Changes to the vortical and turbulent structure of jet flows due to mechanical tabs

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Abstract: The effect of mechanical tabs on the vortical and turbulent structures in the near fields of jet mixing flows is investigated in the present paper. In order to compare the changes of the vortical and turbulent structures of jet flows with and without mechanical tabs, flow visualization and instantaneous quantitative concentration field measurements were conducted in a water channel by using a laser induced fluorescence (LIF) technique. The flow visualization confirmed the existence of a pair of counter-rotating streamwise vortices produced by each mechanical tab in a jet flow. The generated streamwise vortices can cause an inward indentation of ambient flow into the core jet flow and an outward ejection of core jet flow into the ambient flow. It also showed that the process of Kelvin–Helmholtz vortex pairing was accelerated, the small-scale vortical structure appeared earlier and a large-scale helical coherent structure was found in the near fields of tabbed jet flows. Based on the flow visualization and instantaneous quantitative concentration field measurements, two aspects of the effect of the streamwise vortical pairs induced by mechanical tabs on the jet mixing flows were suggested.

Keywords: jet mixing flow, mixing enhancement, mechanical tab, laser induced fluorescence (LIF) technique

NOTATION

C	concentration of disodium fluorescein in the jet mixing flow
C_0	concentration of disodium fluorescein in the jet supply tank
D	diameter of the tested nozzle
f	aperture of the CCD camera
$H(c)$	pixel grey value of the image detected by the CCD camera
Re	Reynolds number, which is 1800 and 3000 in the present research $= \rho UD/\mu$
U	mean velocity of the jet flow at the exit of the tested nozzle
X, Y, Z	streamwise, horizontal and vertical direction
XY plane	horizontal plane, which is called the top view in the present paper
XZ plane	vertical plane, which is called the side view in the present paper
YZ plane	plane normal to the flow direction, which is called the cross plane
μ	viscosity of the water flow
ρ	density of the water

1 INTRODUCTION

In an effort to increase mixing in free jet flows, a passive control method using vortex generators in the form of 'mechanical tabs' has been under investigation for the past several years. Bradbury and Khadem [**1**] were the first to study the effect of mechanical tabs on jet flows in detail. They reported that, at low jet speeds, mechanical tabs or small protrusions into jet flows at the exit of nozzles can increase the jet spread rate significantly, reduce the potential core length (from $6D$ for the conventional jet to $3D$) and even bifurcate the jet flows. Ahuja *et al.* [**2**, **3**] and Zaman *et al.* [**4**–**6**] began to investigate the mixing enhancement performance of mechanical tabs systematically. They found that mechanical tabs can not only increase the jet mixing at low speeds but also have the better mixing enhancement performance at high speeds and high temperatures. Ahuja [**3**] reported that,

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for a round jet flow of Mach number 1.12 and total temperature 664 K, the potential core length of the jet flow could be reduced from six diameters to under two diameters by using two diametrically opposed mechanical tabs. He also found that the mixing enhancement produced by the two mechanical tabs can reduce the temperature along the jet centre-line from 655 to about 472 K at a distance of five jet diameters downstream, and the mechanical tabs can reduce low-frequency noise by up to 5 or 6 dB. However, most of these investigations were focused on the overall mixing enhancement performance of mechanical tabs and the application of mechanical tabs to jet noise reduction. Not until 1993, based on the flow visualization of laser sheet and cigar smoke illumination and pressure measurement of a jet flow, did Zaman *et al.* [**7**, **8**] propose that the distortion introduced by a mechanical tab is due to a pair of streamwise vortices and postulate two sources of the streamwise vortices.

In an investigation on the effect of a mechanical tab on the turbulent boundary layer, Gretta *et al.* [**9**] found that a mechanical tab can generate counter-rotating streamwise vortices that can stimulate a strong ejection of boundary layer flow into high-speed flow. It resulted in a very rapid cross-stream mixing and a significantly thickened turbulent boundary layer.

In research on molecular mixing in jet mixing flow with mechanical tabs, Zhang *et al.* [**10**] reported that mechanical tabs can reduce the jet transitional Reynolds number. They also found that two diametrically opposed mechanical tabs can increase the molecular mixing by about 35 per cent at a streamwise distance of six diameters ($X/D = 6$).

However, the flow mechanism relating to the effect of mechanical tabs on the jet flow has not been fully explored and much work still needs to be done, especially in relation to research on the vortical and turbulent structure changes in the jet flow caused by mechanical tabs and the mechanism of how the streamwise vortices caused by mechanical tabs enhance the mixing process of a jet flow.

The object of this paper is to investigate the effect of mechanical tabs on the vortical and turbulent structures in the near field ($X/D < 8$) of jet mixing flows. A laser induced fluorescence (LIF) technique was used to accomplish the flow visualization and instantaneous quantitative concentration field measurements in a water channel in order to compare the changes in the vortical and turbulent structures of the jet flows with and without mechanical tabs.

