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MIXING PROCESSES IN A COAXIAL GEOMETRY WITH A CENTRAL LOBED MIXER-NOZZLE

A DISSERTATION

Presented in Partial Fulfillment of the Requirements for the Degree
of Doctor of Philosophy in the Graduate School of
The Ohio State University

By

Vincent Michael Belovich

The Ohio State University
1995

Dissertation Committee:

S. Nakamura

M. Samimy (Advisor)

K. Vafai

Approved by:

Department of Mechanical
Engineering

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ABSTRACT

An experimental investigation was undertaken to study the mixing processes in a coaxial jet geometry where the inner nozzle is a lobed mixer. Seven different inner jet nozzle geometries were explored: a baseline circular jet, three different six-lobed nozzles and three different four-lobed nozzles. In addition, three different velocity ratios of 3:1, 1:1 and 1:3 (inner:outer) were examined at two velocity levels. Flow visualizations of the inner stream using a passive scalar (tobacco smoke) were performed using a laser sheet from a Nd:YAG laser as the light source. The laser has a 9 nsec pulse duration, which effectively freezes the flow. Instantaneous cross-sectional images were taken at various distances downstream; streamwise views were also taken. Quantitative information on the mixing was obtained by processing sets of images. All three components of velocity for one of the nozzles were also obtained using a two component, coincident LDV system. The effects of various parameters such as the increase in interfacial area due to the lobed nozzle geometry, the strength of streamwise vortices, and the large-scale structures on the mixing process is evaluated and discussed.

The results showed enhanced mixing as the strength of the streamwise vortices increased. The results also showed that the presence of large-scale structures, due to the

Kelvin-Helmholtz instabilities and their interaction with the streamwise vortices generated by the lobes, is crucial for enhanced mixing. There was generally a wider spread for the 3:1 velocity ratio, followed by the 1:1 and then the 1:3. There were also different mixing processes for each velocity ratio. The 3:1 velocity ratio behaved similarly to a single jet, except that the Kelvin-Helmholtz instability and the streamwise vorticity interacted together to enhance the mixing. The LDV results showed that the streamwise vortices spread radially with the jet for the 3:1 velocity ratio case. The 1:1 velocity ratio, with the Kelvin-Helmholtz instability minimized, relied almost exclusively on the streamwise vorticity to mix the two streams. For this case, the LDV data showed the streamwise vortices much more confined and not spreading as much as for the 3:1 case. The 1:3 velocity ratio flow condition, on the other hand, behaved more like a wake flow because of the inward roll-up direction of the interface. This condition produced the lowest jet spread in general, although it was sometimes comparable to the 1:1 case. The LDV results for this velocity ratio showed that the streamwise vorticity that did develop dissipated very quickly within a few diameters. The inner jet was also greatly influenced by the outer shear layer, i.e., between the outer flow and the ambient air, and it was this shear layer that had the greatest effect on the spread of the inner jet.

The fraction of mixing enhancement due to streamwise vorticity (relative to mixing enhancement due to increased interfacial contact area) was found to increase as velocity ratio increased. In addition, this fraction increased with downstream distance.

This dissertation is dedicated to my wife, Janet.

May we now have a

(somewhat)

normal life together.

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VITA

13 May 1961	Born - Cleveland, Ohio
1982 - 1984	Co-op Student, Union Carbide Corporation
1984	B.S.M.E., University of Akron
1986	M.S.M.E., Purdue University
1986 - 1990	Research Engineer The Babcock and Wilcox Co.
1990 - 1991	Research Assistant University of Dayton
1991 - Present	Palace Knight Program United States Air Force At The Ohio State University

PUBLICATIONS

- V. M. Belovich, M. Samimy, M. F. Reeder, "Dual Stream Axisymmetric Mixing in the Presence of Axial Vorticity," AIAA Journal of Propulsion and Power, to appear.
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FIELDS OF STUDY

Major Field: **Mechanical Engineering**

Areas of Interest: **Fluid Mechanics, Heat Transfer, Turbulence,
Laser Diagnostics, Combustion**

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NOMENCLATURE

Roman Symbols

D	diameter
D_h	hydraulic diameter
nm	nanometers
r	radial distance
t	time
u	axial velocity
v	cross stream velocity
w	cross stream velocity
x	downstream distance
y, z	Cartesian distance in cross-sectional plane

Greek Symbols

Δ	change in
λ	wavelength
σ	standard deviation

Subscripts

l	primary/inner/central stream
---	------------------------------

- 2 secondary/outer/annular stream
- i primary/inner/central stream, individual data point
- o secondary/outer/annular stream

CHAPTER I

INTRODUCTION AND BACKGROUND

Mixing is an important phenomena in all combustion systems from subsonic systems such as coal-fired boilers, oil- and gas-fired furnaces, and gas turbine engines, to supersonic systems such as scramjets and flows downstream of supersonic aircraft. Several current areas of attention in aerospace propulsion research involving mixing are advanced air breathing propulsion systems like scramjets, air augmented rockets, multimode engines for hypersonic aircraft, and stoichiometric combustion systems. A critical technical problem to be solved in many of these applications is the mixing between two gaseous streams. How quickly and how well a fuel and oxidant can be mixed will have a major influence on the combustion efficiency, heat release rate, pollutant formation, combustor size, and many other pertinent parameters. It is widely accepted that vorticity dynamics greatly impact the mixing process. The streamwise vortices generated in a flow, in addition to the well known spanwise (in planar shear layers) or ring type (in axisymmetric shear layers) vortex roll-up processes have been found to mix fluid streams quickly and efficiently. Generating these vortical structures using a lobed mixer and investigating their mixing enhancement capabilities are the subject of the present study.

Mixing takes place on all levels, or scales, of the flow, although the term is often reserved for the molecular scale. The process of entrainment is considered to be mixing on a macro scale and it is controlled by large-scale structures in the flow and the geometric boundaries of the flow. A smaller scale at which mixing can take place is of the order of the smallest eddies in a flow where viscosity becomes important, while the molecular scale is that at which chemical reactions, such as combustion, take place.

Mixing has been studied in many different flow configurations over the years including shear flows, wake flows, and jets. The mixing process begins in a flow due to the presence of a velocity gradient. This velocity gradient becomes unstable (Kelvin-Helmholtz instability) and creates large-scale vortices and shear stresses that transfer momentum between the two streams. The region of interaction between these two streams is called the free shear layer and/or mixing layer. The generation of turbulence in this layer, through the interactions among the different scales, further enhances the mixing. The mixing layer grows as the fluid from both streams is entrained downstream.

Mixing in flows can be divided into two main categories: natural mixing and forced mixing. The natural mixing process is made up of the phenomena just discussed. Attempting to enhance the natural mixing process by some direct means is known as forced mixing. Forced mixing can be split into two branches, active and passive. Active mixing occurs when the flow is perturbed by, for example, an acoustic signal placed at some region of interest, or by forcing some periodic condition on the upstream

flow and studying its effects downstream. In active control, the perturbation is often controlled by a feedback signal from the mixing region.

