Dual-Plane Stereoscopic PIV Measurements in a Lobed Jet Mixing Flow

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The measurement results in a lobed jet mixing flow by using an advanced Particle Image Velocimetry (PIV) system, called Dual-Plane Stereoscopic PIV (DP-SPIV) system, were presented to investigate the evolution and interaction of streamwise vortices and azimuthal Kelvin-Helmholtz vortex structures in a lobed jet mixing flow. Unlike conventional two-dimensional PIV or stereoscopic PIV systems that can only measure one component of vorticity vectors in flow flows, the DP-SPIV system used in the present study can achieve the simultaneous measurements of all three components of flow velocity and vorticity vectors in two parallel planes simultaneously. Both the streamwise vortices and azimuthal Kelvin-Helmholtz vortex structures in the lobed jet mixing flow were revealed quantitatively and simultaneously in the DP-SPIV measurement results. The unprecedented measurement results presented in the present paper uncover several new and crucial features about the evolution and interaction of streamwise vortices and azimuthal Kelvin-Helmholtz vortex structures in the lobed mixing flow, which are very important and helpful to understand the fundamental mechanism of the mixing enhancement in lobed mixing flows.

Nomenclature

\( D \) = the diameter of the test lobed nozzle
\( H \) = the height of the lobes
\( U_0 \) = the axial velocity of the jet flow at the exit of the test nozzle
\( u, v, w \) = the components of velocity vectors in the \( x, y \) and \( z \) directions
\( \alpha_{in}, \alpha_{out} \) = the penetration angles of the lobes
\( \omega_x, \omega_y, \omega_z \) = the components of the vorticity vectors in the \( x, y \) and \( z \) directions
\( \omega_{in-plane} \) = the strength of the vorticity components parallel to the measurement plane

I. Introduction

Lobed mixers/nozzles, which are essentially splitter plates with corrugated trailing edges, are fluid mechanic devices used to augment mixing in a variety of applications. Such devices have been applied widely in turbofan engine exhausts and ejectors to reduce take-off jet noise and Specific Fuel Consumption (SFC).\(^1\)\(^2\) Lobed mixers/nozzles have also been used in military aircraft to enhance the mixing process of high temperature and high-

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speed gas plume exhausted from aero-engines with ambient cold air to suppress infrared radiation signal to improve the survivability of the military aircraft. More recently, lobed mixers/nozzles have emerged as an attractive approach for enhancing mixing between fuel and air in combustion chambers to improve the efficiency of combustion and reduce the formation of pollutants.

Due to outstanding mixing enhancement performance and widely potential applications of lobed mixers/nozzles, extensive studies about the mechanism by which lobed nozzles/mixers substantially enhance mixing have been conducted in past years. Based on pressure, temperature measurement data as well as three-dimensional Laser Doppler Velocimetry (LDV) measurements of velocity field downstream a lobed nozzle/mixer, Paterson revealed the existence of large-scale streamwise vortices due to the secondary flow induced by the special geometry of the lobed nozzle/mixer. Horseshoe vortices with smaller scale were also found to exist at the lobe troughs. Although the contribution of these vortices to overall mixing process was not clear, the large-scale streamwise vortices were believed to be responsible for the enhanced mixing because of their much greater size.

Much of the later work on lobed mixers/nozzles concentrated on discovering the underlying physics of lobed mixing process by using two-dimensional lobed mixers. Werle et al. and Eckerle et al. found that large-scale streamwise vortices in lobed mixing flows follow a three-step process by which the streamwise vortices form, intensify, and then break down. They also found that the breakdown of the streamwise vortices was accompanied by a significant increase in turbulent mixing. Elliott et al. suggested that there are three primary contributors to mixing processes in lobed mixing flows. The first is the azimuthal (or spanwise) vortices, which occur in any free shear layers due to the Kelvin-Helmholtz instability. The secondary is the increased interfacial contact area due to the convoluted trailing edge of the lobed nozzles/mixers. The last element is the streamwise vortices produced by special geometry of lobed nozzles/mixers. Based on pulsed-laser sheet flow visualization with smoke and three-dimensional velocity measurements with Hot Film Anemometer, McCormick and Bennette suggested that it is the interaction of azimuthal Kelvin-Helmholtz vortices with streamwise vortices produces high levels of mixing. As azimuthal Kelvin-Helmholtz vortices shed from the trailing edge of lobed nozzles/mixers, streamwise vortices deform them until they are eventually pinched off and subsequently broken down. Turbulence measurements showed the regions of high-turbulence kinetic energy that were consistent with flow visualization of the pinch-off effect of the azimuthal Kelvin-Helmholtz vortex tubes.