2 EXPERIMENTAL SET-UP

2.1 Laser induced fluorescence (LIF) technique

Laser induced fluorescence is a non-intrusive experimental technique that has been used to investigate mixing flows in recent years by many researchers, such as Sheng and Jin [**11**], Liepmann and Gharib [**12**], Yoda *et al.* [**13**], Southerland and Dahm [**14**], Coppeta and Rogers [**15**] and Hui *et al.* [**16**]. It can be used not only to visualize the mixing flow qualitatively but also as a quantitative flow experimental technique to measure the concentration, temperature, pressure and velocity fields of the mixing flow.

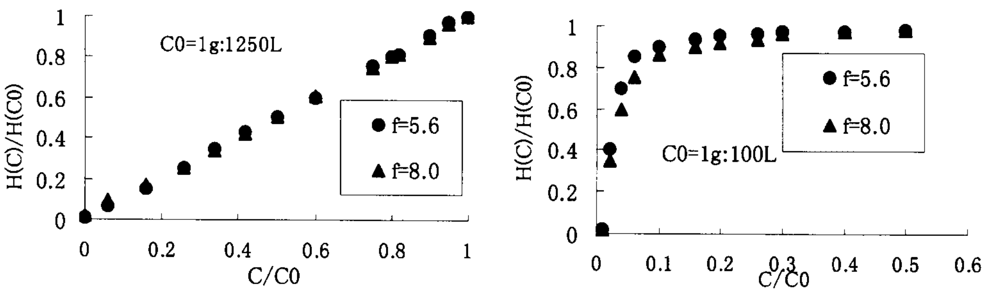
In this study, disodium fluorescein was used as a fluorescent dye. Figure 1 shows the calibration profiles of the disodium fluorescein solution. From the figure it can be seen that only a low concentration of disodium fluorescein can ensure that the normalized strength of the fluorescent rays is linear with the normalized concentration of disodium fluorescein and the effect of laser light attenuation being negligible as the laser light sheet propagates through the flow. In the present study, the concentration of the solution was 1 g of disodium fluorescein to 1250 L of water. The argon ion laser beam was supplied by a continuous laser (COHERENT INNOVA 70) with a power of 2.5 W.

2.2 Test model

Figure 2 shows the tested circular nozzle and mechanical tabs used in the present study. The diameter of the nozzle exit was 30 mm and the tested mechanical tab was a triangular-shaped tab with a 90° apex angle and a 135° orientation angle, just like the 'delta tab' studied by Zaman *et al.* [**7**]. Each mechanical tab had a 1.5 per cent blockage area of the nozzle exit area. During the experiment, two mechanical tabs were placed diametrically opposed at the exit of the nozzle.

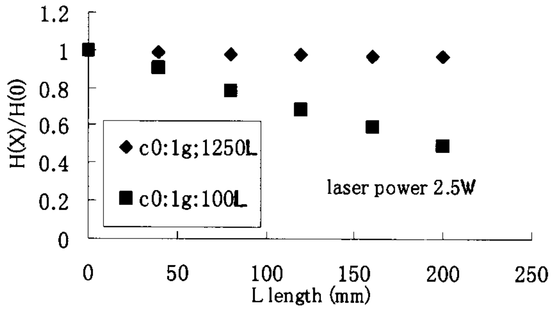
2.3 Test facility

Figure 3 shows the schematic of the facility used for the present study. The water in the water channel was still and the studied nozzle was installed in the middle of the water channel. The jet flow of the nozzle was supplied by a pressurized cylindrical reservoir tank. The velocity of the jet flow can be adjusted. Fluorescent dye (disodium fluorescein, Schmidt number $Sc = 2075$) was premixed with the water in the reservoir tank. A cover plate was placed at the top of the water channel to ensure the jet flow had a symmetrical boundary condition. The beam of the argon ion laser passed through an optical system to form a plane sheet. The sheet can be streamwise or normal across the central line of the jet flow. The investigated area was focused on a CCD camera and then digitized by an eight-bit grey-scale image processing board (DT2861/DT2851) with a 16-image memory at a spatial resolution of 512 × 512 pixels, which also can be stored by an IBM/PC (personal computer) and displayed on a PC monitor.



