Study of Active Jet Control by Acoustically Driven Secondary Film Flow Influence of Velocity Ratio and Acoustic Strouhal Number

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Active control of the diffusion of a circular jet was attempted by application of a secondary film flow around the jet. Sinusoidal acoustic excitation of the film flow was carried out for VR values of 0.5 and 1.0, where VR is the ratio of the film flow velocity to the main jet velocity. For VR = 0.5, the diffusion of the jet was suppressed compared to that of a single jet but it was somewhat enhanced by the acoustic excitation. The acoustic excitation shortened the potential core of the jet; however, the entrainment of the ambient flow was far less than in the case of a single jet, regardless of degree of excitation. For VR = 1.0, diffusion was enhanced by acoustic excitation. Both turbulence intensity and ambient flow entrainment increased downstream of the jet. We conclude that film flow can control diffusion and that acoustic excitation can enhance the diffusion of jet flows. It is worth investigating this mechanism in detail in future studies.

Key Words: Jet, Flow Control, Acoustic Control, Secondary Film Flow, Mixing

1. Introduction

Jet flows have been investigated in detail for some time. Control of jet flows is an important area of research because of their broad industrial applications, such as burner flame stability, air curtains, enhancing mixing, and in heating, cooling or drying devices. A variety of methods for controlling jets have been studied, including changing the nozzle shape, setting small projections, sound waves[1], and flap-type actuators[2]. Reynolds and Lee were able to create a bifurcating jet and a blooming jet by combining a precessing nozzle with disturbances in the axial direction of flow[3]. Kiwata et al.[4] have studied the effect of acoustic excitations, produced by two loudspeakers, on the inner and outer shear layers of a coaxial jet.

They varied the phase difference between the loudspeakers and analyzed the turbulence intensity and visualization of the mixing layer to evaluate the extent of mixing. They found the turbulence intensity of the mixing layer was strongest at a phase difference of 0° and weakest at a phase difference of 260°.

In the present study, active control of the diffusion of a circular jet is attempted by the application of a secondary film flow around the jet. The secondary film flow is a thin annular flow around the circumference of the circular jet[5]. There were two main control factors in the experiment performed here. The first was the velocity ratio, VR, the ratio of the film jet velocity to the main jet velocity, which was set at 0.5 and 1.0. The other factor was the acoustic excitation of the film flow, where the Strouhal number, St—based on the acoustic excitation frequency, main nozzle diameter, and main flow velocity—was set at 0, 0.3, 0.6, and 0.9. The mean velocity and turbulence intensity distributions were measured using Laser Doppler Velocimetry (LDV) and flow visualizations were carried out with laser light sheets. We then evaluated the extent of control by measuring the length of the main jet’s potential core, development of turbulence intensity along the jet axis, and the entrainment of the ambient fluid.
2. Experimental Apparatus

2.1 Nozzle

The nozzle used in this study (see Fig. 1) was an axisymmetric coaxial jet with main flow nozzle diameter, \( d = 8 \text{ mm} \), rim thickness = 0.5 mm, and slit gap, \( \alpha = 1.5 \text{ mm} \), for the film flow. The mainstream velocity, \( V_0 \), was adjusted for Reynolds number, \( Re = 3000 \) \((V_0 = 5.81 \text{ m/s})\), and the main flow nozzle diameter. The origin of the coordinate system was set at the center of the mainstream jet, with the axial direction defined as the \( x \) direction and the radial direction defined as the \( y \) direction.

2.2 Experimental methods and ejecting conditions

The experimental apparatus is shown in Fig. 2. Air was supplied by an air compressor, using two separate systems for the main flow and the secondary film flow. The mainstream volume flow rate was measured by an orifice-type flow meter and film flow was measured by a float-type flow meter. Both flows were seeded with oil mist in the particle generator for both LDV and flow visualization. The film flow was acoustically pulsed by a loudspeaker driven by the sine wave of a frequency equal to each Strouhal number. The acoustic pressure amplitude was adjusted by an audio amplifier to the root mean square of \( P_s = 5 \text{ Pa} \), as measured at the nozzle entrance. The Strouhal number—based on the frequency of excitation, \( f \), the main nozzle diameter, \( d \), and the main jet velocity, \( V_0 \)—was set at 0, 0.3, 0.6, and 0.9. The Strouhal number is defined as:

\[
St = \frac{f V_0}{d}
\]

3. Results and Discussion

3.1 Velocity distributions and visualizations of jets

Figure 3 shows the mean velocity and turbulence in-
tensity distributions for a single jet, as a reference with which to compare the effects of film flow and acoustic excitation. In Fig. 3, the $x$-axis was normalized by the nozzle diameter, the $y$-axis was normalized by the nozzle radius, $r$, and the mean velocity distribution was normalized by the mainstream velocity at the nozzle exit. The potential core was defined as that region where the local velocity, $V \geq 0.95V_0$. The length of the potential core in this case was about $X/d = 5$.

Figure 4 shows the results for film flow with $VR = 0.5$. When there was no acoustic excitation, that is, $St = 0$, the potential core length was $X/d = 10$—twice as long as for the single jet. As the Strouhal number increased, the potential core length decreased, with a minimum at $St = 0.6$, at which point it asymptotically increased to $X/d = 8$. For all Strouhal numbers considered, the potential core was shorter than in the case of film flow without acoustic excitation.

Figure 5 shows the turbulence intensity distributions under the same conditions as in Fig. 4. When the film flow was acoustically excited, the region of high turbulence intensity shifted upstream. This region of high turbulence intensity was closest to the nozzle at $St = 0.6$. The free shear layer between the main stream and the film flow was then acoustically excited, resulting in a transition to turbulent flow in the upstream region, consequently shortening the potential core.

