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Visualization of Flows behind the Lobed Forced Mixers Using the Smoke-wire Technique

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***Abstract*:** Flow visualization studies have been conducted using the smoke-wire technique to examine the flows behind lobed forced mixers of different trailing edge configurations (namely a square wave, semi-circular wave and a triangular wave) at a velocity ratio 1:1 across the lobe. The wake region shed by a lobe is found to be the largest with lobe geometry consisting of straight parallel sidewalls. Streamwise vortices are formed within the first four wavelengths downstream of the trailing edge in the square and semi-circular lobed mixers. These vortices are largely responsible for intense mixing at downstream locations. However, similar observation is not found in the case of triangular lobed mixer. The present visualization tests agree qualitatively with the velocity measurements obtained by authors using a laser-Doppler anemometer.

***Keywords*:** lobed mixer smoke-wire technique

1. Introduction

Forced lobed mixers are passive, fluid mechanical devices which generate three-dimensional shear layer with strong streamwise vorticity into the co-flowing streams. As shown Fig. 1, their geometry is characterized by periodically alternating, lobed trailing edge surfaces, such that large scale streamwise vorticity is shed at trailing edge. The downstream flow field is embedded with arrays of streamwise vorticity of alternating sign. This results in a rapid exchange of energy by means of intense mixing between the two streams on either side of the lobed mixer, with a nearly uniform flow achieved within a short downstream distance. Application of the lobed mixers can be found in the turbofan engine exhausts where the mixing of core and the bypass flows can achieve noise reduction as well as thrust enhancement. In a recent investigation by the authors, (Yu, Yip and Liu, 1996) it is shown that streamwise vorticity can be further enhanced by about 30% via scalloping the lobes, i.e. by removing part of the straight sidewalls at the penetration regions.

Based on the flow visualization tests in a water tunnel, Werle et al. (1987) suggested that the flow structure of the wake region behind a two-dimensional lobed mixer followed a three-step process by which the streamwise vortex cells form, intensify, and thereafter break down where high turbulence regions dominated. Velocity measurements by Eckerie et al. (1992) appears to support Werle et al.'s findings. However, one obvious disadvantage of using water tunnel dye injection visualization method is that at the flow regions subjected to the effects of streamwise vorticity, the dye tends to disperse rapidly. It may not be too clear whether it is due to diffusion effects as a result of the thinning of the dye or due to high turbulence as suggested by Werle et al. (1987). Recent velocity measurements by McCormick and Bennett (1994) (using a hot-wire anemometer) and Yu, Xu and

Yip (1996) (using a three-hole pressure probe) and Yu and Yip (1997) (using a laser Doppler anemometer), however, argued that intense mixing is due largely to the decay of streamwise vorticity and the accompanied diffusion effects. Similar conclusions are also drawn from the results in a coaxial jet with a central lobed nozzle (Yu and Xu, 1997, 1998).

The purpose of the present paper is to show that a better understanding of the formation of the streamwise vortex at the wake region behind the forced lobed mixers may be obtained using the smoke-wire visualization technique. Three forced lobed-mixers of different convoluted trailing edge configurations have been tested at velocity ratio between the two streams (on either side of a lobed mixer) of 1:1. The configurations chosen to test here are identical to those for flow measurements by Yu, Yeo and Teh (1995). Preliminary analysis on the results can be found in Yu (1994). The results obtained here are limited to only one velocity ratio. It should be noted that when there is a velocity ratio across the lobe, some differences in the results are expected. In particular, the normal vortex shed at the trailing edge would be inclined at an angle equivalent to the lobe penetration angle, as shown in the investigation of McCormick and Bennett (1994).

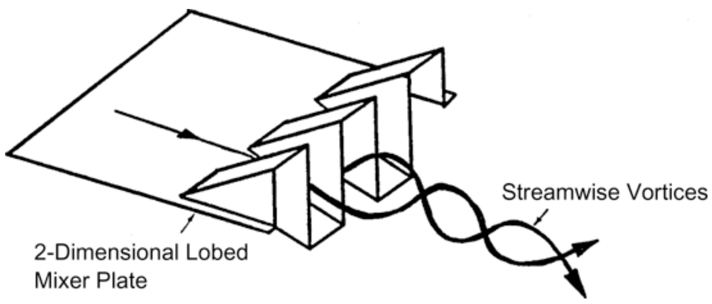


Fig. 1. Two-dimensional lobed forced mixer.

