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# Experimental Investigation of Lobed Mixer Performance

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**An experimental study has been conducted to investigate the effect of the geometrical parameters of the lobed mixers on the process of mixing. The height, wavelength, and penetration angle of the lobed mixers were varied to study its effect on the mixing process downstream the trailing edge. A mixedness parameter has been defined to assess quantitatively extent of mixing. Fluid velocity components, static pressure, and wall static pressures were measured for different velocity ratios at several cross sections distributed along the axial direction downstream of the trailing edges. The results showed that the mixedness of the lobed mixer increases with the increase of penetration angle and reaches a maximum value at a penetration angle of 20 deg. It also increases with the increase in lobed mixer height and reaches a maximum value when the height becomes equal to the wavelength. However, increasing the wavelength slightly decreases lobed mixer mixedness at the vicinity of the trailing edge. At a far distance, mixedness shows a slight increase with the increase of the wavelength. The effects of geometrical parameters on the mixedness were similar for the tested velocity ratios. The improvement in the mixing process is attributed to the enhancement of large-scale streamwise vortices generated downstream of the trailing edge. The effect of streamwise vortices was identified as producing convective transport in the crossflow plan, which increases the mean fluid interface area, thus leading to mixing enhancement.**

## Nomenclature

$A$ = mixing duct cross-sectional area
$H$ = mixing duct height
$h$ = lobed mixer height
$M$ = mixedness
$U$ = measured axial velocity
$U_1$ = inlet high stream velocity
$U_2$ = inlet low stream velocity
$\bar{U}$ = average of inlet velocities
$u'$ = perturbation of axial velocity
$w$ = lobed mixer wavelength
$x$ = axial distance downstream trailing edge of lobed mixer
$y$ = vertical distance measured from upper wall of test section, Fig. (10a)
$\alpha$ = lobed mixer penetration angle
$\Delta U$ = inlet velocity difference

## Introduction

THE lobed mixer is an effective device for mixing two coflowing streams of different velocities, temperatures, and/or species. It consists of a splitter plate with a convoluted trailing edge, as shown in Fig. (1a), which alternately turns the upper and lower streams into the lobe troughs. Because of these convolutions, strong streamwise vortices are shed at the trailing edge resulting in periodic streamwise vortices in the downstream mixing field. The streamwise vortices develop into an array of counter-rotating large-scale vortices, which are believed to be primarily responsible for the enhancement of mixing process.

Because of the remarkable performance of lobed mixers, they are extensively used in many applications, for example, in jet engines to improve mixing of the exhaust jets and to reduce jet noise level. In turbofan engines, significant performance gains (thrust and specific fuel consumption) are achieved at various flight conditions by using lobed mixers to mix the hot core stream with the cooler fan stream before expansion through the exhaust nozzle. A significant increase in both pumping and thrust augmentation of low-pressure ratio ejector systems was obtained by using lobed mixers. The use of lobed mixer in an ejector system results in nearly complete mixing in very short ejector duct length and allows the use of aggressive diffuser designs without stall. In chemical industries, lobed mixers are used to enhance mixing between reactants.

Therefore, lobed mixers have been the subject of many studies. A number of studies were carried out to compare performances of lobed mixers with those of other mixing devices, for instance, the studies performed by Kozlowski and Kraft,[1] Kozlowski and Larkin,[2] Kuchar,[3] and Shumpert.[4] Those studies showed that lobed mixers were more effective in promoting mixing for the same length of mixing duct than other tested configurations. Abolfadl and Sehra[5] investigated the lobed mixer effect on mixing of turbine and fan exhausts in turbofan engines. Paterson[6] and Povinelli and Anderson,[7] to understand the relation between the mixing enhancement and the lobed mixer configuration, measured the total temperature and total pressure distributions downstream of lobed mixers. The flowfield downstream of the trailing edge of a lobed mixer was measured using a laser Doppler velocimeter (LDV) by Eckerle et al.[8] and Yu and Yip.[9] A flow visualization technique was used by Driscoll[10] to investigate flow structure downstream of lobed mixers. The effects of inlet conditions such as boundary-layer thickness and velocity ratio on the strength of the streamwise vortices were investigated by Yu et al.[11] and Sullivan et. al.[12] The results indicate that flow separation occurs for penetration angles higher than 22 deg. In addition, the influence of the velocity ratios on the mixing process downstream the trailing edge of a lobed mixer was investigated by Belovich and Samimy.[13] An experimental and numerical study was conducted by Abolfadl[14] to establish a procedure for optimizing the design of lobed mixers used for high-bypass-ratio turbofan engines. Mixing characteristics of scalloped lobed mixers were investigated by Yu et al.[15] Scalloping and scarfing effects on the performance of the lobed mixer were investigated recently by Yu et al.[16] The results indicate that scalloping the mixer lobes enhances the mixing process.

Although the published studies indicate that the lobed mixer geometry has significant effect on its performance, there are limited

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experimental studies to address quantitatively the effect of lobed mixer geometrical parameters on the mixing process. Therefore, an attempt has been made, in this work, to quantify experimentally the effect of lobed mixer main geometrical parameters (height, wavelength, and penetration angle) on the mixing process downstream of the lobed mixers. For comparison, the mixing downstream of a flat-plate splitter and convoluted plate Fig. (1b) were evaluated, as well. These geometrical parameters are shown in Fig. (1c).

It is not the objective of this paper to offer a detailed physical description of the flowfield structure downstream of the mixer trailing edge. Rather, the emphasis is on the overall performance evaluation for sets of lobed mixers with different geometry.