On the macro scale, it is well known that the large coherent structures in a flow can be controlled to some degree [e.g., Ho and Huerre, 1984; Roberts and Roshko, 1985; and Kennedy and Yip, 1988; Wicker and Eaton, 1992] and this has led to research on large-scale mixing enhancement in combustors, noise reduction from jet exhausts, and many other areas. In addition to the large-scale phenomena, since chemical reactions take place on the molecular level, knowing the molecular mixing characteristics of a flow aids in understanding the combustion process and how pollutants are formed, and possibly leads to methods of controlling these processes.

Passive mixers, unlike active mixers, are designed to perturb the flow without any feedback from the mixing region. This is effected by either using vortex generators and/or novel nozzle shapes. The present study will concentrate on passive mixing techniques. Use of vortex generators, such as tabs, placed at the nozzle lip of an axisymmetric jet, is one passive mixing technique that was studied by Reeder [1994], Samimy et al., [1993], and Reeder and Samimy [1993] for subsonic and supersonic flows. They found that the tabs had a marked influence on enhancing the jet mixing in both subsonic and supersonic flows and reduced the noise level of the supersonic jet. The tabs were found to produce streamwise vortices at the jet exit that were able to entrain the ambient fluid more effectively. Since the tabs produced similar effects on the flow in the Mach number range of 0.34 to 1.81, the effect on mixing was independent of compressibility and therefore dependent on vorticity dynamics. Thus,

controlling the vortex interaction is essential to controlling the mixing process. The lobed mixer, which is the subject of this study, is a passive mixing device that induces streamwise vortices; it will be discussed in a later section.

1.1 NATURAL MIXING

1.1.1 The Planar Mixing Layer

In general, the mixing process begins due to the presence of a velocity gradient. An inflection point in the velocity profile causes the interface between the adjacent fluid layers to become inviscidly unstable, which is known as the Kelvin-Helmholtz instability. The unstable layer rolls up into large-scale eddies [Brown and Roshko, 1974; Winant and Browand, 1974] as diagramed in Fig. 1.1. The flow is from left to right in the figure with the faster stream on the top. This figure illustrates how effective large-scale eddies are at distributing fluid across an interface by rolling fluid layers around each other. Depending on the incoming flow conditions, the overall geometry of the test apparatus, the background laboratory noise, and other flow parameters, the eddies may break up, coalesce with other eddies, or translate with the flow for a time. Freymouth [1966], while studying sound-excited, laminar-turbulent transitional shear layers, and Winant and Browand [1974], also studying planar mixing layers, discovered that these vortices normally coalesce in pairs. Brown and Roshko [1974] found similar behavior in their mixing layer flow visualization experiments. They also witnessed three and four vortices combining, but much less frequently. Qualitatively, the process

of pairing begins as adjacent vortices rotate about each other due to their mutually induced velocity fields [Cantwell, 1981]. As they rotate, they combine into a single vortex, usually of a larger scale.

These predominantly two-dimensional structures have been observed at very high Reynolds numbers in fully turbulent (gaseous) mixing layers [Brown and Roshko, 1974; Mungal et al. 1985], in high speed water mixing layers [Dimotakis and Brown, 1976], and by Clemens and Mungal [1990,1992] and Elliott et al., [1992] for supersonic mixing layers. Winant and Browand [1974] proposed that the spreading of the mixing layer was due primarily to the pairing of these spanwise vortices. Figure 1.2 (from Elliott [1993]) shows a schematic of vortices pairing as well as other evolutionary processes of eddies in a two-dimensional shear layer with the flow traveling from right to left. If the trajectories of the eddies in a shear layer were plotted on a position versus time diagram, the results would be similar to that in Fig. 1.3 (adapted from Brown and Roshko [1974]). This plot shows that as the eddies travel downstream, after a time they can no longer be discretely identified, but a new eddy can be seen to take the place of two or more others. Similar behavior was found to take place in jet mixing layers [Bouchard and Reynolds, 1978, as referenced in Cantwell, 1981; Liepmann and Gharib, 1992], where similar graphs of eddy trajectories showed that the eddies will sometimes orbit around each other before pairing. However, Browand and Laufer [1975] did not observe the eddy paths crossing each other in their jet flow.

The concept of the mixing layer that evolved from these studies is one of a double structure, composed of large-scale vortices, moving, interacting, and entraining

fluid on a large-scale, superimposed on a background of small scale turbulence. Examples of this can be seen in Roshko [1976] and/or Ballal and Lefebvre [1975], which show large-scale flow structures at different Reynolds numbers that are similar in appearance. However, within the large-scale structures, smaller scale motions become more prominent as the Reynolds number increases.

This concept helps illustrate the difference between what is meant by *stirring* and *mixing*. *Stirring* is caused largely by the large-scale (inviscid) motions in a flow. It is the mechanical, kinematical process by which these large eddies (Fig. 1.1) redistribute a fluid within a given volume, i.e., the interfacial area between different fluids of unequal velocities is increased. On the other hand, *mixing* usually refers to the scale of the microscopic interfacial areas where substances diffuse across these boundaries and mix on the molecular level. Stirring can promote mixing by creating more interfacial area over which diffusion can take place, but it is possible to stir two fluids that do not mix completely. Mixing depends on material properties such as diffusivities, whereas stirring is a purely kinematical process, dependent on flow parameters.

Entrainment is analogous to stirring. Entrainment is seen as an engulfing action by the large eddies (also Fig. 1.1). Free stream fluid is drawn into the vortices and distributed into the mixing layer where it is made turbulent and ingested by the smaller eddies and eventually dissipated by viscosity.

Although physical evidence for the existence of large-scale structures in a flow was given a tremendous boost with the work of Brown and Roshko [1974], the idea of

large-scale motions had been around for some time. Roshko [1954] made extensive measurements of the large-scale vortices being shed in the wakes of cylinders and rings. Grant [1958] also studied the wake downstream of a cylinder in cross flow. By measuring the Reynolds shear stress tensor at various locations in the flow, Grant found large-scale motions "to be more ordered than has usually been supposed" and postulated the existence of a counter-rotating vortex pair shed from the cylinder to explain the data.

The ordered motions of Townsend and Grant differed from the Brown-Roshko structures in that their large-scale motions were more of a vague idea of slow moving, randomly interacting, three-dimensional eddies, and were thought to be either flow specific behavior, such as Grant's wake flow, or associated with transition, as in Freymouth's work [Cantwell, 1981]. The mixing layer observations, on the other hand, were the first to clearly show large-scale structures at various Reynolds numbers under various flow conditions. These observations brought the concept of large-scale structures to a point where they could be easily visualized.

Roll up and pairing of mixing layers have also been studied extensively using two-dimensional numerical simulations [e.g., Acton, 1976; Patnaik et al., 1976; Riley and Metcalfe, 1980; Corcos and Sherman, 1984; Jacobs and Pullin, 1989], where many of the same physical flow structures have been observed in the calculations..