2. Flow Configurations and Wind Tunnel

The experiment is performed in a low-speed, low turbulence, open-circuit wind tunnel designed specially for smoke-wire visualization applications, as shown schematically in Fig. 2. The test section is 100 mm high, 200 mm wide and 700 mm long. The bulk velocity could be varied from 1 to 2.5 m/s. The longitudinal-turbulence level for this velocity range within the test section is less than 0.5% of the bulk velocity measured by a constant temperature anemometer. The experiments are carried out at an average flow velocity of 1 m/s. Such flow velocity has been chosen, after some preliminary experiments, in order to obtain the most recordable course of the examined phenomenon.

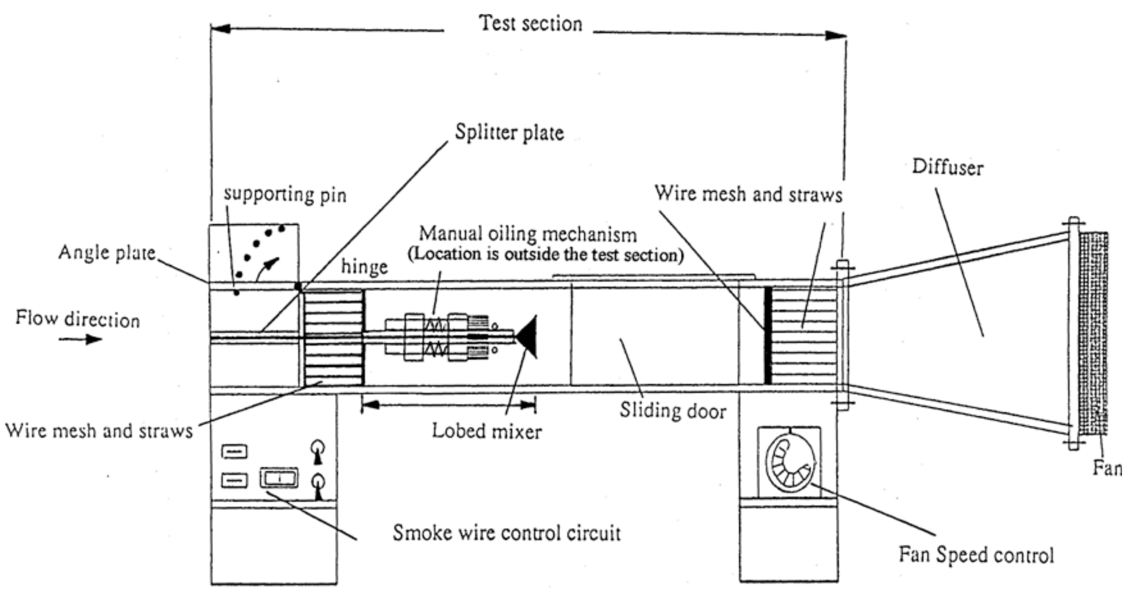


Fig. 2. Schematic view of the wind tunnel used.

The smoke-wire visualization method used in the experiment consisted of thin wires with 180 mm length and 100 Ω/m specific resistance. The wire is heated at a voltage of 20 - 30 V during the course of experiment. The heating time is adjusted within 100 - 400 ms. Positions of the wires are indicated in Fig. 2. The smoke in the wake region is illuminated by two methods; a light sheet (of 1 mm thick) from a 1W Argon laser combined with a cylindrical lens and by a multiple flash which synchronizes with the camera's shutter speed.

For Fig. 4, the position of the camera is at the side of the rig and the flow was illuminated by a multiple flash located above the rig. For Figs. 6 to 9, the flow was illuminated by the laser light sheet at the cross-sectional planes of interest. The position of the camera was positioned above the rig at an angle 30 degrees with respects to the horizontal plane.

The three configurations of the forced mixer trailing edge under investigation include a square wave, a semi-circular wave (similar to the E^3 type lobed mixer described by Barber et al. (1988)) and a triangular wave. A nominal wavelength of 33 mm and a penetration angle of 44 degrees are used for the three mixers, as shown in Fig. 3. Reynolds number based on the wavelength of the lobe and bulk mean velocity of the two streams at 1 m/s is about 1,500.

