

文章编号: 1000-8055(2008)07-1266-13

# Vortex structures downstream a lobed nozzle/mixer

Hui Hu<sup>1</sup>, Toshio Kobayashi<sup>2</sup>

(1. Iowa State University, Ames, Iowa 50011-2271;

2. Japan Automobile Research Institute, Tokyo 105-0012, Japan)

**Abstract:** An experimental study was conducted to investigate the evolutions of unsteady vortex structures downstream a lobed mixer/nozzle. A novel dual plane stereoscopic PIV system was used to measure all 3 components of vorticity distributions to revealed both the large scale streamwise vortices produced by the lobed mixer/nozzle and the Kelvin Helmholtz vortex structures generated due to the Kelvin Helmholtz instabilities simultaneously and quantitatively for the first time. The instantaneous and the ensemble averaged vorticity distributions displayed quite different aspects about the evolutions of the unsteady vortex structures. While the ensemble averaged vorticity distributions indicated the overall effect of the special geometry of the lobed nozzle/mixer on the enhanced mixing process, the instantaneous vorticity distributions elucidated many details about how the enhanced mixing process was conducted. In addition to quantitatively confirming conjectures of previous studies, further insight about the formation, evolution and interaction characteristics of the unsteady vortex structures downstream of the lobed mixer/nozzle were also uncovered quantitatively in the present study.

**Key words:** jet mixing enhancement; vortex flow; jet flow; lobed nozzle/mixer; dual plane stereoscopic PIV technique

**CLC number:** V231

**Document code:** A

## Nomenclature

$D$  = diameter of the lobed mixer/nozzle

$H$  = the height of the lobe

$u, v, w$  =  $X, Y$  and  $Z$  components of flow velocity vector

$U_0$  = flow velocity at the inlet of the test nozzle

$\bar{\omega}_x$  = normalized vorticity component along  $X$ -axis,

$$\bar{\omega}_x = \frac{D}{U_0} \left( \frac{\partial w}{\partial y} - \frac{\partial v}{\partial z} \right)$$

$\bar{\omega}_y$  = normalized vorticity component along  $Y$ -axis,

$$\bar{\omega}_y = \frac{D}{U_0} \left( \frac{\partial u}{\partial z} - \frac{\partial w}{\partial x} \right)$$

$\bar{\omega}_z$  = normalized vorticity component along  $Z$ -axis,

$$\bar{\omega}_z = \frac{D}{U_0} \left( \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y} \right)$$

$\bar{\omega}_{\text{plane}}$  = The magnitude of the vorticity inside the

measurement plane,  $\bar{\omega}_{\text{plane}} = \sqrt{\bar{\omega}_y^2 + \bar{\omega}_z^2}$

## Introduction

There are numerous aerospace applications where methods to enhance mixing between co-

flowing streams have been identified as critical or enabling technologies. Examples include low emissions combustors, ejectors for high lift or jet noise reduction, infrared suppressor nozzles, turbofan core bypass mixers and supersonic combustion ramjets. It has been well recognized that an efficient mechanism for mixing enhancement is to introduce strong streamwise vortices between the co-flowing streams. Lobed nozzles/mixers, which are essentially splitter plates with corrugated trailing edges, are widely considered as an extraordinary means of generating strong streamwise vortices to enhance mixing between co-flowing streams. Due to their outstanding mixing enhancement performance, lobed mixers/nozzles have been given great attention by many researchers in recent years.

Besides the continuous efforts to optimize the geometry of lobed mixers/nozzles for better

**Received:** 2008-04-06; **revision received date:** 2008-06-14

Hui HU, Assistant Professor; Research interests: Experimental aerodynamics and laser based flow diagnostics;

E-mail: huhui@iastate.edu.

mixing enhancement performance and to widen the applications of lobed mixers/nozzles<sup>[1-5]</sup>, extensive studies about the fundamental mechanism by which lobed mixer/nozzles substantially enhanced mixing have also been conducted. Based on pressure, temperature, and velocity measurements of the flow field downstream of a lobed mixer/nozzle, Paterson<sup>[6]</sup> revealed the existence of large-scale streamwise vortices induced by the special geometry of the lobed nozzle/mixer. Large-scale streamwise vortices were suggested to be responsible for the enhanced mixing. Werle et al.<sup>[7]</sup> and Eckerle et al.<sup>[8]</sup> suggested that the streamwise vortices downstream lobed mixers would follow a three-step process by which the streamwise vortices form, intensify, and then break down, and the high turbulence resulting from the vortex breakdown improved the overall mixing process. The study of McCormick and Bennett<sup>[9]</sup> revealed more details about the evolution and interaction of unsteady vortex structures downstream of a lobed mixer. Based on qualitative flow visualization with smoke and quantitative velocity measurements with hot film anemometer, McCormick and Bennett<sup>[9]</sup> suggested that the interaction between the large-scale streamwise vortices produced by the special geometry of the lobed mixer and the “normal” vortex structures generated due to the Kelvin-Helmholtz instabilities (i.e., Kelvin-Helmholtz vortex structures called in the present study) would produce high levels of mixing. As the Kelvin-Helmholtz vortices shed from the trailing edge of the lobed mixer, the streamwise vortices would cause deformation to the Kelvin-Helmholtz vortices until they were pinched off and subsequently broken down. Quantitative turbulence measurements showed the regions of high turbulence kinetic energy that were consistent with the qualitative flow visualization of the pinch-off effect of the Kelvin-Helmholtz vortex structures. Yu and Yip<sup>[10]</sup> conducted velocity measurements downstream of a lobed mixer with a Laser Doppler Velocimetry (LDV) system. They suggested that the intense small-scale turbulence and intensive mixing

downstream of a lobed mixer would be caused by the deformation of the Kelvin-Helmholtz vortices into pinch-off structures as conjectured by McCormick and Bennett<sup>[9]</sup>. Waitz et al.<sup>[11]</sup> summarized the findings of previous studies and suggested that there are three primary contributors for the enhanced mixing processes downstream lobed nozzles/mixers. The first is the large-scale streamwise vortices produced by the special geometry of the lobed nozzle/mixer, the second is the Kelvin-Helmholtz vortices, which occur in any free shear layers due to the Kelvin-Helmholtz instabilities, and the third is the increased interfacial contact area due to the convoluted trailing edge of the lobed mixer/nozzle.

