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Visualization of the Vortical Structure of a Circular Jet Excited by Axial and Azimuthal Perturbations

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***Abstract*:** The vortical structure of a circular water jet was investigated by a flow visualization technique. The jet was excited by axial and azimuthal perturbations to stabilize and enhance the large-scale axisymmetric and streamwise vortices. A laser fluorescent dye and a laser light sheet were used to visualize the vortical structure, and the whole view of the structure was captured by applying the Taylor hypothesis to the cross-sectional images and by scanning a laser light sheet in the streamwise direction. The visualized images reveal the details of the complicated structure of axisymmetric and streamwise vortices, and it is confirmed that the streamwise vortices have fundamental effect on the entrainment of ambient fluid. From the images, the length of jet boundary was calculated to estimate the mixing effect. The result suggests that the jet mixing is significantly increased by the break-down of the vortices enhanced by axial and azimuthal perturbations. We also discussed the jet diffusion effect in consideration of the jet widths obtained by velocity measurement. The result indicates that the vortical structure including streamwise vortices plays an important role to enhance diffusion.

***Keywords*:** jet, vortical structure, laser light sheet, image processing, three-dimensional structure, mixing, diffusion.

1. Introduction

The characteristics of jets such as entrainment, mixing and diffusion are closely related to the motions of vortices evolved in jets. In circular jets, large-scale axisymmetric and streamwise vortices play an important role to entrain ambient fluid. It is well known that axisymmetric vortices are enhanced by axial perturbation and that streamwise vortices are enhanced by azimuthal perturbation. Thus, the simultaneous evolution of large-scale axisymmetric and streamwise vortices enhanced by axial and azimuthal perturbations is expected to result into significant increase of entrainment, mixing and diffusion. To make sure the effect of the perturbations, it is crucial to clarify the details of the vortical structure enhanced by the perturbations.

The above-mentioned vortical structure is three-dimensionally complicated and very difficult to detect by any other method except a flow visualization technique. Various efforts have been made to understand the structure by flow visualization experiments. Lasheras et al. (1991) studied the effects of axial and azimuthal perturbations on the three-dimensional vortical structures of co-flowing jets, using a nozzle with a corrugated exit. Liepmann and Gharib (1992) showed the role of streamwise vortices in the near-field entrainment of circular jets. Samimy et al. (1993) and Reeder and Samimy (1996) obtained simultaneous cross-sectional and side views of the jet issued from a nozzle with tabs, and discussed the vortical structures focusing on the generating mechanism of streamwise vortices. Grinstein et al. (1996) investigated the near field of an azimuthally excited circular jet, and discussed the streamwise and spanwise vortex interaction.

Although the previous works give us useful information on the vortical structures, the visualization results are not sufficient to understand the mechanism of entrainment and mixing in relation to the evolution and the interaction of axisymmetric and streamwise vortices. The insufficient points are as follows.

(a) The jet boundary, which is crucial to mixing, is not visualized clearly.
(b) There are few clear images showing the interaction between axisymmetric and streamwise vortices, since the vortices are unstable in space and time.

The objectives of the present study are to obtain clear visualization images overcoming the above-mentioned insufficient points and to discuss the entrainment, mixing and diffusion mechanism.

2. Experimental Apparatus and Procedures

The water tunnel used in the experiments is shown in Fig. 1. A vibrator is installed upstream to stabilize and enhance vortex evolution in jets, and the vibrator is controlled by a personal computer. A reflector is fixed on the downstream side of the test section to obtain cross-sectional views of jets. The water tunnel is an overflow type, and the water head upstream is kept at a constant level during the experiments. The nozzles used in the experiments are shown in Fig. 2. Two nozzles were used: one is a circular nozzle with an inner diameter De = 46 mm and the other is that with six vortex generators along the circumference of the exit to exert azimuthal perturbation on jets. The water issued from the nozzle through the honeycomb at the settling chamber so that the jet was generated under low turbulence. The jet exit velocity was 0.12 m/s and the Reynolds number $Re = Ue \cdot De/\nu$ was 3.2×10^3. The jet was excited by the vibrator at a half of natural frequency of the shear layer near the jet exit to evolve large-scale axisymmetric vortices.