The experiments of Chandrsuda et al., [1978] suggest that in highly turbulent mixing layers, two-dimensional roll-up and pairing may not occur to the extent seen in Brown and Roshko [1974]. A highly turbulent free stream flow causes three-

dimensionality to occur much more quickly (i.e., further upstream) in a planar shear layer, and therefore the Brown-Roshko structures break down sooner, possibly before they can combine with each other. Similar observations were made by Browand and Troutt [1985] who state: "In a sense, the mixing layer that develops from a turbulent boundary layer begins closer to its final condition--there is no strong transition." In agreement with these observations, it was apparently necessary to add two-dimensional disturbances to random three-dimensional initial conditions to trigger coherent roll-ups in several numerical simulations [Riley and Metcalfe, 1980; Metcalfe et al., 1987]. Also, three-dimensional perturbations in an otherwise two-dimensional array of spanwise rollers [Browand and Troutt, 1980, 1985] and highly three-dimensional roller vortices [Nygaard and Glezer 1991] have been observed.

In addition to the spanwise rollers, there is abundant experimental evidence that predominantly streamwise vortical structures (also called rib vortices) reside in the region between the Kelvin-Helmholtz rollers, known as the braid region [Brown and Roshko, 1974; Konrad, 1976; Breidenthal, 1978, 1981; Bernal and Roshko, 1986]. A schematic of this is shown in Fig. 1.4 (adapted from Elliott [1993]) where flow is from right to left with the faster flow on top. Numerical simulations have also shown the existence of rib vortices [Riley and Metcalfe, 1980; Metcalfe et al., 1987; Ashurst and Meiberg, 1988]. They have been seen to arise from both initial conditions designed to produce them as well as from random three-dimensional initial conditions. In experiments, the spanwise location of these streamwise vortices has been found to correlate with upstream disturbances in the experimental facility [Jimenez, 1983; Bernal

and Roshko, 1986; Lasheras et al., 1986; Bell and Mehta, 1989]. Lasheras et al. [1986] also found that the first appearance of streamwise structures always took place in the braid region. The structures were subsequently amplified due to stretching (from spanwise vortices) until they became strong enough to be visualized. Similar results were found in jet shear layers in Liepmann [1991] and Liepmann and Gharib [1992]. However, beyond a certain downstream location a reorganization seems to occur for the planar shear layer, which increases the characteristic spanwise spacing and apparently uncouples the ribs from the inlet disturbances [Jimenez, 1983; Bernal and Roshko, 1986].

The circulation of the streamwise vortices was estimated by Jimenez [1983], O'Hern [1990], and Bell and Mehta [1990]. They found similar values for the magnitude of this circulation, values which were on the order of ten percent of the spanwise vortex circulation.

Some details of the roller and rib structures have been determined in several experiments using controlled inlet conditions. Ho and Huang [1982] investigated the long time evolution of nonpairing rollers and observed that the rollers became elliptical and re-entered the braid region, an observation also seen in numerical simulations by Jacobs and Pullin [1989]. In experiments where the three-dimensionality was controlled by forcing, it was found that the roller core became bent in the direction opposite to that of the ribs [Lasheras and Choi, 1988; Nygaard and Glezer, 1991]. Nygaard and Glezer also found that the bending of the roller was associated with a concentration of spanwise vorticity on either the top or bottom of the roller (see Fig.

1.4). This is apparently caused by alternate spanwise stretching and compression of the vorticity, in agreement with the results of Rogers and Moser [1989] and Buell and Mansour [1989].

Much theoretical work has also been done for the planar mixing layers. The linear stability of mixing layer velocity profiles (usually hyperbolic tangent or error functions) has been well documented [Michalke, 1964; Monkewitz and Huerre, 1982; Huerre and Monkewitz, 1985]. Kelly [1967] and Pierrehumbert and Widnall [1982] found a two-dimensional secondary instability that leads to pairing.

1.1.2 Axisymmetric Mixing Layers

The axisymmetric mixing layer, or jet, has been studied extensively. Many researchers have studied either subsonic or supersonic jets; jets issuing into static or flowing streams; free or confined jets; and heated or cold jets issuing into cold or heated flow fields. A jet is characterized generally by a core of fast moving fluid ejected into a slower moving, or quiescent fluid.

Axisymmetric jets exhibit two distinct regions of flow. The first is called the potential core region, in which the jet centerline velocity remains constant. The mixing layer has not yet penetrated to the axis of symmetry in this region. The second region is a decay region where the centerline velocity decays in proportion to the reciprocal of the distance downstream, due to vortex interaction and viscous interaction. If the jet is heated, the reduction in density reduces the length of the potential core. Further increases in jet temperature reduce the potential core until a limiting temperature ratio is

reached, above which there is no further reduction in core length. Supersonic jets have an added complexity due to their many different operating regimes and the existence of shock and expansion waves. Other geometries such as triangular [Schadow et al. 1988], elliptic [Ho and Gutmark 1987] and rectangular [Sfeir 1976] have been used to obtain better mixing. Noncircular jets generally have the same basic mixing mechanisms of the axisymmetric jet, however, there are some important overall differences that distinguish them from the circular case. The cross-section of an elliptic jet changes its shape as it evolves downstream [Ho and Gutmark 1987]. This change is so drastic that the jet profile aspect ratio is opposite to the nozzle aspect ratio at sufficient downstream distances, i. e., the major and minor axes interchange. The entrainment of the elliptic jet is much greater than the circular jet, which is attributed to streamwise vortices.

Schadow et al. [1984] measured temperature and turbulence quantities in a confined flame issuing from an elliptic nozzle. They showed that the peak flame temperature was attained in a much shorter distance downstream than for a circular jet and the combustion efficiency increased by up to 10%. This shows that the microscopic scale mixing is also more intense in elliptic jets.

Rectangular nozzles have also been studied in jet mixing. The area (i.e. perimeter) over which the shear forces act is greater than for a round jet for a given cross-sectional area. Thus the generation of turbulence in the mixing layer is higher, which causes greater mixing. This effect increases with aspect ratio.

Most of the main features of rectangular jets can be found in the work of Sfeir [1976]. In this study, Sfeir measured mean velocity and temperature profiles of

rectangular jets having different aspect ratios and nozzle geometries. The velocity and temperature measurements were made using a hot wire anemometer probe. Nozzles with aspect ratios up to 30 were tested. In all cases, three distinct flow regions were found to exist in the flow field downstream of the jet exit. They are called the potential core, the two-dimensional region, and the axisymmetric region. The nozzle aspect ratio was found to influence the locations of these three regions, which are different for the velocity and temperature distributions. Both the velocity and temperature behave similarly to the flow of an axisymmetric nozzle at sufficiently large downstream distances.