Although the unsteady vortex structures such as large-scale streamwise vortices and Kelvin-Helmholtz vortices have been suggested to play very important roles to the enhanced mixing process downstream lobed mixers/nozzles, most of the previous studies were based mainly on qualitative flow visualizations to investigate the formation, evolutions and interactions of the unsteady vortex structures. Detailed measurements to quantify the behaviors of the unsteady vortex structures have not become available until recently. By using advanced flow diagnostic techniques such as planar laser induced fluorescence (LIF), particle image velocimetry (PIV) and stereoscopic PIV techniques, Hu et al.<sup>[12-13]</sup> conducted a series of experimental investigations to study the evolution of the unsteady vortex structures downstream lobed nozzles/mixers instantaneously and quantitatively. However, it should be noted that since only one component of the vorticity distributions could be derived from conventional PIV or stereoscopic PIV measurement results, only either streamwise vortices or Kelvin-Helmholtz vortex structures could be revealed from the PIV measurement results presented in Hu et al.<sup>[12-13]</sup>.

It is highly desirable to reveal both the streamwise vortices and the Kelvin-Helmholtz vortex structures simultaneously and quantitatively in order to elucidate underlying physics to further

our understanding about the formation, evolution and interaction characteristics of the large scale streamwise vortices and the Kelvin-Helmholtz vortex structures in lobed mixing flows. In the present study, a novel dual plane stereoscopic PIV (DP-SPIV) system<sup>[14]</sup>, which is capable of measuring all three components of flow vorticity distributions simultaneously, is used to conduct detailed measurements to reveal both the large scale streamwise vortices and the Kelvin-Helmholtz vortex structures in a lobed mixing flow for the first time. The objectives of the present study are to quantitatively confirm conjectures suggested in previous studies based on qualitative flow visualizations, as well as to gain further insight about the formation, evolution and interaction characteristics of the large scale streamwise vortices and Kelvin-Helmholtz vortex structures to improve our understanding about the fundamental mechanism of the lobed mixing process. It should be noted that the lobed nozzle/mixer, jet supply rig and flow conditions used in the present study are the same as those used in Hu et al.<sup>[13]</sup>, where a conventional stereoscopic PIV system was used to conduct flow velocity field measurements, therefore, the work presented here could be considered an extension of the work reported in Hu et al.<sup>[13]</sup>. Since extensive discussion about the characteristics of the lobed mixing process revealed from the velocity and turbulent kinetic energy distributions have already been given in Hu et al.<sup>[13]</sup>, only vorticity distributions will be presented here to quantify the formation, evolution and interaction characteristics of the large scale streamwise vortices and Kelvin-Helmholtz vortex structures in the lobed mixing flow.

1 Experimental setup and dual plane stereoscopic PIV system

Figure 1 shows the schematic of the circular lobed nozzle/mixer used in the present study. It has six lobe structures as the nozzle trailing edge. The width of each lobe is 6 mm and the lobe height is 15 mm ( $H = 15\text{ mm}$ ). The inward and outward penetration angles of the lobed

structures are  $\theta_{in} = 22^\circ$  and  $\theta_{out} = 14^\circ$  respectively. The diameter of the lobed nozzle/mixer is 40 mm ( $D = 40\text{ mm}$ ). A centrifugal compressor was used to supply air jet flows. Downstream of the centrifugal compressor, a cylindrical plenum chamber with honeycomb and mesh structures was used to settle the airflow. Through a convergent connection (convergent ratio 50 : 1) downstream to the plenum chamber, the airflow was exhausted from the lobed nozzle/mixer. The velocity range of the air flow out of the test nozzle is adjustable from 5 to 35 m/s. In the present study, the jet velocity at the inlet of the lobed nozzle/mixer was set as  $U_0 = 20.0\text{ m/s}$ , which corresponds to a Reynolds number of  $5.5 \times 10^5$  (based on the nozzle diameter  $D = 40\text{ mm}$ ). The jet flow was seeded with  $1 \sim 5\text{ }\mu\text{m}$  DEHS (Di-2-Ethyl-Hexyl-Sebac) droplets generated by a seeding generator<sup>[15]</sup>. The DESH droplets out of the seeding generator were divided into two streams; one is used to seed the core jet flow and the other for ambient air seeding.

Figure 2 shows the schematic of the dual plane stereoscopic PIV (DP-SPIV) system used in the present study. The DP-SPIV system was developed recently by taking advantage of the polarization conservation of Mie scattering in air to achieve stereoscopic PIV measurements at two spatially-separated parallel planes instantaneously and simultaneously<sup>[14]</sup>. As shown in the Fig. 2, two sets of commonly-used double pulsed Nd:YAG lasers (New Wave, 50 mJ/pulse) with additional optics (half wave plate, mirrors, polarizer and cylindrical lens) were used to illuminate the lobe jet flow at two parallel planes with orthogonally-polarized laser sheets (thickness of

