Fluid-dynamical Characteristics of Bifurcating Jet inside Diffusion Flame under Transverse Acoustic Excitation

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1 Introduction

Acoustic forcing has potential to control combustion by inducing flame instability and/or changing flame shape. The acoustic waves interact with flames both directly and indirectly. The direct interaction between the waves and flames occurs in the flame zone, whereas the indirect interaction occurs in the flow field, regardless of the flame characteristics, by means of inducing velocity fluctuations, sinuous oscillations, or steady streaming.

The authors have explored the bifurcating behavior of flames under transverse acoustic forcing. We have visualized the fuel jet inside a flame by utilizing shadowgraphy [1], and have shown that the acoustic excitation of the flame is resulted from the indirect interaction, namely, the effect of the acoustic forcing on the fuel jet. The shadowgraphy indicates that the fuel jet ejected from the nozzle runs straight for a certain distance, and then bifurcates into a “Y” shape after meandering (, which can be seen later in Fig. 2).

In order to elucidate this interesting bifurcating behavior, we should reveal the reason why the single, straight jet branches into two streams. In the present study, velocity distribution in the flow field of the jet inside the acoustically-excited flame is experimentally examined by means of particle tracking method, and the mechanism of the bifurcating phenomenon is investigated.

2 Experimental

Experimental apparatus for producing the acoustically-excited flame is basically the same as the one in the previous work [1]. Figure 1 shows the schematic of the devices added in this work for conducting particle tracking velocimetry. The origin of the coordinates is placed at the center of the nozzle exit. Axes x, y, and z represent the horizontal direction normal to the propagating direction of the sound wave, the direction parallel to it, and the vertical direction, respectively. Methane gas together with tracer particles (Sumitomo 3M: Glass Bubbles, 65 μm in mean diameter) is ejected vertically from the nozzle, which is of a pipe having 3 mm in inner diameter. The length of the pipe is 100 times longer than its inner diameter so that the fully-developed Hagen–Poiseuille flow is obtained at the exit.

A laser beam is utilized as the source of sheet light for illuminating the tracer particles in the two-dimensional slice of the flow. The image of scattered light from the particles is amplified by an image intensifier and recorded by a high-speed video camera (frame rate: 500 fps, spatial resolution: 320×280). The phase of sound is determined by the strobe signal from the camera together with the

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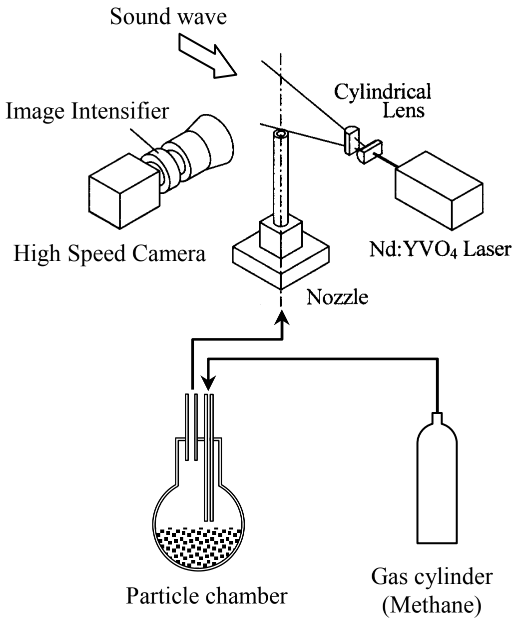

Fig.1 Experimental apparatus.

