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Mixing Processes in a Coaxial Geometry with a Central Lobed Mixer-Nozzle

V. M. Belovich* and M. Samimy†
Ohio State University, Columbus, Ohio 43210

An experimental investigation was undertaken to study mixing processes in a coaxial jet, where the inner jet geometry is a lobed mixer. Various inner jet nozzle geometries were explored at three velocity ratios (3:1, 1:1, and 1:3, inner:outer). Detailed flow visualizations were performed and have been reported elsewhere. Results of velocity measurements of one of the nozzles that generates strong streamwise vortices are presented. Three components of velocity were measured using the laser Doppler velocimetry (LDV) technique. The LDV data, when taken in combination with flow visualizations, revealed different mixing mechanisms for each velocity ratio. The 3:1 ratio behaved similarly to a single jet, with the structures due to the Kelvin–Helmholtz instability and the streamwise vortices interacting together to substantially enhance mixing. The 1:1 velocity ratio, which minimizes the Kelvin–Helmholtz instability, relied mainly on the streamwise vortices to also substantially increase mixing. The 1:3 case behaved like a wake flow, with the LDV data showing the streamwise vortices much more confined radially and dissipating quickly. The inner stream, for this case, was greatly influenced by the outer stream and its interaction with the ambient air.

Introduction

LOBED mixers are passive mixing-enhancement devices, generally used to efficiently mix two different flow streams. In a two-dimensional flow geometry, they are essentially splitter plates with convoluted trailing edges. The periodic convolutions, or lobes, induce alternately directed, secondary velocities, perpendicular to the mean flow direction. The secondary velocities quickly evolve into periodic streamwise vortices of alternating sign and of a scale comparable to the half-width of the lobe. It is the presence of the large-scale streamwise vortices that is generally believed to be responsible for the enhanced mixing. The present study focuses on an axisymmetric lobed mixer.

Paterson[1] studied axisymmetric lobed nozzles by taking pressure, temperature, and velocity measurements. It was found that the streamwise vortices were of low intensity but large scale and formed due to the secondary flow induced by the nozzle shape. Werle et al.[2] found that the vortex formation process was an inviscid one, taking place in three basic steps: the vortices form, intensify, and then rapidly break down into smaller scale turbulence.

Barber et al.[3] confirmed the inviscid nature of the streamwise vortex formation process and also found that the boundary layers formed in the lobe trough regions have a large impact on the strength of the streamwise vortices. Thicker boundary layers reduce the effective lobe height and, therefore, reduce circulation. Eckerle et al.[4] found that the breakdown of the vortices was accompanied by a significant increase in turbulent mixing, confirming the results of Werle et al.[2] However, Yu et al.[5] did not notice this increase for a 1:1 velocity ratio but did for velocity ratios of 1:2 and 1:3.

The work of Manning[6] (summarized in Ref. 7) showed that there are three primary contributors to the mixing processes in lobed mixers. The first is the Brown–Roshko type structures, which occur in free shear layers due to the Kelvin–Helmholtz instabilities. In the context of lobed mixers, they are called normal vortices. The second is the increased interfacial contact area due to the convoluted trailing edge of the lobed mixer. The last element is the streamwise vortices produced by the lobed mixer. Manning[6] found that at a velocity ratio of 1:1, the increased mixing is due mainly to the increased contact area, whereas the streamwise vortices have the larger role at a velocity ratio of 2:1. Belovich et al.[8] showed similar results for an axisymmetric lobed nozzle.

McCormick[9] and McCormick and Bennett[10] showed that it is the interaction of the normal vortex with the streamwise vortices that produces the high levels of mixing. As the normal vortex sheds from the trailing edge of the lobed mixer, the streamwise vortices deform it until it is eventually pinched off and subsequently broken down as it advects downstream. Turbulence measurements showed regions of high-turbulence kinetic energy that were consistent with the flow visualizations of the pinch-off effect.