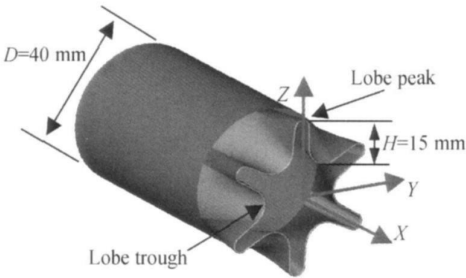


Fig. 1 The test lobed nozzle/mixer

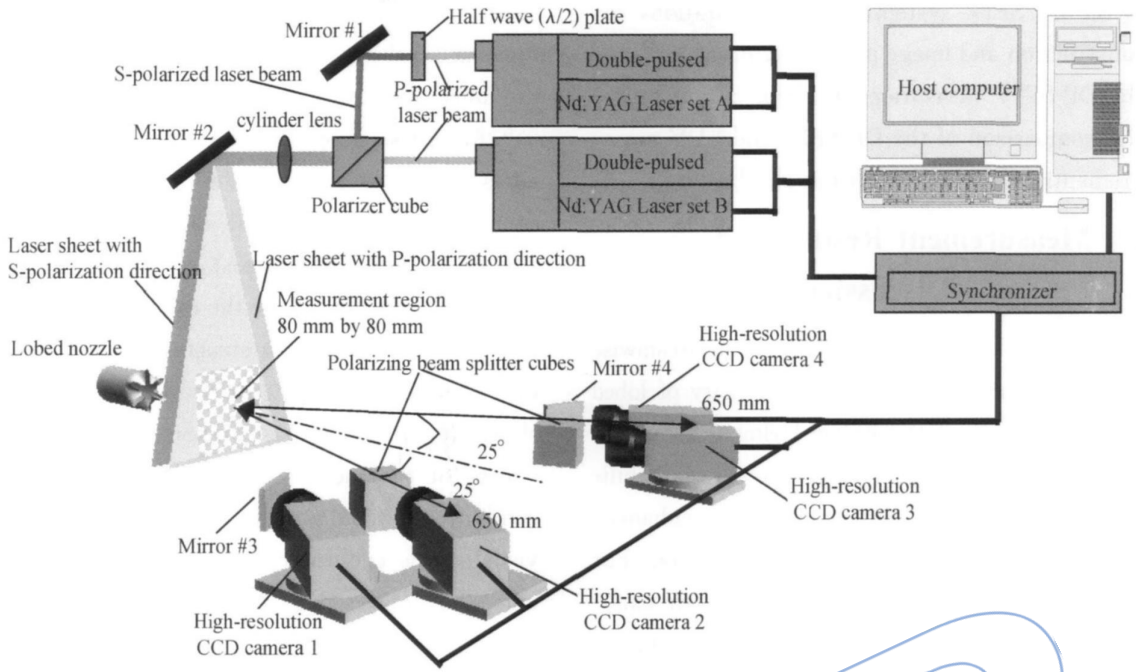


Fig. 2 The schematic of the dual plane stereoscopic PIV system

each laser sheet was about 2.0 mm). Since the polarization of Mie scattering in air flows is conservative, the scattering light from the seeded PIV tracer particles in the two orthogonally polarized laser sheets will keep their original polarization. A specially-designed imaging system composed of four high-resolution CCD cameras (1 K pixels by 1 K pixels) with a pair of polarizing beam splitter cubes and mirrors was devised to capture the scattering light selectively. By using such optical setup, the DP-SPIV system can achieve the stereoscopic PIV measurements of all three components of velocity vectors at two parallel planes simultaneously. As the curl of flow velocity vectors, the distributions of all three components of the vorticity vectors could be derived from the measured velocity fields.

The gap between the two parallel, simultaneously-illuminated laser sheets was set to be 2.0 mm in the present study. For the PIV image processing, 32 pixels by 32 pixels interrogation windows with 50% overlap were used to derive flow velocity vectors, therefore, the spatial resolution of the present measurement is expected to be about 2.5 mm × 2.5 mm × 2.0 mm. In order to evaluate the accuracy of the DP-SPIV measurements, a LDV system and the DP-SPIV

system were used to conduct simultaneous measurements of a jet flow, and the measurement results were compared quantitatively. It turned out that the differences between the DP-SPIV and the LDV measurements of the streamwise velocity ( $u$  component) were less than 2.0% ( $\sim 0.36$  m/s) at the compared points. As shown in the Fig. 2, since the half-view angle for the stereoscopic image recording is about 25 degree in the present study, the measurement uncertainty for the in-plane velocity components ( $v$ -component and  $w$ -component) would be about 1/3 of the out-of-plane velocity component ( $u$  component) according to Lawson and Wu<sup>[16]</sup>. Therefore, the uncertainties for the velocity measurements are expected to be about 0.36 m/s for the  $u$  component, and 0.12 m/s for the  $v$ -component and  $w$ -component in the present study. An adaptive scheme<sup>[17]</sup> was used in the present study to derive vorticity distributions from the measured velocity fields. Based on the accuracy level and the spatial resolution of the measured velocity distributions, averaged uncertainty level of the vorticity data given in the present study is expected to be within 10.0% according to the discussions given in reference [18]. Further information about the technical basis and system setup

of the DP-SPIV system, in-situ calibration, reconstruction and image processing procedures for the DP-SPIV measurements, and the quantitative comparison of the DP-SPIV and LDV measurements is available at Hu et al.<sup>[14]</sup>.

## 2 Measurement Results and Discussions

It is well known that the large-scale streamwise vortices produced by the special geometry of lobed nozzles/mixers and the Kelvin-Helmholtz vortices generated due to the Kelvin-Helmholtz instabilities play very important roles in the enhanced mixing process downstream lobed mixers. For the large-scale streamwise vortices, their existence was revealed very clearly from the instantar

neous streamwise vorticity distribution shown in Fig. 3(a), which was measured near the exit of the lobed nozzle/mixer (i.e.  $X/D = 0.25$ ,  $X/H = 0.67$  cross plane). Corresponding to the six lobes of the lobed nozzle/mixer, six pairs of counter rotating streamwise vortices were generated with their size almost equivalent to the height of the lobes. Since the rotation axis of the Kelvin-Helmholtz vortex structures is parallel to the laser illuminating planes ( $Y-Z$  plane as shown in Fig. 1), the  $\omega_z$ -component and  $\omega_y$ -component of the measured vorticity vectors were combined to calculate  $\omega_{irplane}$  vorticity in order to visualize the evolution of the Kelvin-Helmholtz vortex structures more clearly. The instantaneous in-plane vorticity distribution in the  $X/D = 0.25$