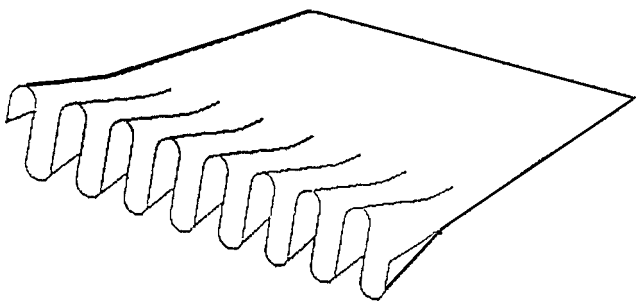

**Fig. 1a Schematic of a lobed mixer.**

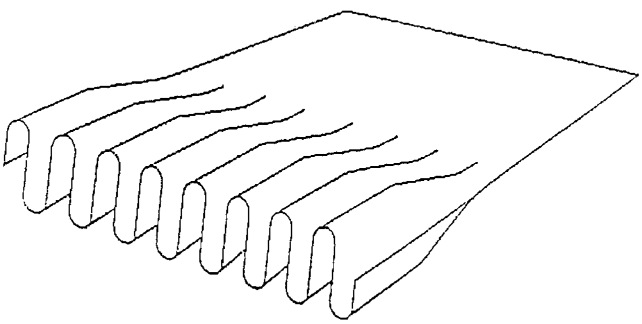

**Fig. 1b Schematic of a convoluted plate.**

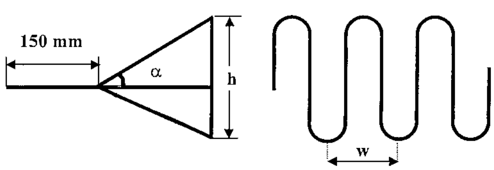


**Fig. 1c Lobed mixer geometry.**

## Experimental Technique

### Test Facility

The study has been conducted using the test rig shown in Fig. 2. The main components of the test rig are a blower, a diffuser, a plenum, wind tunnels, and a mixing duct (test section). A variable-speed centrifugal air blower is used to supply a sufficient amount of air to the mixing duct. The air is supplied to the air plenum through a three-dimensional straight wall diffuser with an angle of 15 deg. The plenum has a cross section of 400 × 450 mm. It is provided with two overflow valves for air regulation. After the air plenum, the tunnel is divided into two-equal cross-sectional area tunnels. An adjustable flat-plate flap is installed at the inlet of the tunnels to help adjust the flow speed. Each tunnel has a height of 225 mm and a width of 400 mm. The tunnels are provided with a square-mesh (20 × 20 mm) flow straighter to enhance flow uniformity at the inlet to the mixing duct. The straighter dimensions were selected based on American Society of Mechanical Engineers (ASME)[17] recommendation. Three-dimensional bell mouth entrance of smooth walls and corners, followed by a nozzle with area reduction of more than three to one are connected to the exit of each tunnel to reduce the tunnel areas to the required mixing duct area and to minimize the boundary-layer thickness at the inlet to the mixing duct. Straight constant-area ducts (throat) are installed between nozzle exits and mixing duct. The throat length was selected according to ASME[17] specifications to ensure flow uniformity and to maintain low-turbulence level at the mixing duct inlet. The prescribed test rig components are made from 2-mm galvanized steel sheets. The rectangular cross section mixing duct is made from Plexiglas®. The mixing duct has a constant width of 300 mm, whereas its height was varied to ensure a constant ratio of gap-to-lobed mixer height. Based on the heights of lobed mixers, the mixing duct height was changed from 120 to 200 mm. Variation of mixing duct height was accompanied with replacement of the nozzle and throat. Accordingly, the nozzle area ratio was varied from 3:1 to 5:1 according to lobed mixer heights. This contraction ratio was large enough to produce uniform core flow with a relatively low-turbulence level. Static pressure taps were installed along the central plan of upper and lower walls of the mixing duct. The lobed mixers are fixed horizontally at inlet along the axis of the mixing duct.

### Lobed Mixers

To study the effect of lobed mixer geometry on the momentum mixing process, sets of lobed mixers, having different geometrical parameters (height, wavelength, and penetration angle) are manufactured from 1-mm stainless steel. Figure 1c shows these parameters and Table 1 lists the values for the tested lobed mixers. These tested mixers can be classified into three sets. Representing the first set are mixers 1, 2, and 3 with constant wavelengths and penetration angles at 30 mm and 20 deg, respectively, with heights of 45, 60, and 75 mm. Mixers 3, 4, and 5 represent the second set with a constant

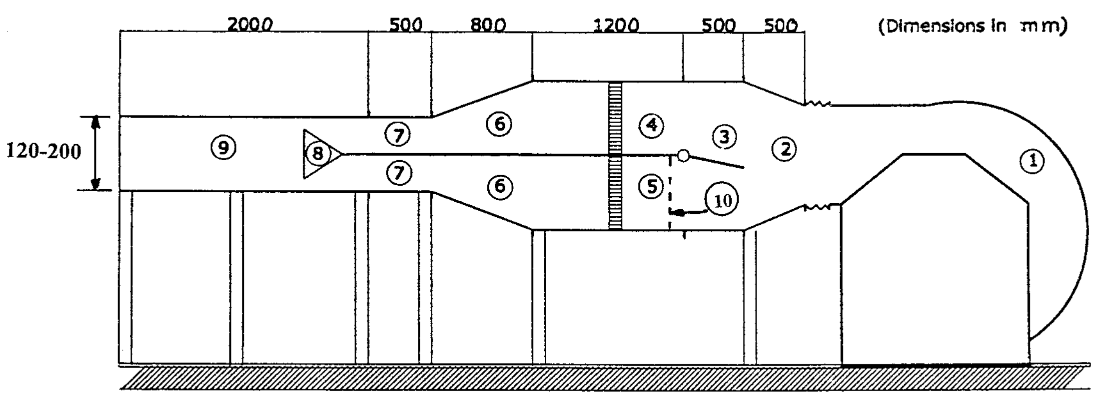


**Fig. 2 Schematic of test rig: 1, blower; 2, diffuser; 3, plenum; 4, tunnel; 5, tunnel; 6, nozzle; 7, throat; 8, lobed mixer; 9, mixing duct; and 10 screen.**