Although large-scale streamwise vortices and azimuthal Kelvin-Helmholtz vortex structures in lobed mixing flows have been suggested to play important roles in lobed mixing processes in previous studies, detailed quantitative measurement results like instantaneous whole-field flow velocity and vorticity distributions to reveal the evolution and interaction characteristics of vortical and turbulent structures in lobed mixing flows have not become available until recent work of the authors. By using advanced whole-field flow diagnostic techniques like Planar Laser Induced Fluorescence (PLIF), two-dimensional Particle Image Velocimetry (PIV) and Stereoscopic Particle Image Velocimetry (SPIV), Hu et al. conducted a series of studies to investigate the evolution characteristics of large-scale streamwise vertical structures in lobed mixing flows.

It is well known that conventional two-dimensional PIV systems or Stereoscopic PIV systems can only provide one component of vorticity vectors, therefore, only either streamwise vortices or azimuthal Kelvin-Helmholtz vortical structures in lobed jet mixing flows can be revealed from the measurement results of Hu et al. As suggested by McCormick and Bennette, the interaction of azimuthal Kelvin-Helmholtz vortices and streamwise vortices plays a very important role for the mixing enhancement in lobed mixing flows, it is highly desirable to reveal of both streamwise vortices and azimuthal Kelvin-Helmholtz vortical structures simultaneously in order to understand the characteristics of the evolution and interaction of these vortex structures. This requires simultaneous measurements of all three components of vorticity vectors.

Recently, an advanced PIV system, called Dual-plane Stereoscopic PIV (DP-PIV) system, has been developed by the authors. The DP-PIV system is capable of measuring all three components of velocity and vorticity vectors in fluid flows simultaneously. In the present paper, the measurement results in a lobed jet mixing flow by using the DP-PIV system will be presented to investigate the evolution and interaction of large-scale streamwise vortices and azimuthal Kelvin-Helmholtz vortex structures in lobed mixing flows.

The objectives of the present study are twofold: The first objective is to gain insight into the evolution and interaction characteristics of the streamwise vortices and azimuthal Kelvin-Helmholtz vortex structures in lobed mixing flows. Based on the measurement results of the DP-PIV system in the near field of a lobed jet mixing flow, the characteristics of the mixing process downstream of a lobed nozzle/mixer will be discussed in the terms of instantaneous and ensemble-averaged velocity fields, instantaneous and ensemble-averaged streamwise vorticity distributions, instantaneous and ensemble-averaged azimuthal Kelvin-Helmholtz vorticity distributions.

As mentioned above, although extensive studies about lobed mixing flows have been conducted, detailed whole-field quantitative measurements in lobed mixing flows, especially in lobed jet mixing flows, appear to be very
scarce. Therefore, the second objective of the present study is to provide detailed whole-field measurement data for the verification of CFD numerical simulation results and assessment of different turbulence models to predict this type of industrial flow.

II. Experimental Setup

A. Lobed nozzle/mixer and experimental rig

Figure 1 shows the geometry parameters of the lobed nozzle/mixer used in the present study. The lobed nozzle has six lobes. The width of each lobe is 6mm, and the height of the lobe is 15mm (H=15mm). The penetration angles of the lobed structures are $\alpha_{in} = 25^\circ$ and $\alpha_{out} = 14^\circ$ respectively. The diameters of the lobed nozzles is D=40mm.

Figure 2 shows the experimental rig used in the present study. The air jet was supplied by a centrifugal compressor. A cylindrical plenum chamber with honeycomb structures was used for settling the airflow. Through a convergent connection (contraction ratio is about 50:1), the airflow is exhausted from the test nozzle. The velocity of the air jet exhausting from the test nozzle is adjustable. In the present study, the jet velocity at the exit of the tested nozzle ($U_0$) was set at about 20m/s. The Reynolds number of the jet flow, based on the lobed nozzle diameter (D) and the jet velocity is about 55,000.

A seeding generator, which is composed by an air compressor and several Laskin nozzles, was used to generate 1–5µm DEHS (Di-2-EthlHexyl-Sebact) droplets as tracer particles for the DP-SPIV measurement. The seeding DEHS droplets from the seeding generator are divided into two streams; one is used to seed the core jet flow, and another for the ambient air seeding.