Krothapalli et al., [1981] also studied a rectangular, incompressible jet. They confirmed the existence of these three distinct regions of flow. The two-dimensional region begins when the shear layers, separated by the short dimension, meet. Further downstream, the axisymmetric region begins when the shear layers, separated by the long dimension, meet. One interesting result of their work is that the shape of the (similarity) velocity profile did not seem to depend greatly on the nozzle aspect ratio. However, the downstream distance where the profile assumes its similarity shape does.

The mixing process for rectangular jets is thus very similar to that for axisymmetric and elliptic jets. As expected, for a constant area jet, as the aspect ratio increases, the potential core length decreases and mixing is enhanced. Since the mixing layers grow approximately linearly, the core length is determined by the short dimension of the nozzle. The two-dimensional region begins after the potential core and ends when the mixing layers across the jet's long dimension meet.

One of the first studies to show the existence of large-scale structures and their connection to jet instabilities was by Crow and Champagne [1971]. Through the use of Schlieren photography and hot wire anemometry, they showed the existence of axisymmetric structures in incompressible jets up to Reynolds numbers of 10^5 . They also used acoustic forcing and discovered that at a Strouhal number of 0.3, a preferred mode of excitation existed in the jet. By forcing at the proper frequency, the large-scale structures were strengthened and entrainment was found to increase.

Browand and Laufer [1975] tried to determine the role of large-scale structures in the development of a circular water jet in the Reynolds number range of 5,000 to 15,000. They found that the ratio of jet radius to momentum thickness (R/θ) is an important parameter in jet mixing. They also noticed three distinct instabilities affecting large-scale structures. At a Reynolds number of 5,000 their observations indicated that flow structures are mostly axisymmetric, or donut shaped. In the range of 10,000-15,000, the axisymmetric rings attained an azimuthal (i.e., circumferential) dependence, as lobes are seen to develop on the donut-shaped vortex. At a Reynolds number of 15,000 the flow structure appeared to be mostly helical.

The axisymmetric mode of a jet, shown in Fig. 1.5 (Fig. 1.5a adapted from Reeder [1994]; Fig. 1.5b adapted from Liepmann [1991]), is a donut shaped, or ring-like, structure similar to a Kelvin-Helmholtz structure. It is formed from the roll-up of the interface surrounding the jet. The azimuthal mode, shown in Fig. 1.6 for a supersonic jet (from Arnette et al., [1993]), is a combination of streamwise structures that originate in the braid region of the jet [Liepmann, 1991; Liepmann and Gharib,

1992]. These instabilities are amplified by the stretching induced by the axisymmetric mode and evolve into pairs of counter rotating vortices that move radially outward from the jet axis. They entrain the outer quiescent fluid, but can also be reentrained into the jet themselves. In a subsonic jet, after the potential core region, the ring structures tend to die off, but the streamwise structures have been observed to still be strong. The helical mode is a ring-like structure that is elongated into a continuous helical pattern, much like a coil spring. A schematic of this mode is shown in Fig. 1.7 (Fig. 1.7a adapted from Reeder [1994]; Fig. 1.7b adapted from Tso and Hussain [1989]). The helical mode is generally found downstream of the potential core of a jet and at higher Reynolds numbers.

Dimotakis et al. [1983], using laser induced fluorescence (LIF) in a low Reynolds number water jet, determined large-scale structures to be the dominant mixing mechanism in the turbulent regime and found them to be either helical or nearly axisymmetric. Studies of an air jet at a Reynolds number of $Re = 69,000$ by Tso and Hussain [1989] showed the helical structure was the preferred mode in the fully developed region. They also found that this helical structure has a strong radially outward movement and suggest that this could be a major mechanism in jet spreading. This study lends some support for the linear stability analysis of Batchelor and Gill [1962], who showed that the helical mode was the most unstable mode for the jet far field velocity profile. The large-scale structures, in the turbulent regime are relatively insensitive to Reynolds number [Crow and Champagne 1971].

Yule [1978] also used flow visualization and hot wire techniques to study large structures in round jets. Similarly to what Browand and Laufer [1975] discovered, vortex rings are shed from the jet exit in the potential core region. These rings travel downstream, coalesce, and lose coherence somewhat as they reach the fully turbulent region where they may or may not continue to exist as vortex rings [Davies and Yule, 1975].

In describing jet structures, Yule [1978] uses the term "vortex ring" to describe the structures in the transition region, just downstream of the nozzle exit where the instabilities are growing and are relatively easy to visualize. He used the term "eddy" to describe the less coherent, yet still strong, structures in the turbulent region. As the ring vortices progress downstream, they coalesce, distort, and become three-dimensional, leading to a fully turbulent region. Yule proposed that vortex pairing is the "mechanism by which the jet structure tends to forget the conditions of the jet nozzle." Further downstream, the flow structure is less dependent on Reynolds number, which is in agreement with Browand and Laufer [1975]. Yule did not observe vortex rings or pairing in the turbulent region.

Visualizations by Yule also showed outward jets of fluid being shed from the regions between the vortex rings. The axisymmetric vortex rings were seen to develop lobe-shaped disturbances that grew with increasing distance downstream. The phenomena was studied analytically and experimentally by Widnall and Sullivan [1973]. They show that a vortex ring in an ideal fluid is almost always unstable. However, viscosity can stabilize the ring.

The visualizations by Liepmann and Gharib [1992] and others were performed for relatively low Reynolds numbers, where the detailed structures of the flow were readily seen. At a much higher Reynolds number, Mungal et al. [1992] have observed many of the same structures. By studying flow visualizations from a TITAN IV rocket motor ($Re \sim 200 \times 10^6$) and from a hydrogen jet diffusion flame ($Re \sim 30 \times 10^6$), they observed the passage and growth of large-scale structures, the occasional pairing of structures, axial velocity decay, and similar entrainment patterns to low Reynolds number jets.

1.1.3 Coaxial Jets

The subject of coaxial jets will be briefly reviewed because of the similarity to the present flow set up. For the present study, the central jet is actually a lobed mixer nozzle, therefore the coaxial, axisymmetric jet system is an appropriate base line case.

The fundamental differences between an axisymmetric jet and a coaxial jet system exhausting into quiescent ambient air are illustrated in Fig. 1.8 (adapted from Wicker and Eaton [1994]). The shear layer that develops between the outer (annular) flow and the still, ambient air is similar to that for a single jet because essentially vorticity of only one sign is present. The mixing layer that develops between the inner and outer jets, being a combination of a boundary-layer-induced wake and a velocity-difference-induced shear layer, can have initial vorticity of both signs at the exit plane. Following Dahm et al. [1992] it is helpful to view the exit velocity profile as being composed of an even component, due to the wake effect, and an odd component, due to

the shear layer effect. An illustration of this is given in Fig. 1.9. The instabilities associated with coaxial jets are therefore related to both shear layer and wake instabilities. For the case where both jets have the same velocity, the wake instabilities would be dominant. However, as the velocity difference between the two jets increases, the importance of the shear layer instability (Kelvin-Helmholtz) increases.