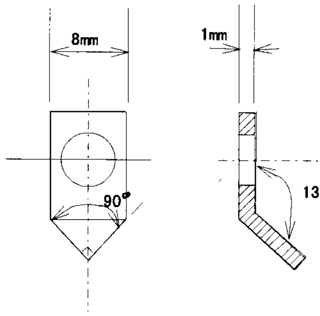
A. at low concentration B. at high concentration (f is the aperture of the CCD camera)

a. The changes of the normalized induced fluorescent ray intensity with the normalized disodium concentration

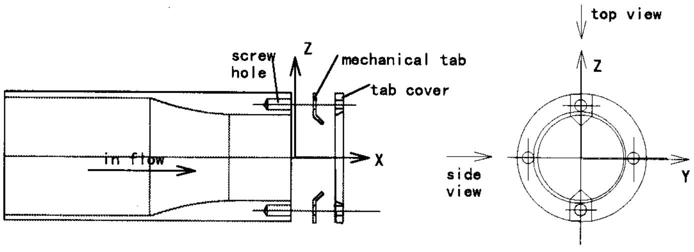


b. Light attenuation performance of the disodium

Fig. 1 Calibration profiles



(a) Tested mechanical tab



(b) Circular nozzle used in the test

Fig. 2 Tested nozzle and mechanical tab

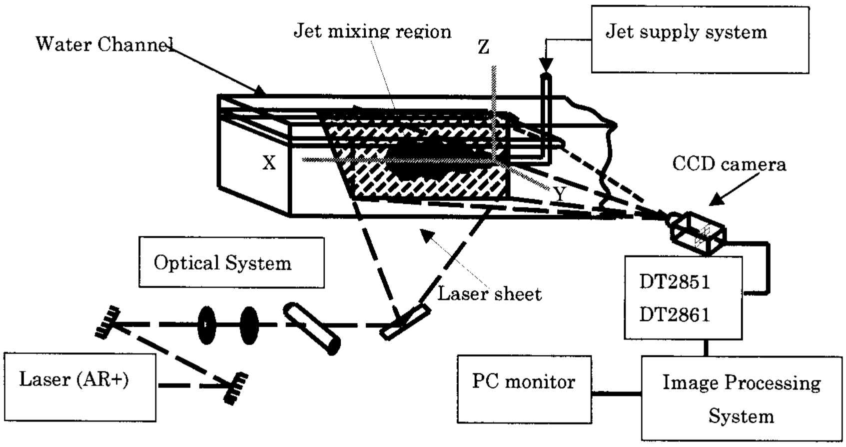


Fig. 3 Experimental set-up

2.4 Experimental procedure

During the experiment, the flow visualization and instantaneous quantitative concentration field measurements of the flow structure in the axial slices (*XY* and *XZ* planes, Fig. 2) were conducted firstly to study the changes in the spanwise vortices and coherent structure of the jet flow caused by the mechanical tabs. Then the streamwise vortices and the mixing flow structures in the cross planes (*YZ* plane, Fig. 2) at several different streamwise locations were studied. The Reynolds numbers of the jet flows, based on the nozzle exit diameter and average velocity of the jet flow at the nozzle exit, were 1800 and 3000.

3 TEST RESULTS AND DISCUSSION

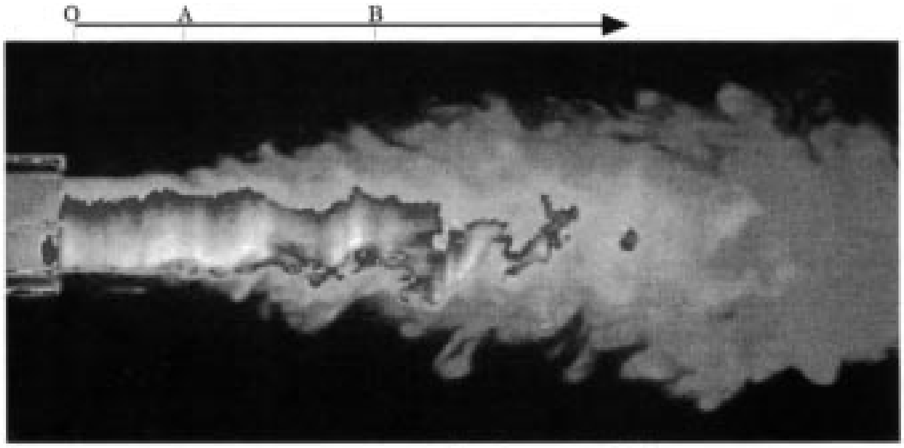
3.1 LIF visualization

The visualization of the flow structure of a natural jet flow is shown in Fig. 4a. As shown in this figure, three different regions, the laminar region, the transition region and the turbulent region, can be identified clearly for the natural jet flow, which is similar to the results reported by Liepmann *et al.* [**12**]. At the end of the laminar region ($X/D = 1.5$), spanwise Kelvin–Helmholtz vortices were found to roll up. The pairing and combining of these spanwise vortices was conducted in the transition region. In the turbulent region, much small-scale turbulence and vortical structures began to appear, and the jet flow was transitional to turbulence.

