Mixing Flow Structures of Scalloped, Forced Lobed Mixers using PIV and PLIF Measuring Techniques

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MIXING FLOW STRUCTURES OF SCALLOPED, FORCED LOBED MIXERS USING PIV AND PLIF MEASURING TECHNIQUES

by

Nathan J. Cooper

A Thesis
Submitted to the
Faculty of The Graduate College
in partial fulfillment of the
requirements for the
Degree of Master of Science in Engineering (Mechanical)
Department of Mechanical and Aeronautical Engineering

Western Michigan University
Kalamazoo, Michigan
December 2005
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2005
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Nathan J. Cooper
MIXING FLOW STRUCTURES OF SCALLOPED, FORCED LOBED MIXERS USING PIV AND PLIF MEASURING TECHNIQUES

Nathan J. Cooper, M.S.E.
Western Michigan University, 2005

An Experimental study of internal forced lobed mixers similar to those used in jet aircraft engines is performed using whole field species concentration and velocity measuring techniques. Planar temperature and velocity measurements using Planar Laser Induced Fluorescence (PLIF) and 2D Particle Image Velocimetry (PIV) are performed for lobed, lobed scalloped and splitter mixers in aqueous solution. Specific emphasis is given to study scallops or notches cut into the mixer trailing edge and their role in mixing enhancement. Mixing is compared through velocity and species concentration measurements on axial and streamwise planes for the three dimensional, forced mixers in a confined constant area mixing duct.

Scalloped lobed mixer results indicate additional mixing over that of a lobed mixer of the same geometry. The scalloped nozzle shows more rapid shear layer growth and scalar mixing in sidewall regions in comparison with the lobed mixer in the enhanced mixing region. Additionally, impingement of the cross stream velocity on the mixing duct is further downstream than for the lobed mixer under same test condition. Lastly, the decay of cross stream velocity shows the scalloped mixer to decay from the exit plane while the lobed mixer indicates initial rise in magnitude before decay.
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CHAPTER 1

INTRODUCTION

Mixer and thrust augmenting mixer/ejector systems have been a key topic in the development of gas turbines exhibiting; propulsive efficiency gains, diminished noise and reduced heat signature throughout the last 40 years. Such gains are realized when compact, passive mixers are incorporated to enhance the mixing rate between the core and bypass streams prior to expansion through the nozzle. It is widely known that one powerful mechanism to achieve high mixing rates within short axial distances is by introducing strong streamwise vortices between the co-flowing streams. However, it is not easily determined the most effective method for their introduction. Therefore much research to date concentrates on obtaining the optimum mixer geometry for a specific application, balancing gains created by enhanced mixing versus its pressure loss byproduct.

Modifying the trailing edge geometry is the most common method for introducing strong, large-scale streamwise vortices into the core-bypass stream. Typical trailing edge treatments consist of complex corrugated lobe shapes imposed onto an annular ring. Further modifications studied by researchers include asymmetric lobes, alternating deep-shallow lobe penetrations, cutback lobes, asymmetric cutback lobes and notches or
scallops cut into the trailing edge. Results indicate modest gains for lobed mixing devices increasing efficiency as much as 3% [5] at specific operating conditions.

The remainder of Chapter 1 summarizes the research to date on lobed mixing devices and introduces the rationale for the current thesis. In addition it is important to add that mixing enhancement of co-flowing streams is also of great interest to other aerospace devices outside of mixed turbofan cycles. Examples include, low emission combustors, ejectors for high lift or jet noise reduction, infrared suppressor nozzles and supersonic combustion ramjets.

Literature Review

Mixed turbofan cycles are used primarily for high-speed aircraft which require thrust augmentation by way of an afterburner during operation. The advantages [16] of a mixed cycle, include the option to incorporate a variable-area exhaust, an afterburner and to cool the afterburner liner using the bypass air. Additionally, smaller transports such as business jets benefit by incorporating a mixed cycle as they can achieve higher overall propulsive efficiencies over separately exhausted cycles of similar bypass ratios. That is to say that the separately exhausted cycle for fixed fan pressure ratios are optimized at higher bypass ratios. A comprehensive discussion on the advantages of mixed cycles can be found in textbooks [12, 16, 19] and published papers by Pearson [24], Heiser [6] and Oates [20]. It is sufficient to say for this research that the aforementioned texts underscore the importance of incorporating mixers that do not incur large viscous losses or add additional weight that would offset any gains due to mixing.
Early researches [13, 14, 15, 23, 25] concentrated in identifying mixer shapes that increased overall gross thrust, optimizing mixer geometries for specific flight operating conditions. This research was propelled by the Energy Efficient Engine (E³) program initiated by NASA in 1978. The results of such experiments could be directly applied to the engine tested with good confidence. However, the complex fluid structures responsible for reported performance gains remained largely undetermined for use in later designs. Most recent lobed mixer research has concentrated on elucidating the flow structures that promote enhanced mixing. These are often conducted using measuring techniques that restrict flow speeds, temperatures and in some cases fluids. Typically gross thrust changes are not measured directly and the actual performance when applied to full-scale engines must be inferred into the design process. Often this is through verification by CFD. The premise of this thesis concentrates on the revealing the mixing process in scalloped lobed mixers. The following literature review lists notable contributions to our understanding of the mixing process in lobed mixers.

Paterson[21, 221] is credited with the first quantitative look into lobed mixer flow structures at simulated flight conditions. Paterson incorporated LDV to measure mean and turbulent velocity components in the wake of the lobed mixer. He suggested that mixing is accomplished by three main transport mechanisms. Convection by mean velocity components in the radial and circumferential directions dominate initial mixing followed by large-scale turbulent motions with length scales proportional to that of the
lobe height. The exhaust flow is further mixed by gradient type turbulent diffusion of small-scale turbulent structures.

Elliot et al. [4] sought to gain insight into the mixing mechanisms by separating the effects of the streamwise secondary circulations discussed by Paterson [21, 22] and the shear layer spanwise Kelvin-Helmholtz vortices present in any free shear layer. This was accomplished by using two different mixer configurations. Both mixers have the same wavelength (lobe spacing) but incorporate different slopes leading to the trailing edge. The sloped mixer produced streamwise circulations similar to those observed by Paterson [22] while the convoluted plate (straight section prior to trailing edge) did not exhibit these circulations. From experimental results Elliot et al. conjectured that mixing increases were largely from the spanwise normal vortices (formed by Kelvin-Helmholtz instabilities) followed by the increased lobed mixer interfacial contact (as compared to free splitter) and lastly from the streamwise vortices.

McCormick et al. [17, 18] performed extensive flow visualizations and quantitative hot-film anemometry measurements on a forced mixer similar to Elliot et. al. [4] and Eckerle et al.[3]. Through smoke flow visualizations, the presumed existence of horseshoe shaped vortices found in the lobe troughs at the mixer trailing edge were verified. He concluded that high levels of mixing were accomplished by the interaction between the normal spanwise vortices and the secondary streamwise circulations. Additionally, he observed minimal difference in momentum thickness development for approaching laminar and turbulent boundary layers to the lobed mixers. This is quite
different than the shear layer development for plain splitter mixers where tripping the boundary layer caused slower momentum thickness growth.