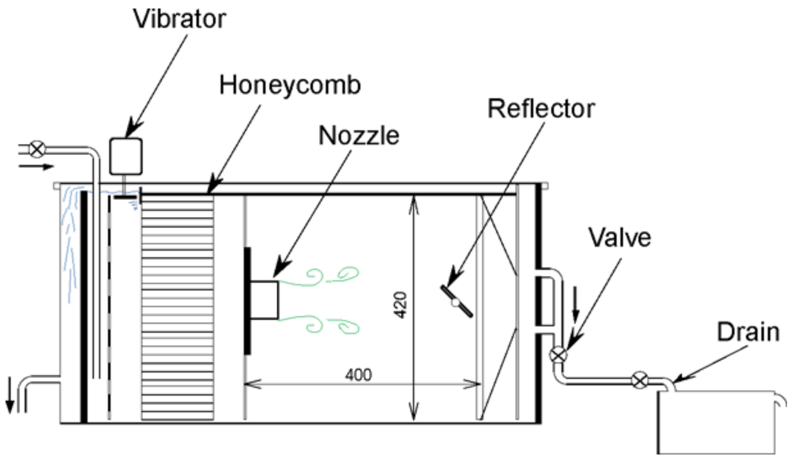

Fig. 1. Water tunnel.

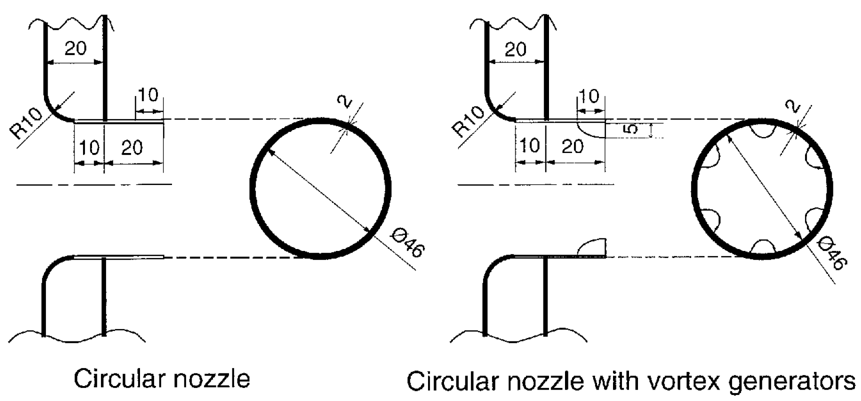

Fig. 2. Nozzles.

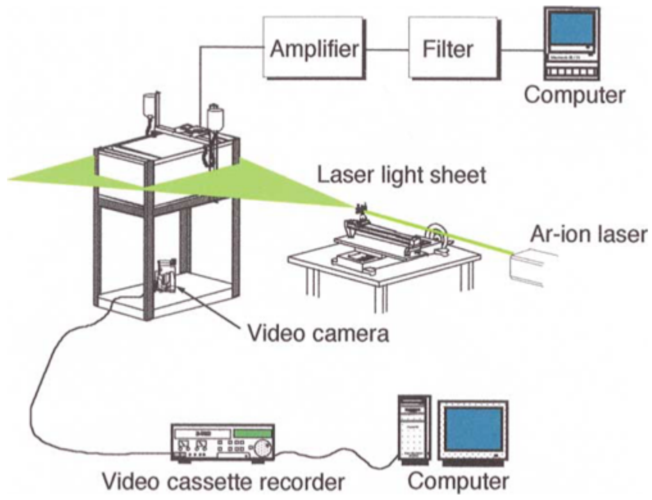

Fig. 3. Excitation and flow-visualization system.

The excitation and flow-visualization system is shown in Fig. 3. To visualize jets, a laser fluorescent dye (uranin) and a 2W Ar-ion laser were used. The test section of the water tank was dyed with uranin at a low concentration in advance of issuing water from the nozzle. A cylindrical lens flared a beam of laser light into a thin sheet to illuminate the plane of the interest of the flow field, and the jet boundary was visualized by the laser light sheet.