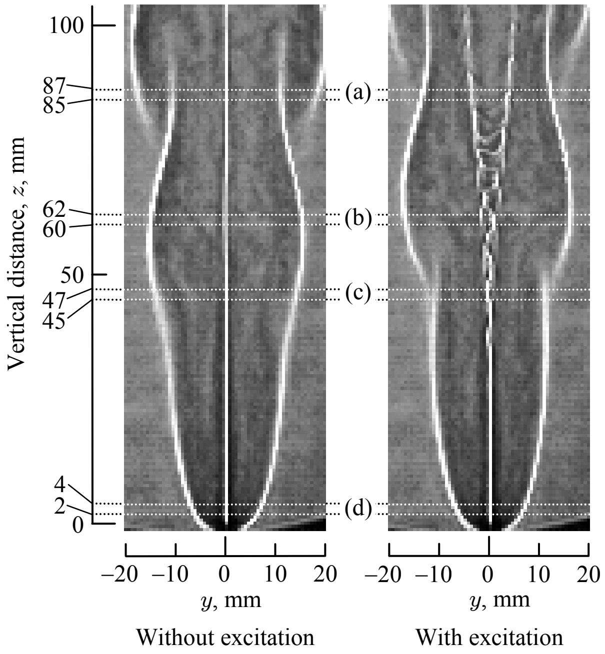

Fig.2 Position of velocity measurement.

input signal to the speaker unit. The velocity distribution is obtained by accumulating the data measured at the same phase of sound at every 90° phases. The measurement of velocity distribution under acoustic forcing was conducted under the condition of 10 m/s in mean jet velocity at the nozzle exit and 2000 Hz in sound frequency. The positions of the measurement are (d) just above the nozzle exit ($2 \text{ mm} \le z \le 4 \text{ mm}$), (c) the position around which the meandering starts ($45 \text{ mm} \le z \le 47 \text{ mm}$), (b) the position of transition from meandering to bifurcating ($60 \text{ mm} \le z \le 62 \text{ mm}$), and (a) the position of apparent bifurcation ($85 \text{ mm} \le z \le 87 \text{ mm}$)), which are shown in Fig. 2. It has been confirmed prior to the measurement that the influence of the addition of particles on the acoustically-excited flow is neglegible.

3 Results and Discussion

Effects of Acoustic forcing on Velocity Profile

The measured velocity profile inside the jet diffusion flame is shown in Fig. 3. The profile measured under unforced condition is shown in (1) in this figure, and that under forced condition at every 90° phases is shown in (2)-(5).

At $z = 3$ mm (d), the profile has a parabolic shape, which is corresponding to the theoretical Hagen-Poiseuille distribution, regardless of the presence of sound. At $z = 46$ mm (c), although the profile is deformed into a triangular shape, the effect of acoustic forcing is still indistinguishable. At $z = 61$ mm (b), on the contrary, the deformation due to acoustic forcing becomes clear: the profile of unforced condition (1) shows a triangular shape with single, sharp peak at the center, whereas those of forced condition (2)-(5) show broadened shapes with two, round peaks on both sides around the center. It should be noted that the shape noticeably varies with the phase of sound: the profiles are symmetry at $\theta = 0°$ (2) and 180°(4), whereas asymmetry at $\theta = 90°$ (3) and 270°(5). At the further downstream position ($z = 86$ mm, (a)), the broadening deformation due to acoustic forcing becomes larger while the variation between the phases becomes small again.

The results infer that the bifurcating behavior is originated from not the effect of steady streaming but that of linear instability. If the behavior is dominated by the mechanism of steady streaming, it is

