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Three-dimensional Vortical Structure and Mixing Mechanism of a Circular Jet

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***Abstract*:** The three-dimensional vortical structure and the mixing mechanism of a circular water jet were investigated by a flow visualization technique. The jet was excited by axial and azimuthal perturbations to stabilize and enhance axisymmetric and streamwise vortices. A laser fluorescent dye and a laser light sheet were used to visualize the jet. The three-dimensional views of vortical structure were constructed by applying the Taylor hypothesis to the jet cross-sectional images. The views reveal the details of the complicated vortical structure. From the three-dimensional views, the areas of jet-boundary surface were calculated to discuss the jet mixing mechanism. The areas of the unmixed region were also discussed to evaluate the mixing rate on the inside of the jet. The result suggests that the enhancement of axisymmetric and streamwise vortices is very effective to increase mixing.

***Keywords*:** jet, vortical structure, visualization, laser light sheet, mixing.

1. Introduction

Mixing is an important feature of jets in practical applications. Since the mixing is affected by the vortices evolving in jets, it is crucial to clarify the vortical structures related to the mixing mechanism. In circular jets, axisymmetric and streamwise vortices evolve, interact and break down. The vortex motions are three-dimensionally complicated and very difficult to detect experimentally. Although a few works have been reported on the vortical structure (Lasheras et al., 1991; Liepmann and Gharib, 1992; Samimy et al., 1993; Reeder and Samimy, 1996; Grinstein et al., 1996), they do not give us enough information to understand the three-dimensional structure related to the mixing mechanism.

In our previous work (Toyoda et al., 1999), we discussed the three-dimensional vortical structure of a circular jet excited by axial and azimuthal perturbations, considering the jet cross-sectional images obtained by flow visualization. In the present study, the details of the structure are made clear with the three-dimensional views constructed by applying the Taylor hypothesis to the jet cross-sectional images, and the mixing mechanism is discussed focusing on the areas of jet-boundary surface and of the unmixed region on the inside of the jet.

2. Experimental Apparatus and Procedures

The experimental apparatus is shown in Fig. 1. The water tunnel is an overflow type, and the water head is kept at a constant level during the experiments. A vibrator is installed upstream to stabilize and enhance vortex evolution in jets. A plastic plate connected to the vibrating rod shakes the water surface, and the longitudinal perturbation is transmitted to jets. The excitation turbulence intensity at the exit was about 2% of the mean velocity. Two nozzles were used as shown in the previous report (Toyoda et al., 1999): one is a circular nozzle with an inner diameter *De*

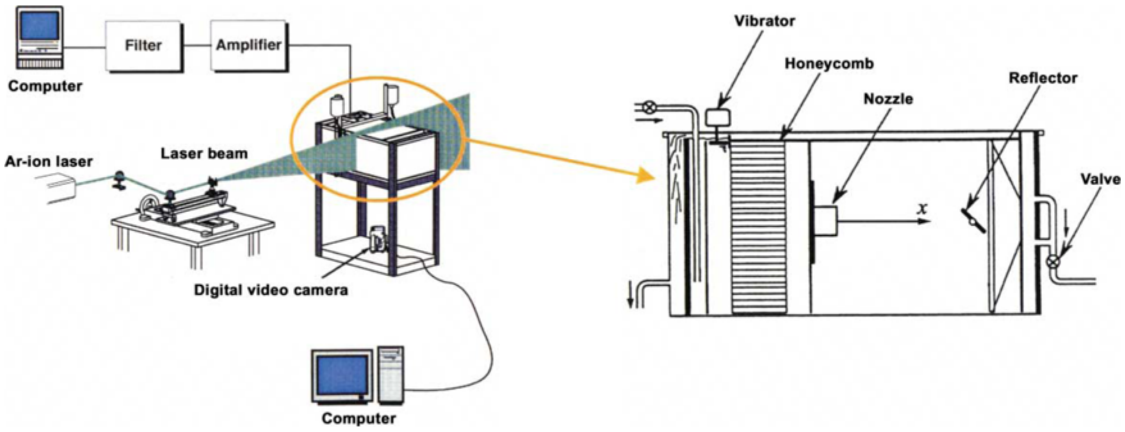

Fig. 1. Experimental apparatus.

of 46 mm and the other is that with six vortex generators (VG) along circumference at the exit to exert azimuthal perturbation on jets.