The side and cross-sectional views of jets were recorded by a video camera fixed under the water tunnel. The shutter speed of the camera was set at 1/100 second, and the framing rate is a 30 frames per second. Each frame consists of two image fields which result in 60 recorded images per second. The cross-sectional views were recorded at streamwise positions of x/De = 0.5〜2.0 (x: the distance from the jet exit). The visualization of jet cross sections by scanning the laser light sheet in the streamwise direction was also carried out to obtain the whole view of vortical structure. The scanning velocity of the laser light sheet was four times as high as the convection velocity of the axisymmetric vortices. The recorded images were analyzed with an image-processing computer system.

Mean velocities were measured by a hot-film probe over the flow field to determine jet diffusion. The traversing of the probe was controlled by a personal computer, and the velocity signals were recorded in a personal computer via an A/D-converter. The data were analyzed with a data-processing computer system.

3. Results and Discussions

The visualized views of the circular jet excited by axial perturbation are shown in Fig. 4. The side view is shown in Fig. 4(a), where the flow direction is from left to right. The vortex evolution is enhanced under the excitation, and the vortex sheet rolls up at $x/De \approx 0.5$, entraining ambient fluid. Every two vortices pair, merge at $x/De \approx 2.0$, and break down further downstream. The cross-sectional view at x/De = 1.5 (Fig. 4(b)) shows clear azimuthal

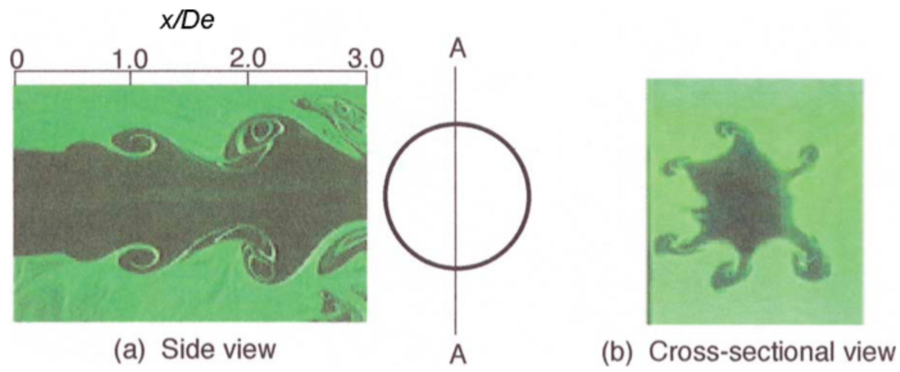

Fig. 4. Circular jet excited by axial perturbation.

instability. The image is captured in the braid region between two large-scale axisymmetric vortex rings. Note that the azimuthal lobe number M is six, suggesting that the most amplified azimuthal mode is $M = 6$ under the present experimental condition.

Considering the result shown in Fig. 4(b), six vortex generators were installed along the circumference of the nozzle exit to enhance stable streamwise vortices. Figure 5 shows the side view of the jet issued from the nozzle with six vortex generators. The view indicates that the large-scale vortical structure is evolved in the jet. Note that the vortex sheet rolls up faster downstream behind the vortex generator than behind the nozzle trailing edge without the vortex generator. The cross-sectional views of the excited jet are shown in Fig. 6, which reveals clear streamwise vortical structures inside and outside of the jet. In the section crossing the large-scale vortex ring, stable mushroom-type vortices are shown inside and outside of the jet. In the braid region, ambient fluid is entrained into the inside of the jet. Since the sequential images of the cross-section are recorded in the videotape, they are very useful to analyze the details of the vortical structure. By using 39 images and the Taylor hypothesis, the three-dimensional view of the vortical structure was made as shown in Fig. 7, where the convection velocity of the vortical structure is assumed to be constant. The view shows how the streamwise vortices are superposed on the axisymmetric vortices.