![Figure1. Test lobed nozzle/mixer](image1.png)

![Figure2. The schematic of the experimental rig](image2.png)
B. Dual-plane stereoscopic PIV system

Figure 3 shows the schematic setup of the Dual-Plane Stereoscopic PIV (DP-SPIV) system used in the present study. The DP-SPIV system was developed by taking advantage of the polarization conservation of Mie scattering in order to separate the scattering light from two measurement planes simultaneously. As shown in Fig. 3, two sets of commonly-used double-pulsed Nd:YAG lasers (New Wave, 50mJ/pulse) with additional optics (half wave plate, mirrors, polarizer and cylindrical lens) were used to illuminate the studied air flow at two parallel planes with orthogonally polarized laser sheets. Since the polarization of Mie scattering is conservative in airflow, the scattering light scattered by PIV tracer particles in the two orthogonally polarized laser sheets will keep their original polarization direction. A specially designed imaging system that composed by four high-resolution CCD cameras with a pair of polarizing beam splitter cubes and mirrors were devised to capture the scattering light selectively. By using such optical arrangement, the DP-SPIV system can achieve the simultaneous measurements of all three components (stereoscopic PIV measurements) of velocity vectors at two parallel planes. Further information about the technical aspects and system set-up of the DP-SPIV system is available at Reference 15 and 16.

![Figure 3. The schematic set-up of the DP-SPIV system.](image)

III. Experimental Results and Discussions

Figure 4 shows a typical DP-SPIV measurement result. The two velocity fields (all three components) were measured simultaneously in two parallel cross planes (Z=10mm and Z=12mm) near exit of the lobed nozzle. As it is expected, the lobed jet flow is found to be in the same geometry as the lobed nozzle trailing edge. The “signature” of the lobe nozzle in the form of “six-lobe structure” can be seen clearly from the instantaneous velocity fields.

According to the definition of vorticity vector, all three components of the normalized vorticity vectors in measurement planes can be calculated by using following questions:

\[
\sigma_x = \frac{D}{U_0} \left( \frac{\partial v}{\partial y} - \frac{\partial u}{\partial z} \right) \tag{1}
\]

\[
\sigma_y = \frac{D}{U_0} \left( \frac{\partial u}{\partial z} - \frac{\partial w}{\partial x} \right) \tag{2}
\]

\[
\sigma_z = \frac{D}{U_0} \left( \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y} \right) \tag{3}
\]
It should be noted that since conventional two-dimensional PIV systems or Stereoscopic PIV systems conduct velocity measurement only in a single plane, the terms like \( \frac{\partial u}{\partial z} \) and \( \frac{\partial v}{\partial z} \) in the above equations can not be determined from their measurement results. Therefore, only one component of the vorticity vectors (the out-of-plane component, \( \sigma_z \)) can be determined instantaneously for conventional two-dimensional PIV systems or Stereoscopic PIV systems.

The DP-SPIV system used in the present study can measure velocity vectors (all three components) at two parallel planes simultaneously, all the terms in above equations can be calculated quantitatively. Besides the out-of-plane component \( \sigma_z \), the other two in-plane components of the vorticity vectors (\( \sigma_x \) and \( \sigma_y \)) can also be obtained in either of the two measurement planes with first-order approximation and in the central plane between the two illuminating laser sheets with second-order approximation accuracy. By using the two simultaneously measured velocity fields shown in Fig. 4, all three components of the instantaneous vorticity vectors in Z=10mm cross plane were calculated, and the results are shown in Fig. 5.

As described above, there are two kinds of vortex structures that were suggested to play very important roles for the enhanced mixing in lobed jet flows: One is the large-scale streamwise vortices generated by the special geometry of the lobed nozzle; another is the azimuthal vortices rolled up at the interface of the two streams due to the Kelvin-Helmholtz instability. For the large-scale streamwise vortices generated the lobed trailing edge of the test nozzle, they are revealed very clearly and quantitatively from the instantaneous streamwise vorticity distribution (Fig. 5c). Corresponding to the six lobes of the test nozzle, six pairs of counter rotating streamwise vortices were generated in the lobed jet mixing flow. The size of these streamwise vortices is found to be almost equivalent to the height of the lobes.

Since the direction of the azimuthal Kelvin-Helmholtz vorticity vectors is parallel to the two measurement planes, a quantity called in-plane vorticity strength is introduced in the present study in order to reveal the azimuthal Kelvin-Helmholtz vortex structures clearly. The in-plane vorticity strength is defined by the following equation:

\[
\sigma_{in-plane} = \sqrt{\sigma_x^2 + \sigma_y^2}
\]  \hspace{1cm} (4)

By using the Equation (4), the strength of the azimuthal (in-plane) vorticity vectors in the Z=10mm cross-plane was calculated, and the result is shown in Fig. 5(d). As it is expected, the azimuthal Kelvin-Helmholtz vortex structure is found to form a vortex ring that has the same geometry as the lobed nozzle trailing edge.

