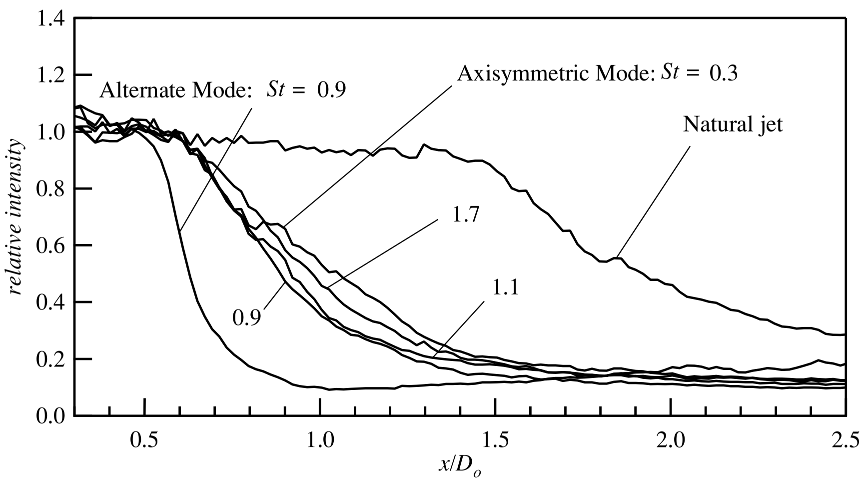

Figure 4. Axial mean concentration variations of the natural and controlled jets : Axisymmetric Mode (St = 0.3, 0.9, 1.1, 1.7 ; St =0.7, 1.2, 1.3, 1.5, 1.9 were measured,but these are not shown here.), Alternate Mode (St = 0.9).

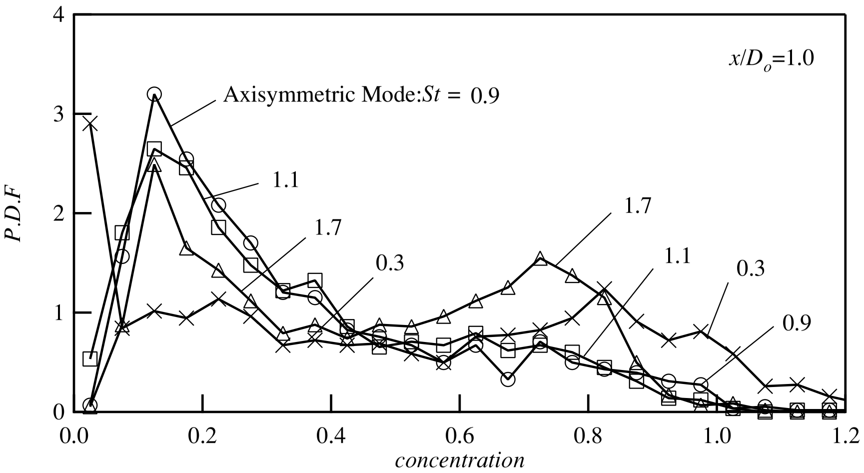

Figure 5. Probability density function of concentration of the jets controlled by Axisymmetric Mode measured at x/D_o = 1.0 for various Strauhal numbers.

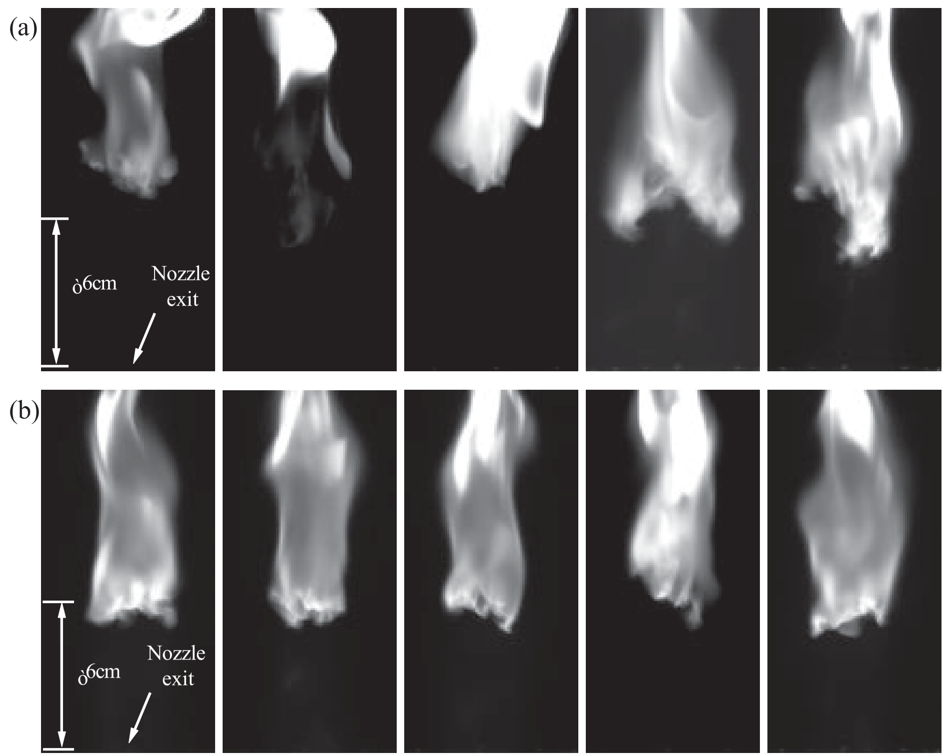

Figure 6. Instantaneous images of a lifted flame: (a) natural, (b) Axisymmetric Mode (St = 0.9).