The present work is a continuation of a study of an axisymmetric, coaxial, freejet geometry, where the central jet is a lobed mixer nozzle. Through a combination of flow visualization and laser Doppler velocimetry (LDV) measurements, the details of the mixing processes for different nozzle geometries and flow conditions are explored. Comparisons between the flow visualization results of the different nozzles have been reported elsewhere in Ref. 8. This study focuses on the different mixing processes induced by the different velocity ratios, by presenting velocity results for one of the six-lobed nozzles. Further details for other nozzles can be found in Refs. 11 and 12.

Experimental Setup

The experiments for this work were conducted at the Aeronautical and Astronautical Research Laboratory at Ohio State University. The air supply for the tests was provided by two four-stage compressors, then stored in two tanks of 42.5 mm^3 (1500 ft^3) volume at pressures up to 16.9 MPa (2450 psi). The air is throttled through several valves and plumbed to two separately metered branches that supply the central jet flow and the outer annular flow. Figure 1 shows a scale cross-sectional view of the exit plane. The central jet is the lobed mixer and the outer circle represents the coaxial outer flow (63.5 mm i.d.).

A two-component, coincident, fiber-optics-based LDV system was used to collect velocity data. The light source was a Spectra-Physics model 2020-05, 5-W argon ion laser, and the signal analyzer was a TSI Model IFA 750. The probe volume was approximately 110×1100 μm. Directional ambiguity was eliminated by frequency shifting each component at 40 MHz. Generally, 4096 data points were taken for each location. However, at the outer radial locations where the seed density dropped off, occasionally only 1024 points were taken. Seeding was implemented by atomizing olive oil in a

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*Graduate Student, Department of Mechanical Engineering, Air Force Palace Knight Program; currently Research Engineer, Combustion Branch, U.S. Air Force Wright Laboratory, Wright–Patterson Air Force Base, OH 45433. Member AIAA.

†Professor and Associate Chair, Department of Mechanical Engineering. Associate Fellow AIAA.

TSI model 9309 atomizer, producing particles generally less than 1 μm diameter. The LDV probe was rotated in order to measure the third components of the velocity. For details see Ref. 11.

Results and Discussion

Velocity results are presented for a lobed nozzle with ramp angles of 20 deg, which is shown to produce the highest level of streamwise vorticity for the nozzles explored.[8] This lobed nozzle also produced a substantial increase in both large-scale mixing[8] and small-scale mixing.[13] In the results to follow, the flow parameters are scaled using the average velocity (or convective velocity) of the two streams. This is also equivalent to using the velocity difference of the two streams for the 3:1 and 1:3 cases.

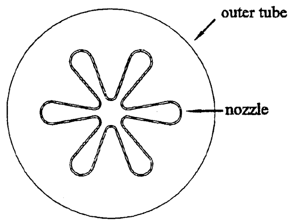

Fig. 1 Scale drawing of exit cross section.

Figure 2 shows three-dimensional surface plot perspectives of the axial velocity, and vector plots of the cross stream velocity, for the 3:1 (30:10 m/s) velocity ratio, at three locations downstream. The midpoints of the vectors are located at the points of measurement, and the maximum cross stream velocity is labeled. At $x/D = 1$, the surface plot shows a slightly rounded profile over the nozzle region. There are seven well-defined peaks, representing the six lobes and the central core. The vector plot reveals that the cross stream flow is, indeed, radially outward in the lobe regions and inward in the trough regions. Both streams are, thus, generally following the inward and outward contours of the nozzle. The plot also indicates the presence of distinct, counter-rotating, streamwise vortex pairs located approximately on either side of the lobe peaks. The locations of the streamwise vortices match very well with the smoke patterns of the flow visualizations.[8,12,13]