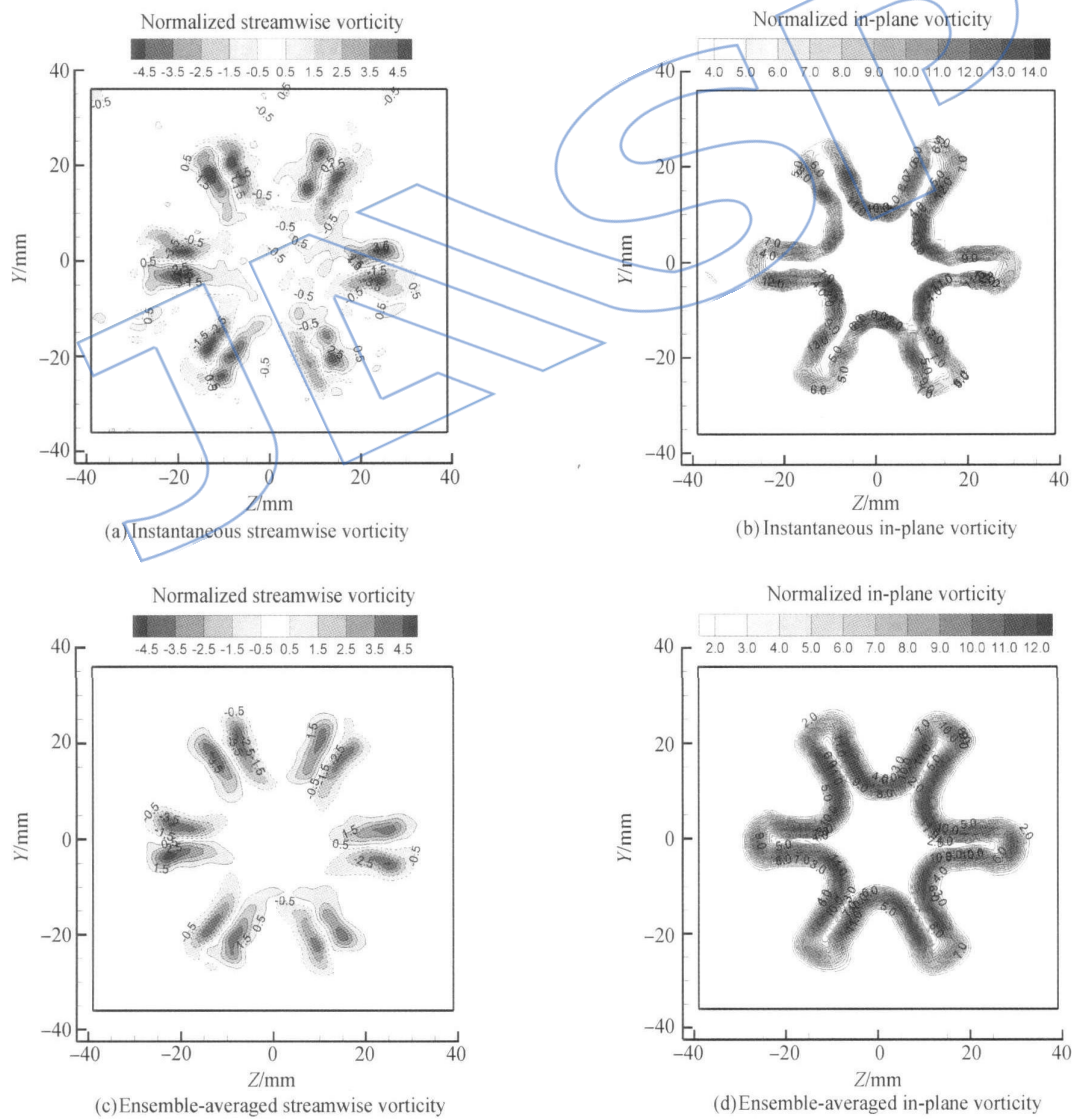


Fig. 3 Measured vorticity distributions in the  $X/D = 0.25$  ( $X/H = 0.67$ ) cross plane

( $X/H = 0.67$ ) cross plane is given in Fig. 3(b). As expected, the Kelvin-Helmholtz vortex structures were found to form vortex rings with the same shape as the trailing edge of the lobed nozzle/mixer. Although the existence of the large scale streamwise vortices and Kelvin-Helmholtz vortices downstream lobed nozzles/mixers have been visualized qualitatively in previous studies, the results shown at here are believed to be the first measurement to visualize them quantitatively and simultaneously.

Based on 400 frames of instantaneous measurements, ensemble averaged streamwise vorticity and in-plane vorticity distributions were calculated, and the results are given in Fig. 3(c) and Fig. 3(d). Compared with those shown in the instantaneous vorticity distributions, the iso-vorticity contour lines in the ensemble averaged fields were found to be smoother. However, they were found to have almost the same distribution pattern as their instantaneous counterparts, which could indicate that the generation of the large scale streamwise vortices and the Kelvin-Helmholtz vortex rings at the exit of the lobed nozzle/mixer was quite steady.

Figure 4 gives the measured vorticity distributions in the  $X/D = 0.5$  ( $X/H = 1.33$ ) cross plane. The instantaneous streamwise vorticity distribution revealed that the large scale streamwise vortices generated by the lobed nozzle/mixer began to break into smaller vortices. Besides the streamwise vortices at lobe peaks, smaller streamwise vortices could also be identified at the lobe troughs from the instantaneous streamwise vorticity distribution. These smaller streamwise vortices are believed to be the “horseshoe vortex” structures named by Paterson<sup>[6]</sup> and visualized qualitatively in the LIF images of Hu et al.<sup>[12]</sup>. Six pairs of large scale streamwise vortices could still be seen clearly from the ensemble averaged streamwise vorticity distribution, the centers of the streamwise vortices were found to move outward radially compared with those at the exit of the lobed nozzle/mixer.

Same phenomena were also found from the LDV measurements of Bleovich and Samimy<sup>[19]</sup>. The instantaneous in-plane vorticity distribution shows that the instantaneous Kelvin-Helmholtz vortex ring, which had the same shape as the lobed trailing edge at the exit of the lobed nozzle/mixer, was deformed and even torn to open due to “stretch effect” of the streamwise vortices at lobe peaks and lobe troughs as conjectured by Hu et al.<sup>[12]</sup>. The ensemble averaged in-plane vorticity distribution shows that the ensemble averaged Kelvin-Helmholtz vortex ring was still in the same shape as the lobed trailing edge of the lobed nozzle/mixer with its size growing and spreading slightly outward.

As the downstream distance increased to  $X/D = 1.0$  ( $X/H = 2.67$ , and Fig. 5), the six pairs of large scale streamwise vortices seen in the instantaneous streamwise vorticity distributions upstream could not be seen here any longer. The large scale streamwise vortices were found to break into many smaller streamwise vortices. However, it should be noted that the maximum vorticity of the smaller streamwise vortices was found to be almost the same as their “parent” streamwise vortices, i.e., the large scale streamwise vortices were found to break down into smaller, but not weaker streamwise vortices. Six pairs of large scale streamwise vortices could still be identified from the ensemble averaged streamwise vorticity distribution shown in Fig. 5(c), however, the strength of the ensemble averaged streamwise vortices was found to decay significantly compared that at the exit of the lobed nozzle/mixer. The instantaneous in-plane vorticity distributions in this cross plane shows that the Kelvin-Helmholtz vortex rings, which were in the same shape as the lobed trailing edge at the exit of the lobed nozzle/mixer, were found to break down into disconnected vortex fragments. The ensemble averaged in-plane vorticity distribution displays that the ensemble averaged Kelvin-Helmholtz vortex structures were seriously de-