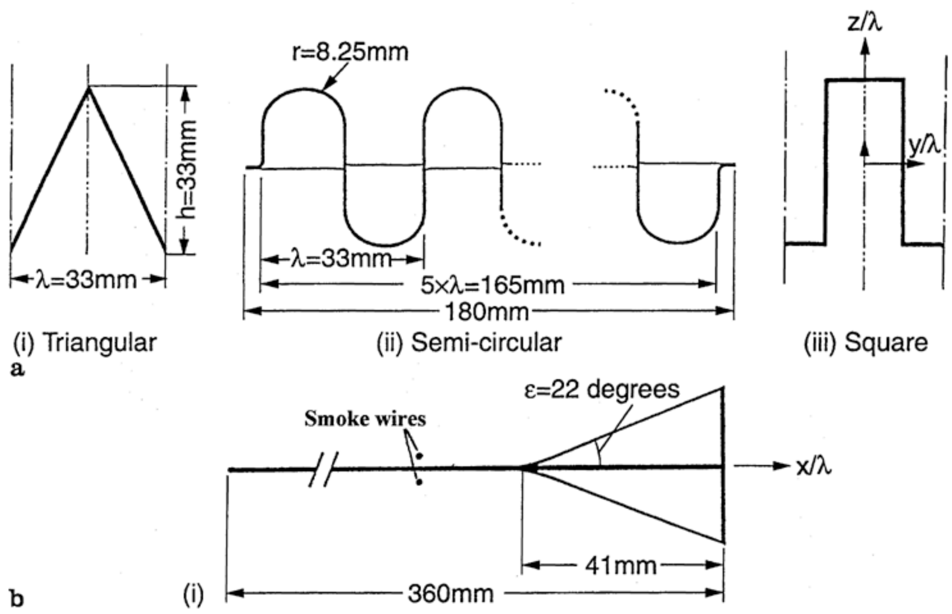


Fig. 3. Lobe configurations under considered.

3. Results and Discussions

Figures 4(a) to (c) illustrate the size and structure of the wake region behind respective mixers in relation to the trailing edge configuration at velocity ratio 1:1. The wake region for the square wave mixer, Fig. 4(a), increases in size with downstream distance and intense mixing is also found within the wake region. Similar trend for the flow in the wake region is also found for the semi-circular lobed mixer. However, in the case of triangular mixer, streamwise acceleration of the flow is obvious as the flow goes through the lobe penetration region. It should be noted that the region of acceleration is extended beyond the trailing edge to about two to three wavelengths downstream. The traverse extent of the wake region generated by the triangular mixer is also smaller (by about two fold) than the other two cases. Thus, the size of this wake region is the largest in the case of the square lobed mixer and is followed by the semi-circular and triangular mixers. The present observation is found to be in good qualitative agreement with the measurements obtained by Yu, Yeo and Teh (1995). As shown in Fig. 5, the measurements for the secondary flow velocities at half wavelength (x/λ=0.5) downstream of the trailing edge show that the square mixer has a maximum of 45% of the bulk mean velocity (of the two streams) comparing to 39% and 19% for the semi-circular and triangular mixer. This may explain why the square mixer has a larger wake region.

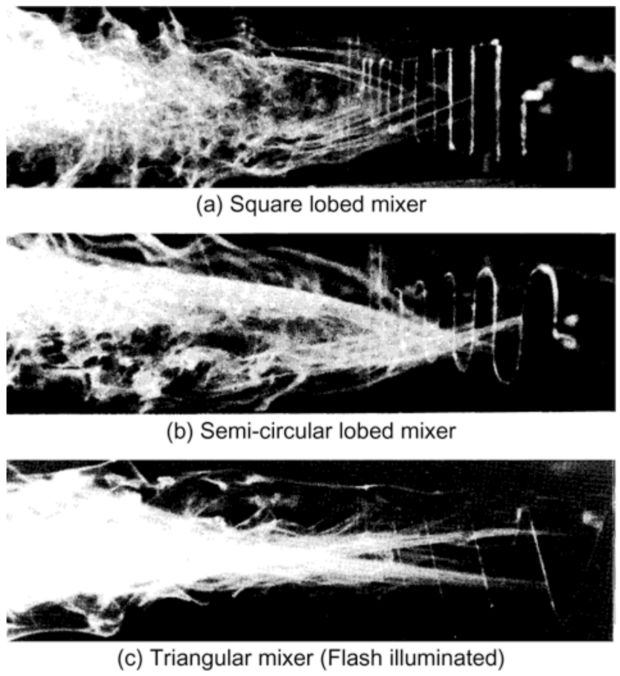


Fig. 4. Visualization of the wake region for respective lobed mixers:
(a) Square lobed mixer, (b) Semi-circular lobed mixer, (c) Triangular mixer (Flash illuminated)