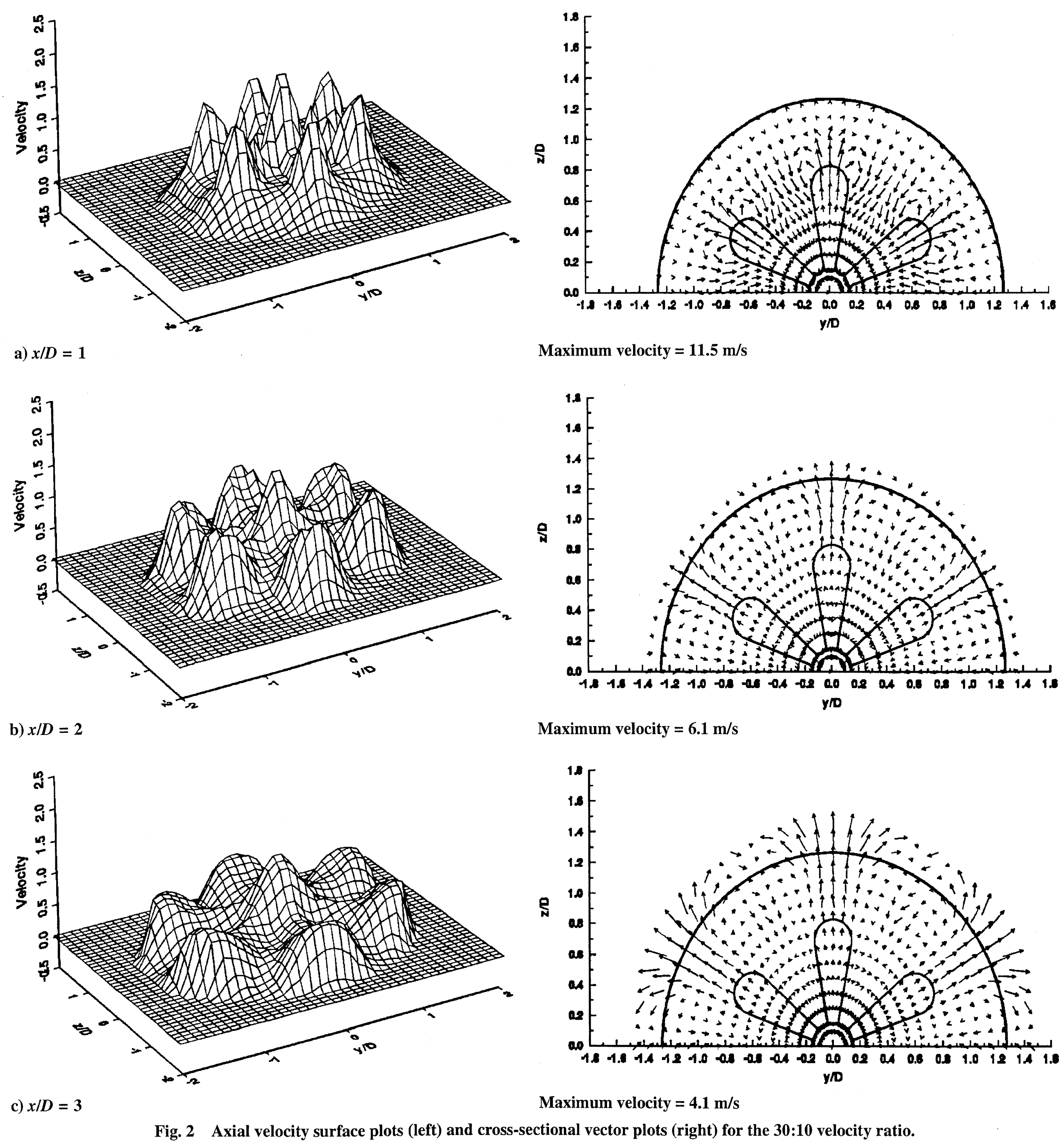

Fig. 2 Axial velocity surface plots (left) and cross-sectional vector plots (right) for the 30:10 velocity ratio.