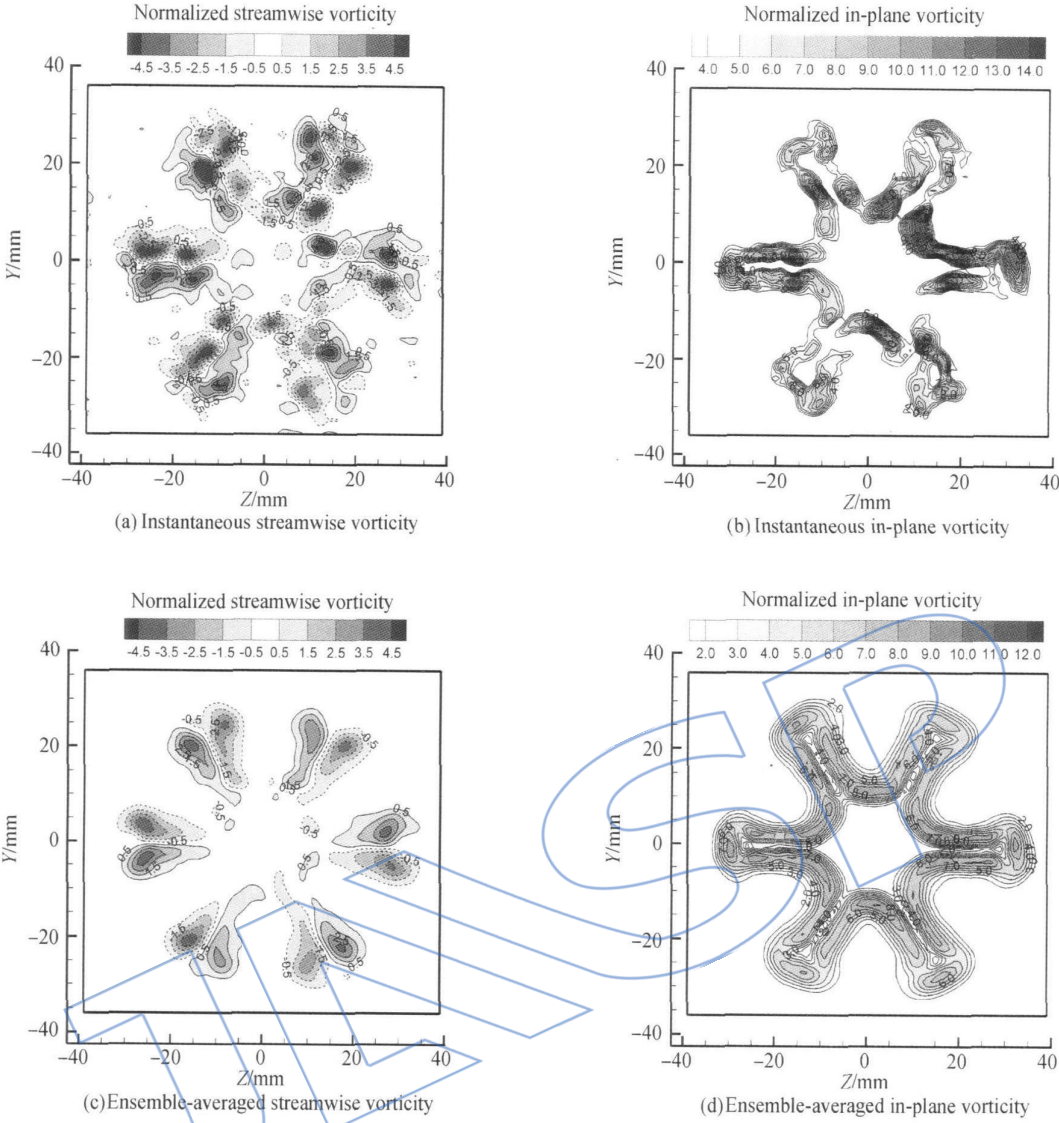


Fig. 4 Measured vorticity distributions in the  $X/D = 0.50$  ( $X/H = 1.3$ ) cross plane

formed. Based on qualitatively flow visualization, McCormick and Bennett<sup>[9]</sup> suggested that the Kelvin-Helmholtz vortex structures would be pinched off due to the interaction with the streamwise vortices, which would result in intense mixing. The pinch-off effect of the Kelvin-Helmholtz vortex structures was revealed clearly and quantitatively from the ensemble-averaged in-plane vorticity distribution shown in Fig 5 (d). It should be noted that the present measurement result is believed to be the first to visualize the pinching-off of the Kelvin-Helmholtz vortex structures from the vorticity distribution measurements, which verifies the conjecture of McCormick and Bennett<sup>[9]</sup> quantitatively.

Figure 6 gives the measured vorticity distributions in the  $X/D = 1.5$  ( $X/H = 4.0$ ) cross plane.

The instantaneous streamwise vorticity distribution shows that there were more and more small-scale streamwise vortices appearing in the jet mixing flow with the maximum vorticity of the smaller streamwise vortices being still at the same level as their “parent” vortices. The ensemble-averaged streamwise vortices were found to break down with their strength substantially dissipated. The typical instantaneous in-plane vorticity distribution reveals that the Kelvin-Helmholtz vortex structures kept on breaking into smaller fragments and being dissipated as they traveled downstream. The ensemble-averaged in-plane vorticity distribution displayed that the Kelvin-Helmholtz vortex ring