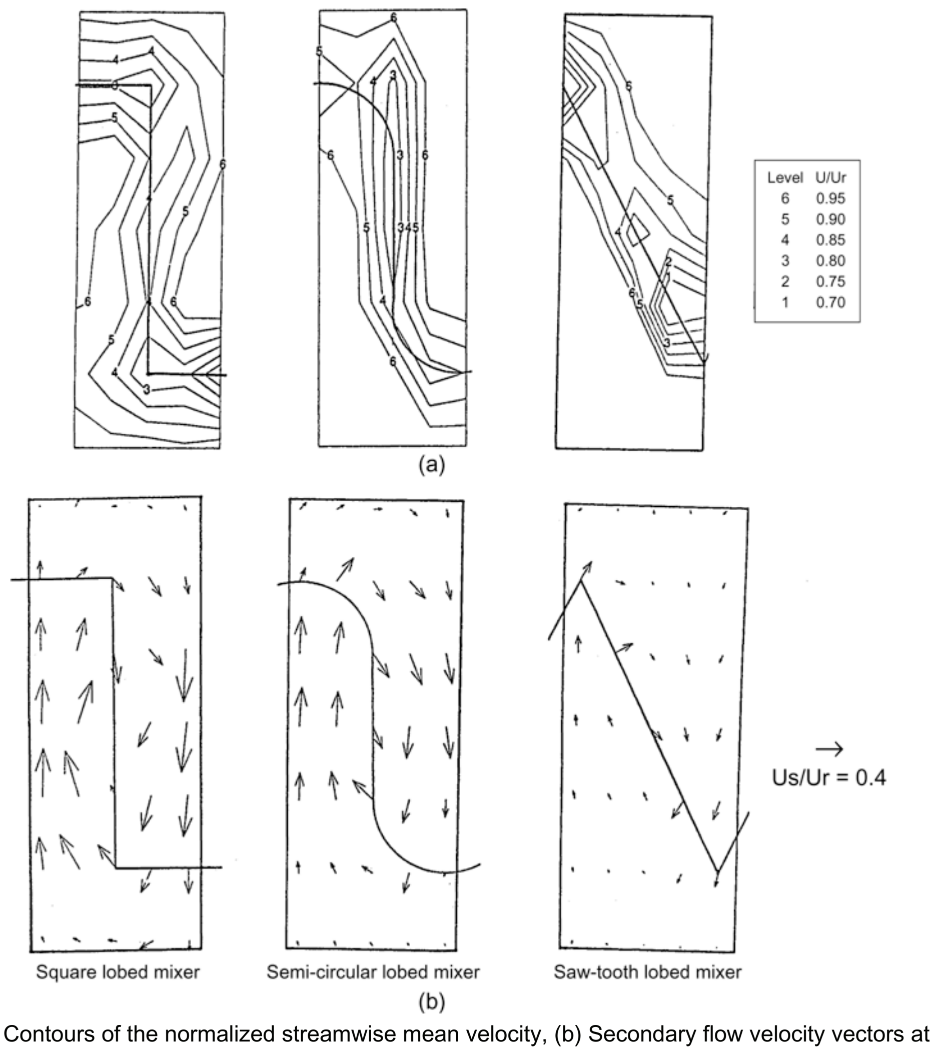
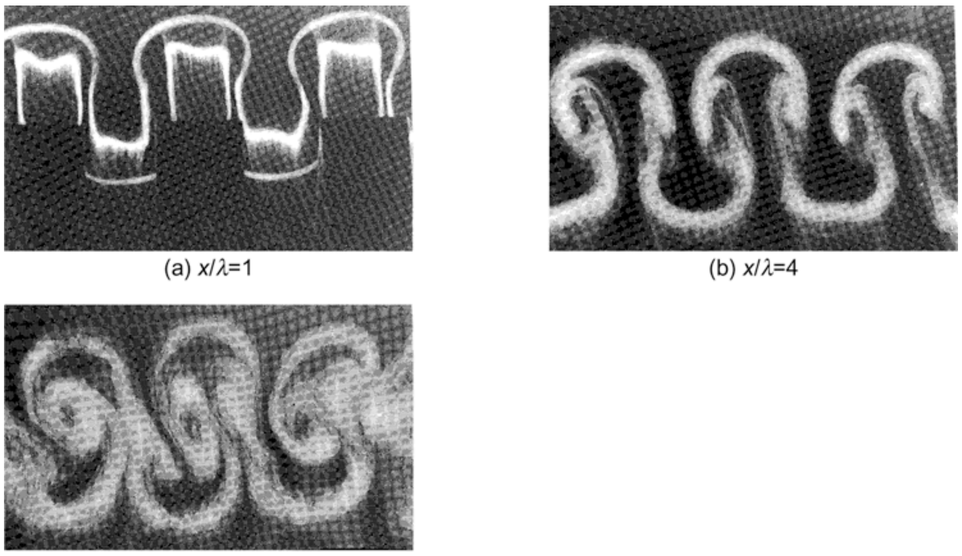