Previous researchers have predicted that the vortical and turbulent structures in lobed mixing flows play important roles in mixing enhancement. Only in recent years, has detailed quantitative experimental techniques been developed that are capable of revealing the evolution and interaction of whole-field unsteady velocity and vorticity in lobed mixing flows. By using modern whole-field flow diagnostic techniques like Planar Laser Induced Fluorescence (PLIF), Particle Image Velocimetry (PIV), Stereoscopic Particle Image Velocimetry (SPIV) and Dual-plane Stereoscopic PIV techniques, Hu et al. [7-11] conducted a series of studies to address the evolution and interactive characteristics of various vortical and turbulent structures in lobed jet mixing flows instantaneously and quantitatively. Hu concluded that enhanced mixing was accomplished through the breakup of streamwise vortices from large to small scales without losses in intensity. This explains the increase in both the large and the small scale mixing documented by Paterson [21, 221] and Werle et. al. [26]

Lobe Scalloping

These experiments have done much to further our understanding of mixing structures in lobed mixer/ejector flows. Still more is needed to continue to advance in this area. These experiments mentioned are fundamental studies of the flow structures for conventional lobe geometries. Detailed studies of trailing edge treatments have not been sufficiently addressed. Cutback lobes, and scallops have showed promise for thrust
enhancement but the flow structures remain relatively unstudied. Research by Kozlowski and Kraft [14], Kuchar and Chamberlin [15], Shumpert [25], Abolfadl and Sehra [1] and Hu [7] have all showed the possible benefit by incorporating scallops into the trailing edge through increased mass flow pumping or thrust increases. However, Yu et. al.[27] has preformed the only study of scalloped trailing edge treatments known to date. Velocity measurements were conducted for a two-dimensional mixer using a two component LDV system. In it he suggests that an additional pair of streamwise vortices is formed initially due to the scalloped lobes that provide an additional mechanism for enhance mixing.

Scope of Project

The objective of the present research is to provide additional insight into the flow structures generated by scalloped trailed edge treatments through high resolution PIV measurements and quantitative mixing measurement of a passive scalar (PLIF). The lobe geometry, namely lobe height, penetration angle and width are designed similar to Elliot et. al. [4], McCormick [17, 18] and Eckerle [3]. The modification here along with scalloping is that the mixer is not two-dimensional but three-dimensional and mixing is confined in a circular mixing duct typical to its traditional application. Figure 1 illustrates the difference between two dimensional and three-dimensional lobed mixers.
Figure 1. 2D versus 3D lobed mixers.
CHAPTER 2

EXPERIMENTAL CONFIGURATION

This chapter describes the test equipment and measuring techniques used throughout testing. Included is a detailed description of the water tunnel, test section, PIV/PLIF arrangement and lobed mixer configurations.

Water Tunnel

All experiments were performed in a closed circuit water tunnel manufactured by Rolling Hills Research (formerly Eidetics) Corporation. The water tunnel, model 1520K, was modified from its original configuration to produce the desired core and bypass flow rates to the lobed mixer and test section. The un-modified portion of the water tunnel is first described. A free surface supply plenum, clear test section and return make up the three segments of the water tunnel. Figure 2 and Figure 3 show a schematic and photograph of the water tunnel used in this study. Water is supplied to the plenum where it passes through a series of screens and a honeycomb straightener prior to entering the test section. Plenum walls are smooth and accelerate the fluid slowly to the test section using a 6:1 contraction ratio. Fluid leaving the test section returns to the pumps via two screen-covered outlets. The plenum supply pump is powered by a 2 Hp motor coupled to an 20cm impeller that produces up to 3.4 m$^3$/min or 30.5 cm/sec through the test section.
Figure 2. Water tunnel schematic.

Figure 3. Photograph of water tunnel (without flow conditioners).
In addition, the water tunnel was modified for this project to generate a shear flow between two co-flowing streams. The goal was to design and build a piping system that would supply higher velocity core flows, creating velocity ratios on the order of 2:1 relative to the bypass stream. Stock centrifugal pumps were initially selected as the source for the core flow but were found to generate small air bubbles preventing the use of optical measuring techniques proposed in this experiment. Therefore it was determined that an axial style pump, similar to the original water tunnel pump, was necessary to generate the core flow momentum. This was designed and constructed at WMU and composed of all stainless steel components. Figure 4 shows the pump that was machined and fabricated using standard 4-inch schedule 40 stainless pipe and elbow fittings. A modified personal watercraft impeller serves as the pump rotor that is supported by two Teflon friction bearings and coupled to ½ Hp DC motor. Core flow average velocity reaches maximum at 2.1 m/s and is controlled by an AC to DC motor speed controller equipped with a digital indicator. Core flow is plumbed into the water tunnel through 4-inch PVC pipe.
Figure 4 (a-c). Stainless core flow pump, (a) Pump inlet, (b) Impeller assembly, (c) Core flow pump assembly.
A de-swirl and straightening plenum is constructed and installed inline with the 4-inch pipe approximately 23 pipe diameters upstream of the nozzle exit plane. This is necessary to remove residual swirl from the impeller-stator and piping corners. The plenum uses a standard 6-inch PVC pipe with machined nozzle inserts to provide smooth transition from the incoming and outgoing 4-inch pipe. A screen followed by a 5cm thick plastic honeycomb straightener, with hole sizes 3.1mm, are used to condition the flow. Figure 5 shows a cut-away view of the core flow conditioner.

Similarly, flow conditioning was required for the bypass fluid prior to entering the mixing duct. During initial testing of the rig, PIV data and streaked dye visualizations revealed excessive curvature of the fluid streamlines entering the mixing duct. To correct this, a nozzle and flow straightener were added at the entrance of the mixing duct. The nozzle was constructed from fiberglass formed by machining and polishing a wooden
plug mold. The resulting nozzle has an area contraction ratio of 1.5. Figure 6 shows a
cutaway view of the flow straightener.

Figure 6. Bypass flow conditioner.

Test Section, Mixers

The test section consists of a clear glass bottom and sidewalls measuring 0.508m
× 0.381m × 1.524m (H x W x L). A clear acrylic open-ended cylinder forms the mixing
duct and is located in the center of the water tunnel test section. The mixing duct is
supported from the top by vertical airfoil shaped struts at the fore and aft ends of the pipe.
Stainless-steel hose clamps are used to attach the duct to the struts and are adjustable
(axially) to allow optical access throughout all sections of the duct. Lobed mixers attach
on the upstream side and are counter-bored to pilot onto the mixing duct assuring both the
cylinder and nozzle center are concentric with each other. Figure 7 shows side and rear
views of the lobed mixer and mixing duct. Note the eight struts that connect the center of
the nozzle to the nozzle hub and mixing duct. Struts are located 20cm upstream and are
standard NACA 0013 airfoils, 2.5mm thick.

Figure 7. Front and side view of test section.

Three separate mixer nozzles are studied. They include a splitter nozzle (no trailing edge treatment), conventional lobed and scalloped lobed trailing edges. The lobe and scalloped lobe mixers incorporate the same basic dimensions with the scalloped mixer further modified by removing approximately 50% of the lobe sidewalls. Both lobed nozzles were designed using solid modeling software, Pro/E and constructed using rapid prototyping techniques (stereolithography). The resulting prototypes were composed of an ABS plastic material and are well suited for submersion in the water tunnel. The splitter nozzle was machined from 4-inch cast acrylic pipe (11.4 cm outside diameter) and tapered to thin trailing edge.

A total of eight lobes spaced equally on 45 degree intervals make up the trailing edge of the nozzles. Detailed lobe dimensions are given in Figure 8. Lobe height and
width measure 41mm and 15.9mm with corresponding inner and outer penetration angles measuring a conservative 15 degrees each (30 degrees included). In essence, the lobe trailing edge studied here is nearly identical that reported by McCormack [17], except in this case, it is rolled into an annular ring. This circular lobed nozzle is referred in literature as a 3 dimensional mixer-nozzle while the study conducted by McCormack uses a 2-dimensional mixer. The area ratio between the bypass flow and the core flow is 1.97. Inner diameters of the core and mixing duct are 108mm and 197 mm respectively. The mixing duct measure 91cm long giving room to measure six nozzle diameters downstream comfortably. Figures 9 and 10 show lobed scalloped and splitter mixers tested.

Figure 8. Lobed and scalloped lobed mixer dimensions.
Figure 9. Scalloped (left) and lobed (right) mixers.