Figure 4. A typical DP-SPIV measurement result near the exit of the test nozzle.
Figure 5. Vorticity distributions in the Z=10mm (Z/D=0.25, Z/H=0.67) cross plane
It should be noted that although the existence of large-scale streamwise vortices and azimuthal Kelvin-Helmholtz vortices in lobed mixing flows has been suggested by other researchers in previous studies. Quantitative measurement results of these vortex structures in the terms of instantaneous streamwise vorticity and azimuthal vorticity distributions have never been obtained. The measurement results given in the present study are believed to be the first quantitative and instantaneous vorticity measurement results to reveal the large-scale streamwise vortices and the azimuthal Kelvin-Helmholtz vortex structures in lobed mixing flows quantitatively and simultaneously.

Based on 250 frames of instantaneous DP-SPIV measurement results, the ensemble-averaged streamwise vorticity and azimuthal (in-plane) vorticity distributions were calculated, which are given in Fig. 5(e) and Fig. 5(f). Compared with the instantaneous streamwise and azimuthal vorticity fields, the ensemble-averaged streamwise and azimuthal vorticity fields are found to be much smoother. The ensemble-averaged streamwise vorticity and azimuthal vorticity fields have almost the same distribution pattern and magnitude as their instantaneous counterparts, which indicate that the generations of the streamwise vortices and the azimuthal vortex ring at the exit of the lobed nozzle are quite steady.

Figure 6 to Fig. 10 show the DP-SPIV measurement results at several typical cross planes in the downstream of the lobed nozzle. The DP-SPIV measurement results shown in the figures include instantaneous velocity fields and ensemble-averaged velocity fields, instantaneous streamwise vorticity and azimuthal vorticity distributions, and ensemble-averaged streamwise vorticity and azimuthal vorticity distributions.

In the Z=20mm (Z/D=0.5, Z/H=1.33) cross plane (Fig. 6), the lobed jet flow is found to be still in the same geometry as the lobed nozzle trailing edge. The “signature” of the lobe nozzle in the form of “six-lobe structure” can be seen clearly from both the instantaneous and ensemble-averaged velocity fields. Seven high-speed peaks can be seen from the ensemble-averaged velocity field, which represent the six lobes and the central core. A strong cross stream (secondary flow) is found to exist in the lobe jet mixing flow. The core jet flow expanded outward in the lobe regions and ambient flow injected inward in the lobe trough regions. Both the core jet flow and ambient flow were generally following the inward and outward contours of the lobed nozzle, which resulted in the large-scale streamwise vortices seen in the lobed jet mixing flow.

Figure 6(c) shows a typical instantaneous streamwise vorticity distribution in this cross plane. The six pairs of counter-rotating large-scale streamwise vortices generated by the lobed nozzle are found to be deformed in the instantaneous streamwise vorticity distribution. Some of the large-scale streamwise vortices were even found to begin to break into smaller vortices. Besides the six pairs of large-scale streamwise vortices corresponding to the six lobes of nozzle trailing edge, some smaller and weaker streamwise vortices at the six lobe troughs can also be identified from the instantaneous streamwise vorticity distributions. These smaller and weaker streamwise vortices at lobe troughs are believed to be the “horseshoe vortex structures” called by Paterson.  

Compared with the instantaneous streamwise vorticity field, the ensemble-averaged streamwise distribution is found to be much smoother. The six pairs of the large-scale streamwise vortices can still be seen very clearly in the ensemble-averaged streamwise vorticity distribution. However, the maximum magnitude of the ensemble-averaged streamwise vorticity (4.0), is found to be smaller than that of its instantaneous counterpart (which is about 4.5). Since the lobed jet mixing flow is a free jet, it can also be seen that the centers of the large-scale streamwise vortices have spread outward as they travel downstream. The same phenomena are found in the LDV measurement results of Bleovich and Samimy.

The azimuthal vorticity distribution given in Fig. 6(e) reveals that the azimuthal vortex ring was deformed seriously in this cross plane; it was even torn into disconnected vortex tubes at some points. The large azimuthal vortex-ring with the same geometry as the lobed nozzle trailing edge can still be seen from the ensemble-averaged azimuthal vorticity distribution. However, the maximum magnitude of the ensemble-averaged azimuthal vorticity (11.0), is found to be smaller than that of its instantaneous counterpart, which is about 15.0. From the ensemble-averaged azimuthal vorticity distribution, it can also be see that the azimuthal vortex ring is found to spread outward as it travels downstream.