**Table 1 Lobed mixers geometrical parameters**

| Lobed mixer no. | Height $h$ mm | Wavelength $w$ mm | Penetration angle $\alpha$, deg |
|---|---|---|---|
| 1 | 45 | 30 | 20 |
| 2 | 60 | 30 | 20 |
| 3 | 75 | 30 | 20 |
| 4 | 75 | 60 | 20 |
| 5 | 75 | 50 | 20 |
| 6 | 75 | 50 | 15 |
| 7 | 75 | 50 | 25 |

height of 75 mm and a constant penetration angle of 20 deg and the wavelength varies from 30 to 60 mm. In the third set, mixers 5, 6, and 7, have constant height of 75 mm, constant wavelength of 50 mm, and variable penetration angles of 20, 15, and 25 deg. Each set has two constant parameters while the third parameter is varied to investigate its effect on the mixing process.

### Test Conditions

To study the momentum mixing downstream of the lobed mixers, the flow velocities at the inlets of the lobed mixers were varied. The velocity variation was achieved by installing screens and wire meshes at the entrance of the low-speed wind tunnel. The fine adjustment of flow speeds was achieved by adjusting the flap sheet installed at the entrance of the wind tunnels. The flow velocity in the upper tunnel was kept at a constant value of 40 m/s (known as the high stream velocity $U_1$), which corresponds to a Mach number of 0.117. Reynolds number varies from $8.2 \times 10^4$ to $1.64 \times 10^5$ (based on the wavelength of the tested mixer). The stream velocity in the lower tunnel was varied from 14 to 26 m/s, (known as low stream velocity $U_2$), which resulted in a Reynolds number range from $2.7 \times 10^4$ to $1.07 \times 10^5$. According to Yu et al.,[15] the lobed mixer performance becomes independent of the Reynolds number after a value of $1.2 \times 10^4$. As a result, the selected velocity ratios ($U_2/U_1$) at the lobed mixer inlets were 0.36 and 0.66. The inlet stream velocities were monitored during measurements to ensure its steadiness. All measurements were carried out at room temperature of $20 \pm 2°$C.

### Experimental Method

A calibrated 5-mm-diam spherical-head five-hole probe was used to measure the velocity components, static pressure, and flow directions in the mixing duct. The probe was mounted on a two-dimensional traversing mechanism with an accuracy of ±0.1 mm. A pressure transducer was used to measure probe pressure heads. It has an accuracy of 0.025% full scale and is equipped with a temperature compensation unit to account for the temperature variations during the measurements. The operating range of the transducer was set at 600-mm water to achieve an accuracy of ±0.15 mm water. The pressure transducer was connected to a 20 channels pressure scanning box. The pressure transducer output signals are fed to a computerized data acquisition system. Flowfield velocity components were determined and stored electronically. The measurements were conducted at eight cross sections downstream of the lobed mixers and distributed along the mixing duct axis as shown in Table 2. The measurements covered the entire cross-sectional area with 5-mm distance apart. The axial velocity component was used to calculate mixedness at each cross section. Ali[18] describes details of velocity components calculations.

To minimize sidewalls effects, measurements presented in this work are those taken for the three inner most lobes. There were at least seven lobes scanned by the five-hole probe for each configuration. Note that, although sidewalls effect was found to be minor, it exists for all tested mixers, and the objective here is to carry out a comparative and parametric study for the tested mixers.

### Mixedness

To assess quantitatively the effect of a lobed mixer on mixing, it was necessary to define an overall measure for mixing. As a measure

**Table 2 Distribution of measurement cross sections along the axis of the mixing duct**

| Cross section | Downstream distance $x$, mm |
|---|---|
| 1 | 00 |
| 2 | 150 |
| 3 | 300 |
| 4 | 450 |
| 5 | 700 |
| 6 | 950 |
| 7 | 1200 |
| 8 | 1450 |

of the momentum mixing, it is proposed here to utilize an integrated mixedness parameter $M$ that depends on axial velocity perturbation. When an approach similar to that adapted by Yuan[19] is followed, momentum mixedness may be defined as follows:

$$M = \frac{1}{A}\int\left[1-\left(\frac{2u'}{\Delta U}\right)^2\right]\mathrm{d}A \qquad (1)$$

where $\Delta U$ is the axial velocity difference of the unmixed steams. It is given by

$$\Delta U = U_1 - U_2 \qquad (2)$$

In Eq. (1), $u'$ is the axial velocity perturbation and is given by

$$u' = U - \bar{U} \qquad (3)$$

where $U$ is the measured axial velocity downstream of the trailing edge of the lobed mixer. $\bar{U}$ is the average of the inlet velocities, which also represent the full mixing velocity. It is given by

$$\bar{U} = (U_1 + U_2)/2 \qquad (4)$$

The mixedness parameter $M$ has a form similar to that commonly used for scalar mixedness. However, it is physically sounder to take the integral of velocity squared (as a measure of momentum) rather than the integral of its absolute value.[19] Note that mixedness will be zero if the value of measured axial velocity is equal to the value of either of the stream velocities, which indicates no mixing. However, for complete mixing, the perturbation velocity will be zero and mixedness will be one. Based on the accuracy of the instrumentation, error analysis results indicate that the accuracy of mixedness is ± 2.5%. Ali[18] presents details of these error analyses.