Figure 10. Splitter mixer.
CHAPTER 3

INSTRUMENTATION

The instruments and their arrangements used in this project are described in this section. These include the PIV and PLIF components and physical description of the individual components.

Particle Image Velocimetry (PIV)

Non-intrusive measuring techniques for extracting fluid velocity two and three dimensional components have been widely developed throughout the last 25 years. Techniques such as Laser Doppler Velocimetry (LDV), Particle Tracking Velocimetry (PTV) and Particle Image Velocimetry (PIV) are now a commonplace in experimental aero/fluid dynamics laboratories. Furthermore, more advanced techniques such as Stereo PIV, Dual-Plane Stereo PIV and Holographic PIV are gaining popularity. Comprehensive reviews of such techniques are given in literature by Adrian [35], Raffel et. al. [40] and Stanislas et. al. [41].

Standard particle image velocimetry is used in the present experiment. In this manner, two components of the velocity are obtained at multiple spatial locations at the same instant in time. The flow is seeded with tracer particles that ideally, match the fluid velocity everywhere. Thus, tracer particles selected, are small (order 1-50 microns
diameter) and have nearly the same density as the working fluid. When the particles faithfully follow the flow, the velocity of the fluid is determined indirectly by tracking the particle movements over a known time interval. In practice this is realized by pulsing a region of the flow with a 2 dimensional sheet of laser light (thickness $<<$ length or height) under a known time interval. The illuminated particles in the plane of the laser sheet scatter light that is recorded with an analog or digital camera. If the time interval is short, then the majority of the particles imaged during the first pulse will be in the image of the second pulse only translated due to the fluid movement. To extract velocity, the recorded images are discretized into small interrogation areas. The interrogation area in the first image is cross correlated with its corresponding area in the second image to calculate the average velocity of the particles in each area obtaining a single velocity vector for each. This implies that for high resolution, the interrogation area should be small (typically 8 x 8 – 32 x 32 pixels once digitized). The size is dictated by the seeding density which should be on the order of 12 particles per interrogation as reported by Keane and Adrian [39].

The working fluid in this experiment is water, so hollow glass spheres (Dantec) with density 1.1 g/cm$^3$ and mean diameter of 10 microns were selected as the tracer. Two separate laser systems were used in the project. A 30 mJ Nd:YAG ultraPIV laser system manufactured by Big Sky Laser was used for axial planes while a larger 200 mJ Nd:YAG System manufactured by New Wave Research was used for streamwise planes. Images were recorded using a full frame interline transfer CCD camera, PIVCam 10-30. This camera, Model 630046, is distributed by TSI and has image size, 1008(H) x 1018(V)
pixels with 8-bit resolution. Both camera and lasers are controlled using a synchronizer, Model 610032 and PIV software, Insight v5.0, manufactured by TSI. Insight both collects and processes the images to obtain the velocity field for each image pair. Cross-correlation is performed using the Hart algorithm (implemented in Insight) with erroneous vectors removed and replaced by mean and standard deviation filters. 16 x 16 pixel interrogation areas (~ 2.5mm x 2.5 mm axially and ~ 3.4mm x 3.4mm streamwise in physical space) were used, ensuring the adequate number of particles mentioned previous. Additional data smoothing was not required.

Post processing of velocity data was accomplished using software developed specifically for this project. The programming was written and compiled using LabView v.7.1 which uses Insight generated ASCII data files as input and outputs additional calculated quantities in standard Tecplot format. Supplementary features included options to translate, rotate and process points inside only user defined polygon(s).

Planar Laser Induced Fluorescence (PLIF)

Planar laser induced fluorescence is a non-intrusive measuring technique that is used to extract qualitative and quantitative measurements of concentration or temperature in a fluid. This method exploits the behavior of short-lifetime fluorescence which when excited by laser light, fluoresce proportional to temperature and its local concentration. Rhodamine B dyes (both RhB 6G and RhB) are the fluorescent dye of choice in many applications as their peak absorption falls in the Nd:Yag (532nm) and Argon Ion (514nm) laser wavelengths used for PIV. Conveniently, (at least for fluid dynamicist) the peak
emission of the fluorescence signal is 575 – 585nm (RhB) in water allowing optical separation from the illumination source by means of highpass or band pass filters placed in front of the recording device.

Preliminary work in laser induced fluorescence can be found in papers by Owen [36] and Koochesfahani and Dimotakis [34] using fluorescein dye and an Argon-ion continuous wave laser. This initial research focused largely on measuring the fluorescence emission from single point and lines illuminated in a given flow. With advancements in recording devices and lasers, quantitative measurements of whole planes illuminated by laser sheets are commonly performed. Papers by Hishida and Sakakibara [32], Coolen et. al. [30], Webster et. al. [37], Nash et. al. [35], and Hu et. al. [33]. describe the application of PLIF for both temperature and concentration.

The emitted fluorescence below saturation is governed by Equation (1) below. Where $I_f$ is the emitted fluorescence, $\alpha$ is a constant determined by optical setup, $\Phi$ is the quantum efficiency of the dye, $C_d$ is dye concentration, $I$ is the illuminating intensity and $I_{bkg}$ is the background shot noise without dye present. The quantum efficiency is temperature (T) dependant with RhB and decreases approximately 2% per 1 degrees C increase in Temperature.

$$I_f = \alpha \cdot \Phi(T) \cdot C_d \cdot I + I_{bkg} \quad (1)$$
Additionally the absorption of light by a participating medium is governed by the radiative transfer in Equation (2). Where \( \varepsilon \) is the absorption coefficient of the dye and \( ds \) is the infinitesimal path length along a single light ray, \( s \).

\[
dI = -\varepsilon \cdot I \cdot C_d \cdot ds
\]  

Integrating (2) yields:

\[
I = I(0) \cdot e^{-\int_0^s C_d \cdot ds}
\]

Combining Equations (1) and (3) gives an expression relating measured fluorescence intensity to the concentration as a function of position along the illuminating light ray path, \( s \).

\[
\left( I_f - I_{bkg} \right) = \alpha \cdot \Phi(T) \cdot C_d(s) \cdot I(0) \cdot e^{-\int_0^s C_d \cdot ds}
\]

In practice, constants \( \alpha \) and \( I(0) \) of Equation (4) are determined during calibration and can be combined into a new constant \( \beta \) for every ray (estimated by horizontal row in image). Additionally, in this study, the interest is quantitative measurements of dye concentration and not temperature. This allows combination of \( \Phi \) with \( \beta \) as the temperature is kept constant everywhere in the fluid. Note that \( \beta \) is a constant along each ray of the laser and is determined along with \( \varepsilon \) during calibration. This simplification results in Equation (5). Dye concentration is then calculated by approximating Equation (5) by Equation (6) below. Indices \( i \) and \( j \) refer to pixel location in the image frame. \( \varepsilon_j \) and
\( \beta_j \) are determined by illuminating the test section with a known, uniform concentration. Furthermore, \( ds \) in Equation (5) is replaced by unit length of one pixel in Equation (6).

\[
\begin{align*}
(I_f - I_{bkg})(s) &= \beta \cdot C_d(s) \cdot e^{-\varepsilon \int_0^s C_d \cdot ds} \\
C_{d(i,j)} &= \frac{(I_f - I_{bkg})(i,j)}{n^{-1} \sum_{i=0}^{n-1} C_d(i)}
\end{align*}
\]

The measuring equipment setup is described. PLIF equipment used in the experiment is identical to that described for PIV. The only modification was the installation of a bandpass filter (550nm) in front of the camera during PLIF measurements. Lasers are mounted to the hydraulic lift table as shown in Figure 11 while the camera is mounted to a rail system attached to either side or rear of the water tunnel as revealed in Figure 12.