In the Z=40mm (Z/D=1.0, Z/H=2.67) cross plane (Fig. 7), the typical instantaneous velocity field indicates that the lobed jet flow become turbulent. However, the “signature” of the lobed nozzle still can be seen for the ensemble-averaged velocity field. Due to the outward spreading of the free jet, the “six lobe structures” revealed in the ensemble-averaged velocity field is found to be stretched out radially.

The instantaneous streamwise vorticity distribution shown in Fig. 7(c) indicates that the six pairs of large-scale streamwise vortices revealed in the upstream cross planes can not be seen in this cross plane any more. The six pairs of large-scale streamwise vortices are found to break into many smaller streamwise vortices. It should be noted that the maximum vorticity values of the smaller vortices are found to be almost at the same level as their parent streamwise vortices, i. e., the large-scale streamwise vortices are found to break down into many smaller, but not
weaker streamwise vortices. The adjunct streamwise vortices are found to merge with each other to form a “streamwise vortex wreath” in the lobe troughs.

From the ensemble-averaged streamwise vorticity distribution shown in Fig. 7(d), the six pairs of ensemble-averaged large-scale streamwise vortices can still be seen clearly. They are found to continue to grow and expand radially. The strength of these ensemble-averaged streamwise vortices are found to decrease quite much with the maximum value of the ensemble-averaged streamwise vorticity only about the half of that at the exit of the lobed nozzle (i.e. Z=10mm, Z/D=0.25, Z/H=0.67 cross plane).

From the instantaneous azimuthal vorticity distribution given in Fig. 7(e), it can be seen that the azimuthal vortex ring, which has the same geometry as the lobed nozzle at the nozzle exit, has broken into many disconnected vortical fragments in this cross plane. The broken azimuthal tubes at the lobe troughs are found to begin to reconnect to form a new wreath-like-structure in the center of the jet flow. Same phenomena have been revealed clearly form the planar LIF flow visualization images of the earlier work of the authors.\textsuperscript{12,13}

The ensemble-averaged azimuthal vorticity distribution indicates that the azimuthal Kelvin-Helmholtz vortex ring has deformed pretty much. The vortex ring is found to expand radially. The indications of the breaking of the large azimuthal vortex ring at the lobe peaks, and the reconnecting of the breaking azimuthal vortex tubes at lobe troughs to form a new wreath-like-structure in the center of the lobed jet flow can also be seen from the ensemble-averaged azimuthal vorticity distribution. Based on qualitatively flow visualization results, McCormick and Bennett\textsuperscript{11} suggested that streamwise vortices deform azimuthal Kelvin-Helmholtz vortical tube into pinch-off structures due to the interaction between streamwise vortices and azimuthal Kelvin-Helmholtz vortices in lobed mixing flows. Such pinched-off effect of azimuthal vortex tubes can be seen very clear and quantitatively from the ensemble-averaged azimuthal vorticity distribution shown in Fig 7(f).

It should be noted that almost all the previous studies about lobed mixing flows were conducted by using Pitot probe, hot wire or LDV techniques for velocity field measurements, and the discussions about lobed mixing process were based on ensemble-averaged measurement results. From the comparison of the instantaneous velocity field, instantaneous streamwise vorticity and instantaneous azimuthal vorticity distributions with their ensemble-averaged counterparts shown in Fig. 7, it can be seen that there are significant differences to reveal the behavior of the vortex structures in the lobed jet mixing flow based on the ensemble-averaged results or based on the instantaneous measurement results. For example, the large-scale streamwise vortices generated by the lobed nozzle are found to break into smaller, but not weaker, streamwise vortices in the instantaneous vorticity distributions, while the ensemble-averaged streamwise vorticity distribution reveals that the large-scale streamwise vortices keep on growing radially, and the vorticity of the large-scale streamwise vortices is dissipated. The significant differences indicate that, for complex turbulent flows like lobed jet mixing flows, many critical features revealed clearly from the instantaneous measurement results may not be able to see from the ensemble-averaged measurement results. These significant differences between the ensemble-averaged results and instantaneous measurement results also verify that advanced diagnostic techniques like DP-SPIV system are highly desirable and essential to understand the fundamental mechanism of complex flow phenomena like lobed mixing flows.