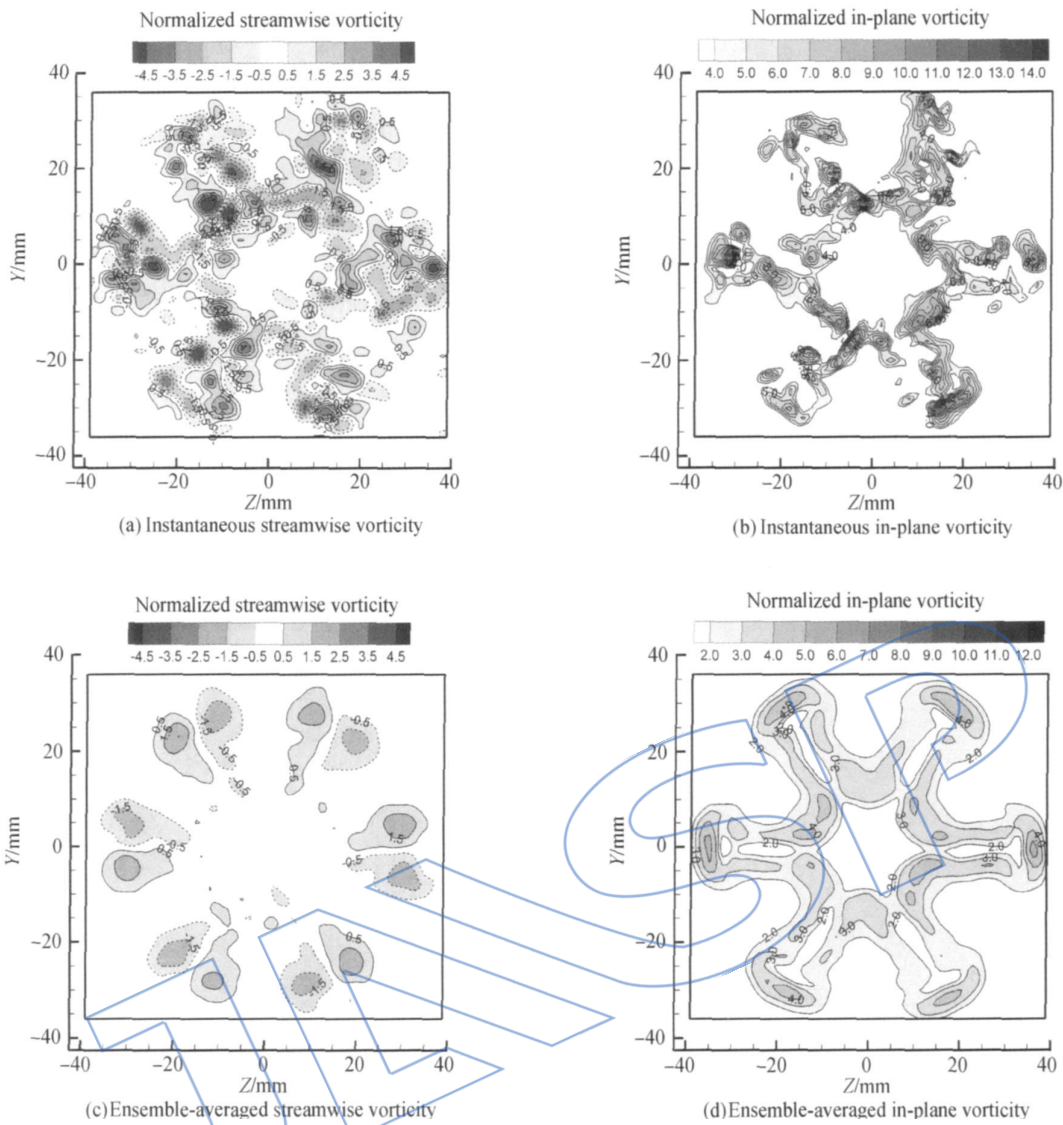


Fig. 5 Measured vorticity distributions in the  $X/D=1.00$  ( $X/H=2.7$ ) cross plane

was found to break down into substructure after pinched off to form a wreath-like structure surrounded by six “crescents”.

As the downstream distance continually increased, the number of the smaller streamwise vortices originating from the breakdown of the large scale streamwise vortices was found to increase at first, reaching its maximum in the neighborhood of downstream region of  $X/D=2.0$  ( $X/H=5.3$ ), and then beginning to decrease. After breakdown into smaller structures, the ensemble averaged streamwise vortices were dissipated rapidly, and no apparent ensemble averaged streamwise vortex structures could be identified anymore at farther downstream of  $X/D>2.5$  ( $X/H>7.0$ ). Fewer and fewer fragments of the broken Kelvin-Helmholtz

vortex tubes could be identified from the instantaneous in-plane vorticity distributions. As the downstream distance increased, the “crescents” seen from the ensemble averaged in-plane vorticity distributions were found to fade out quickly, and eventually vanish. The wreath-like structures revealed upstream were found to be rounded up to be circular vortex rings, which are similar to those found in the far fields of a circular jet flow. Such results were found to agree with the findings of Bell and Mehta<sup>[20]</sup>, who suggested that a jet flow with added streamwise vortices to enhance the mixing process would resume back to a normal jet flow after the large-scale streamwise vortices were dissipated in the far field.