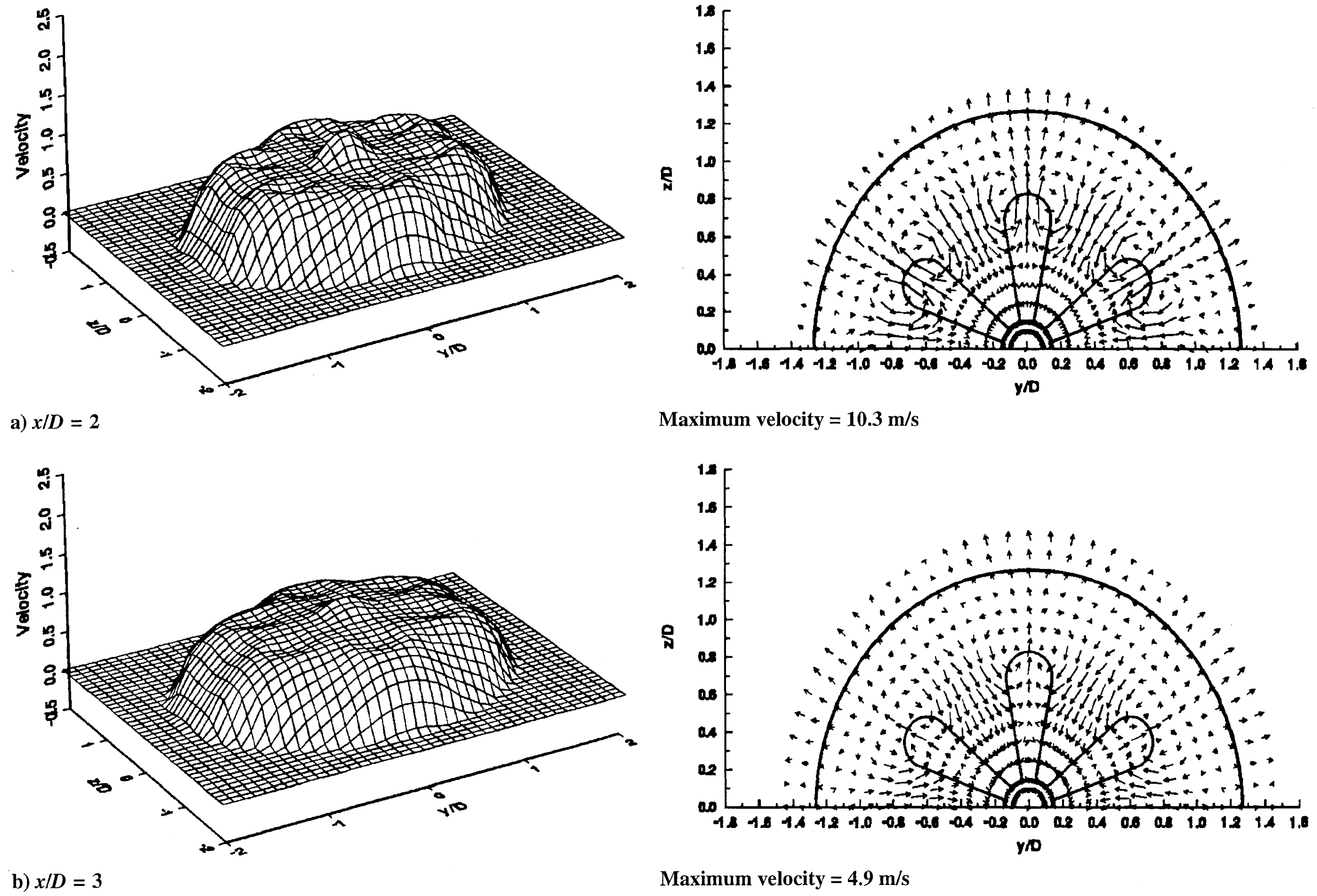

Fig. 3 Axial velocity surface plots (left) and cross-sectional vector plots (right) for the 30:30 velocity ratio.