Previous coaxial jet researchers [Champagne and Wygnanski 1971; Chigier and Beer 1964; Ko and Kwan 1976; Kwan and Ko 1977; Ko and Au, 1981, 1982, 1985; Au and Ko 1987] measured many different properties of coaxial jets, including velocity, static pressure, temperature and various turbulence quantities. Champagne and Wygnanski [1971] found that the potential core length of the annular jet was dependent on the width of the annular jet, but independent of velocity ratio. The inner potential core was found to be dependent on velocity ratio, as well as the area ratio of the two streams. Similar results were also found by Au and Ko [1987] for an outer to inner velocity ratio greater than unity. Turbulence intensity measurements of Ko and Kwan [1976] along the jet radius showed twin peaks, indicating two mixing regions that corresponded to the shear/wake layers of the jet. By six inner jet diameters downstream, the two peaks merged into a single mixing region. Many of the above studies found that many of the measured flow properties showed similar behavior to single jets. Thus they concluded that the flow dynamics of a coaxial jet were very similar to those of a single jet.

The above mentioned studies, while providing essential flow field data, did not explain the characteristics of coaxial jets in terms of vortex structure and dynamics.

Dahm et al. [1992] attempted to make this connection in their water flow visualization experiments of the near field of coaxial jets. Using a two color LIF technique they were able to simultaneously illuminate fluid coming from both streams. Their results showed a wide variety of vortex patterns and interaction dynamics in the jet near field that not only depended on velocity ratio, but also on the absolute velocity of the two streams. These patterns would be difficult to discern from the time-averaged flow data of the previous studies. The vortices that developed in the near field mixing region can be either axisymmetric or helical and possess shear-layer-like and/or wake-like characteristics. They also noticed a coupling between the development of the inner and outer mixing layers, with the outer layer generally dominating the flow. This coupling could have been a result of the relatively thin annular jet of their system.

Wicker and Eaton [1994] studied a coaxial air jet for both forced and unforced flows. They alternately seeded the inner and outer jets with smoke while recording instantaneous images of the flow patterns. For the unforced cases, the outer jet appeared to act like an axisymmetric jet by exhibiting typical ring vortices at all velocity ratios. The inner jet, however, was not independent of the velocity ratio. When the inner jet velocity was greater than the outer jet velocity, the inner jet started out with a high frequency, short wavelength instability that evolved into a lower frequency, longer wavelength (i.e., larger) structure further downstream. When the annular jet velocity is greater, the development of the larger scale structure is inhibited, and the annular jet appears to dominate the inner jet by approximately four inner jet diameters downstream. Acoustically exciting the inner flow did not produce any

significant effects on the outer jet. However, excitation of the outer jet produced large-scale outer layer structures similar to those found in a single jet. These induced structures caused the inner and outer streams to be strongly coupled.

Khodadadi and Vlachos [1987] studied confined, coaxial jets both experimentally and numerically. Measurements showed peaks in turbulence intensity in the mixing layer region until approximately 2-3 diameters downstream, where the profile began to smooth out as the potential core ended. Strouhal numbers of the large-scale structures measured along the centerline were found to decrease from 0.51 to 0.33 at about 4 diameters downstream. The lower frequencies, associated with larger structures, were found to decay more quickly closer to the nozzle, whereas higher frequencies decayed more quickly further downstream. Also downstream, the lower frequencies were seen to be amplified. Depending on the velocity ratio for the confined jet case, a recirculation zone was found to exist 4-5 diameters downstream. When the secondary (outer) flow is below a certain range, there is not enough mass flow to satisfy the entrainment requirements of the central jet, and reverse flow occurs.

Schadow et al. [1990] studied mixing downstream of supersonic coaxial jets. The center jet had a fully expanded Mach number of 3.0 and the outer jet was $M=1.8$. Three different center jet nozzles were used in their study: a circular supersonic nozzle, and two rectangular nozzles. The difference between the rectangular nozzles was that the divergence angle was along the minor axis in one, and along the major axis in the other. By using a combination of helium and air mixtures, and by heating the gases to different temperatures, they were able to test six different compressibility levels

(convective Mach numbers). Overall, it was found that the spreading rate of the coaxial jet varies with the convective Mach number in a similar manner to the plane shear layer. The spreading rate decreased from the incompressible rate at low convective Mach number, to a constant level for convective Mach numbers greater than 1.4. The compressible spreading rate was approximately 25-30% of the incompressible rate. Generally, the rectangular nozzles had higher spreading rates than the circular nozzles, although similar growth rates were found in all three jets at the highest convective Mach number of 2.25.

1.2 FORCED MIXING

1.2.1 The Lobed Mixer

One class of passive mixer nozzles is known as the lobed mixer. It uses a novel geometric shape to enhance mixing. The lobed mixer is shown in both planar and axisymmetric representations in Fig. 1.10 (Fig. 1.10a adapted from Eckerle et al. [1990]; Fig. 1.10b adapted from Barber et al. [1988]). It produces streamwise vortices because the alternating ramp directions force the flow to have cross stream components. These vortices are on the order of the nozzle dimensions and consequently constitute large-scale mixing. The streamwise vortices aid the mixing process by entraining additional fluid from the secondary stream into the mixing layer, and conversely, sweeping the primary flow into the secondary stream. The natural mixing processes previously described for jets and shear layers are still present, however they are

accelerated because the sweeping action of the large-scale axial vortices allows the natural processes to act over a larger volume of the flow field. In addition, the cross stream velocity components introduce three-dimensional disturbances into the shear layer sooner than they would normally develop and thus transition occurs sooner.

Most of the early studies of lobed mixers were greatly influenced by the gas turbine industry, as many of the test configurations were scale models of turbo-fan engine exhaust sections. The geometry consisted of a central solid body around which flowed the hot core fluid with the bypass air surrounding the core. The lobed mixer was an axisymmetric shape separating the two fluid streams which were essentially two annular streams. A typical set up is shown in Fig. 1.11 (adapted from Paterson [1982]).

To the author's knowledge, the earliest lobed mixer study was performed by Frost [1966]. Frost studied the mixing of two annular fluid streams such as would be found in the exhaust of a turbo-fan jet engine. By taking total pressure and temperature data for various mass flow rates and temperatures, it was found that the lobed mixer could theoretically produce a thrust gain, due to its high mixing ability and low pressure drop.

As a byproduct of their mixing abilities, lobed mixers were also used to reduce jet noise by using them to shape exit velocity profiles [Packman et al. 1976; Crouch et al. 1976]. Full scale noise reduction tests were conducted by Meade [1994], who found a reduction in noise level when a lobed mixer was used instead of the standard design.

Mixing was studied in detail by Shumpert [1980], Kuchar and Chamberlin [1980], and Kozlowski and Kraft [1980], also in gas turbine engine configurations.