Figure 6 shows the visualized images where the seed particles were mixed with the main stream only. In the case of $St = 0$, vortices were generated in the free shear layer between the main stream and the film flow at $X/d = 4 \sim 6$. With acoustic excitation of the film flow, the vortex-generating point shifted upstream in all cases. As the Strouhal number increased, the distance of the vortex-generating point in the free shear layer decreased. In the case of $St = 0.6$, the vortices were the largest and the gen-
erating and collapsing points shifted upstream. In the case of $St = 0.3$, the sizes of the vortices were the same but the vortex-generating point shifted downstream. In the case of $St = 0.9$, the vortex-generating point was the same but the vortex row did not mix downstream. It is therefore believed that $St = 0.3$ and $St = 0.9$ result in longer potential cores than $St = 0.6$.

Figure 7 shows the visualized images where the seed particles were mixed with the film flow only. In the case of $St = 0$, vortices were generated in the free shear layer between the main stream and the secondary film flow at $X/d = 4 \sim 6$. With acoustic excitation of the film flow, the vortex-generating point shifted upstream in all cases. There were some differences in vortex-generating points for different $St$ values. In the case of $St = 0.6$, the film flow reached the centerline of the jet and was mixed with the main flow at a point closer to the nozzle than for other values of $St$.

Figures 8 and 9 are the mean velocity distributions and turbulence intensity distributions, respectively, for $VR = 1.0$. Compared with the case where $VR = 0.5$, the potential core length was considerably shorter and the velocity distributions were wider in the radial direction. The region of high turbulence intensity shifted upstream and diffused widely. When the film flow was acoustically excited, the potential core length decreased and the region of high turbulence intensity shifted upstream, as compared with the case of $St = 0$. Comparing among cases with different Strouhal numbers, we found the potential core to be shortest for $St = 0.6$; however, the jet diffused most widely for $St = 0.3$.

Figure 10 shows the visualized image of the secondary film flow for $VR = 1.0$ only. It was understood that film layer turbulence would be higher than in the case of
$VR = 0.5$. Acoustically exciting the film flow affects it in the same way as when $VR = 0.5$. The point where the film flow reaches the centerline was most upstream at $St = 0.6$, but the highest turbulence in the film layer was reached at $St = 0.3$.

**3.2 Effect of secondary film flow with acoustic excitation**

Figure 11 shows the increase in turbulence intensity along the jet axis for different Strouhal numbers for the cases where $VR = 0.5$ and $VR = 1.0$. In the case of $VR = 0.5$, when there was no acoustic excitation to the film flow, turbulence intensity was reduced when compared with that for a single jet. With acoustic excitation to the film flow, turbulence intensity was stronger than that for a single jet, both at $X/d = 9$ and further downstream. In the case of $VR = 1.0$, when there was no acoustic excitation to the film flow, turbulence intensity was almost the same as for a single jet. With acoustic excitation of the film flow, turbulence intensity increased for $St = 0.3$. Figure 12 shows the axial flow direction change of the flux ratio $Q/Q_0$, where $Q$ is the volume flow rate in each cross section:

$$Q = \int_0^\infty 2\pi rVdr$$

(2)

$Q_0$ is the volume flow rate at the main and film flow nozzle exits. In the case of $VR = 0.5$, because the shear stress between the film flow and the ambient air was small, the increase in flux ratio was smaller than in the case of the single jet in all conditions. In the case of $VR = 1.0$, the flux ratio increased more than in the case of the single jet at $St = 0.3$. It can be said that mixing was enhanced in this case.

Figure 13 shows the normalized turbulence energy $E/E_0$ in cross section, where $E$ is defined as

$$E = \int_0^\infty 2\pi r\left(\frac{1}{2}u'v'^2\right)dr$$

(3)

and $E_0 = (AV_0^2 + A'v^2)/2$ is the kinematic energy at the main and film flow nozzle exits. In the case of $VR = 0.5$, entrainment of the perimeter fluid was suppressed for all Strouhal number values and, accordingly, turbulence energy was decreased in the initial region. Therefore, the axial turbulence intensity in Fig. 11 (a) and the flux ratio in Fig. 12 (a) were both reduced in the initial region. In the case of $VR = 1.0$, as the film flow was activated, shear stress appeared to entrain the perimeter fluid and, therefore, turbulence energy increased. Downstream, turbulence energy at $St = 0.3$ was higher than at $St = 0.6$.

With these results, we were able to demonstrate that a jet can be controlled by adjusting the outer film flow velocity ratio and by acoustic excitation to promote or suppress mixing.
Active control of the diffusion of a circular jet was attempted by application of a secondary film flow around the jet. The ratio of the film flow velocity to the main jet velocity, $\text{VR}$, was chosen to be 0.5 and 1.0, and sinusoidal acoustic excitation of the film flow was carried out.

(1) For $\text{VR} = 0.5$, diffusion of the jet was suppressed compared to that of a single jet, but was somewhat enhanced by the acoustic excitation.

(2) Acoustic excitation shortened the potential core of the jet; however, entrainment of the ambient flow was far less than for the single jet, regardless of the degree of excitation.

(3) For $\text{VR} = 1.0$, diffusion was enhanced by the acoustic excitation. Turbulence intensity and entrainment of the ambient flow increased in the downstream region of the jet.

(4) We conclude that film flow can either suppress or enhance diffusion and that acoustic excitation can effectively promote the diffusion of jet flows. It is worth investigating this mechanism in detail in future studies.

References