## Results and Discussion

### Wavelength Influence

Figure 3 shows the variations of the momentum mixedness downstream of the trailing edge of the lobed mixers having different wavelengths (30, 50, 60 mm) at a velocity ratio ($U_2/U_1$) of 0.36. Figure 3 indicates that the momentum mixedness increases continuously in the downstream direction. The variation of the mixedness along the axial distance can be divided into three zones: First zone with $x/h \le 4$, second zone with $4 \le x/h \le 6$, and third zone $x/h > 6$. In the first zone, the momentum mixedness rapidly increases with the axial distance. This is attributed to the rapid mixing created by the evolution of large-scale streamwise vortices generated by the lobed mixer. In the second region, where $4 \le x/h \le 6$, the momentum mixedness increases at a relatively lower rate than the first zone. In this zone, the flow is characterized by stream contraction and vortex intensification in which a wake sheet is rolled up into the core, which drives the mixing. This results in a lower rate of momentum mixing. In the third zone, where $x/h > 6$, the vortex cores are broken down resulting in nearly complete mixing of the two streams. In this zone, the mixing is driven mainly by local diffusion. This results in a slight increase of the mixedness reaching an asymptotic value of fully mixed streams. These results agree with the conclusion of the study conducted by Werel and Paterson.[20] Figure 3 also indicates that, for $x/h \le 4$, the lobed mixer with small wavelength

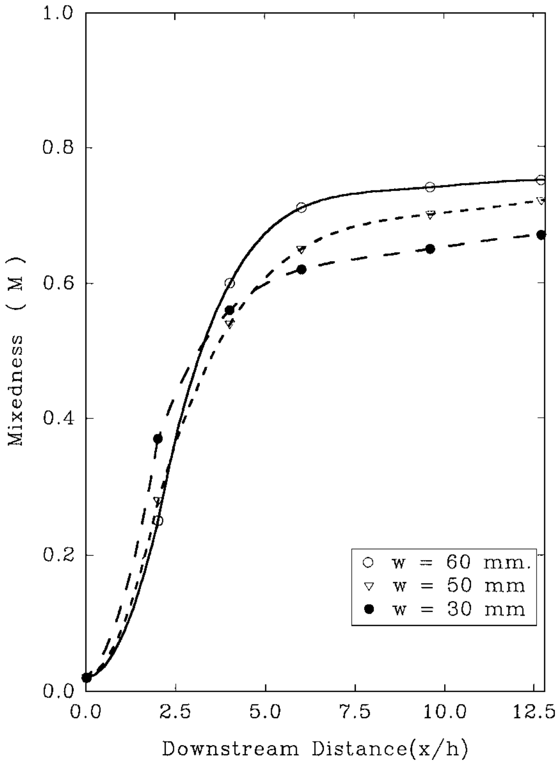


**Fig. 3 Variation of mixedness along the axial direction for different wavelengths at $U_2/U_1 = 0.36$.**

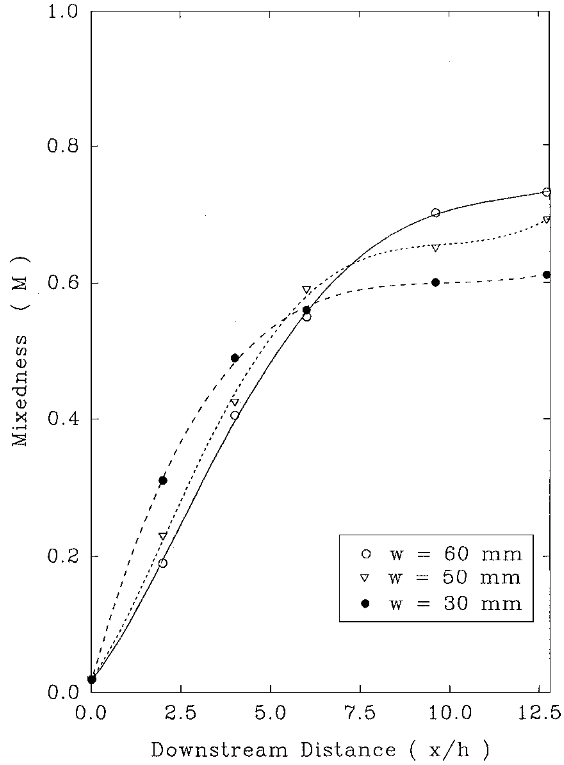


**Fig. 5 Variation of mixedness along the axial direction for different wavelengths at $U_2/U_1 = 0.66$.**

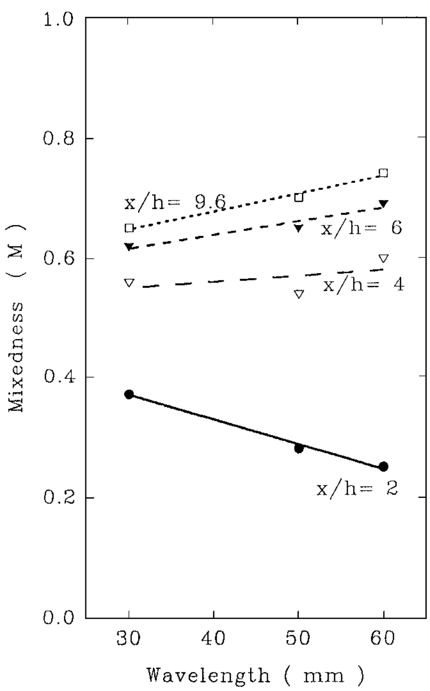


**Fig. 4 Variation of mixedness with the wavelength at different axial locations at $U_2/U_1 = 0.36$.**

offers better mixing than the ones with larger wavelength. This indicates that the momentum mixedness is reduced with the increase of the wavelength, whereas, for $x/h < 6$, the trend is reversed because the mixedness for the smaller wavelength mixer is lower. This can clearly seen in Fig. 4, which shows the variation of the momentum mixedness with the tested lobed mixers wavelength. These results agree with the conclusion of the theoretical study conducted by Yuan.[19]

At a higher velocity ratio ($U_2/U_1 = 0.66$), the variation of the momentum mixedness along the axial direction for different wavelengths is shown in Fig. 5. Momentum mixedness variation shows a similar behavior to that shown in Fig. 3. Comparison of Figs. 3 and 5 indicates that the momentum mixedness reaches maximum value at $x/h \cong 12$ for a velocity ratio of 0.66 and at $x/h \cong 7$ for velocity ratio of 0.36. This indicates that the distance required achieving approximately complete mixing increases with the increase of the velocity ratio between the two inlet streams.