Shumpert tested four different mixer nozzles and one conventional nozzle. By measuring total pressures and mixing effectiveness, a slight decrease in pressure drop was found, from which a thrust augmentation was calculated. The data showed that a 1.6% improvement in thrust specific fuel consumption was attainable using a lobed mixer, relative to a splitter plate. Other findings in the above studies include: scalloping the lobes aids in mixing; and lobe penetration into the fluid streams has the most significant effect on mixing effectiveness, assuming the flow does not separate. Separation increases the pressure losses and decreases the mixing effectiveness. Scalloping the lobes induces mixing processes similar to those studied in crown-shaped nozzles by Longmire et al. [1992].

Numerical studies were also performed [Birch et al. 1977; Anderson et al. 1980; Povinelli et al. 1980; Blackmore and Thompson 1981] to analyze the complex flow patterns downstream of a lobed mixer. Birch et al. [1977] performed a three-dimensional numerical simulation of the flow field downstream of a lobed mixer used as a mixer nozzle in a gas turbine engine. The study was geared toward code development and the ability of the numerical model to predict the complex flow field. Overall, the predictions were thought to be adequate, and any discrepancies between the predictions and the data were attributed to the initial conditions.

Povinelli et al. [1980] also performed numerical and experimental work on the lobed mixer. They predicted the existence of large-scale secondary flow inside the mixer and determined it to be an important mechanism in addition to the conventional shear layer mixing. They concluded that there are three basic mechanisms in the forced

mixer flow field: the turbulent transport process, the induced secondary flow within the mixing nozzle, and the streamwise vortices downstream of the mixer nozzle. The work by Birch et al. did not include these secondary flows in their initial conditions.

Anderson et al. [1980] used pressure, temperature and velocity measurements downstream of a nozzle as initial conditions for a numerical analysis of the mixing region downstream. Their findings confirmed the existence of a strong secondary flow downstream of the lobed mixer and showed it to be a dominant feature of the mixing process.

Blackmore and Thompson [1981] performed a three-dimensional viscous analysis of the flow inside a lobed mixer for several different geometries. They found good agreement with experimental data for velocity and static pressure distributions and also correctly predicted relative pressure drop rankings for the nozzles tested.

Paterson [1982, 1984] studied subsonic flow issuing from a lobed nozzle for both cold and heated flows. Detailed pressure and temperature data were taken, as well as three-dimensional laser Doppler velocimetry measurements. Paterson found that large-scale secondary flows, set up by the nozzle, produced streamwise vortices of low intensity and length scale on the order of the nozzle radius. Also, a horseshoe vortex on the order of the lobe half width was found to exist in the lobe troughs. The contribution to the overall mixing process of each was not clear, however the secondary flow vortices were expected to be dominant because of their much greater size. The lobed mixer was found to rapidly mix flows at large-scale, thus beginning the cascade process to the smallest scale.

Later work on lobed mixers concentrated on discovering the underlying physics of the lobed mixing process. The geometry of choice changed to the two-dimensional lobed mixer representation of Fig. 1.10b, which is basically a flat plate with a convoluted trailing edge. In 1987, Werle et al. found that the vortex formation process was an inviscid one. Also, the mixing process was proposed to take place in three basic steps: the vortices form, intensify and then rapidly break down into small scale turbulence. In effect, the lobed mixer acts as a 'fluid stirrer' initially to mix the flow, until the rapid breakdown of the vortices produces molecular mixing.

Other studies performed during the last ten years dealt with various aspects of lobed mixers. Presz et al. [1986, 1994] studied ejector pumping using a nozzle in the form of a two-dimensional lobed mixer. It was found that the entrainment abilities of this configuration doubled the performance of conventional nozzle ejectors. Skebe et al. [1988] studied several geometric and fluid dynamic parameter effects on ejector performance and noted performance increases up to two hundred percent. Presz and Nelson [1994] also studied lobed mixers for use in cooling exhaust gases for gas turbines in applications other than jet aircraft, such as stationary power.

Lobed mixers were also studied in supersonic flows. Tillman et al. [1988] applied the lobed mixer concept to supersonic jets. Their lobed mixer did not have round lobes but instead used sawtooth triangular shapes. The objective was to introduce axial vorticity into a supersonic fluid stream to see if mixing performance could be enhanced as in subsonic studies. By measuring total pressure, temperature, and velocity, they concluded that mixing was enhanced. Narayanan and Damodaran

[1994] studied supersonic coaxial jets with the lobed mixer as the central jet, for both confined and unconfined flow. They used a convergent-divergent nozzle that was circular up to the throat, then branched into six separate lobes. The nozzle was designed for an exit Mach number of 1.65 and all tests were run at this condition while adjusting the outer flow to change convective Mach number. Shadowgraphs of the central flow without the outer flow showed a distinctly higher spreading rate for the lobed nozzle compared to a fairly straight exit for a conical baseline nozzle.

McVey [1988] and McVey and Kennedy [1989] studied combustion downstream of a lobed mixer. The rate of spread of the flame was found to be higher downstream of the lobed splitter plate than for a flat plate. Also, the flame propagation speed was higher. A numerical study of mixing in a low NO_x combustor by Toh et al. [1994] suggested that using a lobed mixer was not as good at reducing NO_x as a configuration that injected fuel and air in oppositely swirling directions. No data regarding relative pressure drops for the different geometries were given.

Work by Eckerle et al. [1990], using a two component LDV to measure velocities and turbulence quantities, more fully defined the three mixing mechanisms downstream of a lobed mixer. Initially the lobe shape generates counter rotating vortices with length scales on the order of the lobe width. These vortices eventually break down, resulting in a significant increase in turbulent mixing. The viscous, small scale effect was determined to be an important part of the whole process.

Barber et al. [1988] studied three different two-dimensional lobed mixers both analytically and experimentally. They performed a one dimensional inviscid analysis to

predict lobe circulation and geometrical scaling relations. This analysis was found to be in reasonable agreement with their data, further emphasizing the inviscid nature of the origin of the streamwise vorticity. It was found that circulation scaled well according to the following relation,

$$\Gamma \propto CU_{\text{ref}} \frac{h^2}{L} \quad (1)$$

where C is a constant, U_{ref} is a reference velocity, h is the lobe height and L is the length of the lobe. For a straight contour lobe, the ramp angle, α , can be found by

$$\alpha = \tan^{-1}\left(\frac{h}{L}\right) \quad (2)$$

One of their conclusions was that lobed mixers with parallel side walls produce higher streamwise circulation than lobes of sinusoidal or triangular shapes. The close proximity of the walls in the lobe peak region for the latter shapes creates thicker boundary layers, which reduces the effective lobe height, and therefore reduces circulation. Their two nonparallel wall mixer shapes were of symmetrical geometry and differed only in lobe height, or lobe penetration. The parallel wall mixer was not a symmetrical shape and, more importantly, the duct walls were modified to simulate a more realistic geometry that was representative of a jet engine exhaust. This geometry change produced a reduction of flow area through the nozzle which caused an approximately 50% increase in average velocity through the lobe. This area change

was also nonsymmetrical so it is possible that the velocity ratio across the lobed mixer was no longer 1:1 and thus Kelvin-Helmholtz roll-up may have aided in the enhanced mixing for this case. The effect of the Kelvin-Helmholtz instability had previously not been specifically studied at all in previous lobed mixer studies. Previous studies concentrated on the streamwise vortices that were produced, without regard to interface roll-up. These studies may have had velocity ratios other than 1:1 as many of them were simulating high bypass ratio engines. Moreover, the velocity ratios were not varied. Not until the work of Manning [1991], to be discussed next, was the effect of roll-up specifically studied.