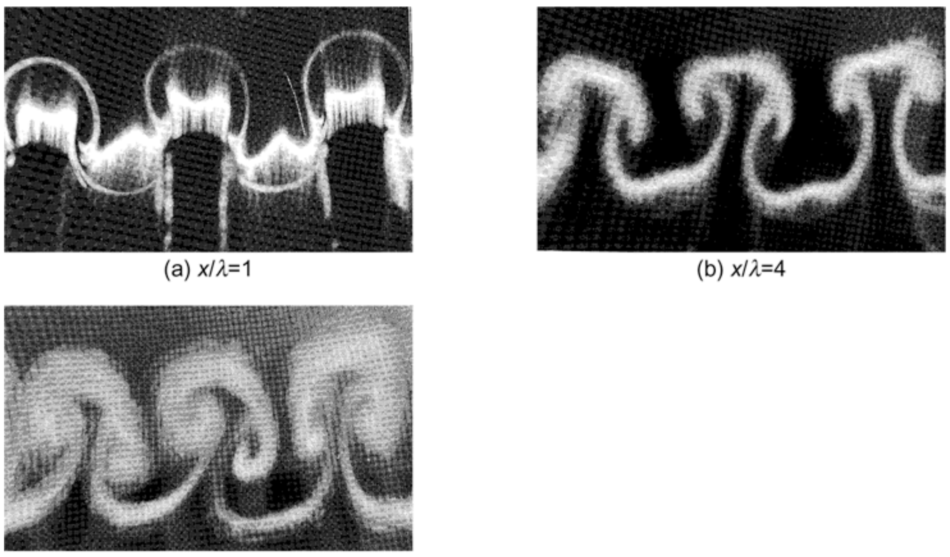
Fig. 5. (a) Contours of the normalized streamwise mean velocity, (b) Secondary flow velocity vectors at x/λ=0.5. (taken from Yu, Yeo and Teh (1995))

Figures 6, 7 and 8 illustrate the streamwise vortex structure of the square, semi-circular and triangular lobed mixer. The visualization is achieved by illuminating the flow at a particular cross-section of interest using the laser-sheet technique. The initial formation of vortex lines shed along the top and bottom of the mixer follows closely to the shape of the trailing edge and are clearly shown in Figs. 6a, 7a and 8a at about one wavelength downstream of the mixer trailing edge. At regions close to the lobe trough, the vortex lines appeared to be thicker in the cases of the square and semi-circular lobed mixers. This may be explained by the observation on the surface flow patterns upstream of the trailing edge, Figs. 9a to 9c. The flows at the peaks of the lobes are pushed sideway towards the trough in the cases of the square and semi-circular mixers. This appears to be the results of the pressure gradients setup between the peaks and the troughs resuled in thicker boundary layers at the troughs. Thus, thicker smoke lines would be expected at the trough regions. At four wavelengths downstream of the trailing edge, the two lines merge into one by diffusion effect and a pair of counter-rotating vortices can be clearly seen at each lobe, see Figs. 6b and 7b. By seven wavelengths downstream, the size of the vortices increase and intense mixing by diffusion are obvious, see Figs. 6c and 7c. However, no indication of vortex break-down can be found.



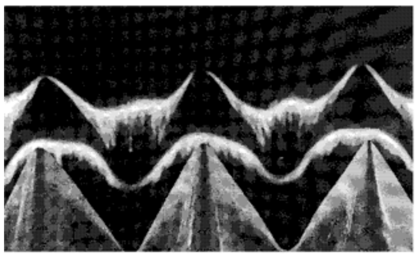
(a) $x/\lambda=1$ (b) $x/\lambda=4$ (c) $x/\lambda=7$

Fig. 6. Visualization of the streamwise flow patterns of the wake region at successive downstream locations for the square lobed mixer (viewing downstream from the trailing edge; laser sheet illumination).