### Penetration Angle Influence

Figures 6–9 show mixedness for various penetration angles. The momentum mixedness along the axial direction downstream of the trailing edge of lobed mixers with different penetration angles is shown in Figs. 6 and 8 for velocity ratios of 0.36 and 0.66, respectively. The results of a flat-plate splitter are presented in Figs. 6 and 8 for comparison. Note that the penetration angle of the flat-plate splitter is zero. Figures 6 and 8 show continuous increase of the momentum mixedness as the mean fluid moves downstream. At the beginning, the mixedness increases rapidly because of large-scale streamwise vortices. Farther downstream, the changes in mixing rate become negligible. Variation of the mixedness with the penetration angle is shown in Figs. 7 and 9 for different velocity ratios of 0.36 and 0.66. Figures 7 and 9 show mixedness at different distances from the trailing edge and indicate that mixedness increases in the downstream direction for all tested angles. It could easily be concluded from Figs. 7 and 9 that the mixedness increases with the increase of the penetration angle and reaches maximum at an angle of 20 deg. It is believed that the increase of the penetration angle is accompanied by stronger streamwise vortices, which enhance the mixing process. However, at angles higher than 20 deg, flow separation occurs and results in poor mixing. To demonstrate that, Fig. 10a shows the variation of measured total pressure at the exit plane for mixer 7, which has a penetration angle of 25 deg. These measurements were taken at plane BB, shown in Fig. 10b. The zone of separation is shown in Fig. 10a next to the mixer wall into the low stream region.