Concentrated Rhodamine B solution is delivered to the core flow via a constant pressure metering system. Dye is injected before the pump about 72 pipe diameters upstream of the nozzle exit ensuring a fully mixed solution. PLIF measurements in the core pipe upstream verified a fully mixed solution at the exit of the nozzle. The exit
concentration of the core stream contains 50 micrograms/liter of Rhodamine B as used by Hu et al. [33].

Figure 11. Laser(s), optics and scissor lift mount.

Figure 12. Camera mount.
CHAPTER 4

TEST DESCRIPTION

High-resolution measurements for velocity and scalar mixing of dye are conducted in this research. The fluid structures relevant to the mixing process are revealed through measurements of velocity, turbulence intensity, vorticity and scalar mixing on 21 axial cross planes between $Z/D = 0.1$ and 6.0. Axial velocity profiles are obtained on three streamwise planes through the lobe peak, midplane (middle of lobe sidewall) and valley (trough) planes. Furthermore, streamwise flow visualizations are conducted on each of these three planes. In the following discussion, X and Y coordinates represent the cross-stream components, while Z is the axial coordinate.

The Reynolds number defined by Equation (7), where $\nu$ is the kinematic viscosity, velocity scale, $(V_{\text{avg}})$ is the average velocity of the core and bypass streams and the characteristic length is the nozzle diameter, D. Also in literature the lobe height, H is used as the characteristic length scale (two-dimensional mixers) and is included here. Reynolds numbers for this and other reported mixing studies is given in Table 1.

\[
\text{Re} = \left[ \frac{V_{\text{avg}} = (V_{\text{core}} + V_{\text{bypass}})}{2} \right] \cdot (D \text{ or } H) \quad (7)
\]
<table>
<thead>
<tr>
<th>Research</th>
<th>Reynolds Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cooper</td>
<td>33,060</td>
</tr>
<tr>
<td>Eckerle [3]</td>
<td>NA</td>
</tr>
<tr>
<td>Hu [7]</td>
<td>3,000</td>
</tr>
<tr>
<td>McCormick [17,18]</td>
<td>NA</td>
</tr>
<tr>
<td>Yu [27]</td>
<td>NA</td>
</tr>
</tbody>
</table>

Table 1. Reynolds number of related research.

Mean core and bypass velocities are obtained through PIV data obtained 3 nozzle diameters upstream of the mixing interface for lobed and scalloped mixers. The resulting velocity profiles are integrated to obtain the average velocity in each of the core and bypass streams where $\rho$ is the fluid density, $A$ is the cross-sectional area and $n$ is the unit vector normal to $A$ in Equation (8). The numeric approximate of the integral in Equation (8) is given in Equation (9). The limits of integration for the core are $(R_1 = 0, R_2 = D_{core}/2)$ and for bypass $(R_1 = D_{core}/2, R_2 = D_{bypass}/2)$ respectively.

$$\bar{V} = \frac{\rho \cdot \int \mathbf{V} \cdot \hat{n} \cdot dA}{\rho \cdot A} = \frac{2 \cdot \pi \cdot \rho \cdot \int U(r) \cdot r \cdot dr}{\pi \cdot \rho \cdot \left( \frac{R_2^2 - R_1^2}{2} \right)}$$  (8)

$$\bar{V} = \frac{\sum_{i=R_1}^{R_2} U_i \cdot r_i \cdot \Delta r}{\left( \frac{R_2^2 - R_1^2}{2} \right)}$$  (9)

The inlet velocity profiles for the splitter mixer is given in Figure 13. Note that the splitter profile is obtained upstream of the exitplane by 1.5 nozzle diameters as the splitter
is made from clear plexiglass. From these profiles in conjunction with Equation (9), the mean velocities are calculated. Background turbulence intensity measures 3.3% with respect to mean core velocity using [9] for turbulence intensity instead of velocity. The mean velocity of the core and bypass stream are given in Table 2 for lobed, scalloped and splitter mixers. Additionally, $V_{avg}$, used to nondimensionalize reported data is tabulated in Table 2. Core velocity ratio measured and bypass ratio are included in Table 2. Differences in average incoming velocity are expected from the pressure drop associated with each mixer. During testing, the pump voltage was held constant for each mixer, which allows the incoming velocity to vary slightly. Therefore, reported data is non-dimensionalized by averaged core velocities and mean of core and bypass average velocities, $V_{avg}$. 
Figure 13. Upstream velocity profile.

<table>
<thead>
<tr>
<th>Mixer Type</th>
<th>Vcore (m/s)</th>
<th>Vbypass (m/s)</th>
<th>V_avg (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lobed Mixer</td>
<td>0.44</td>
<td>0.215</td>
<td>0.33</td>
</tr>
<tr>
<td>Scalloped Mixer</td>
<td>0.42</td>
<td>0.214</td>
<td>0.32</td>
</tr>
<tr>
<td>Splitter Mixer</td>
<td>0.45</td>
<td>0.215</td>
<td>0.33</td>
</tr>
</tbody>
</table>

Table 2. Average mixer core and bypass velocities.
CHAPTER 5

MEASURED RESULTS

Axial cross-planes provide an excellent means of describing the mixing characteristics of the lobed nozzles. Through measurement of cross-stream fluid velocity and turbulent mixing of dye from the core to bypass streams, insight into the mechanisms by which enhanced mixing occurs is obtained. Streamwise vorticity, is obtained by post processing of the cross stream fluid velocity components. The decay of streamwise vorticity measurement is arguably, the best indicator of the mixing performance and location of enhanced mixing region of the nozzle. Although the spanwise normal vorticity (due to Kelvin Helmholtz instability) is of greater magnitude (Hu et. al. [10]), the cut and connect interaction between these two vorticies appears in the decay rate of streamwise vorticity. Additionally, the physical experimental setup here restricts the use of dual-plane stereo PIV which can measure the spanwise normal or Kelvin Helmholtz vorticity. Streamwise vorticity and its directly related Streamwise circulation are used heavily by previous researches to characterize mixer performance [4, 7-11, 17, 27]. Additionally, quantitative molecular mixing shall provide a direct means of determining the degree of mixing with axial distance from the exit plane.

Cross Stream Velocity Fields

Axial results are presented for one lobe period at successive downstream locations. This region is illustrated by the blue wedge shaped outline on the raw PLIF image in Figure 14. Note that presented velocity is rotated 90 degrees counter-clockwise
from that in Figure 14 for comparison between scalloped and lobed mixers. Cross-stream velocity components of the splitter mixer are not given as there is no dominant streamwise structure present.

Ensemble averaged cross-stream fluid velocity vectors for lobed and lobe-scalloped nozzles are given in Figures (15 – 25). Ensemble average velocities indicate the large-scale dominant flow structures present. Also included in these Figures are sample instantaneous velocity fields. Instantaneous velocity fields provide snapshots in time of smaller scale turbulent structures and eddies that appear intermittently in the flow. Cross-stream velocity results are discussed by referring to the sub index in each Figure. Sub-index (a) and (b) refer to scallop lobed ensemble averaged and instantaneous vector fields. Sub-index (c) and (d) refer to the lobed ensemble averaged and instantaneous vector fields.
Figure 15 gives the velocity field obtained closest to the mixer exit plane at $Z/D = 0.10$. Images obtained closer to the exit plane exhibited the nozzle outline illuminated by side scatter laser light preventing velocity measurements. Readily observed in the ensemble averaged fields are two shear layers formed by the large scale counter rotating streamwise vortices. The scalloped field, Fig (15-a), indicates slight bulging at the top and bottom of each shear layer while the lobed field, Fig (15-c) remains vertical. Instantaneous captures for scalloped and lobed (Fig 15-b, d) reveal additional small scale but intense vortices shed into the wake. Specifically, Figure 15-b, shows an additional eddy possibly formed due to the scallops (see highlighted region) as suggested by Yu et. al. [27]. This structure appears periodically in the flow but is not readily apparent in the ensemble average.