As the downstream distance increases to Z=60mm (Z/D=1.5, Z/H=4.00) (Fig. 8), the lobed jet flow becomes much more turbulent. The “signature” of the lobed nozzle can only be seen ambiguously from the instantaneous velocity field (Fig. 8a). The ensemble averaged velocity field (Fig. 8b) shows that the “six lobe structures” keeps on growing radially. The instantaneous streamwise vorticity distribution in this cross plane (Fig. 8c) reveals that there are more and more small scale streamwise vortices appearing in the lobed mixing flow. The maximum vorticity of these smaller streamwise vortices are found to be still at the same level as their parent vortices revealed in the upstream cross planes. From the ensemble-averaged streamwise vorticity distribution shown in Fig 8(d), it can be seen that the large-scale streamwise vortices revealed in the ensemble-averaged streamwise vorticity distributions are found to be stretched radially. The strength of these ensemble-averaged streamwise vortices decays substantially, and the maximum value of the ensemble-averaged streamwise vorticity is found to be only about one fourth of that at the exit of the lobed nozzle (in Z=10mm, Z/D=0.25, Z/H=0.67 cross plane).

The azimuthal vortex ring, which has the same geometry as the lobed nozzle trailing edge at the nozzle exit, is found to break into many disconnected vortical fragments completely in this cross plane. A new wreath-like-structure due to the reconnecting of the broken azimuthal vortex tubes at the lobe troughs is found in the center of the jet flow. The wreath-like-structure can be seen more clearly from the ensemble-averaged azimuthal vorticity distribution. The broken azimuthal vortex tubes corresponding to lobed peaks are found to form six “crescents” in this cross plane. Due to the intensive mixing between the core jet flow and ambient flow, the strength of the azimuthal vortices revealed in the ensemble-averaged azimuthal vorticity distribution has been dissipated very much. The maximum value of the ensemble-averaged azimuthal vorticity is found to be only about one fourth of that at the exit of the lobed nozzle.
As the downstream distance increases to Z=80mm (Z/D=2.0, Z/H=4.0) (Fig. 9), the lobed jet mixing is found to become much more turbulent. The “six lobe structures” of the core jet flow are nearly indistinguishable in the instantaneous velocity field. Although seven humps still can be found in the ensemble-averaged velocity field, which represent the high speed flow from the nozzle core and six lobes, they have become much more rounded than those in the upstream cross planes. The cross stream velocity vector shown in the ensemble-averaged velocity plot also indicates that the magnitudes of the cross stream velocity have decreased quite a lot compared with those in upstream cross planes. The size of the high-speed region in the center of the jet flow and six lobes are found to decrease substantially due the intensive mixing of the core jet flow with ambient flow.

The instantaneous streamwise vorticity distribution shows that the smaller, but not weaker, streamwise vortices originated from the breakdown of the large-scale streamwise vorticity generated by the lobed nozzle almost fully filled the measurement window (Fig. 9c). Since these smaller streamwise vortices are so unsteady, and they appear in the flow field very randomly, only very weak streamwise vortical structures can be identified from the ensemble-averaged streamwise vorticity distribution. The ensemble-averaged streamwise vorticity distribution also reveals that the ensemble-averaged streamwise vortices have been dissipated so seriously that their strength is only about one tenth of that at the exit of the test nozzle.

Due to the intensive mixing between the core jet flow and ambient flow, the azimuthal vortices are found to be dissipated substantially. Only a few broken azimuthal vortex fragments are found in the instantaneous azimuthal vorticity distribution (Fig. 9e). The number of the broken azimuthal vortex fragments revealed in this cross plane is found be much less compared with that in the upstream cross planes. The six “crescents” formed by the broken azimuthal vortex fragments at lobed peaks are found to fade out in this cross plane, and only the wreath-like-structure in the center of the jet flow can be identified from the ensemble-averaged azimuthal vorticity distribution with its strength dissipated substantially.

When the downstream distance increases to Z=120mm (Z/D=3.0, Z/H=8.0) (Fig. 10), the lobed jet mixing flow became so turbulent that the “six-lobe structure” of the core jet flow can not be identified in the instantaneous velocity field any more. The flow field is almost fully filled with many small-scale vortices. The ensemble-averaged velocity distribution also shows that the distinct hump in the center of the jet flow representing the high-speed core jet flow has dissipated so seriously that the iso-velocity contours of the core jet flow have become small concentric circles. The ensemble-averaged cross stream velocity in this cross plane is so weak that it almost can not be identified from the velocity vector plot.