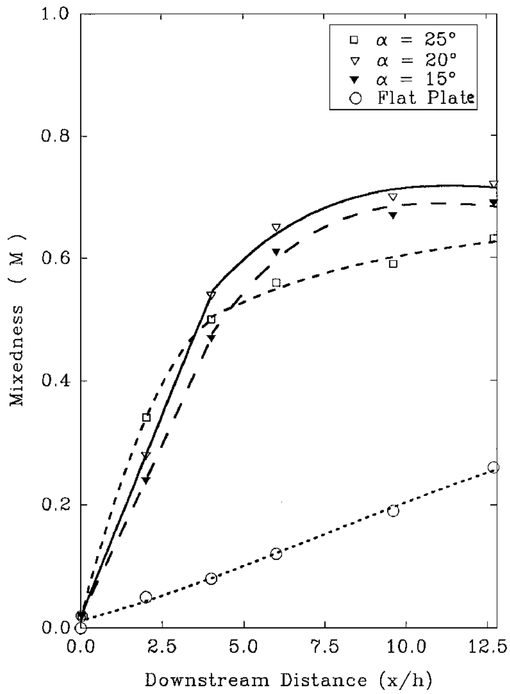


**Fig. 6 Variation of mixedness along the axial direction for different penetration angles at $U_2/U_1 = 0.36$.**

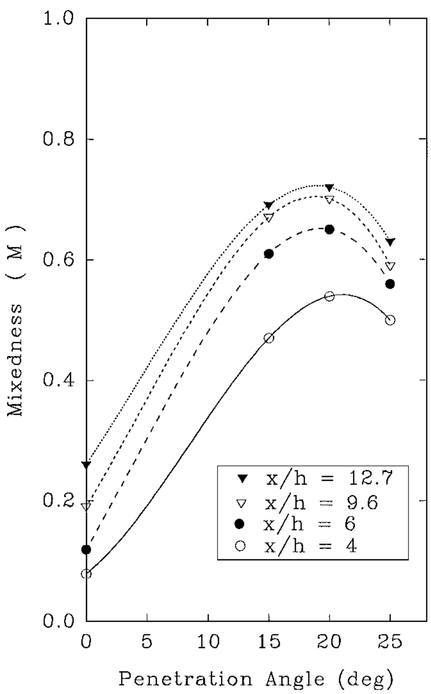


**Fig. 7 Variation of mixedness with the penetration angle at different axial locations at $U_2/U_1 = 0.36$.**

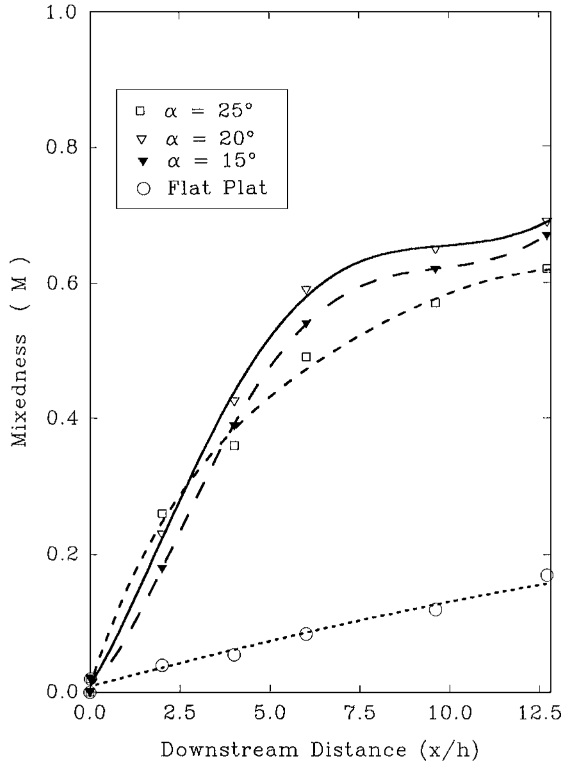


**Fig. 8 Variation of mixedness along the axial direction for different penetration angels at $U_2/U_1 = 0.66$.**

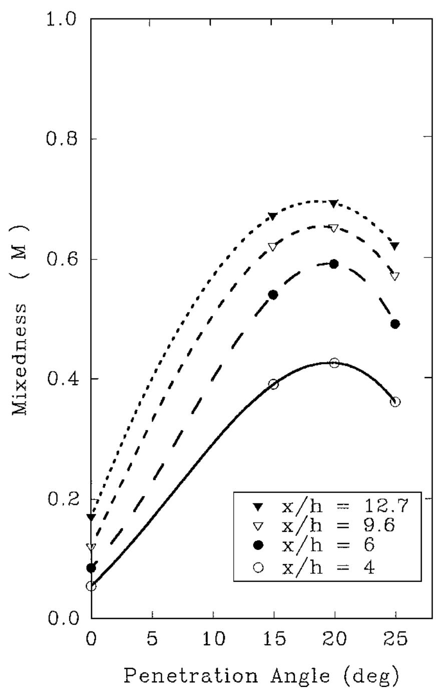


**Fig. 9 Variation of mixedness with the penetration angle at different axial locations at $U_2/U_1 = 0.66$.**

### Height Influence

Figures 11–14 show variation of mixedness for different height: The variation of mixedness in the downstream direction of the trailing edge for lobed mixers 1, 2, and 3 and the flat-plate splitter are shown in Figs. 11 and 13 at two velocity ratios of 0.36 and 0.66, respectively. For both velocity ratios, the variation pattern is similar right after the trailing edge; the mixing rate has higher values, which then decrease farther downstream. For the tested lobed mixers, the mixedness decreases with the decreases of the lobe height. Figures 12 and 14 present the variation of mixedness with the lobed mixer height at different distances downstream of the trailing edge and for velocity ratios of 0.36 and 0.66, respectively. Again, the flat plate splitter is considered as a lobed mixer with zero height. Figures 12 and 14 reveal that the optimum value of mixedness is obtained at $h/w = 1$, approximately. To confirm this conclusion, an additional lobed mixer having $h/w = 0.83$ was tested at a velocity ratio of 0.36.

### Influence of Streamwise Vortices on Mixing

To study the effect of streamwise vortices generated downstream of the trailing edge of the lobed mixer on the mixing process, the

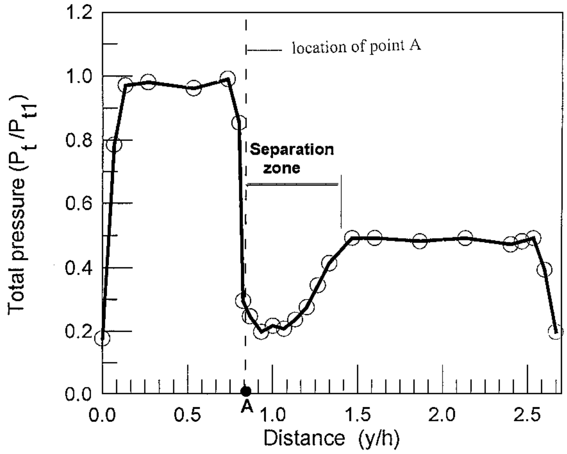


**Fig. 10a Total pressure variation along line BB of Fig.10b at mixer exit plane with $U_2/U_1 = 0.36$ for lobed mixer 7.**