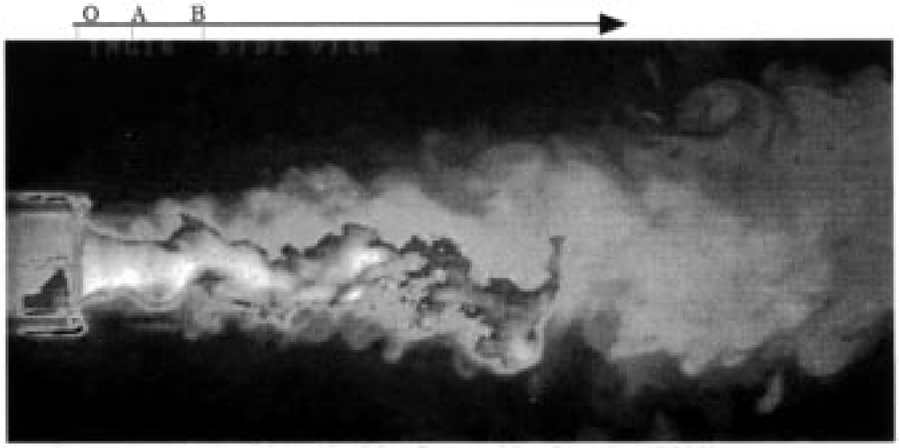
Figure 4b shows the visualization of the flow structures in the axial slice (*XZ* plane, side view) for the jet flow with mechanical tabs. Compared with the natural jet flow, the laminar region of the tabbed jet flow was no longer 'clean' and straight. It became a convergent region instead, and the length of this region ($X/D = 0.5$) was much smaller than that of the natural jet flow ($X/D = 1.5$). This can be explained by the presence of a local contraction at the exit of the nozzle owing to the existence of the mechanical tabs. In the transition region it was also found that the scale of the first spanwise vortex rolled up by the Kelvin–Helmholtz instability was smaller than that of the natural jet flow and the process of the spanwise vortices pairing and combining was accomplished in a shorter streamwise distance. Unlike in the natural jet flow, the small-scale vortices appeared earlier in the tabbed jet flow, and the large-scale coherent structure in the tabbed jet flow was the zigzag (helical) model instead of the axisymmetrical model in the natural jet flow.

The visualization of the flow structure in another axial slice (*XY* plane, top view) for the jet flow with mechanical tabs is given in Fig. 4c. From the figure it can be seen that, similarly to the case in the natural jet flow, there was also a 'clean' straight laminar region in the tabbed jet flow at this axial slice. However, its length was shorter, about a diameter of the nozzle. At a streamwise distance of about $X/D = 1.0$ the first spanwise vortex rolled up and then the spanwise vortices paired in the transition region. The pairing process of the spanwise vortices was accelerated in comparison with the case of the natural jet flow. When the small-scale vortices appeared in the tabbed jet flow, the jet flow spread angle [**17**] increased rapidly up to 45°, while the angle of the natural jet flow was about 30°.

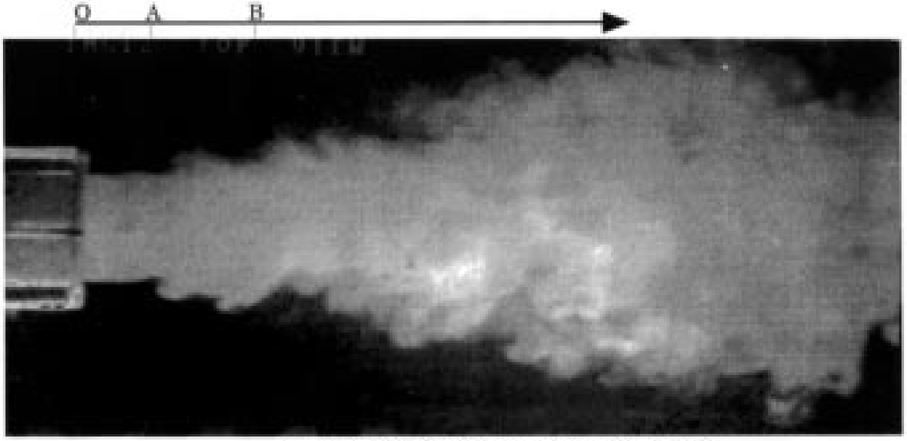
Figure 5 shows the flow visualization of the jet flow, with and without mechanical tabs, in the cross planes (*ZY* plane) at different streamwise locations. A pair of streamwise vortices can be clearly seen in the jet flow owing to the existence of the mechanical tab. An inward indentation of ambient flow into the core jet flow and the outward ejection of core jet flow into the ambient flow can be observed owing to the 'engulf effect' of the streamwise vortices (see Fig. 6). This resulted in the jet spread rate in the *XY* plane (top view) being faster than that in the *XZ* plane (side view). This may be the reason why the jet spread angle of the tabbed jet flow in the



a. natural jet flow (Re=3000)