Figures (16-23) illustrate the spreading of the large scale streamwise vortices in the enhanced mixing region, $Z/D = 0 < \text{Enhanced mixing} < Z/D = 2.0$. The ensemble average in the enhanced mixing region show increasing azimuthal spreading with increased axial distance. This is consistent with three dimensional lobed ejector results by Hu [11] and two dimensional mixer results by McCormick [17, 18]. In addition Figure 19(c), reveal the cross stream velocity impingement for the lobed mixer on the mixing duct wall occurs at $Z/D = 1.0$. Cross stream impingement for the scalloped nozzle (Figure 20-a) is delayed and occurs further downstream at $Z/D = 1.25$. This impingement point of the hot core gasses in practical gas-turbine applications are important as local hot spots on the liner may lead to failure. Results suggest early azimuthal spreading across
the scallops dissipates some of the outward radial momentum, thus delaying and weakening the impingement.

Figures 24 and 25 give the cross stream vector fields past the enhanced mixing region. The ensemble averages show rapid decay in cross stream in these planes. The large scale structures continue to expand in size until reaching the outer limits of the periodic wedge shaped boundary. This boundary interface is actually the boundary created by the neighboring lobe’s pair of streamwise vortices. It is important to note that even in these locations the instantaneous captures at these regions contain small scale vortices with relatively undiminished intensity similar to findings of Hu et. al.[11].
Figure 15 (a-d). Ensemble average and instantaneous cross-stream velocity field at $Z/D = 0.10$. 

(a) Ensemble average vector field, scallop lobed

(b) Instantaneous vector field, scallop lobed

(c) Ensemble average vector field, lobed

(d) Instantaneous vector field, lobed
Figure 16 (a-d). Ensemble average and instantaneous cross-stream velocity field at \( Z/D = 0.25 \).
Figure 17 (a-d). Ensemble average and instantaneous cross-stream velocity field at $Z/D = 0.50$. 
Figure 18 (a-d). Ensemble average and instantaneous cross-stream velocity field at \( Z/D = 0.75 \).
Figure 19 (a-d). Ensemble average and instantaneous cross-stream velocity field at Z/D = 1.00.
Figure 20 (a-d). Ensemble average and instantaneous cross-stream velocity field at $Z/D = 1.25$. 
Figure 21 (a-d). Ensemble average and instantaneous cross-stream velocity field at $Z/D = 1.50$. 
Figure 22 (a-d). Ensemble average and instantaneous cross-stream velocity field at Z/D = 1.75.
Figure 23 (a-d). Ensemble average and instantaneous cross-stream velocity field at $Z/D = 2.00$. 

(a) Ensemble average vector field, scallop lobed  

(b) Instantaneous vector field, scallop lobed 

(c) Ensemble average vector field, lobed  

(d) Instantaneous vector field, lobed
Figure 24 (a-d). Ensemble average and instantaneous cross-stream velocity field at $Z/D = 3.00$. 
Figure 25 (a-d). Ensemble average and instantaneous cross-stream velocity field at $Z/D = 4.00$. 
Cross Stream Velocity Magnitude and Turbulence Intensity

Normalized cross stream velocity magnitude, $V_{cs}$, and turbulence intensity contours are given in Figures 26 – 36. As before, sub-indices a, b refer to the scalloped mixer and c, d the lobed mixer, for cross stream velocity magnitude and turbulence intensity. Cross stream velocity magnitude is normalized by the average core velocities (obtained by Equation (8)) for each mixer. Normalizing in this manner provides a method for checking the validity of the obtained cross stream velocities. Based upon lobe penetration angle of 15 degrees, the cross stream component can be estimated by Equation (10). Resulting max cross stream velocity should measure approximately 26% of the average core velocity. Figure 26 (a, c) indicated max cross stream components between 26% and 27% of average core velocity.

$$V_{cs}(\text{max}) \approx V_{\text{core}} \cdot \sin(\theta_{\text{out}})$$  \hspace{1cm} (10)

Cross stream velocity contours at $Z/D = 0.1$ (Figure 26) illustrate initial differences between scallop and lobed mixers. The contours for the scalloped nozzle indicate, as speculated above, that the outward velocity is dissipated in regions closer to the bottom of the lobe, adjacent to scallops. Also noted is the radially inward dip near the peak of the lobe caused by the physical boundary of the lobe restricting outward momentum and thickening of the boundary layer in the lobe valleys or troughs. Thickening of the boundary layers in the lobe valley is also noted by McCormick [17, 18] which made smoke flow visualizations difficult. With increasing axial distance from the exitplane, the wedge-shaped cross stream contours are shown to move radially outward as
described in section previous. This is depicted in Figures (27-36). From these contours, the maximum cross stream velocity is extracted and plotted versus axial distance in Figure 37. Interestingly, the lobed mixer indicates an initial increase in cross stream velocity, maximizing at $Z/D = 0.5$, before decaying. Contrary, the scalloped mixer does not exhibit this phenomenon and begins its decay from the first measured plane, $Z/D = 0.10$. The behavior of the scalloped mixer is similar to that reported by Hu [8] for the lobed ejector exhausting to a large fluid volume. It is unclear the exact cause for the initial increase in cross-stream velocity for the lobed mixer.

Turbulence intensity of the cross-stream components is given in Figures (26-36). Initially at $Z/D = 0.1$ (Figure 26), the maximum locations of turbulence intensity is located in the shear layer between streams, concentrated in the lobe troughs. Observe that the scalloped mixer turbulence intensity is spread azimuthally outward while the lobed mixer remains in vertical outlining the ‘lobe signature’. With increasing axial distance, Figure (27-36) show regions of high turbulence intensity that concentrate toward the center of the lobe and begin expanding outward (radially). The overall trend of cross stream turbulence intensity is given in Figure 38, by calculating the area averaged turbulence intensity versus axial distance. The scalloped mixer on average, exhibits higher turbulence intensity over the lobed mixer (approximately 1% over entire axial range). The rate of increase for the lobed mixer in the enhanced mixing region is greater than that of the scalloped. However, early mixing caused by the scallops allows for higher overall turbulence intensity. Peak values of maximum turbulence intensity for lobed and scalloped mixers are 11.2% ($Z/D = 1.50$) and 11.8% ($Z/D = 1.75$).
Figure 26 (a-d). Ensemble average cross stream velocity magnitude and turbulence intensity for scallop and lobed mixer at $Z/D = 0.10$. 
Figure 27 (a-d). Ensemble average cross stream velocity magnitude and turbulence intensity for scallop and lobed mixer at Z/D = 0.25.
Figure 28 (a-d). Ensemble average cross stream velocity magnitude and turbulence intensity for scallop and lobed mixer at $Z/D = 0.50$. 
Figure 29 (a-d). Ensemble average cross stream velocity magnitude and turbulence intensity for scallop and lobed mixer at $Z/D = 0.75$. 
Figure 30 (a-d). Ensemble average cross stream velocity magnitude and turbulence intensity for scallop and lobed mixer at $Z/D = 1.00$. 
Figure 31 (a-d). Ensemble average cross stream velocity magnitude and turbulence intensity for scallop and lobed mixer at $Z/D = 1.25$. 
Figure 32 (a-d). Ensemble average cross stream velocity magnitude and turbulence intensity for scallop and lobed mixer at $Z/D = 1.50$. 