Mixing downstream of a lobed mixer can be attributed to three separate effects. The first is the generation of streamwise vorticity due to the lobe shape, which has been the focus of the bulk of the research on lobed mixers. Another effect is the increase in interfacial area between the two fluid streams because of the convoluted trailing edge of the lobed mixer. The third effect is the Brown-Roshko structure which occurs in any shear layer. Manning [1991], tried to separate the effects of these three mixing mechanisms by using a chemical reaction based flow visualization technique in a water tunnel. By studying a flat plate (for use as a baseline case) and two different lobed mixers--one of which had a convoluted, yet straight extension section to decrease the streamwise vorticity--it was shown that, at velocity ratios close to 1, the increased mixing is due mainly to the increased contact area, whereas the streamwise vorticity has the larger role at a velocity ratio of 2. Manning tested velocity ratios of 1, 1.5 and 2.0 at low Reynolds number. It was also found that the mixing performance of the lobed

mixer exceeds the performance of the convoluted plate by an amount that increases with velocity ratio. Manning's work, and the work of his colleagues at MIT are summarized in Elliott et al. [1992].

A very detailed and systematic study by McCormick [1992] revealed several more details of the flow patterns downstream of a lobed mixer. Extensive flow visualizations for laminar and turbulent air flow, and three-dimensional hot wire velocity measurements, showed that the Kelvin-Helmholtz vortices, which are normal to the flow direction, play a major role in the mixing process. It is the interaction of these normal vortices with the streamwise vortices that produces the high levels of mixing. A schematic of this effect is shown in Fig. 1.12 (adapted from McCormick, [1992]). Note how the streamwise vortices pinch off the normal vortices, thus enhancing the stirring effect in the flow. This pinching causes the normal vortices to merge within 1.5 lobe heights downstream, where they were observed to break down shortly thereafter, leading to intense turbulent mixing. An interesting finding of the study was that the results for laminar flow were similar to those for turbulent flow (turbulent flow was generated by tripping the boundary layer).

Although the existence of horseshoe vortices wrapped around the lobe peaks had been discovered earlier [Paterson, 1982], McCormick was the first to show their existence through flow visualization. Another interesting observation by McCormick is that the scale of the normal vortices shed from the lobed mixer is about 1/4 that shed for a planar baseline case. Thus, it seems that the lobed mixer introduces smaller scales

into a flow sooner, which could enhance molecular mixing [McCormick and Bennett, 1993, 1994].

Presz et al. [1994] studied axisymmetric lobed mixers used in ejector applications. They found that an aggressively designed mixer, having ramp angles of 45° inward, 30° outward and scalloped lobes, produced pumping performance approaching ideal values. Scalloping the lobes had also been used before with success by (Kozlowski and Kraft [1980]).

The geometry of the present study is similar to earlier studies of gas turbine related mixing because it is also an axisymmetric geometry. The difference is that the earlier work needed to use a center body (Fig. 1.11) to represent the core/shaft of the jet engine. The center body, in effect, created an inner annular flow (hot core flow), surrounded by the lobed mixer nozzle, that was to be mixed with the outer annular flow (bypass, or fan flow). Presz et al. [1994] and the present study use the lobed mixer as a central round jet that mixes with an outer (annular) flow. The center body of the gas turbine models tended to squeeze the flow into the lobes and kept it from separating. Earlier researchers were able to use high ramp angles because of the decreasing inner flow area. Only two researchers [Kuchar and Chamberlin, 1980; Kozlowski and Kraft, 1980] mentioned separation in their tests, and that was for geometries where the outward ramp angles were in the 30° - 40° range. Preliminary tests on an axisymmetric lobed mixer without a center body in the present study showed a high degree of separation. The nozzle was designed with a 20° outward ramp angle and a 10° inward ramp angle. This produced a modest area increase through the nozzle of only 15%.

The only flow conditions under which no separation was noticed were when the outer annular velocity was on the order of three times the center velocity. The nozzles tested by Presz, et al. [1994] have ramp angles up to 45 degrees, but the inward ramp angles were larger than outward ramp angles, which would cause a favorable pressure gradient and reduce the possibility of separation. To minimize separation in the present study, the nozzles were designed to have a constant flow area.

O'Sullivan et al. [1994] presented results of a three-dimensional computational study of viscous effects in a planar lobed mixer. They found that separation was a factor for ramp angles of 35° and greater. Increasing the ramp angle beyond that point provided little increase in streamwise vorticity because of increased blockage due to boundary layer growth and separation. A comparison of loss mechanisms revealed that at a velocity ratio of 1:1, the boundary layer and mixing losses were comparable. However, at more realistic nonunity velocity ratios (e.g. 0.5 in the study) the mixing losses were dominant. The study also showed that a convoluted plate (lobed-shaped trailing edge, zero degree ramp angle) had higher thrust than any of the lobed mixers tested because of less overall flow losses. This thrust is achieved, however, only after a much greater flow distance for fluid mixing than for the lobed mixers.

1.3 MOTIVATION

1.3.1 Rationale

The present study will explore the axisymmetric lobed mixer geometry. A central (primary) flow, using a lobed mixer nozzle geometry, will be surrounded by an outer annular (secondary) flow. Unlike the early axisymmetric studies, a center body will not be used. Recent interest in lobed mixers has extended their use from mixing two flow streams to mixing fuel and oxidant streams in combustion systems, thus eliminating the central body. This geometry has recently been studied for ejectors [Presz et al. 1994] and for supersonic coaxial streams [Narayanan and Damodaran, 1994]. The geometry and flow system is still expected to be unique to the present study because both flows will be subsonic and the secondary flow is an actual flow, not induced by entrainment as in an ejector. Other unique features are discussed below.

The nozzles are designed to maintain the same area through the nozzle as the 25.4 mm (1 in. nominal) tube diameter upstream to which it is attached. As previously mentioned, preliminary flow visualization for a test nozzle in the present investigation showed a high degree of flow separation. The test nozzle had an outward ramp angle of 20° and an inward ramp angle of 10° , which produced a moderate 15% area increase over its 31.75 mm (1.25 in) length. An adverse pressure gradient was thus produced which was enough to cause separation. Flow visualization revealed that various lobes were intermittently filled with smoke. The only case for which separation was not observed was when the velocity of the secondary flow was approximately three times

the inner velocity. The outer flow needed to be high enough so that the core flow was drawn into the outer regions of the lobe. A closer examination of the literature revealed a case in which separation was specifically mentioned for a nozzle with a 40° outward ramp angle, which is significantly greater than the test nozzle. It appears that separation was not common in the early axisymmetric studies. Many of those geometries had a core flow area decrease through the nozzle and the outward ramp angle tapered off at the outer tip of the lobes (this was done to keep the hot core flow from impinging on the outer shell of the jet engine model). This area decrease helped to squeeze the flow into the full lobe. To minimize separation without a center body, the nozzles of the present study were designed such that the exit area was the same as the inlet.