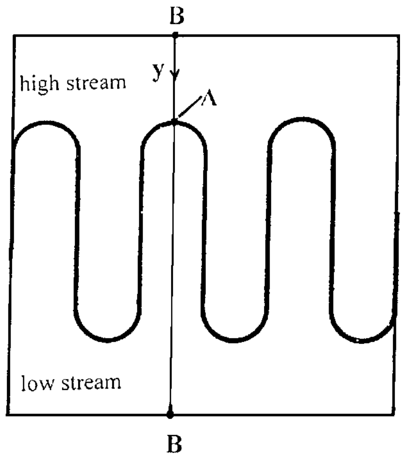


**Fig. 10b Cross-sectional view of test section at exit plane of mixer 7.**

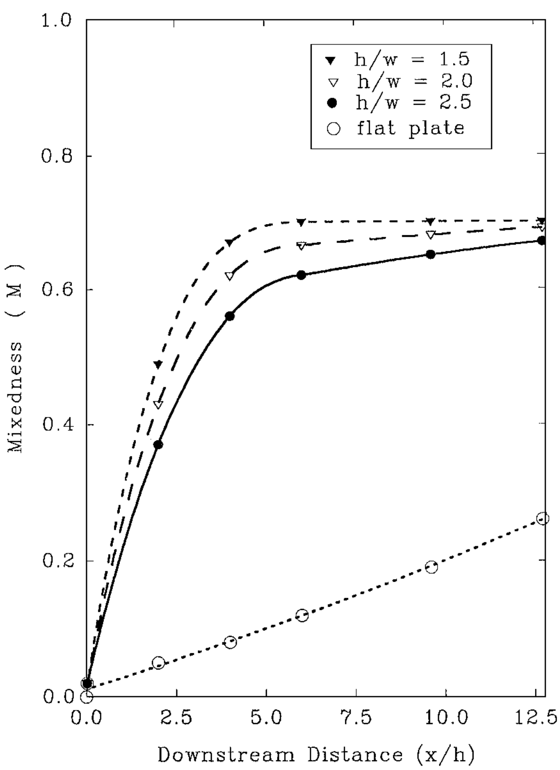


**Fig. 11 Variation of mixedness along the axial direction for different heights at $U_2/U_1 = 0.36$.**

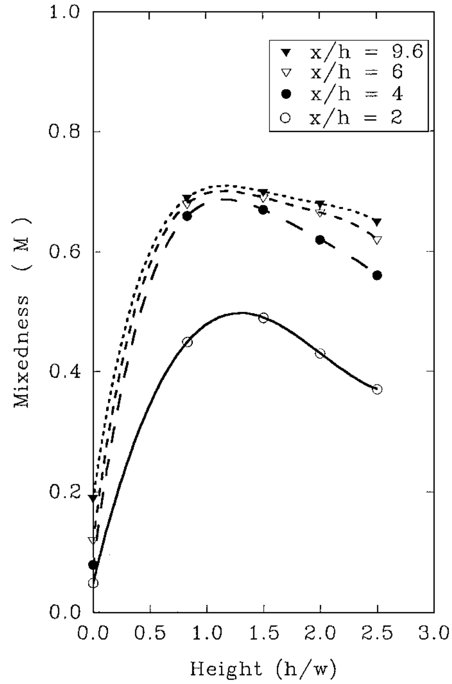


**Fig. 12 Variation of mixedness with the height at different axial locations at $U_2/U_1 = 0.36$.**

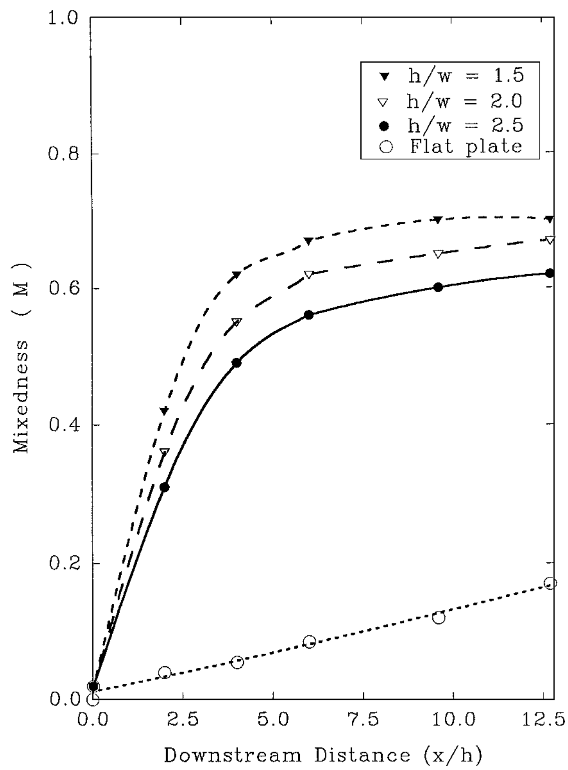


**Fig. 13 Variation of mixedness along the axial direction for different heights at $U_2/U_1 = 0.66$.**

momentum mixedness downstream a flat-plate splitter and a convoluted plate were tested for comparison. A convoluted plate (Fig. 1b) has a geometrical parameter of 50 mm wavelength, has a height of 75 mm, and is similar to the trailing-edge geometry of the lobed mixer 5 (see Table 1). The flat-plate splitter was manufactured from galvanized steel and has a thickness equal to that of both the lobed mixer and the convoluted plate. The parallel extension of the convoluted plate at the trailing edge makes the flow at the trailing

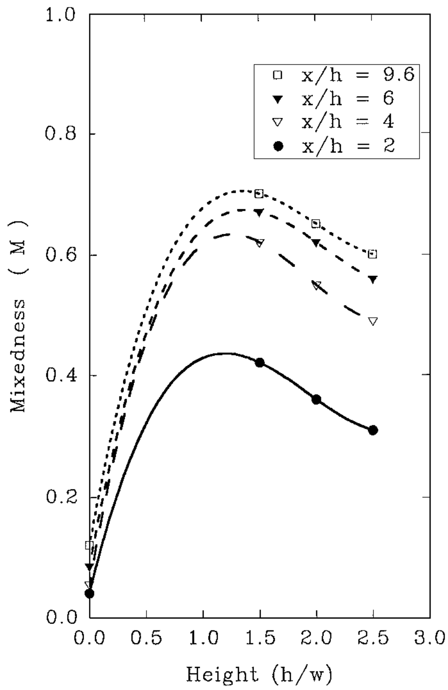


**Fig. 14 Variation of mixedness with the height at different axial locations at $U_2/U_1 = 0.66$.**

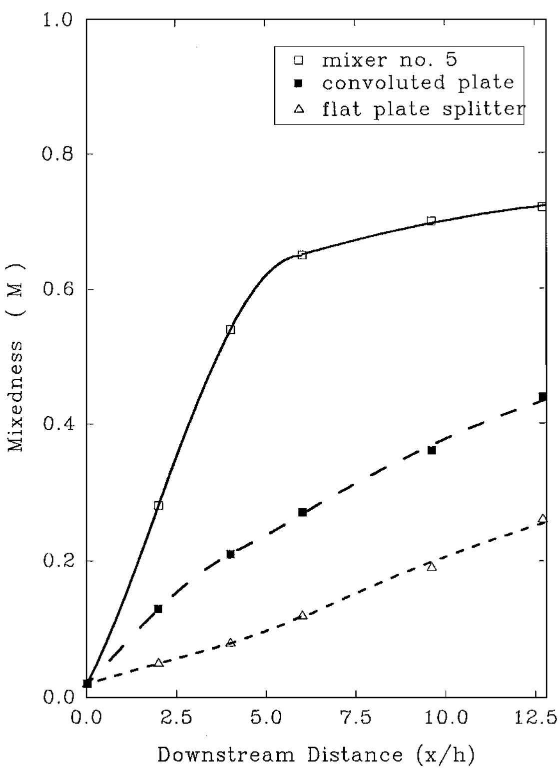


**Fig. 15 Variation of mixedness along the axial direction for different mixing devices at $U_2/U_1 = 0.36$.**

edge essentially parallel, such that there is a very limited streamwise vortex shed downstream.