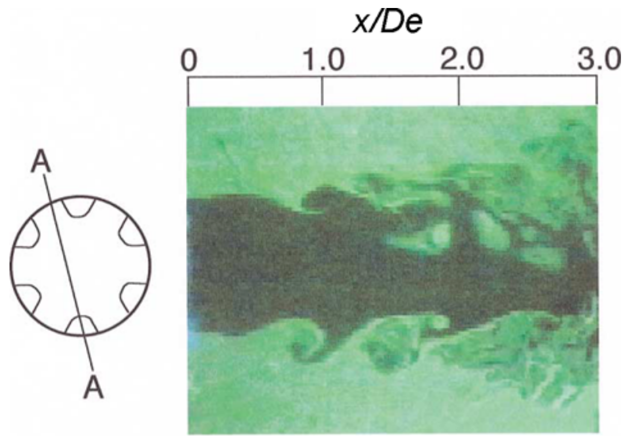

Fig. 5. Side view of the jet excited by axial and azimuthal perturbations.

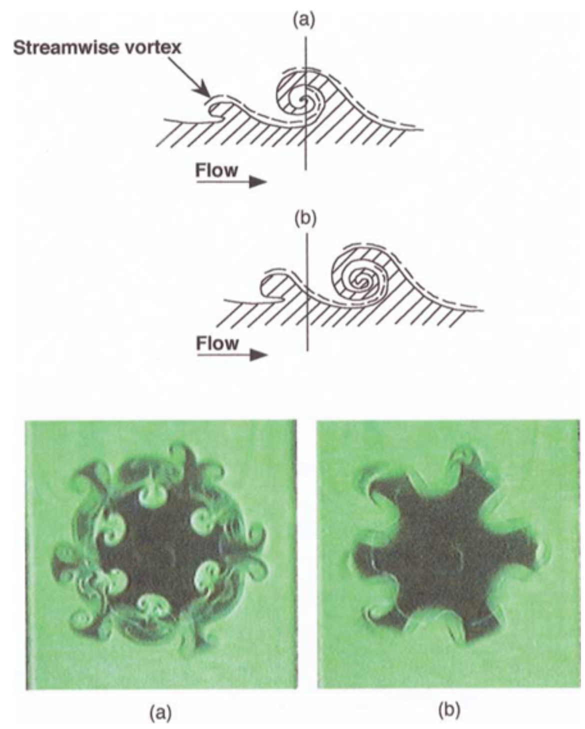

Fig. 6. Cross-sectional views of the jet excited by axial and azimuthal perturbations (x/De = 1.0).

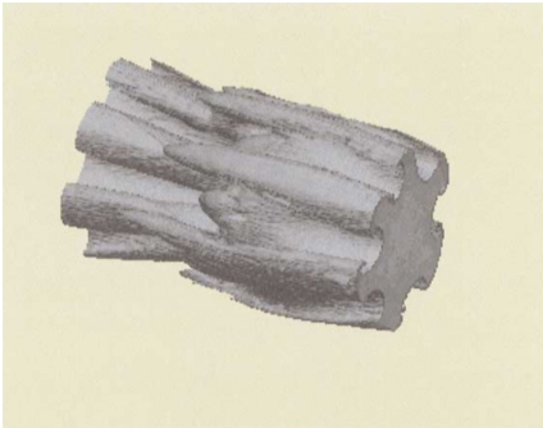

Fig. 7. Three-dimensional vortical structure.

The cross-sectional images obtained by scanning the laser light sheet in the streamwise direction are shown in Figs. 8 and 9, which show how the vortical structures deform in the streamwise direction. Figure 8 is the cross-sectional images of the jet excited by axial perturbation, which were obtained by scanning the jet shown in Fig. 4. The streamwise vortices form and develop in the braid region between axisymmetric vortex rings. Figure 9 shows the images of the jet excited by axial and azimuthal perturbations. The streamwise vortices are enhanced by vortex generators, and entrainment and diffusion are significantly increased. The images give us useful information on the details of the vortical structure. In particular the image at x/De = 1.25, of which the close-up is shown in Fig. 10, is very interesting. From the image we can understand how the jet boundary deforms by the axisymmetric and streamwise vortices.