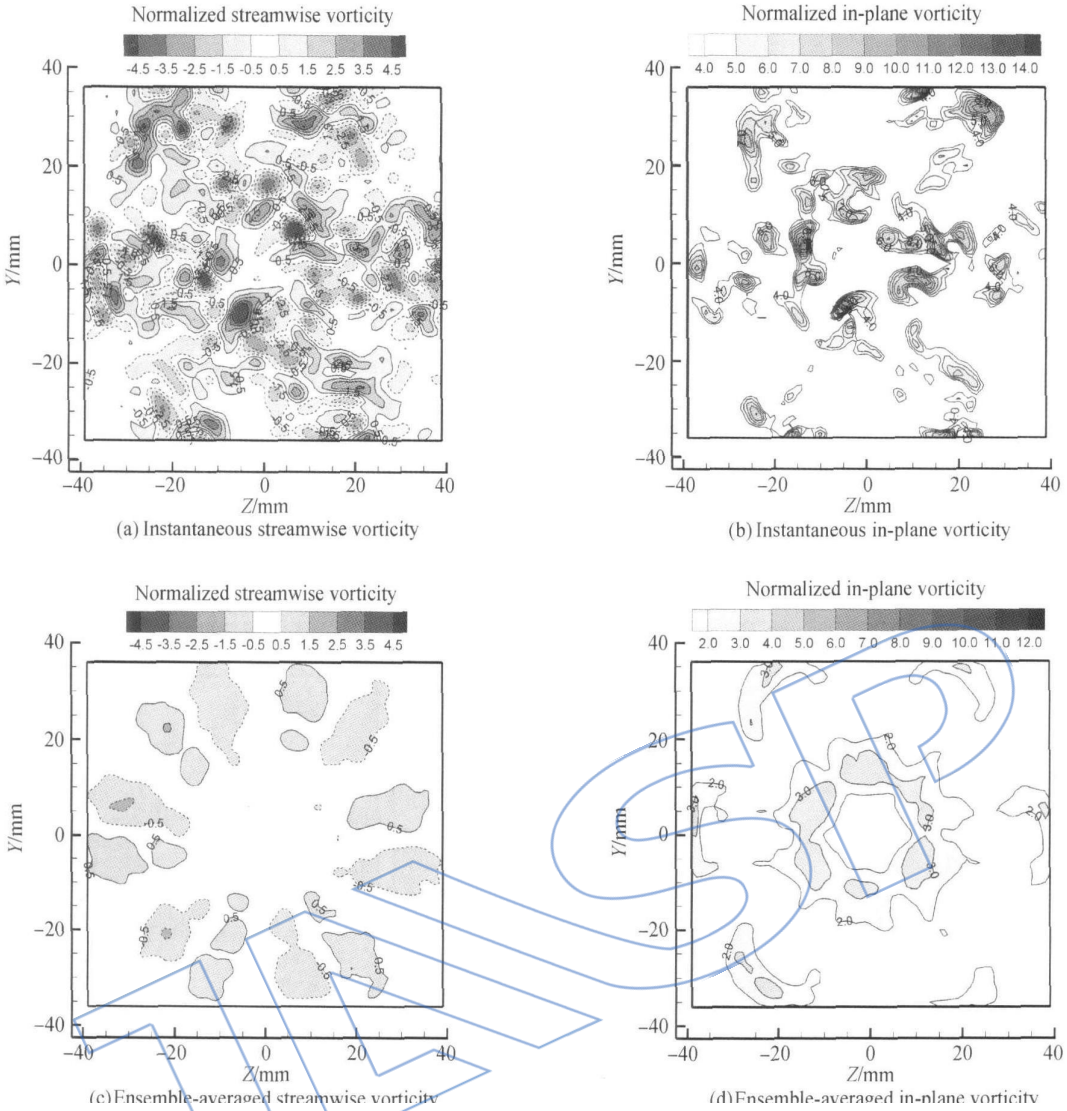


Fig. 6 Measured vorticity distributions in the  $X/D=1.50$  ( $X/H=4.0$ ) cross plane

From the measurement results described above, it can be seen that the instantaneous and the ensemble averaged vorticity distributions displayed quite different aspects of the facts about the evolution of the large scale streamwise vortices and the Kelvin-Helmholtz vortex structures in the lobed mixing flow. The instantaneous streamwise vorticity distributions showed that the large scale streamwise vortices generated by the lobed nozzle/mixer would break into smaller, but not weaker, streamwise vortices as they traveled downstream. The smaller but not weaker streamwise vortices were found to concentrate at the regions downstream of lobe peaks at first, then, migrated everywhere in the mixing flow as the downstream distance increased. This is believed to be the reason why a lobe nozzle/mixer would enhance both large scale mixing and small scale mixing as reported by previous studies<sup>[21]</sup>. The number of the smaller, but not weaker, streamwise vortices was found to increase at first, reaching its maximum number in the neighborhood of downstream region of  $X/D=2.0$  ( $X/H=5.3$ ), and then decreasing further downstream. The instantaneous in-plane vorticity distributions indicated that the Kelvin-Helmholtz vortex structures rolling up at the interface between the lobed jet and ambient flow would form vortex rings. As expected, the Kelvin-Helmholtz vortex rings had the same shape as the lobed trailing edge at the exit of the lobed nozzle/mixer. The Kelvin-Helmholtz vortex rings were deformed and torn open, and broken into many smaller fragments as they traveled

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downstream. The broken Kelvin-Helmholtz vortex tubes were found to be seriously dissipated and eventually vanished farther downstream.

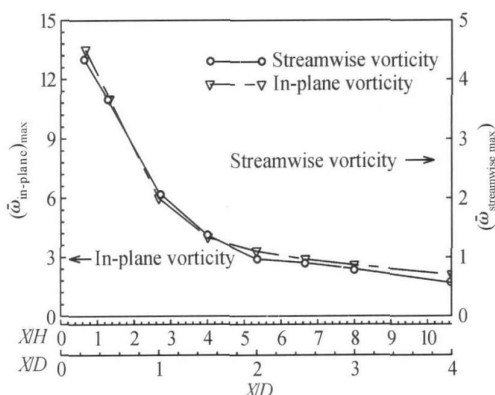


Fig. 7 The decay the streamwise vorticity and in plane vorticity

The ensemble-averaged vorticity distributions could be used to demonstrate the overall effect of the special geometry of the lobed nozzle/mixer on the enhanced mixing process. The large-scale streamwise vortices generated by the special geometry of the lobed nozzle/mixer could be thought to act as “stirrers” to enhance the mix between the core jet flow and ambient flow. The “stirring effect” could be evaluated from the evolution of the ensemble-averaged streamwise vortices in the lobed mixing flow, which was represented quantitatively by the decay profile of the maximum ensemble-averaged streamwise vorticity with the increasing downstream distance. As shown in Fig. 7, the ensemble-averaged streamwise vorticity was found to decay very rapidly within the first diameters of the lobed nozzle/mixer (about first three lobe heights), where the ensemble-averaged streamwise vortices were generated, grew up, and migrated outward radially. The decay rate of the ensemble-averaged streamwise vorticity was found to be more moderate in the regions of  $1.0 < X/D < 2.0$  ( $2.7 < X/H < 5.3$ ), where the ensemble-averaged streamwise vortices were found to break down into smaller structures. After breakdown, the decay rate of the ensemble-averaged streamwise vorticity was found to significantly slow down farther downstream of

$X/D > 2.0$  ( $X/H > 5.3$ ), where the smaller and weaker ensemble-averaged streamwise vortices were dissipated rapidly, and no apparent ensemble-averaged streamwise vortex structures could be identified in the lobed mixing flow. Farther downstream of  $X/D > 3.0$  ( $X/H > 8.0$ ), the ensemble-averaged streamwise vortices became so weak that they were not able to affect the mixing process any longer. Therefore, it could be suggested that the enhanced mixing due to the special geometry of the lobed nozzle/mixer would be concentrated in the upstream of the first two diameters of the lobed nozzle/mixer (about first six lobe heights). The conclusions are found to be consistent with the velocity and turbulent kinetic energy measurement results reported in Hu et al.<sup>[13]</sup>, which also agree with the findings of McCormick and Bennett<sup>[9]</sup> and Glauser et al.<sup>[22]</sup> who suggested that the maximum effectiveness region for a lobed mixer is within the first six lobe heights.