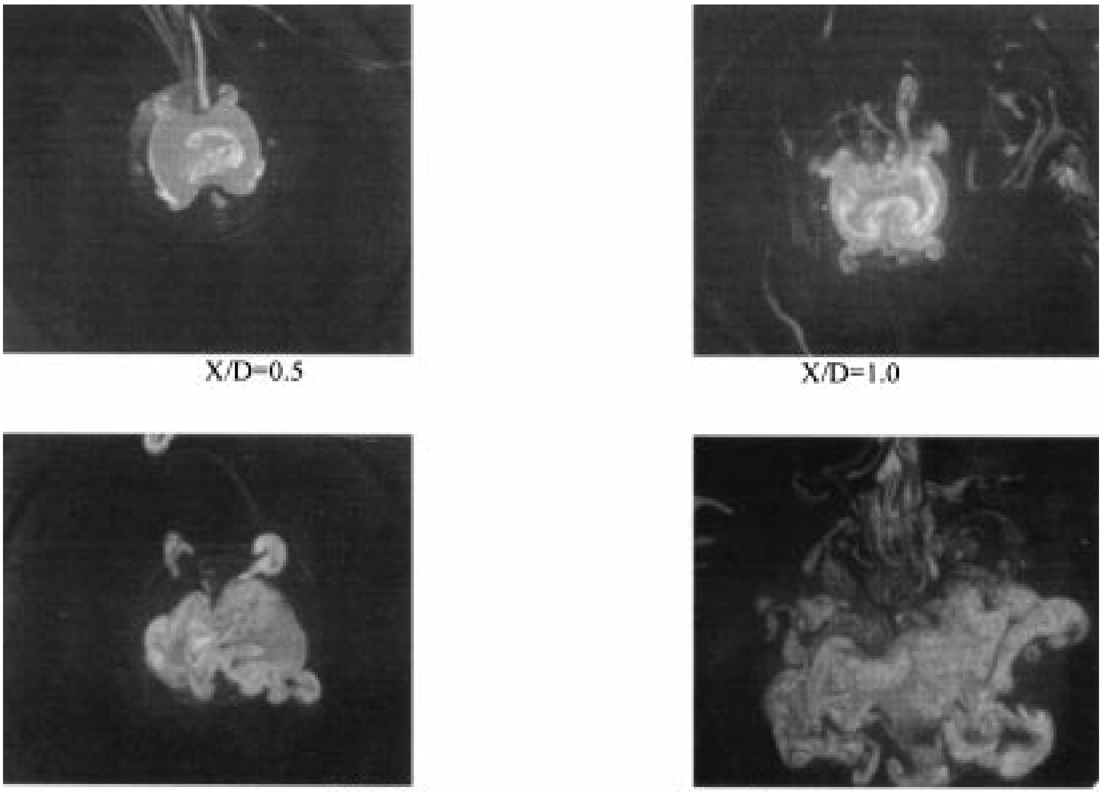
b. tabbed jet flow (side view, Re=3000)



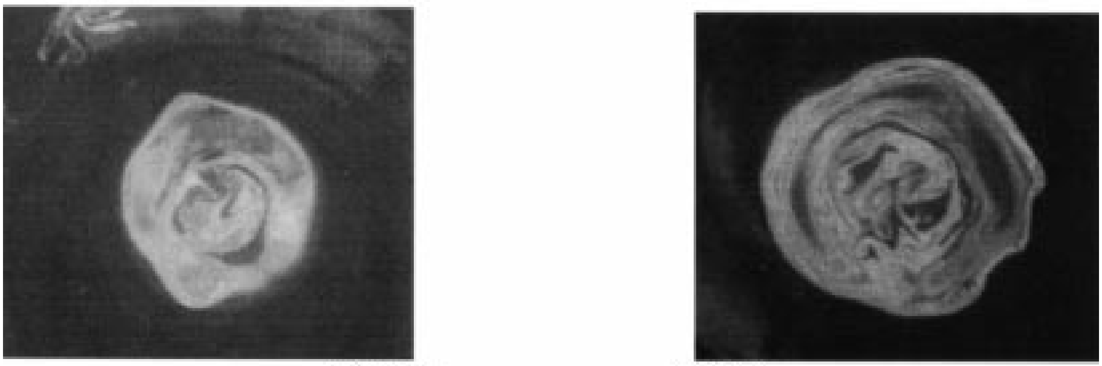
c. tabbed jet flow (top view, Re=3000)

(O-A: laminar region, A-B: transition region, downstream of B: turbulent region)

Fig. 4 Typical flow visualization of natural jet flow and tabbed jet flow in axial slices



a. in the tabbed jet flow



b. In the natural jet flow

Fig. 5 Typical flow visualization of natural jet flow and tabbed jet flows in several cross planes ($Re = 1800$)