Figures 9 and 10 lead to the three-dimensional vortical structure shown in Fig. 11. The azimuthal perturbation by the vortex generators enhances the three-dimensional instability and the streamwise vortices are developed. The streamwise vortices wrap around and interact with the axisymmetric vortex ring. Under the effect of induced velocity generated by the interaction, the vortex ring and the streamwise vortices are deformed as shown in Fig. 11. The streamwise vortex pairs around the vortex ring rush inward and outward by intense self-induced velocity. The vortex pairs are observed clearly in Fig. 10. The vortex pattern indicated by A in Fig. 10 suggests the cross-section of vortex loop connecting inner and outer parts of streamwise vortices.

The length of jet boundary is a measure that may be used to estimate the mixing effect. The length was calculated from the scanned images. The image was transformed to black and white image by certain threshold as

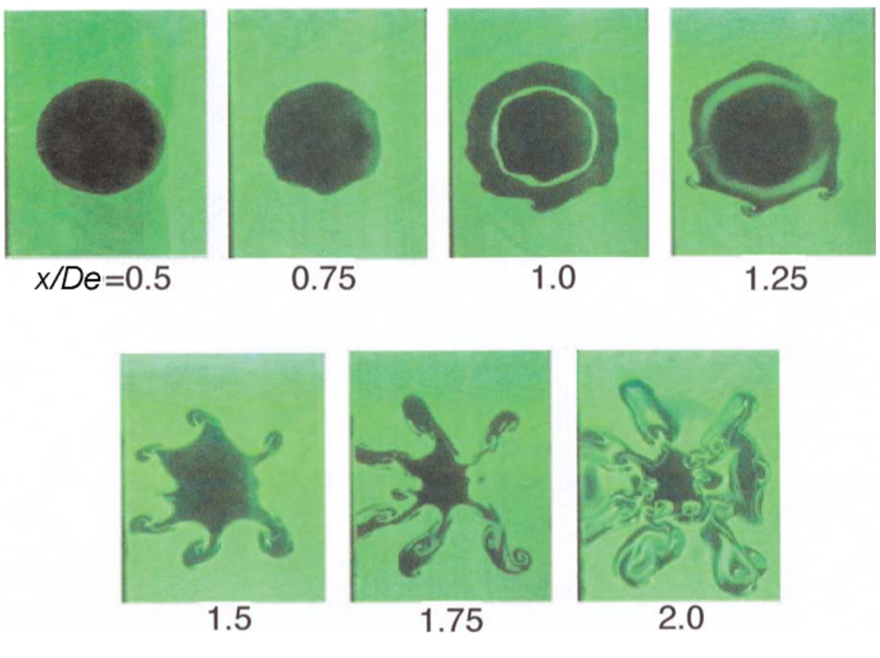

Fig. 8. Scanned images of the jet excited by axial perturbation.