The plots for $x/D = 2$ (Fig. 2b) show the axial velocity has a well-rounded profile that is expanding radially outward. The vector plot also shows that the streamwise vortices have spread outward. The extent of the vortices is slightly beyond the area over which data were taken, but still mostly visible. The cross stream velocities within the boundary of the nozzle have decreased considerably but there is now a strong outward flow along the peak radii beyond the lobe. Because the jet is not confined, the shear layer is free to expand radially outward. This is a difference between this freejet study and previous, confined flow studies. The streamwise vortices of this study are spiraling outward as they travel downstream, whereas when confined, they remain within the lateral range of the lobed mixer.[4,5,9] The spread of the streamwise vortices also coincide with flow visualizations.[8,11,12]

The axial velocity profile at $x/D = 3$ (Fig. 2c) still shows distinct humps representing the flow from the nozzle core and lobe regions, but they have become more rounded. (The steep gradients at the outer edge of the data are seen because data were not taken far enough from the center and, for clarity, points outside the data range were set to zero.) The vector plot shows that the magnitudes of the cross stream components have generally decreased within the border of the outer jet, but still have a strong outward flow along the lobe axes. Note that the scale of the vector lengths has changed from the previous plots. The maximum cross stream velocity component has decreased substantially, but the length of the vectors has increased. The streamwise vortices have moved substantially outward and just the edge of the vortices can be seen at the farthest extent of the data. The center of the vortices is approximately near the outer jet wall, which is approximately where one would expect it to be from previous flow visualizations.[8,11,12]

The axial and cross stream velocity results for the 1:1 (30:30 m/s) velocity ratio at $x/D = 2$ and 3 are presented in Fig. 3. This condition minimizes the Kelvin–Helmholtz instabilities. The axial velocity plot for $x/D = 2$ (Fig. 3a) shows a much flatter profile than the plot for the 3:1 case. The vector plot shows well-defined streamwise vortices that have developed to the outside of the lobe tips. These vortices are what caused the smoke to curl up into U-shaped structures in Belovich et al.[8] Note that for the 30:10 flow condition at this axial distance, the streamwise vortices were partially beyond the reach of the obtained data (Fig. 2b). Here, they are still well within the boundary of the outer jet.

At $x/D = 3$, the axial velocity exhibits slight depressions in the trough regions, which shows the effect of entraining the ambient air. As the vector plot shows, the streamwise vortices are still confined to the data range. It can also be seen that the streamwise vortices are already beginning to exhibit signs of breaking down. The vortices are well defined on the inner portion, but show signs of weakening toward the outside. The breakdown of the vortices near their outer boundary could be due to interaction with the outer flow and/or ambient flow, but that is not likely because the outer shear layer is roughly at the outer edge of the data. The streamwise flow visualizations for this case showed a large discontinuity in the growth of the jet at this downstream location; that is, the jet spread increased markedly at this location.[8,11–13] With the LDV data, it can now be seen that this increase is, at least partially, caused by the breakdown of the streamwise vortices. The breakdown could be initiated by the pinch-off effect of McCormick and Bennett.[10,13] Inasmuch as the Kelvin–Helmholtz vortices (or normal vortex) are minimized for this velocity ratio, it is the streamwise vortices that are mostly responsible for the growth of the jet for the 1:1 velocity ratio. Evidence of vortex breakdown can also be seen in the streamwise images of Belovich and Samimy.[12]

The axial velocity and vector plots for the 1:3 velocity ratio case (30:90 m/s) at $x/D = 1$ are presented in Fig. 4. The inner flow appears as a depression in the surface plot because the outer velocity is much greater, and so very little detail of the inner stream is visible. The vector plot shows that the inner flow is substantially overcome by the outer flow. Only a small region of the lobe section has a large outward velocity component, but this does not reach into the outer flow at the lobe tips, as it did for the previous flow rates.