The jet exit velocity Ue is 0.12 m/s and the Reynolds number $UeDe/n$ is 3.2×10^3. To visualize the jet, the laser fluorescent dye (uranin) and a 2w Argon-ion laser were used. The test section of the water tunnel was dyed with uranin at a low concentration in advance of issuing clean water from the nozzle. The laser light sheet was flared to a thin sheet by a cylindrical lens to obtain the jet cross-sectional views. The cross-sectional views were recorded via a reflector by a digital video camera fixed under the tunnel. The thirty images were recorded per second. The views were recorded at streamwise stations of x/De = 0.5～3.0 (x: the streamwise distance from the jet exit). The image processing was carried out by a personal computer.

3. Results and Discussion

The three-dimensional view of an unexcited circular jet is shown in Fig. 2, which was constructed with the cross-sectional images obtained by scanning a laser light sheet in the streamwise direction (Toyoda et al., 1999). The view reveals the evolution of axisymmetric and streamwise vortices. The streamwise vortices are generated during the pairing process of initial axisymmetric vortices evolving at the natural frequency fn of the shear layer from the trailing edge of the nozzle.

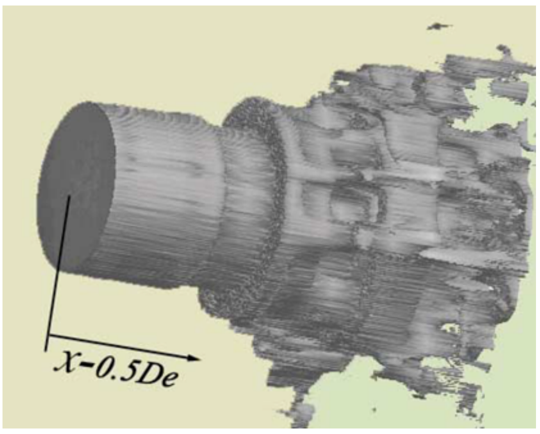

Fig. 2. Unexcited circular jet.

In order to make clear the details of the vortical structure in Fig. 2, the evolution of the vortices was controlled. To stabilize and enhance the pairing of the initial vortices, the jet was excited at a half of fn by the vibrator. The three-dimensional views of the excited jet are shown in Fig. 3, which is constructed by applying the Taylor hypothesis to the cross-sectional images at each streamwise station: the streamwise length Dx is estimated by $Dx = -U_c t$ (U_c: the convection velocity of the vortical structure; t: the time lag of an image from the reference time). The first one of the images corresponds $t = 0$, and the successive ones are regarded as the upstream views with increasing of t. In the figure, U_c is assumed to be equal to $Ue/2$ and t_0 is the time difference between the first image and the last one. The three-dimensional views show the local frozen structures at x/De = 0.5, 1.0 and 1.5. The streamwise length is stretched 1.4 times to make clear the structures. The figures reveal the stable evolution of axisymmetric vortex at the early stage and the generation of streamwise vortices farther downstream.

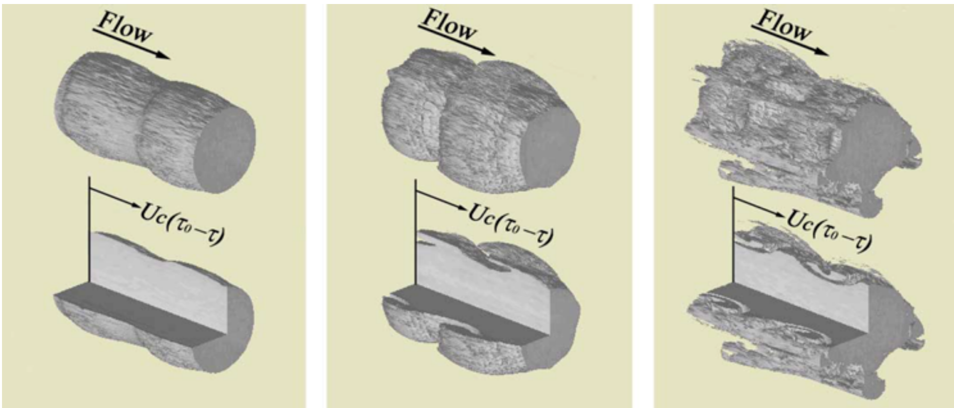

Fig. 3. Excited circular jet.

To enhance the streamwise vortices, the jet was perturbed by the vortex generators at the exit of the nozzle in addition to the axisymmetric excitation in Fig. 3. The three-dimensional views of the jet at x/De =1.0 is shown in Fig. 4. The figures show the jet-boundary surface and the sectional views in transverse and streamwise directions. The views reveal how the streamwise vortices are superposed on the axisymmetric vortex and how the ambient fluid is entrained inside the jet.