Figures 15 and 16 represent the variation of the momentum mixedness along the axial direction for the lobed mixer 5, the convoluted plate, and the flat-plate splitter for two velocity ratios of 0.36 and 0.66, respectively.

The mixer total pressure loss is defined as the difference between the measured total pressure loss with mixer installed and the total pressure loss measured when mixer is removed. Percent total pressure loss was the difference between the area average total pressure

**Table 3 Percent total pressure loss measured at exit of mixing duct as a percentage of area average total pressure at mixer inlet plane, for a velocity ratio of 0.36**

| Lobed mixer number | % Total pressure loss |
|---|---|
| 1 | 2.41 |
| 2 | 2.52 |
| 3 | 2.78 |
| 4 | 2.10 |
| 5 | 1.89 |
| 6 | 2.02 |
| 7 | 3.13 |

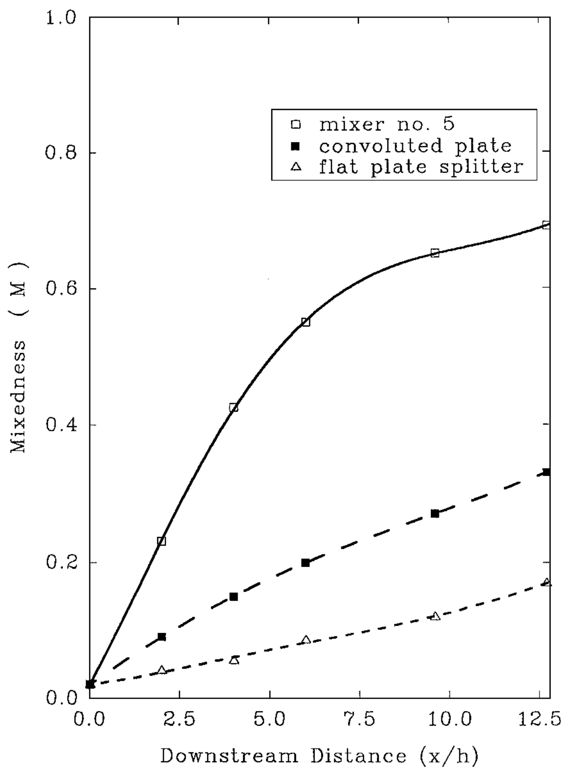


**Fig. 16 Variation of mixedness along the axial direction for different mixing devices at $U_2/U_1 = 0.66$.**

at the mixer inlet plane and that at the mixing duct exit plane divided by the area average total pressure at the mixer inlet. Table 3 shows the measured percent total pressure loss for the tested mixers identified in Table 1.

Mixer 5 was considered in this comparison because it offers the highest mixedness value and minimum pressure loss among all tested mixers. The results indicate that the lobed mixer has the highest mixedness, whereas the flat-plate splitter has the lowest value. This demonstrates the strong effect of streamwise vortices on enhancing the mixing process. The significant difference between the momentum mixedness of the three mixing devices can be attributed to the difference in the main mechanism of the mixing process. The mixing mechanism of the flat-plate splitter and the convoluted plate depends on the conventional perturbed free shear layer shed from its trailing edge. However, the tall trailing edge of the convoluted plate enlarges the shearing layer, which results in a better mixing. On the other hand, the mixing due to the lobed mixer depends on the streamwise vortices shedding from its trailing edge, in addition to the conventional free shear layer of streamwise vortices. Accordingly, the momentum mixedness of the lobed mixer is significantly higher. It could be concluded from these figures that the lobed mixer could achieve mixedness of 90% of theoretical value. These results satisfactory agree with the conclusion of the theoretical study of Yuan.[19] The results also indicate that complete mixing is achieved at a downstream distance of 6.0–7.0 of lobed mixer height. The momentum mixedness of the flat-plate splitter and the convoluted plate show continuous increase over the tested range, which suggests that complete mixing downstream the lobed mixer requires a much shorter distance. The results also show that the mixedness of the lobed mixer is twice that of the convoluted plate and four times the value of a flat-plate splitter, which demonstrates the superiority of the lobed mixer compared to the other mixing devices.

## Conclusions

An experimental study has been conducted to study the effect of lobed mixer height, wavelength, and penetration angle on the mixing process. For comparison a flat-plate splitter and convoluted plate were also tested. To assess quantitatively the mixing capabilities of these devices, a momentum mixedness parameter is defined. Test results are presented to indicate the variation of the mixedness with the tested geometrical parameters downstream of the trailing edge. The results reveal the following.

1) Mixedness increases continuously in the downstream direction. The rate of increase is comparably higher in the zone of streamwise vortices, where most of the mixing takes place.

2) Mixedness increases with the increase of the lobed mixer height, reaching its maximum at a height-to-wavelength ratio of one.

3) Mixedness increases with the increase of lobed mixer penetration angle, reaching its maximum at a lobed mixer angle of 20 deg.

4) Mixedness decreases with the increase of wavelength in the vicinity of the trailing edge, whereas it increases with increase of the wavelength far away from the trailing edge.

5) Lobed mixer offers superior performance compared to the convoluted plate and flat-plate splitter, which reflects the significant effect of the streamwise vortices, generated downstream of the trailing edge of the lobed mixer on the mixing process.

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