(a) Normalized cross-stream velocity magnitude, scallop lobed

(b) Turbulence intensity (%), scallop lobed

(c) Normalized cross-stream velocity magnitude, lobed

(d) Turbulence intensity (%), lobed
Figure 33 (a-d). Ensemble average cross stream velocity magnitude and turbulence intensity for scallop and lobed mixer at Z/D = 1.75.
Figure 34 (a-d). Ensemble average cross stream velocity magnitude and turbulence intensity for scallop and lobed mixer at Z/D = 2.00.
Figure 35 (a-d). Ensemble average cross stream velocity magnitude and turbulence intensity for scallop and lobed mixer at Z/D = 3.00.
Figure 36 (a-d). Ensemble average cross stream velocity magnitude and turbulence intensity for scallop and lobed mixer at $Z/D = 4.00$. 

(a) Normalized cross-stream velocity magnitude, scallop lobed

(b) Turbulence intensity (%), scallop lobed

(c) Normalized cross-stream velocity magnitude, lobed

(d) Turbulence intensity (%), lobed
Figure 37. Normalized maximum cross-stream velocity decay.

Figure 38. Area averaged turbulence intensity (%) versus axial distance.
Streamwise Vorticity

Normalized streamwise vorticity, similar to that used by Hu et. al. [7-11] is given in Equation (11) below. D is the reference diameter of the nozzle, 0.108m and $V_{\text{avg}}$ is obtained by averaging mean core and bypass velocities previously given.

$$\text{Streamwise Vorticity, } \omega_z = \frac{D}{V_{\text{avg}}} \left( \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y} \right)$$

Figure 39 – 49 show streamwise vorticity contours on axial cross planes. At $Z/D = 0.1$ (Figure 39), distinct differences between scalloped and lobed mixers are observed. For scalloped case, four regions of high streamwise vorticity (and low) exist and are located in the lobe peak (two) and lobe valley (two). Conversely, two narrow vertical regions of intense streamwise vorticity exist for the lobed mixer. Note that the contour scale decreases with axial distance in these figures to reveal the change in shape of large scale streamwise vortices. Without decreasing the scale, the change in vorticity is difficult to articulate due to their rapid exponential-like decay. Initial maximum streamwise vorticity at $Z/D = 0.10$ is 15.2 and 12.4 for lobed and scalloped mixers respectively.

Figure 40 indicates slight spreading in all directions for the lobed and scalloped mixers at $Z/D = 0.25$. Four distinct regions for scalloped and two for lobed are remain visible on this plane. Note the rapid decrease in streamwise vorticity to 12.1 and 10.6 for lobed and scalloped mixers. In Figure 41 ($Z/D = 0.50$), the streamwise vortices begin to
bulge outward azimuthally at the lobe peaks. This growth pattern continues on successive axial planes, see Figures (42-49).

Figure 50 further illustrates the decay rate of streamwise vorticity by plotting the maximum streamwise vorticity versus axial distance. In the enhanced mixing region \(0 < Z/D < 2\), the maximum streamwise vorticity decays to approximately 26% (both mixers) of its initial strength. The trend of this plot is consistent with research conducted by Hu et. al.[8] which indicates rapid decay in enhanced region followed by a gradual decay further downstream. Here, the scalloped and lobed mixers tested have similar decay rates with the scalloped mixer having a lower initial strength, \(\sim 81\%\) of lobed mixer measured intensity.
Figure 39 (a-b). Ensemble average normalized streamwise vorticity contours for scallop (a) and lobed (b) mixer at $Z/D = 0.10$. 
Figure 40 (a-b). Ensemble average normalized streamwise vorticity contours for scallop (a) and lobed (b) mixer at $Z/D = 0.25$. 
Figure 41 (a-b). Ensemble average normalized streamwise vorticity contours for scallop (a) and lobed (b) mixer at Z/D = 0.50.
Figure 42 (a-b). Ensemble average normalized streamwise vorticity contours for scallop (a) and lobed (b) mixer at $Z/D = 0.75$. 

(a) Normalized streamwise vorticity, scallop lobed

(b) Normalized streamwise vorticity, lobed
Figure 43 (a-b). Ensemble average normalized streamwise vorticity contours for scallop (a) and lobed (b) mixer at Z/D = 1.00.
Figure 44 (a-b). Ensemble average normalized streamwise vorticity contours for scallop (a) and lobed (b) mixer at $Z/D = 1.25$. 
Figure 45 (a-b). Ensemble average normalized streamwise vorticity contours for scallop (a) and lobed (b) mixer at Z/D = 1.50.
Figure 46 (a-b). Ensemble average normalized streamwise vorticity contours for scallop (a) and lobed (b) mixer at $Z/D = 1.75$. 
Figure 47 (a-b). Ensemble average normalized streamwise vorticity contours for scallop (a) and lobed (b) mixer at $Z/D = 2.00$. 
Figure 48 (a-b). Ensemble average normalized streamwise vorticity contours for scallop (a) and lobed (b) mixer at Z/D = 3.00.
Figure 49 (a-b). Ensemble average normalized streamwise vorticity contours for scallop (a) and lobed (b) mixer at $Z/D = 4.00$. 

(a) Normalized streamwise vorticity, scallop lobed

(b) Normalized streamwise vorticity, lobed
Figure 50. Maximum streamwise vorticity decay.
Scalar Mixing

Elliot et. al. [4] addressed the mixing of a scalar in the wake of a two-dimensional lobed mixer by numerically computing the unsteady Navier-Stokes equations for a nozzle with and without streamwise vorticity. They introduce a mixedness parameter, M, where the scalar field \( \varphi \), is allowed to vary between -1 and 1. In this manner, when \( \varphi \) equals -1, the scalar is at a minimum and when \( \varphi \) equals 1, the scalar is at its maximum. Mixedness is defined by Equation (12) in accordance with Elliot et. al.[4] where A is cross-sectional area of one lobe period outlined previous in Figure (14). For this experiment, obtained scalar concentrations (0 – 50 micrograms/Liter) are scaled between -1 and 1 to obtain mixedness parameter.

\[
M = \frac{1}{A} \int_\Delta (1 - |\varphi|) dA
\]  

Figures 51 - 58 (a-c) illustrate mean scalar concentration, \( C \), on axial cross-planes. Sub indices represent lobed (a), scalloped (b) and splitter mixers respectively. Observe the wedge shaped area of interest is returned to its original horizontal configuration. This facilitates the added splitter mixer for direct comparison with lobed and scalloped mixers.

Figure 51 gives mean concentration for \( Z/D = 0.10 \) axial cross plane. The lobe shape 'signature' is clearly evident in the lobed and scalloped mixers. As expected, scalloping allows early mixing of the core flow to the bypass flow. This is evident
through the azimuthal outward spreading observed in the sidewall region. The splitter nozzle shows minimal mixing at this location.

Mean concentration at $Z/D = 0.50$ is given in Figure 52. The outward regions near lobe peaks for scalloped and lobed mixers exhibit expansion due to large scale streamwise vorticies shown previous. The result in subsequent planes reveal continued spreading in this region consistent with these large scale vorticies. Additionally, scalloped mean concentration continue to show the additional spreading in the sidewall region versus the lobed case. Figure 53 – 58 shows the ‘light bulb-shaped’ mixing region expand radially outward, impinging on the outer wall and splitting. Again this is consistent with the cross stream velocity fields given in Figures (15- 25).

Mixedess parameter, $M$ is extracted from the mean concentration fields and plotted versus axial location in Figure 59. Here the axial distance is non-dimensionalized by the lobe height as opposed to core diameter in previous figures. This allows general comparisons between current results and two dimensional, numerical results given by Elliot et. al. Distinct behavioral difference are evident between these studies in the enhanced mixing region. Results presented here indicate a higher rate of turbulent mixing with negative curvature while Elliot et. al. show a slower rate with positive curvature. Regions downstream of the enhanced mixing region behave similarly. It is important to note, that the flows studied are quite different. However, it does appear that there is a fundamental difference in turbulent mixing rate by the three dimensional, confined, forced mixing flows with streamwise voriticity studied here. The splitter mixer studied
here and the mixer without streamwise vorticity studied by Elliot et. al. show similar mixing trends. The scalloped and lobed mixers exhibit similar development with the scalloped mixer measuring on average, ~0.05 greater than the lobed mixer over the same range. Downstream of the enhanced mixing region, the rate of increase observed between the three mixers tested is quite similar.
Figure 51 (a-c). Mean concentration contours for lobed (a) scallop lobed (b) and splitter (c) mixers at $z/D = 0.10$. 
Figure 52 (a-c). Mean concentration contours for lobed (a) scallop lobed (b) and splitter (c) mixers at $z/D=0.50$. 