The evolution of the ensemble-averaged Kelvin-Helmholtz vortex structures could be shown schematically in Fig. 8. The ensemble-averaged Kelvin-Helmholtz vortex structures were found to form vortex rings with the same shape as the lobed trailing edge at the exit of the lobed nozzle/mixer. The Kelvin-Helmholtz vortex rings would grow in size and expand outward at first as they traveled downstream. Due to the interaction with the large-scale streamwise vortices generated by the lobed nozzle/mixer, the Kelvin-Helmholtz vortex rings would be pinched off as conjectured by the McCormick and Bennett<sup>[9]</sup>. The pinched-off Kelvin-Helmholtz vortex rings would break down into substructures to form wreath-like structures surrounded by “crescents”. The “crescents” were found to rapidly dissipate and eventually vanish farther downstream. The wreath-like structures were found to be rounded up to become circular vortex rings, which were similar to those found in the far field of circular jet flows. As shown in Fig. 7, the decay of the ensemble-averaged Kelvin-Helmholtz vortex structures was found to follow

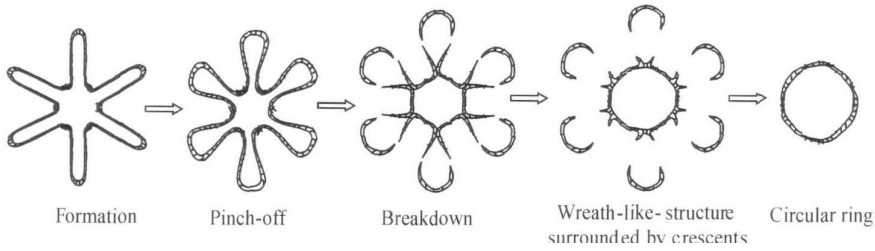


Fig. 8 The evolution of the Kelvin-Helmholtz vortex structures

almost identical trends as that of the ensemble-averaged streamwise vortices. The strength of the Kelvin-Helmholtz vortex structures (in-plane vorticity) was found to decay dramatically at the first diameter of the lobed nozzle/mixer (first three lobe heights), where the Kelvin-Helmholtz vortex ring grew up in size and pinched off due to the interaction with the streamwise vortices. After the pinched-off Kelvin-Helmholtz vortex rings broke down into substructures to form wreath-like structures surrounded by “crescents”, their strength was found to decay at a more moderate rate in the downstream region of  $1.0 < X/D < 2.0$  ( $2.7 < X/H < 5.3$ ). Since the Kelvin-Helmholtz vortex structures had already been dissipated seriously upstream, the decay rate was found to slow down very much farther downstream of  $X/D > 2.0$  ( $X/H > 5.3$ ), where the “crescents” were found to eventually vanish, and the wreath-like structures were rounded up to become circular vortex rings.

## 4 Conclusions

An experimental investigation was conducted to gain further insight about the behaviors of unsteady vortex structures downstream of a circular lobed nozzle/mixer. A novel dual-plane stereoscopic PIV system was used to conduct simultaneous measurements of all three components of vorticity distributions in the lobed mixing flow to quantitatively visualize both the large-scale streamwise vortices produced by the lobed nozzle/mixer and the Kelvin-Helmholtz vortex structures generated due to Kelvin-Helmholtz instabilities simultaneously for the first time. In addition to quantitatively confir-

ming conjectures suggested in previous studies, many more details about the evolution and interaction characteristics of the unsteady vortex structures in the lobed jet mixing flow were also uncovered in the present study.

The presented instantaneous and ensemble-averaged vorticity distributions revealed quite different aspects about the evolution of the large-scale streamwise vortices and the Kelvin-Helmholtz vortex structures. The instantaneous vorticity distributions displayed that the large-scale streamwise vortices generated by the lobed nozzle/mixer broke into smaller, but not weaker, streamwise vortices rapidly as they traveled downstream. The smaller, but not weaker, streamwise vortices were found to concentrate in the regions downstream lobe peaks at first, and then migrate to everywhere in the lobe jet mixing flow. It is proposed as the reason why a lobed mixer/nozzle could enhance both large-scale mixing and small-scale mixing as conjectured in previous studies. The Kelvin-Helmholtz vortex structures rolling up at the interface between the lobed jet and ambient flow were found to form vortex rings with the same shape as the trailing edge of the lobed nozzle/mixer as expected. As they traveled downstream, the Kelvin-Helmholtz vortex rings were found to be deformed, torn open, then broken down into disconnected fragments, and eventually vanished farther downstream of  $X/D > 3.0$  ( $X/H > 8.0$ ).

While the instantaneous vorticity measurement results revealed more details about the evolutions of the unsteady vortex structures, the ensemble-averaged vorticity distributions demonstrated the overall effect of the special geometry of the lobed nozzle/mixer on the enhanced

mixing process. With their size equivalent to the lobe height at the exit of the lobed nozzle/mixer, the ensemble-averaged streamwise vortices were found to grow up and expand outward radially at first, and then break down, which confirmed the conjecture of three-step process (i. e., the streamwise vortices form, intensify, and then break down) suggested in previous studies. The ensemble-averaged Kelvin-Helmholtz vortex structures were found to form vortex rings with their shape the same as lobed trailing edge at the exit of the lobed nozzle/mixer. The Kelvin-Helmholtz vortex rings were found to expand outward, then became pinched off due to the interaction with the large-scale streamwise vortices as they traveled downstream. The pinch-off effect of the Kelvin-Helmholtz vortex rings resulted in breakdown of the vortex rings into sub-structures to form wreath-like structures surrounded by “crescents”. The “crescents” were rapidly dissipated and eventually vanished farther downstream, while the wreath-like structures were rounded up to become circular vortex rings.

The strength the ensemble-averaged streamwise vortices and the Kelvin-Helmholtz vortex structures were found to follow almost identical trends, which decrease monotonically as the downstream distance increasing. Such decay trends suggest that the enhanced mixing due to the special geometry of the lobed nozzle/mixer was concentrated in the regions of the first two diameters of the lobed nozzle/mixer (about first six lobe heights), which agree with the findings of previous studies based on the velocity and turbulent kinetic energy measurements, i. e., the maximum effectiveness region of a lobed mixer is within the first six lobe heights.

It should be noted that although numerous previous studies have been conducted to investigate the behavior of the unsteady vortex structures in lobed mixing flows, the work presented here is believed to be the first to provide detailed vorticity measurements to quantify the evolution of the large-scale streamwise vortices and the

Kelvin-Helmholtz vortex structures simultaneously and instantaneously. Further insight about the evolution of the unsteady vortex structures gained through the present study also highlights the advantages of using advanced diagnostic techniques, such as the DP-SPIV technique, to elucidate underlying physics to improve our understanding about the fundamental mechanism of complex flow phenomena.

### Acknowledgments

The authors would like to thank Mr. Tetsuo Saga and Dr. Nobuyuki Taniguchi of the University of Tokyo and Mr. M. Yasuki of SEIKA Corporation, Japan for their help in conducting the experiments.

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