Fig. 4. Excited jet perturbed by the vortex generators (x/De = 1.0).

The mixing of jet and ambient fluid is occurred on the jet boundary. Thus the length of jet boundary is a measure that may be useful to discuss the mixing rate. The length was calculated by processing the jet cross-sectional image. The image was transformed to a black and white image by a certain threshold, and the number of the pixels (L) on the boundary was counted (Toyoda et al., 1999). Figure 5 shows the time histories of L/L_0 (L_0: the number at the jet exit) and the corresponding vortical structures at x/De = 0.75, 1.25 and 1.75 for the jets, with and without vortex generators, excited at a frequency of $fn/2$. The vortical structure at each streamwise station is constructed with 33 cross-sectional images, and the streamwise length of the vortical structure is shortened 0.67 times. The figures indicate how the boundary lengths vary corresponding to the vortical structures. The boundary lengths have peaks at the cross-sections of the axisymmetric vortices and valleys in the braid regions between the vortices, and increase with the development of axisymmetric and streamwise vortices.

The area of jet-boundary surface was calculated to discuss the jet mixing mechanism. The area at each streamwise station is defined as the area of the jet-boundary surface in Fig. 5. The calculated result for the jets under various conditions is shown in Fig. 6, where S_0 is the area corresponding to the jet-boundary length L =