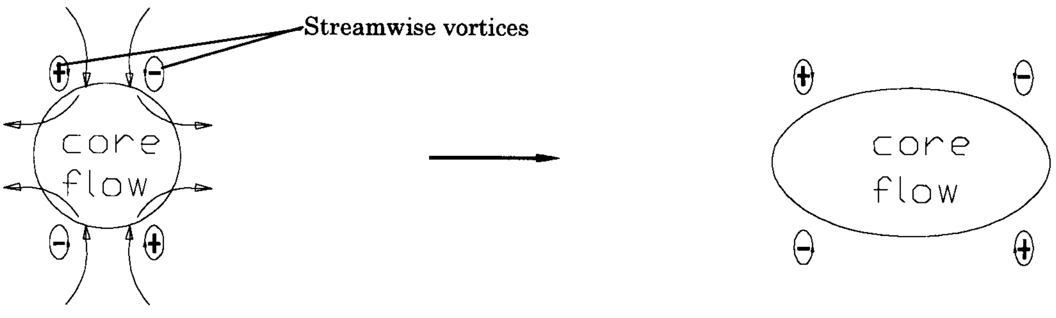


Fig. 6 Engulf effect of the streamwise vortices caused by mechanical tabs on the jet flow profile

top view slice (XY plane) was bigger than that in the side view slice (XZ plane) of the tabbed jet flow and natural jet flow visualized in Fig. 4. The flow structures in the cross planes evolved gradually from a circle to an ‘egg form’. From Fig. 5 it can also be seen that many small-scale vortex structures were observed in the cross plane of the tabbed jet flow downstream of $X/D = 2.0$. However, these cannot be observed in the natural jet flow even in the cross plane of $X/D = 4.0$.

3.2 Instantaneous quantitative concentration field measurements

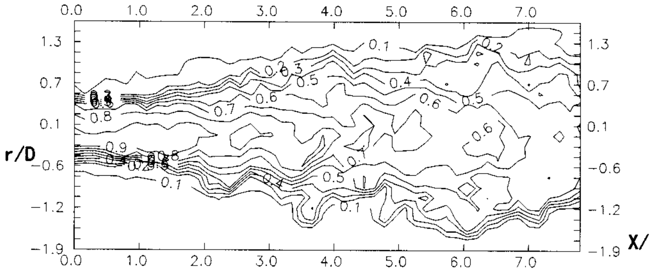
Figure 7 shows the measured instantaneous concentration field distributions of the natural jet flow and the tabbed jet flow. In this figure the concentration value, $C(x)$, of the disodium fluorescein solution (core jet flow) in the flow field was normalized by the concentration of the disodium fluorescein solution in the jet supply tank, C_0. From this figure it can be seen that the concentration decay rate of the tabbed jet flow was faster and the region of high concentration was smaller than those in the natural jet flow. For example, the constant concentration line of $C/C_0 = 0.7$ disappeared downstream of $X/D = 4.0$ in the tabbed jet flow, while in the natural jet flow it extended to downstream of $X/D = 6.0$.

It can also be found that the spread angle of the constant concentration line in the axial slice of the XY plane (top view) of the tabbed jet flow was much larger than that in the axial slice of the XZ plane (side view) of the tabbed jet flow and natural jet flow, which is consistent with the results of the above visualization analysis.

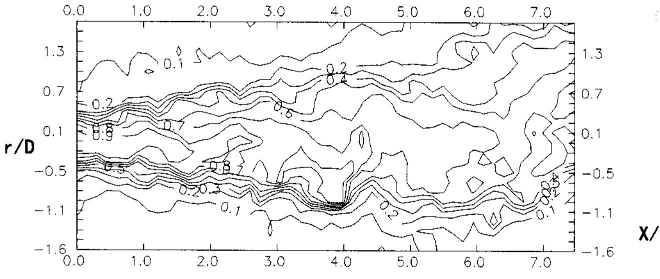
3.3 Mechanism of jet mixing enhancement by the mechanical tab

From the above analysis it can be seen that, as proposed by Zaman *et al.* [**7**, **8**], each mechanical tab was found to produce a pair of counter-rotating streamwise vortices that can change the vortex and turbulent structures of the jet flow and enhance the jet mixing.

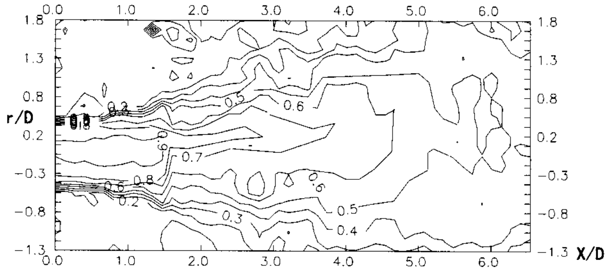
Based on the analysis of the flow instability it can be seen that the circular jet flow had an additional dimensional restriction (i.e. the diameter of the jet nozzle) compared with the two-dimensional plane shear mixing flow. Thus, an additional instability model—the azimuthal



a. Natural jet flow, Re=3000



b. Tabbed jet flow, Re=3000 (X-Z plane, side view)



c. Tabbed jet flow, Re=3000 (X-Y plane, top view)