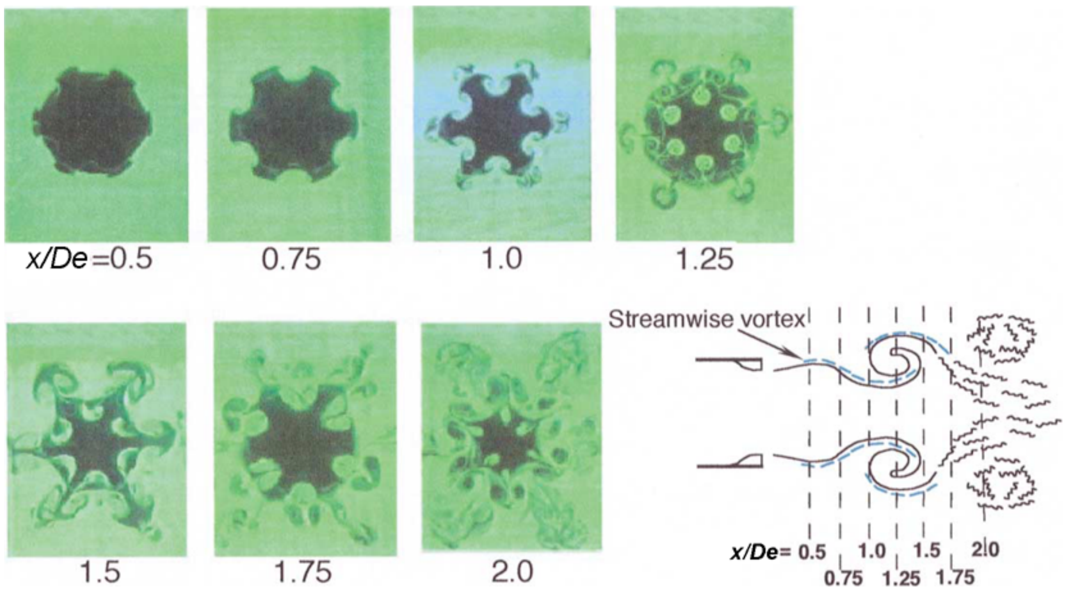

Fig. 9. Scanned images of the jet excited by axial and azimuthal perturbations.

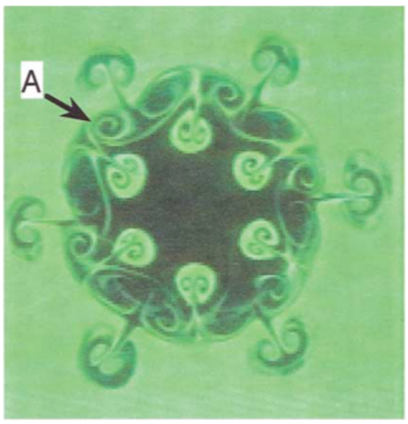

Fig. 10. Image at x/De=1.25.

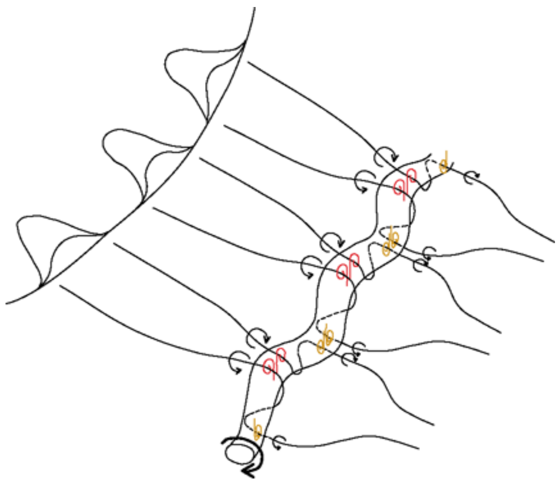

Fig. 11. Model of the three-dimensional vortical structure.

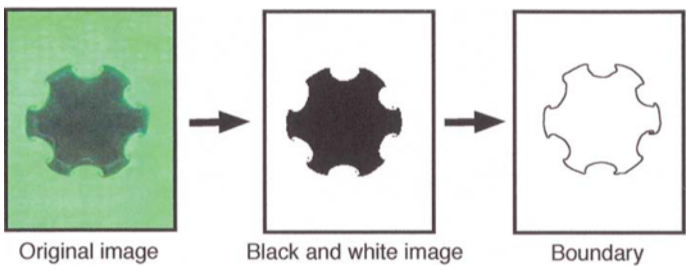

Fig. 12. Calculation of jet boundary length.

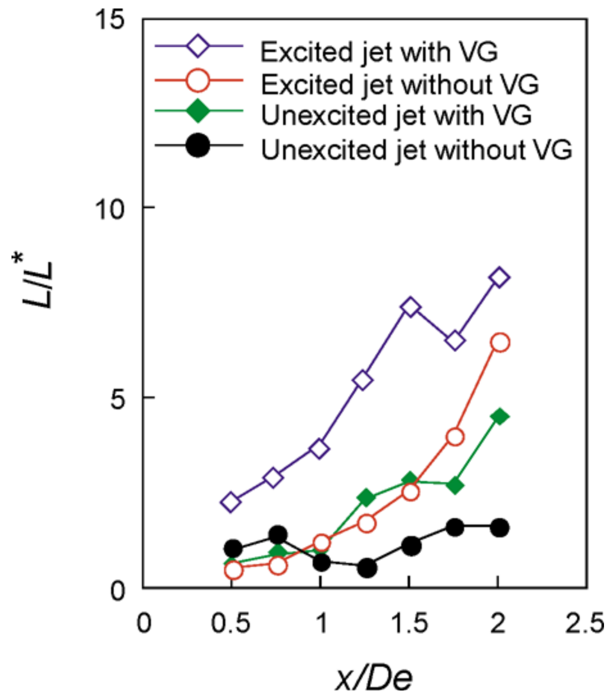

Fig. 13. Lengths of jet boundary.