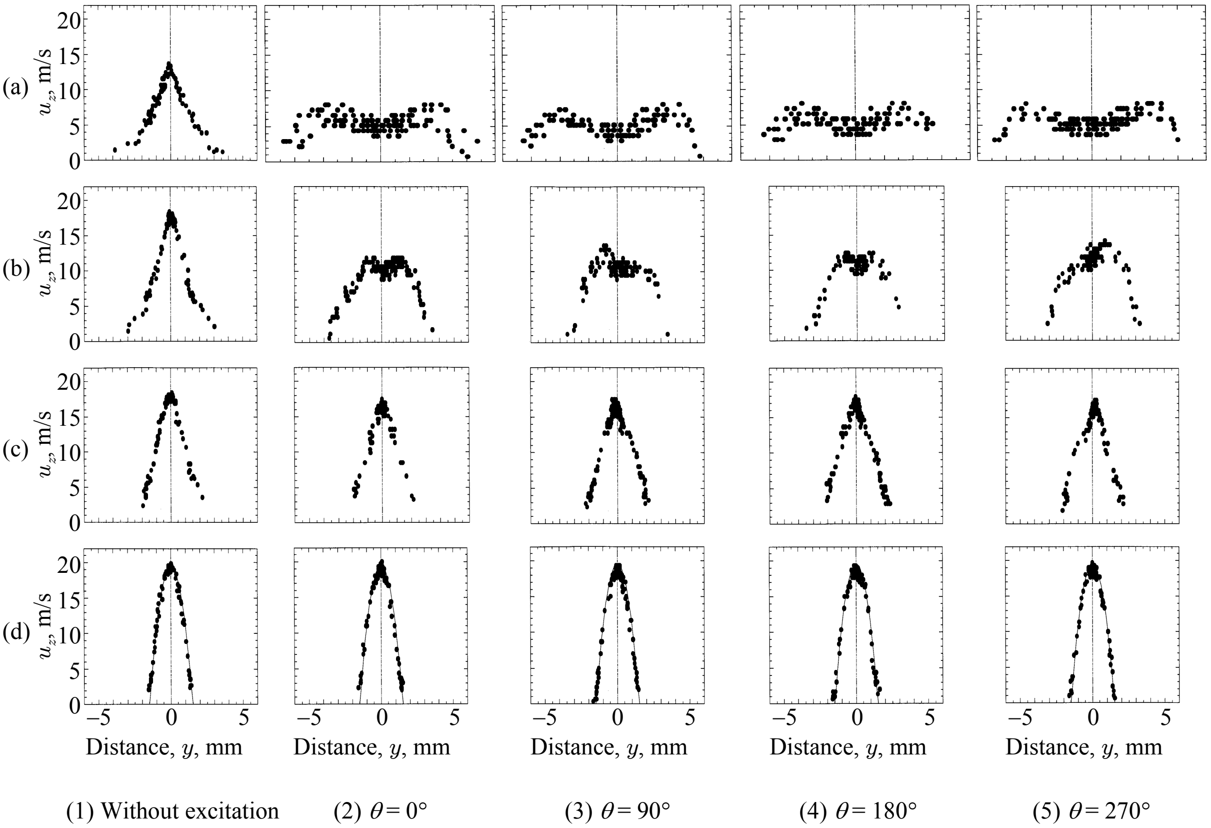

Fig.3 Measured velocity distribution of ascending fuel jet in diffusion flame.
(a) $z = 86$ mm, (b) $z = 61$ mm, (c) $z = 46$ mm, (d) $z = 3$ mm

plausible to assume that the flow should be deformed in the region in which the jet seems to run straight on the shadowgraph image. In other words, since the flow is not deformed in this section, the bifurcating behavior would be dominated by some kind of mechanism explained by the theory of linear instability.

Relation between Periodic Movement and Bifurcation

Regarding the position y_c of the jet axis as the peak position of the velocity profile, the results indicate that the jet axis swings at the same frequency as the sound at $z = 61$ mm, at which the jet is making transition from meandering to bifurcating. It would be plausible to assume that the position y_c oscillates sinusoidally as follows:

$$y_c(t) = y_r \cos(2\pi f t), \tag{1}$$

where t, f, and y_r are time, frequency, and amplitude, respectively. Considering the time average of the above motion, the probability density function $p(y)$ of the position of the jet axis is derived as follows:

$$p(y) = \begin{cases} (|y| \le y_r): & \dfrac{1}{\pi (y_r^2 - y^2)^{1/2}} \\ (|y| > y_r): & 0 \end{cases} . \tag{2}$$

This distribution is shown in Fig. 4, which clearly illustrates that the profile of the probability density has two sharp peaks at both edges of the swinging range.