Fig. 7 Instantaneous concentration (C/C_0) distribution contours of natural jet flow and tabbed jet flow helical instability model—existed in addition to the axisymmetrical instability model which was similar to the instability model of the plane shear mixing flow. Cohen and Wygnanski [**18**] reported that the helical instability model of a circular jet flow was predominant at any frequency when the streamwise distance $X/D > 3.0$, and therefore the spanwise vortices caused by the Kelvin–Helmholtz instability cannot be a two-dimensional vortical ring during its evolution. It should be the combination of many helical vortices, i.e. a toroidal vortical ring. Hussain [**19**] suggested that, owing to the effect of azimuthal instability, the two-dimensional spanwise vortices caused by the Kelvin–Helmholtz instability can be wrapped and developed into a three-dimensional structure through secondary instability. Undergoing the interaction, the large-scale toroidal vortical ring can be broken down into many substructures through the 'cut and connect' process (Fig. 8), which may be responsible for the avalanche of three-dimensional and smaller-scale motions and the generation of high turbulence and Reynolds stress. In the natural jet flow, these processes always proceed very slowly and need a long distance to be completed.

However, in the tabbed jet flow a pair of streamwise vortices was produced in the jet flow owing to the intrusion of each mechanical tab, which made an inward indentation of ambient flow into the core jet flow and an outward ejection of core jet flow into the ambient flow (Figs 5 and 6). This indicated that there was a large perturbation at the azimuth of the circular jet flow that enhanced the helical instability of the jet flow (a large-scale helical coherent structure was found in the tabbed jet flow, Fig. 4); i.e. the 'toroidal effect' of the spanwise vortical structure was enlarged and then the cut and connect process of the toroidal vortical ring was accelerated. The process of the large-scale vortical structure being broken down into a smaller-scale vortical structure was conducted more rapidly, which enhanced the mixing of the jet flow with the ambient flow.

Besides this, the pair of streamwise vortices produced by each mechanical tab and the spanwise vortices produced by the Kelvin–Helmholtz instability were normal to each other, and the interaction between them made the spanwise vortices stretch out (Fig. 9). According to the Helmholtz vorticity conservation law, the scale of the vortices will be reduced if the vortices are stretched, and the 'energy cascade' process of the turbulence will be enhanced. This resulted in a rapid reduction in the scale of the spanwise vortices caused by the Kelvin–Helmholtz instability, which also resulted in the creation of much small-scale intense turbulence and enhanced the mixing of the jet flow with ambient flows. This result was verified by LIF visualization of the tabbed jet flow in the axial slice of the XZ plane (side view, Fig. 4).

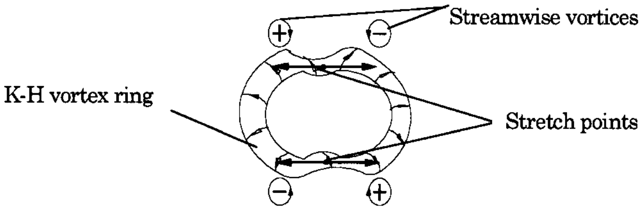


Fig. 9 'Stretch effect' of the streamwise vortices caused by mechanical tabs on the Kelvin–Hemholtz spanwise vortex ring

4 SUMMARY

Flow visualization confirmed the existence of a pair of counter-rotating streamwise vortices induced by each mechanical tab in a jet flow. The generated streamwise vortices can cause an inward indentation of ambient flow into the core jet flow and an outward ejection of core jet flow into the ambient flow. It was also found that, compared with the flow structures of the natural jet flow, the process of Kelvin–Helmholtz vortex pairing was accelerated, the small-scale vortical structure appeared earlier and a large-scale coherent helical structure was found in the near field of the tabbed jet flow.

Based on the flow visualization and instantaneous

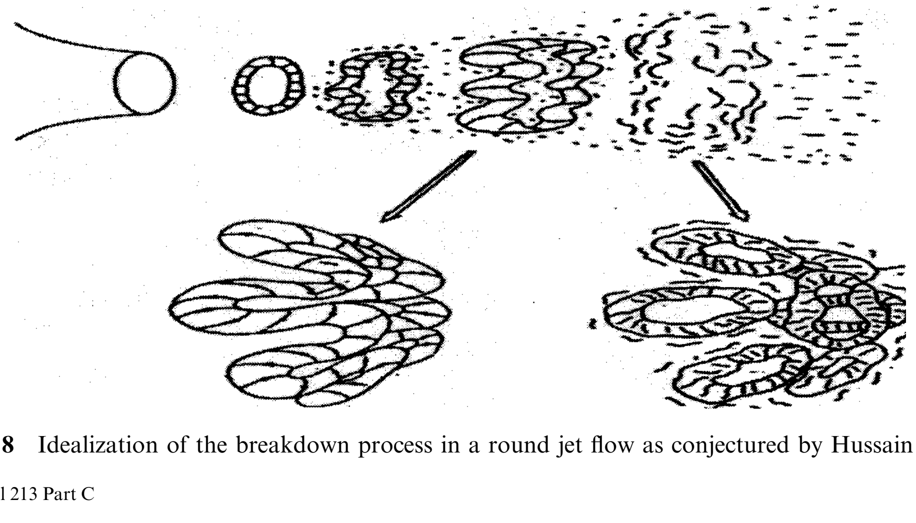


Fig. 8 Idealization of the breakdown process in a round jet flow as conjectured by Hussain [**19**]