shown in Fig. 12, and the number of the pixels (L) on the boundary was counted. The calculated lengths of jet boundary are shown in Fig. 13, where the value of L is non-dimensionalized by the length L^* of the unexcited circular jet at x/De = 0.5. L/L^* increases significantly for the excited jet perturbed by the vortex generators, showing that the streamwise vortices enhance mixing. In the case of circular jets without vortex generators, the boundary length of the excited circular jet is larger at x/De > 1.0 than those of the unexcited one, suggesting that the axial perturbation enhances the three-dimensional instability which leads to the generation of streamwise vortices. The length of jet boundary increases significantly at x/De = 2.0 due to the break-down of the vortical structure. The result indicates that the jet mixing is increased by the break-down of the vortices enhanced by axial and azimuthal perturbations.

Figure 14 shows the variations of jet width in the streamwise direction. The jet width B is non-

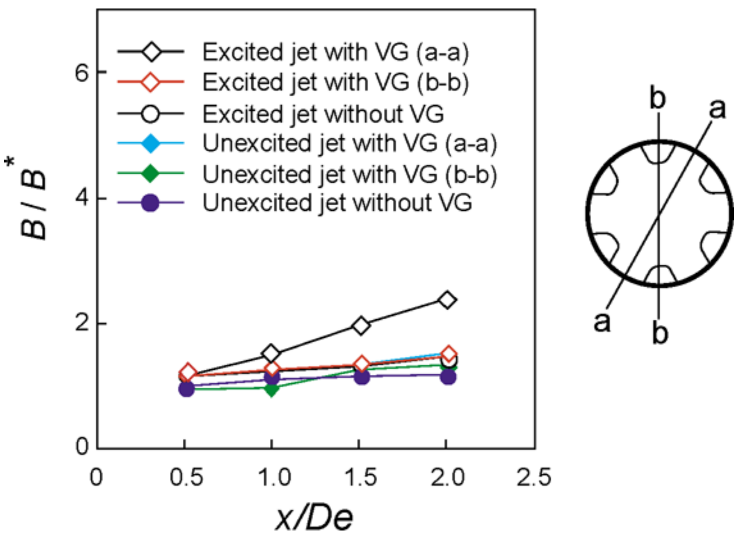

Fig. 14. Variations of jet width.

dimensionalized by the jet width B^* of the unexcited circular jet at $x/De = 0.5$. The width is defined as the location where the velocity is 10% of the jet-center velocity, and the widths were calculated from the mean velocity profiles measured by a hot-film probe. The excited jet with vortex generators diffuses more in the section (a-a) than in section (b-b) due to outward flow induced by the vortical structure shown in Fig. 9. Figure 14 shows that jet diffusion is affected by the vortical structure, and that the jet from the nozzle with vortex generators diffuses more than those from the nozzle without vortex generators. This result reveals the significant effect of the vortical structure including streamwise vortices on jet diffusion.

4. Conclusions

We investigated the vortical structure of a circular jet excited by axial and azimuthal perturbations by using a flow visualization technique. The visualized views show the details of the complicated vortical structure, which reveal the dynamics of the interaction between axisymmetric and streamwise vortices. Under the interaction the streamwise vortex pairs are formed around the axisymmetric vortex ring, and rush inward and outward by intense self-induced velocity.

From the visualization images, the length of jet boundary was calculated to discuss the mixing effect. The result reveals that the jet mixing is significantly increased by the break-down of the vortical structure enhanced by axial and azimuthal perturbations.

We also discussed the diffusion effect in consideration of the jet widths obtained by velocity measurement. The result indicates that the vortical structure including streamwise vortices plays an important role to enhance diffusion.

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