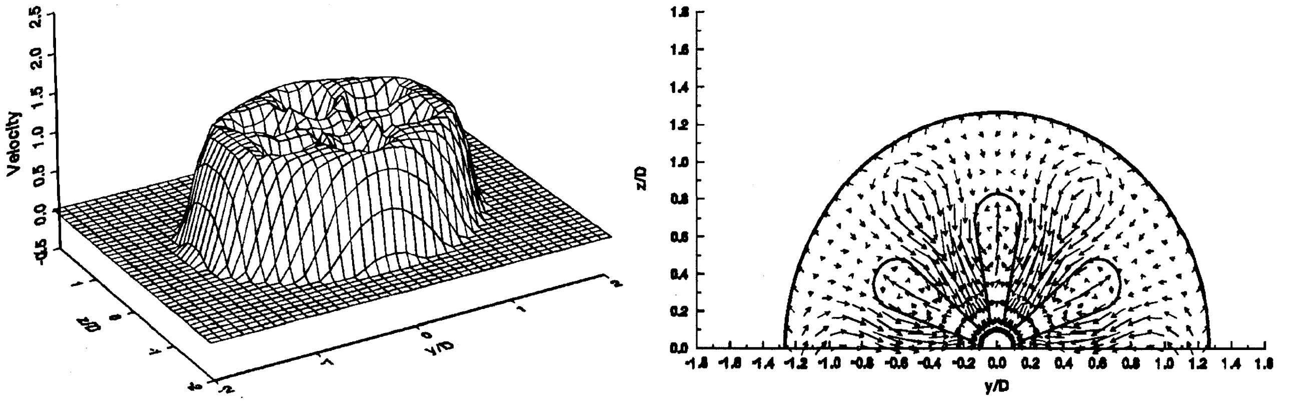

Fig. 4 Axial velocity surface plot (left) and cross-sectional vector plot (right; maximum velocity = 20.9 m/s) for the 30:90 velocity ratio at x/D = 1.

The interface rollup direction is inward, perpendicular to the nozzle perimeter, and this is effectively limiting the spread of the inner flow. A small streamwise vortex pair can be identified in the lobe tip regions within the outline of the lobe. This is a significant difference from the previous flow conditions, where larger vortex pairs were easily discernible and spread out farther radially and azimuthally. The jet spread for this case, however, is expected to be less than the other two cases because this flow condition is similar to a wake flow.

The cross-sectional smoke image at this distance[8,12] showed that the smoke was confined to the lobe tip regions and had minimal spread. Because the streamwise vortices do not appear to have developed as uniformly as the previous velocity ratios, it is likely that most of the jet spread is due to the shear layer mixing processes and not the streamwise vortices, especially because the streamwise vortices that are visible are well within the lobe dimensions. The flow visualizations[8,11,12] for this case show both streams merging and behaving as one farther downstream ($x/D > 3$). Therefore, the outer jet is essentially overpowering the streamwise vortices and controlling the mixing. Dahm et al.[14] and Wicker and Eaton[15] have both observed that an outer annular flow can dominate the behavior of an inner jet, especially when the outer flow is at a higher velocity.

Conclusions

Velocity measurements were taken in a coaxial jet geometry where the inner jet was a lobed mixer nozzle. The measurements showed that strong, spatially stationary streamwise vortices form outside the lobes for the 3:1 and 1:1 velocity ratios. The vortices spiral radially outward as they advect downstream for the 3:1 case but not as much for the 1:1 case. On the other hand, the 1:3 case showed that little streamwise vortices were generated, and they were confined to within the lobe boundary.

By considering the flow visualizations reported earlier and LDV measurements in parallel, it can be inferred that the three different velocity ratios produced three different mixing mechanisms. For the 3:1 case, the streamwise vortices and the normal vortices interacted together to spread the inner jet. The 1:1 velocity ratio relied mainly on the streamwise vortices to mix the two streams. The streamwise vortices were found to break down at the same downstream location where a discontinuity in jet growth appeared in previous flow visualizations. Mixing for the last flow condition, 1:3, was found to be considerably influenced by the outer jet, as little or no streamwise vortices were measured.

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F. W. Chambers
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