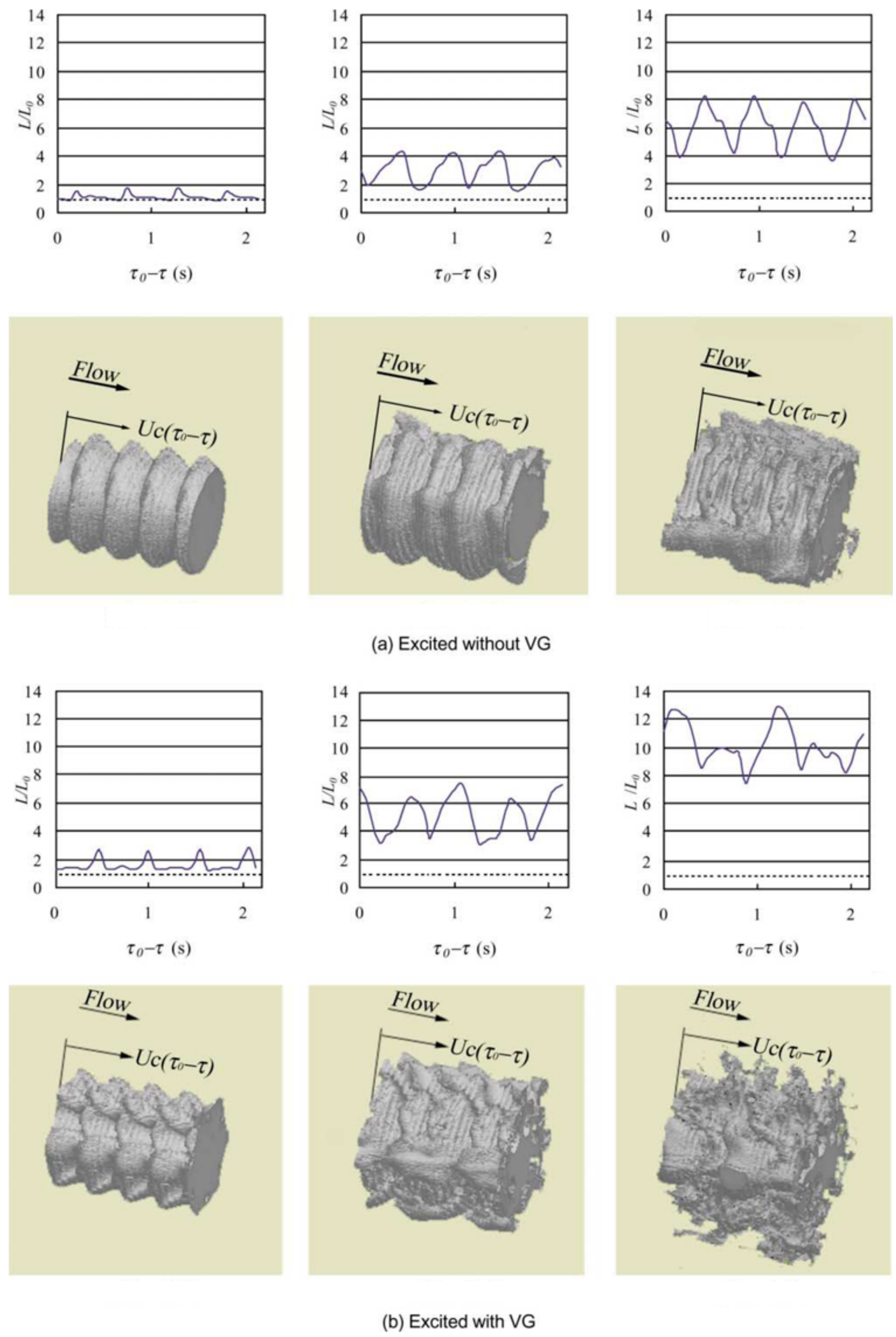

Fig. 5. Time histories of L/L_0 and vortical structures.

constant (L_0). The vortex generators increase the jet-boundary surface due to the generation of streamwise vortices, and the axial excitation increases the surface due to the evolution of large-scale axisymmetric vortices. Comparing the effect of the vortex generators and that of the axial excitation, the former is more effective than the latter in the upstream region, and vice versa in the downstream region. The area increases significantly for the excited jet with the vortex generators: simultaneous enhancement of axisymmetric and streamwise vortices is very effective to increase the jet boundary surface.

The jet mixing is developed by the vortex motions and by the molecular diffusion on the jet boundary. In the present experiments the mixing by the small-scale vortex motions and the molecular diffusion increases

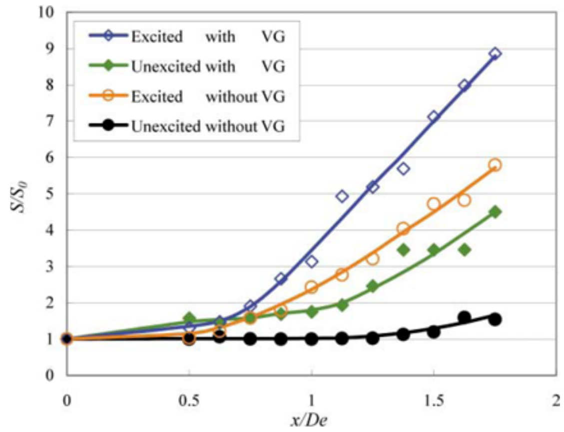

Fig. 6. Areas of jet-boundary surface.

downstream, and it is very hard to distinguish the jet boundary at $x/De > 1.75$. To estimate the small-scale mixing rate inside of the jet, we noted the area of the unmixed region of the cross-sectional image. The unmixed region is defined as the region that is not contaminated by the outer dyed fluid, and the time-averaged area A at each streamwise station was calculated to $x/De=3.0$.

The variations of A/A_0 (A_0: the area of jet exit) in the streamwise direction are shown in Fig. 7. In the figure, the decrease of the area corresponds to high mixing. The figure reveals that the excited jet with vortex generators is very effective to increase mixing, while the excited jet without vortex generators increases the unmixed region. It is noticed that the enhancement of only large-scale axisymmetric vortices increases both of the jet-boundary surface and the unmixed region.

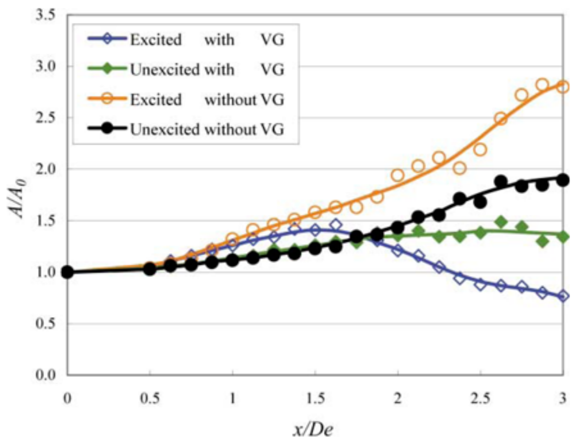

Fig. 7. Areas of unmixed region.

4. Conclusions

The details of three-dimensional vortical structure of a circular jet are clarified by applying the Taylor hypothesis to the visualized cross-sectional images. In particular the three-dimensional views of the complicated vortical structure of the excited jet with vortex generators reveal how the streamwise vortices are superposed on the axisymmetric vortex and how the ambient fluid is entrained inside the jet.

The mixing mechanism is also discussed in relation to the vortical structures, focusing on the areas of the jet-boundary surface and of the unmixed region inside jet. The result reveals that the simultaneous enhancement of axisymmetric and streamwise vortices is very effective to increase the jet-boundary surface and to decrease the unmixed region.

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