The instantaneous streamwise vorticity distribution reveals that the measurement window is fully filled with many small-scale streamwise vortices. The maximum vorticity of these smaller instantaneous streamwise vortices is found to be still at the same level of their parent vortices. Since the lobed jet flow has become so turbulent and the appearance of these smaller streamwise vortices becomes so random, there are almost no apparent streamwise vortices can be identified from the ensemble-averaged streamwise vorticity distribution. Due to the serious dissipation, only very few azimuthal vortex fragments can be identified from the instantaneous azimuthal vorticity distribution. The contours of the wreath-like-structure in the center of the lobed jet flow are found to become quite ambiguous in the ensemble-averaged azimuthal vorticity distribution.

From the DP-SPIV measurement results in different cross planes, it can be seen that, corresponding to six lobes of the nozzle trailing edge, there are six pairs of large-scale streamwise vortex structures generated at the exit of the lobed nozzle. As the downstream distance increasing, more and more streamwise vortices with smaller scale are found in the lobed jet mixing flow. The size of the instantaneous streamwise vortices is found to become smaller and smaller. These results indicate that the large-scale streamwise vorticity generated by the lobed nozzle break into smaller vortices as they travel downstream. However, the maximum vorticity values of the smaller vortices are found to be almost at the same level as their parent streamwise vortices. These results suggests that the dissipation of the large-scale streamwise vortices generated by the lobed trailing edge of the test nozzle does not happen abruptly, but rather appears to be a gradual process. The large streamwise vortices are found to break down into many smaller, but not weaker streamwise vortices as the downstream distance increasing. Thus, besides the mixing enhancement at large scale, mixing at a finer scale could also be achieved in the lobed jet mixing flow. The results, therefore, agree well with those obtained by Milam et al.19
Figure 6. The DP-SPIV measurement results in the Z=20mm (Z/D=0.50, Z/H=1.33) cross plane
Figure 7. The DP-SPIV measurement results in the Z=40mm (Z/D=1.00, Z/H=2.67) cross plane
Figure 8. The DP-SPIV measurement results in the $Z=60\text{mm}$ ($Z/D=1.50$, $Z/H=4.0$) cross plane.
Figure 9. The DP-SPIV measurement results in the Z=80mm (Z/D=2.00, Z/H=6.7) cross plane.
Figure 10. The DP-SPIV measurement results in the Z=120mm (Z/D=3.00,Z/H=8.0) cross plane
The ensemble-averaged streamwise vorticity distribution can be used to indicate the overall effect of the special geometry of the lobed nozzle on the mixing processes in lobed jet mixing flows. The special geometry of the lobed nozzle results in the generation of large-scale ensemble-averaged streamwise vortices in the lobed jet mixing flow. The large-scale ensemble-averaged streamwise vortices are found to grow and expand radially within the first diameter, which may correspond to the streamwise vortex formation and intensification steps suggested by Werle et al. and Eckerle et al. (Their LDV measurement results can only reveal the ensemble-averaged streamwise vortices). The large-scale ensemble-averaged streamwise vortices are found to be stretched radially and dissipated rapidly as the downstream distance increasing. Figure 11 presents the decay of the maximum value of the ensemble-averaged streamwise vorticity in the lobed jet flow. From the figure, it can be seen that at the first diameter of the test nozzle, the ensemble-averaged streamwise vorticity decays very rapidly. At downstream region of \( Z/D > 1.0 \) \((Z/D > 2.67)\), the decay rate of the ensemble-averaged streamwise vorticity slows down. Further downstream \((Z/D > 3.0, Z/H > 8.0)\), the ensemble-averaged streamwise vorticity dissipates so seriously that the strength of the streamwise vortices becomes about one tenth of that at lobed nozzle exit. This may indicate that the overall effect of the special geometry of the lobed nozzle on the enhanced mixing process in the lobed jet flow has almost disappeared at this downstream location.

For the azimuthal vortex structures in the lobed jet mixing flow, they are generated at the interface between the core jet flow and ambient flow due to the Kelvin-Helmholtz instability. Therefore, the azimuthal vortex ring at the lobed nozzle exit has the same geometry as the lobed nozzle trailing edge. Due to the interaction between the streamwise vortices, the azimuthal vortex ring deforms into pinched-off structure at first; then, broke into disconnected substructures as they travel downstream. The broken azimuthal vortex fragments at the lobed troughs are found to reconnect with each other to form a new wreath-like-structure at the center of the lobed jet flow, while the broken azimuthal vortex fragments corresponding to six lobed peaks are found to form six “crescents” structures. The six “crescents” structures are found to dissipate seriously and fade out sequentially at further downstream. Only very indistinct wreath-like-structure can be found at the central of the jet mixing flow at the further downstream of \( Z/D > 3.0 \) \((Z/H > 8.0)\)