Utilizing the above function, time averaged velocity $\bar{u}_z$ can be calculated from the instantaneous velocity as follows:

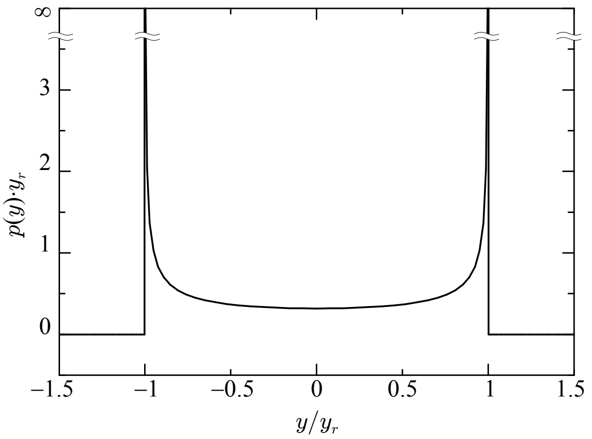

Fig.4 Distribution of probability density $p(y)$.

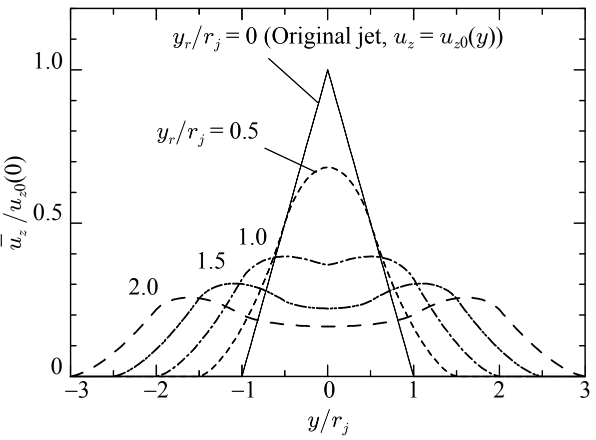

Fig.5 Profiles of time-averaged velocity $\bar{u}_z$ of triangular jet that is oscillating sinusoidally.

$$\bar{u}_z(y) = \int_{-\infty}^{\infty} p(y_c)\cdot u_z(y, y_c)\, dy_c, \tag{3}$$

where $u_z(y, y_c)$ is the instantaneous velocity profile of the jet whose axis is at y_c. Based on the experimental results, the velocity profile u_{z0} of the unforced jet is assumed to be of triangular shape as follows:

$$u_{z0}(y) = \begin{cases} (|y| \le r_j)\colon u_{z0}(0)\,(1 - |y|/r_j) \\ (|y| > r_j)\colon \quad 0 \end{cases}, \tag{4}$$

where r_j is the half-range of the triangle. By assuming that the jet retains its original, unforced shape during the oscillation, namely assuming $u_z(y, y_c) = u_{z0}(y - y_c)$, the time averaged velocity profile can be calculated from Eq. (3). The result of this is shown in Fig. 5. It is seen that the calculated profile resembles that of the experimental results at the position of apparent bifurcation (z = 86 mm), although there is difference between them that the calculation is a time average and the experiment is an instantaneous distribution. Considering the existence of the viscosity of the actual gas, the velocity profile downstream the flow would approximate closely to the time average of the oscillation.

4 Conclusion

The velocity field inside a jet diffusion flame under acoustic forcing is investigated by means of particle tracking velocimetry, and following results are obtained:

1. The velocity profile is not altered by the acoustic forcing in the region in which shadowgraphy shows the jet going straight before meandering.
2. The velocity profile oscillates synchronically with the acoustic forcing in the region in which the shadowgraphy shows the jet meandering.
3. A qualitative explanation of the bifurcation of the jet is successfully obtained by considering the probability density distribution of the oscillating fuel jet based on the interpretation of the experimental results.

Reference

[1] Suzuki, M., Atarashi, T., and Masuda, W. (2007) Behavior and Structure of Internal Fuel-Jet in Diffusion Flame under Transverse Acoustic Excitation, *Combust. Sci. Tech.*, 179, 2581.