Concentration (mg/L)

0.050
0.045
0.040
0.035
0.030
0.025
0.020
0.015
0.010
0.005
0.000

(a) Lobed mixer

(b) Scalloped lobed mixer

(c) Splitter mixer
Figure 53 (a-c). Mean concentration contours for lobed (a) scallop lobed (b) and splitter (c) mixers at $z/D = 1.00$. 

Concentration (mg/L)

0.050
0.045
0.040
(a) Lobed mixer

0.035
0.030
(b) Scalloped lobed mixer

0.025
0.020
0.015
0.010
(c) Splitter mixer

0.005
0.000
Figure 54 (a-c). Mean concentration contours for lobed (a) scallop lobed (b) and splitter (c) mixers at z/D = 1.50.
Figure 55 (a-c). Mean concentration contours for lobed (a) scallop lobed (b) and splitter (c) mixers at z/D = 2.00.
Figure 56 (a-c). Mean concentration contours for lobed (a) scallop lobed (b) and splitter (c) mixers at $z/D = 2.50$. 

Concentration (mg/L)

(a) Lobed mixer

(b) Scalloped lobed mixer

(c) Splitter mixer
Figure 57 (a-c). Mean concentration contours for lobed (a) scallop lobed (b) and splitter (c) mixers at z/D = 3.00.
Figure 58 (a-c). Mean concentration contours for lobed (a) scallop lobed (b) and splitter (c) mixers at $z/D = 4.00$. 
Figure 59. Mixedness comparison for scalloped, lobed and splitter mixers.

Figure 60 – 67 present standard deviation or fluctuating concentration, $(\sqrt{\epsilon'\epsilon'})$. Fluctuating concentration contours ‘outline’ the averaged values discussed previous with maximums located in the conjunction with the lobed trailing edge shape. Scalloped fluctuating results show wider band of fluctuation around the scalloped sidewalls in Figures 60 – 67 relative to lobed results. Splitter fluctuations grow much slower than either lobed mixers in these regions. After the enhanced mixing region, both scalloped and lobed mixers exhibit similar patterns.
Sample, instantaneous realizations of scalar dye concentration are given in Figures 68 – 75 for lobed, scalloped and splitter mixers. Two randomly obtained images are given at each axially location for each mixer. No direct relationship exist between randomly selected images and serve only to enforce turbulent nature between image captures.
Figure 60 (a-c). Standard deviation concentration contours for lobed (a), scallop lobed (b) and splitter (c) mixers at z/D = 0.10.
Figure 61 (a-c). Standard deviation concentration contours for lobed (a) scallop lobed (b) and splitter (c) mixers at $z/D = 0.50$. 
Figure 62 (a-c). Standard deviation concentration contours for lobed (a) scallop lobed (b) and splitter (c) mixers at z/D = 1.00.
Figure 63 (a-c). Standard deviation concentration contours for lobed (a) scallop lobed (b) and splitter (c) mixers at z/D = 1.50.
Figure 64 (a-c). Standard deviation concentration contours for lobed (a) scallop lobed (b) and splitter (c) mixers at \(z/D = 2.00\).
Figure 65 (a-c). Standard deviation concentration contours for lobed (a) scallop lobed (b) and splitter (c) mixers at $z/D = 2.50$. 
Figure 66 (a-c). Standard deviation concentration contours for lobed (a) scallop lobed (b) and splitter (c) mixers at z/D = 3.00.
Figure 67 (a-c). Standard deviation concentration contours for lobed (a) scallop lobed (b) and splitter (c) mixers at z/D = 4.00.
Figure 68 (a-c). Instantaneous concentration fields for lobed (a) scallop lobed (b) and splitter (c) mixers at $z/D=0.10$. 
Figure 69 (a-c). Instantaneous concentration fields for lobed (a) scallop lobed (b) and splitter (c) mixers at $z/D = 0.50$. 
Figure 70 (a-c). Instantaneous concentration fields for lobed (a) scallop lobed (b) and splitter (c) mixers at $z/D = 1.00$. 
Figure 71 (a-c). Instantaneous concentration fields for lobed (a) scallop lobed (b) and splitter (c) mixers at $z/D = 1.50$. 
Figure 72 (a-c). Instantaneous concentration fields for lobed (a), scallop lobed (b) and splitter (c) mixers at z/D = 2.00.
Figure 73 (a-c). Instantaneous concentration fields for lobed (a) scallop lobed (b) and splitter (c) mixers at z/D = 2.50.
Figure 74 (a-c). Instantaneous concentration fields for lobed (a) scallop lobed (b) and splitter (c) mixers at $z/D = 3.00$. 
Figure 75 (a-c). Instantaneous concentration fields for lobed (a) scallop lobed (b) and splitter (c) mixers at $z/D = 4.00$. 
Axial Velocity

Axial velocity profiles are given at select axial locations on three streamwise planes through the lobe peak, middle and valley. Axial velocity is normalized by $V_{avg}$ that is used to normalize streamwise vorticity given previous. Profiles are presented at locations, $Z/D = 0.25$ (a), 1.0 (b), 2.0 (c), 3.0 (d) and 4.0 (e) in Figures 76 - 78. Each figure shows half of the velocity profile (i.e. from centerline to mixing duct wall). Scalloped profiles are right of the centerline while lobed profiles are located left of the centerline.

Figure 76 indicates results for axial velocity on the streamwise plane through the lobe peak. At $Z/D = 0.25$, scalloped and lobed profiles have similar behavior for $0 < Y/D < 0.25$. For $0.5 < Y/D < 0.75$ there is a noticeable decrease in axial velocity in the scalloped profile versus lobed profile due to convection azimuthally outward as shown in cross stream velocity vector fields previous. For $Z/D = 1.0$, a similar trend exists at $Y/D \approx 0.5$. In this location the scalloped mixer indicates lower velocity relative to the lobed by similar reasoning. Increasing the axial distance to $Z/D = 2.0$, axial velocity profiles show the scalloped nozzle velocity outside the core ($0.35 < Y/D < 1$) to be marginally greater than the lobed case. This trend continues for $Z/D = 3.0$ and 4.0 axial locations. The unmixed core region shrinks drastically for both lobed and scallop lobed mixers versus axial distance. For $Z/D = 1$, the unmixed region stretches from $Y/D = 0$ to 0.3. By $Z/D = 4.0$, this unmixed region has diminished to zero.
Figure 77 presents axial velocity profile on the midplane halfway between lobe peak and valley. At $Z/D = 0.25$ the convected core flow through the scallops is readily apparent by the local maximum in axial velocity at $Y/D \approx 0.55$. The lobed profile does not exhibit this peak at $Z/D = 0.1$. However at $Z/D = 1.0$ the lobed profile indicates a secondary peak at $Y/D \approx 0.85$. This peak arises from the large scale streamwise vorticies turning the axial flow azimuthally outward from the peak planes to the midplane and valley planes. This local maximum in axial velocity at $Y/D \approx 0.85$ remains visible in the lobed case at $Z/D = 2.0$. Axial velocity profile at $Z/D = 3.0$ and 4.0 approach the profiles obtained on the streamwise plane passing through the lobe peak previously described.