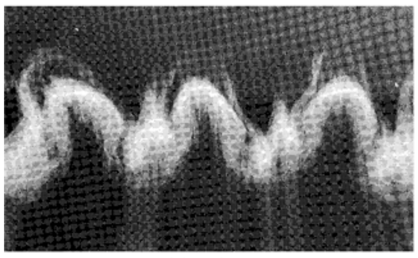
(a) $x/\lambda=1$ (b) $x/\lambda=4$ (c) $x/\lambda=7$

Fig. 7. Visualization of the streamwise flow patterns of the wake region at successive downstream locations for the semi-circular mixer (viewing downstream from the trailing edge; laser sheet illumination).



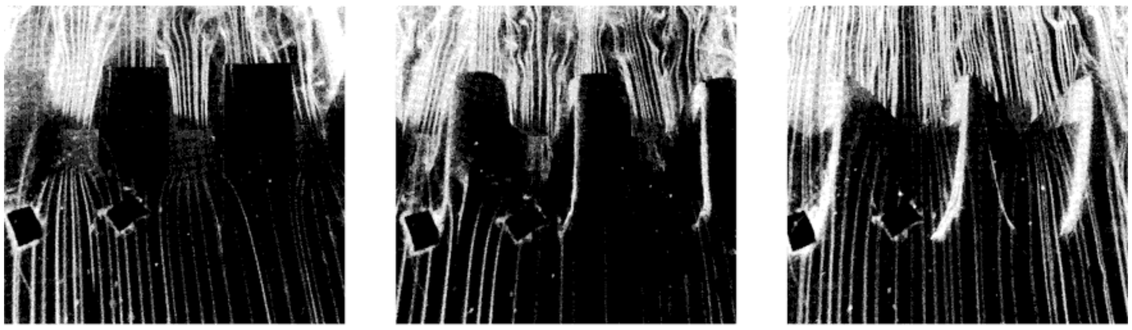
(a) x/λ=1

(b) x/λ=4



(c) x/λ=7

Fig. 8. Visualization of the streamwise flow patterns of the wake region at successive downstream locations for the triangular mixer (viewing downstream from the trailing edge; laser sheet illumination).



(a) (b) (c)

Fig. 9. Surface flow patterns for respective lobed mixers:
(a) Square wave mixer, (b) Semi-circular mixer, (c) Triangular mixer (Flash illuminated).

For the triangular mixer, as may have expected from the velocity measurements of Yu et al. (1995) (Fig. 5), no contra-rotating vortices can be found within four wavelengths downstream of the trailing edge. At seven wavelengths downstream, diffusion appears to be the only dominant mechanism for mixing, see Figs. 8b and 8c. The surface flow pattern upstream of the trailing edge of the triangular mixer also indicates no flow diversion towards the lobe trough region, see Fig. 9c. Thus, the present visualization tests have clearly demonstrated that the dominant effects of the straight parallel sidewalls to the mixing performance downstream of the lobed mixer trailing edge.

It should also be pointed out here that there are actually some differences between the results shown here and the results obtained with a velocity ratio across the lobe. The visualization tests of McCormick et al. (1994) at a velocity ratio of 0.6 showed that the (radial) vortex lines shed from trailing edge are not parallel to the trailing edge. They are actually inclined at about an angle similar to the penetration angle of the lobe. As the flow travels further downstream, the vortex lines are distorted by the formation of streamwise vorticity (i.e. the pinched-off effects). McCormick et al. (1994) attributed the intense mixing has strong correlation with this pinched-off effects. The LDA measurements of Yu and Yip (1997) further suggested that the downstream interactions of the (radial) vortex lines and the streamwise vorticity are the main cause of intense mixing in the cases of higher velocity ratio.

4. Concluding Remarks

Visualization tests of the wake region behind forced lobed mixer with different trailing edge configurations have been performed using the smoke-wire technique. The followings are main findings.

1) Within four wavelengths downstream of the trailing edge, a pair of contra-rotating vortices is formed at each lobe in the cases of the square and semi-circular lobed mixers. Similar observation, however, is not found in the case of the triangular lobed mixer. The results agree favorably with the quantitative velocity measurements obtained by the authors.
2) No indications of vortex breakdown can be found within seven wavelengths downstream of the trailing edge for the three configurations of lobed mixer. The decay of the streamwise vortices and turbulent diffusion appear to be the main mechanism responsible for intense mixing.
3) The dominant effects of the straight parallel sidewalls of the lobe geometry to the mixing performance downstream of the trailing edge are also confirmed.

Acknowledgments

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