quantitative concentration field measurements, two aspects of the effect of the streamwise vortical pair induced by each mechanical tab on the jet mixing flow were suggested:

1. The azimuthal instability of the jet flow was increased by the streamwise vortical pair. This accelerated the cut and connect process of the Kelvin–Helmholtz vortex ring structure in transferring the energy and vorticity from large-scale vortices to small-scale vortices, which was responsible for the avalanche of three-dimensional and smaller-scale motions and the generation of a high degree of turbulence.
2. The interaction between the streamwise vortical pair and the Kelvin–Helmholtz vortex ring also enhanced the energy cascade process of the turbulence, which resulted in the creation of much intense small-scale turbulence and enhanced the mixing of the jet flow with the ambient flow.

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REFERENCES

1 **Bradbury, L. J. S.** and **Khadem, A. H.** The distortion of a jet by mechanical tabs. *J. Fluid Mechanics*, 1975, **70**, 801–813.

2 **Ahuja, K. K., Manes, J. P.** and **Massey, K. C.** An evaluation of various concepts of reduction in supersonic jet noise. AIAA 90-3982, 1990.

3 **Ahuja, K. K.** Mixing enhancement and jet noise reduction through mechanical tabs plus ejector. AIAA 93-4347, 1993.

4 **Zaman, K. B. M. Q., Reeder, M. F.** and **Samimy, M.** Effect of mechanical tabs on the evaluation of an axisymmetrical jet. NASA TM104472, 1991.

5 **Samimy, M., Reeder M. F.** and **Zaman, K. B. M. Q.** Supersonic jet mixing enhancement by vortex generation. AIAA 91-2263, 1991.

6 **Zaman, K. B. M. Q., Reeder, M. F.** and **Samimy, M.** Supersonic jet mixing enhancement by 'delta-tabs'. AIAA 92-3548, 1992.

7 **Zaman, K. B. M. Q.** Streamwise vorticity generation and mixing enhancement in free jet by 'delta-tabs'. AIAA 93-3253, 1993.

8 **Zaman, K. B. M. Q., Reeder, M. F.** and **Samimy, M.** Control of an axisymmetric jet using vortex generators. *Phys. Fluid*, 1994, **6**(2), 778–793.

9 **Gretta, W. J.** and **Smith, C. R.** The flow structure and statistics of a passive mixing mechanical tab. *J. Fluid Engng*, 1993, **115**, 255–263.

10 **Zhang, S.** and **Scheider, S. P.** Molecular-mixing measurements and turbulent structure visualizations in a round jet with mechanical tabs. AIAA 94-3082, 1994.

11 **Shen, G.** and **Jin, J.** LIF quantitative concentration field measurement for the mixing flow of free jets. *Acta Mech. Sinica*, 1992, **24**(4).

12 **Liepmann, D.** and **Gharib, M.** The role of streamwise vorticity in the near field entrainment of round jets. *J. Fluid Mechanics*, 1992, **254**, 643–668.

13 **Yoda, M., Hesselink, L.** and **Mungal, M. G.** Instantaneous three-dimensional concentration measurement in the self-similar region of a round high-Schmidt number jet. *J. Fluid Mechanics*, 1994, **279**, 313–350.

14 **Southerland, K. B.** and **Dahm, W. J. A.** Four dimensional laser induced fluorescence study of the structure of molecular mixing in turbulent flow. AIAA 94-0820, 1994.

15 **Coppeta, J.** and **Rogers, C.** Mixing measurements using laser induced fluorescence. AIAA 95-0167, 1995.

16 **Hui, H., Wu, S.** and **Shen, G.** Experimental investigation on the jet mixing flow of lobed nozzles by using LIF. AIAA 96-1937, 1996.

17 **Cenedese, A., Doglia, G., Romano, G. P., Michele, G. De** and **Tanzini, G.** LDA and PIV velocity measurements in free jets. *Expl Thermal and Fluid Sci.*, 1994, **9**, 125–134.

18 **Cohen, J.** and **Wygnanski, I.** The evaluation of instabilities in the axisymmetrical jet. *J. Fluid Mechanics*, 1987, **176**, 191–219.

19 **Hussain, A. K. M. F.** Coherence structure and turbulence. *J. Fluid Mechanics*, 1986, **173**, 303–356.