Axial velocity profiles along a streamwise plane passing through the lobe valley are given in Figure 78. For $Z/D = 0.25$, the shear layer is clearly evident at $Y/D \approx 0.4$ in both lobed and scalloped profiles. Interestingly, the scalloped mixer exhibits a slightly higher axial speed (by $\approx 0.1$) versus the lobed mixer in the outer regions ($0.4 < Y/D < 0.95$). The local peak in the lobed midplane profile at $Z/D = 1.0$ (Figure 77 (b)) is now evident in the lobed valley profile at $Z/D = 2.0$ and 3.0 (Figure 78 (c, d)). This is consistent with previous conjecture that the flow leaving the lobes is convected azimuthally by the large scale streamwise vorticies.
Figure 76 (a-e). Normalized axial velocity profiles on streamwise plane through lobe peak at Z/D = 0.25 (a) Z/D = 1.00 (b) Z/D = 2.00 (c) Z/D = 3.00 (d) Z/D = 4.00 (e).
Figure 77 (a-e). Normalized axial velocity profiles on streamwise plane through midplane at $Z/D = 0.25$ (a) $Z/D = 1.00$ (b) $Z/D = 2.00$ (c) $Z/D = 3.00$ (d) $Z/D = 4.00$ (e).
Figure 78 (a-e). Normalized axial velocity profiles on streamwise plane through lobe valley at $Z/D = 0.25$ (a) $Z/D = 1.00$ (b) $Z/D = 2.00$ (c) $Z/D = 3.00$ (d) $Z/D = 4.00$ (e).
Streamwise Flow Visualizations

Streamwise flow visualizations are presented on peak (Figure 79), midplane (Figure 80) and valley (Figure 81) planes for each mixer tested. Raw images presented are obtained using PLIF method. Here, flow moves from left to right and the end of the mixer is visible in the left side of each image. Initially, quantitative scalar concentrations were desired on these streamwise planes. During post processing it was determined that the lens used for these planes did not have a linear response (‘washed’ out images toward edges) rendering these images for flow visualization purposes only.

Similar trends between lobed and scalloped mixers exist on the peak streamwise plane in Figure 79. The impingement point on the mixing duct wall is visible and is in agreement with velocity results that indicate delayed impingement by the scalloped mixer. The image presented for the splitter mixer is the same in each of these figures as it is axis-symmetric. Radial spreading of the core flow in the splitter case is drastically lower than either lobed or scalloped mixers.

Streamwise visualization through the midplane of the lobe sidewall are given in Figure 80. Scalloped mixer visualization indicate core flow is moved through the scallops and begin mixing on this plane upstream of the lobed mixer. Note the region above the core flow close to the exitplane is filled with dye in the scalloped case but not in the lobed.
Visualization of streamwise valley planes (Figure 81) are quite interesting. Qualitatively, this plane shows the point at which the core flow extending from the lobes in peak and midplanes ‘roll’ into the valley plane. This plane forms the furthest distance (1/2 lobe period, or 22.5°) dye travels from the lobe peak plane to the lobe valley streamwise plane. The scalloped mixer show small pockets of dye in this plane upstream of similar pockets observed in the lobe case. Between Z/D = 4 and 5, regions outside the core flow, fill with mixed dye rapidly indicating flow is completely turned into the valley plane.
Figure 79 (a-c). Streamwise PLIF dye visualization on peak plane for lobed (a) scallop lobed (b) and splitter (c) mixers.
Figure 80 (a-c). Streamwise PLIF dye visualization on midplane for lobed (a) scallop lobed (b) and splitter mixers.
Figure 81 (a-c). Streamwise PLIF dye visualization on valley plane for lobed (a) scallop lobed (b) and splitter mixers.
Measurement Uncertainties

Sources of error in PIV measurements are typically due to out of plane motion, resolution and velocity variations within a subregion as discussed by Keane and Adrian[39]. In this experiment particle density in the interrogation area are approximately 14 - 16 particle pairs per interrogation area. Error associated with this is approximately 2%. Additionally, poor particle tracking from density and size variations between the test fluid and particles themselves creates some uncertainty in the measured results. In addition, small error enters into the experiment by slight misalignment between desired laser path and actual laser path. Laser alignment devices were built and used to maximize repeatability. Still small deviances are expected. Misalignment in axial cross-planes are estimated to ± 2mm and ± 2° on streamwise planes.

Similarly sources of error in PLIF experiments result from nonuniformities in the laser sheet, shot to shot variation in laser power and absorption along the laser path. In this experiment, absorption is accounted for by integrating along each ray (estimated along each row), accounting for changes in illuminating intensity. Still some error enters in due to curve fitting calibrations to find \( \beta \) and \( \varepsilon \). Associated error is estimated between 3 and 5 percent.
CHAPTER 6

CONCLUSIONS

The experimental results presented here are a culmination of significant work to build a test rig capable of creating a shear flow with desire velocity ratio, developing software to post process PIV and PLIF data and to test and evaluate three separate mixers. The test conducted are unique with regards to numerous research published in lobed mixing devices in the following ways. First, this study is the only known that provides high resolution, quantitative, whole field scalar mixing, data for lobed and scalloped lobed mixers. Secondly, tests conducted here use three dimensional forced mixers, that are confined in a constant area mixing duct which is more representative of its traditional application. Lobe geometry was selected in terms of lobe height, width and penetration angles intentionally similar to previous, well cited, lobed mixing studies.

Several conclusions can be made from the presented data. First, the instantaneous velocity vector fields and streamwise vorticity distributions do not confirm results by Yu et. al. [27] which suggest an additional pair of streamwise vorticies form from scalloping of the lobes. The ensemble averaged cross-stream velocity fields do not identify these structures clearly. It is possible that these small-scale additional vorticies are shed periodically into the flow and are ‘lost’ during the ensemble average. In the future, frther analysis using the method of Proper Orthogonal Decomposition can be used to determine whether second and/or third energy modes contain these additional vortices. Instantaneous concentration contours on the axial cross-stream suggest strongly that there
are multiple, random, small scale vorticies shed into the wake in lobe sidewall region. It is found that lobe scalloping allows early azimuthal shear layer growth from the streamwise voriticies generated by the lobe shape. The lobe sidewall in the un-scalloped configuration prevent this early mixing and thus indicate a slightly lower mixing rate in the enhanced mixing region. The maximum streamwise vorticity decay rate for both mixers does exhibit close similarities with respect to studies by Hu. et. al. [11].

Secondly, the increase in cross-stream velocity for the lobed case between $Z/D = 0.1$ and $0.5$ is a phenomenon quite different from that reported for two and three-dimensional mixers exhausting to large, unbounded volumes. Interestingly, the scalloped mixer performed closer to that expected from results reported in [11]. Axial velocity fields from streamwise PIV results confirmed this initial increase in velocity on the lobe peak plane for the lobed mixer. Additionally it was observed qualitatively (PLIF streamwise flow visualizations) and quantitatively (cross-stream velocity fields) that the impingement location for the scalloped mixer is further downstream than that of the lobed mixer. It is suggested from axial velocity results that the scalloped mixer diffuses the outward radial cross-stream velocity by introduction of lower momentum bypass fluid through the scallops.

Finally, the turbulent mixing behavior in the enhanced mixing region ($0 < Z/D < 2$, Figure 59) reported shows distinct differences with respect to numerical predictions of Elliot et. al.[4] for two dimensional mixers with streamwise vorticity. Results here indicate a higher rate of turbulent mixing (with negative curvature) while Elliot et. al.
indicates a slightly slower rate with positive curvature. Downstream of the enhanced mixing region the slopes are similar with a much slower rate of mixing. The splitter mixer here shows similar behavior to that of the mixer without streamwise circulation reported by Elliot et. al.
BIBLIOGRAPHY

Lobed Mixers


PLIF


PIV