The decay of the maximum value of the ensemble-averaged azimuthal vorticity in the lobed jet mixing flow is also given in the Fig. 11. It can be seen that the decay profile of the azimuthal vorticity is found to be very similar to that of the streamwise vorticity. The ensemble-averaged azimuthal vorticity decay very rapidly within the first one diameter of the lobe nozzle, then turns to a more moderate rate further downstream. This may be explained by that within the first one diameter of the test nozzle \((Z/D < 1.0, Z/H < 2.67)\), due to the stirring effect of the large-scale streamwise vortices revealed in the ensemble-averaged streamwise vorticity distributions, the core jet flow and ambient flow mixed intensively, and the thickness of the mixing layer grows very rapidly. Weaker and weaker
velocity gradients are expected in the lobed jet mixing flow as the downstream distance increasing. Therefore, the magnitude of the azimuthal vorticity decays very rapidly within the first diameter of the lobed nozzle. In the downstream region of 1.0<Z/D<2.0, the large-scale streamwise vortices generated by the lobed nozzle are found to be dissipated very seriously, i.e, the stirring effect of the ensemble-averaged streamwise vortices is weakened. The growth rate of the core jet flow slows down; therefore, the decay rate of the azimuthal vorticity is also found to slow down. The ensemble-averaged streamwise vorticity dissipates so seriously further downstream that they almost can not be identified in the flow field anymore, and the enhancement mixing due to the stirring effect of large-scale streamwise vortices has almost vanished, the mixing between the core jet flow and ambient flow is expected to occur at the same gradient-type mechanism as that for a circular jet flow, therefore, the azimuthal vorticity decay very slowly and almost linearly as that in a circular jet flow.

IV. Conclusions

In the present study, the streamwise vorticity and azimuthal vorticity distributions in a lobed jet mixing flow were measured simultaneously by using a Dual-Plane Stereoscopic PIV (DP-SPIV) system. The evolution and interaction characteristics of the streamwise vortices and azimuthal Kelvin-Helmholtz vortical structures in the lobed jet mixing flow are analyzed based on the DP-SPIV measurement results.

It is found that the large-scale streamwise vortices generated by the corrugated trailing edge of the lobed nozzle break into smaller, but not weaker streamwise vortices as they travel downstream. It is proposed as the reason that a lobed nozzle can enhance both the large-scale mixing and small-scale mixing in flow field as reported in previous studies. The overall effect of the lobed nozzle on mixing process in the lobed jet flow is evaluated by analyzing the ensemble-averaged streamwise vorticity distributions. The ensemble-averaged streamwise vortices in the lobed jet flow are found to expend radially. The strength of the ensemble-averaged streamwise vorticity is found to decay very rapidly over the first one diameter of lobed nozzle, then, decays at a more moderate rate further downstream.

Due to Kelvin-Helmholtz instability, azimuthal vortex structures are found to roll up at the nozzle exit. As it is expected, the azimuthal vortex structures are found to form a vortex ring that has the same geometry as the lobed nozzle trailing edge. Due to the interaction with streamwise vortices, the azimuthal vortex ring deform into pinched-off structures at first, then, breaks into disconnected substructures as it travels downstream. The broken fragments of the azimuthal vortex ring at lobed troughs are found to reconnect with each other to form a new wreath-like-structure in the center of the lobed jet flow, which is similar to that in a circular jet flow. The broken fragments of the azimuthal vortex ring corresponding to the lobe peaks are found to form six “crescents” structures. The six “crescents” structures are found to be dissipated and faded out at further downstream. The decay of the ensemble-averaged azimuthal vorticity in the lobed jet flow is found to be very similar to that of the ensemble-averaged streamwise vorticity. The azimuthal vorticity decays very rapidly within the first one diameter of the lobe nozzle, then turns to be a more moderate rate in the downstream region of 1.0<Z/D<2.0 (2.67>Z/H>5.33). The azimuthal vorticity decays very slowly and almost linearly in the Z/D>2.0 downstream region. These results indicate that the most of the enhanced mixing process caused by the special geometry of the lobed nozzle is concentrated within the first two diameters of the lobed nozzle (first six lobe heights). The mixing between the core jet flow and ambient flow at further downstream occurs by the same gradient-type mechanism as that in a circular jet flow.
References