Early work relied on point measurements of total pressures and temperatures and velocities to determine mixing. Later work with two-dimensional mixer nozzles used flow visualization extensively to explore flow field behavior. These studies were generally operated at low velocities. The present study performed flow visualization in low and high speed flows using smoke as a passive scalar.

Previous researchers tested many different lobed geometries [e.g., Head et al., 1984]. Until the work of Manning [1991] however, there had been no separation between the effects of interfacial surface area (i.e. nozzle exit perimeter) and flow conditions. The present work will test six different geometries, each designed to separate out the effects of perimeter, lobe shape, area and number of lobes.

While high velocities are not new to the earlier gas turbine industry influenced studies, it is new to the present axisymmetric case without the center body. In addition,

many of the later flow visualization studies were performed at low velocities so that the vortical structures could be more clearly visualized. In conjunction with the flow visualization, detailed velocity measurements were taken in the present study. This quantitative information was used to add further insight into the mixing dynamics for this unique geometry.

1.3.2 Objectives

The system to be studied is that of an axisymmetric lobed mixer, with an outer annular flow. Much research has already been performed on lobed mixers with the objectives of determining which flow geometries are better than others, and what role vortex dynamics plays in mixing the two streams. This study will explore different nozzle geometries, for three different velocity ratios at two velocity levels for the purpose of determining the mixing processes involved and how the different nozzles perform. Planar flow visualizations of smoke will be used to determine the mixing characteristics of the nozzles, at velocities of practical engineering interest. Velocity measurements will be performed to help explain the mixing processes seen in the smoke visualizations.

Specifically, the objectives are:

1. to perform flow visualizations for the inner jet at five different flow conditions covering three velocity ratios and two velocity levels.
2. to perform LDV measurements to document the velocity profiles and general flow patterns in the mixing region downstream of the lobed mixer.

3. to determine the effects of lobed mixer geometry on mixing through testing different nozzles that have 4 and 6 lobes, different lobe shapes, and different spreading angles.

4. to separate the effects of Kelvin-Helmholtz roll-up and nozzle perimeter (interfacial contact area) for the axisymmetric geometry. This will be accomplished by testing a lobed nozzle with a straight section at the various flow conditions.

5. to establish the different mixing processes involved for this axisymmetric geometry and how they may affect spreading of the inner jet for the different flow conditions.

6. to ascertain which nozzle produces the 'best' mixing.

Figure 1.1 Schematic of interface roll-up in a two-dimensional shear layer.

Figure 1.2 Various evolutionary processes of large-scale structures (adapted from Elliott [1993]).

Figure 1.3 Typical position versus time plot of eddy trajectories in a mixing layer (adapted from Brown and Roshko [1974]).

Figure 1.4 Schematic of axial vorticity superimposed on Brown-Roshko structure, as suggested by Bernal and Roshko (1986). Flow is from right to left. Adapted from Elliott [1993].

Figure 1.5 Axisymmetric mode of a jet: a) two-dimensional cut (adapted from Reeder [1994]), b) three-dimensional schematic (adapted fro Liepmann [1991]).

Figure 1.6 Photograph of azimuthal mode of a supersonic jet (from Arnette et al. [1993]).

Figure 1.7 Helical mode of a jet: a) two-dimensional cut (adapted from Reeder [1994]), b) three-dimensional schematic (adapted from Tso and Hussain [1989]).

Figure 1.8 Schematic of velocity profile of coaxial jets (adapted from Wicker and Eaton [1994]).

Figure 1.9 Conceptual representation of a coaxial jet profile as a combination of an even profile and an odd profile as suggested by Dahm et al. [1992])

Figure 1.10 Schematic of a lobed mixer shown in both a) two-dimensional (adapted from Eckerle et al. [1990]) and b) axisymmetric (adapted from Barber et al. (1988)) geometries..

Figure 1.11 Schematic of lobed mixer used in a jet engine (adapted from Paterson [1982]).

Figure 1.12 Schematic of flow downstream of a two-dimensional lobed mixer, from McCormick [1992] (used with permission).

CHAPTER II

EXPERIMENTAL FACILITY AND TECHNIQUES

2.1 AIR SUPPLY

The experiments for this work were conducted at the Aeronautical and Astronautical Research Laboratory (AARL) of the Ohio State University. A schematic of the air delivery system used for various wind tunnel facilities within AARL is shown in Fig. 2.1. The air supply is provided by two four-stage compressors and is stored in two tanks of 42.5 m^3 (1500 ft^3) volume at pressures up to 16.9 MPa (2450 psig). Desiccant dryers are used to reduce the moisture content to extremely low levels. The air is throttled through a globe valve and a ball valve that is pneumatically controlled. To further regulate the flow to the Subsonic Coaxial Jet Facility of this study, a second globe valve was used.

2.2 SUBSONIC COAXIAL JET FACILITY

A photograph of the Subsonic Coaxial Jet Facility is shown in Fig. 2.2. A flexible, high pressure hose is used to link the air supply to the jet facility. The jet

facility is mounted on a moveable steel cart to aid in set up and tear down so as to make room for other experiments. The air is separated into three different flow paths on the cart. Two of the branches are constructed of two inch steel pipe and supply the primary (central) flow and the secondary (outer) flow. The third branch is made of one inch pipe and is used as a bypass section to facilitate flow regulation as the pressure in the storage tanks varies. Each branch has its own ball valve so that individual flows can be regulated. The flow rates are metered using Dwyer model DS-200 flow sensors, which are (diametral) averaging pitot probe devices and require the measurement of differential and static pressures. The differential pressures were measured using a Dwyer model 422-23 incline manometer (0.01 in. H₂O resolution) for the central flow and a Dwyer model 1230-16 U-tube manometer (0.1 in. H₂O resolution) for the annular flow. At high flow rates, a 100 in. water manometer was used for the outer flow. Calibrated gauges were used for the static pressure measurements. Temperatures were measured using calibrated type-J thermocouples.

Figure 2.3 shows a schematic of the settling chamber. Primary flow enters through a single central tube while the secondary flow enters through two separate bottom inlets. A small 101.6 mm (4 in.) diameter stagnation chamber, with a smooth transition section, connects to the central flow tube (upstream of the schematic shown). This provides a relatively flat velocity profile to the (primary) air inlet, although this profile was not measured. Since the tube is over 700 mm (27.6 in.) long, the velocity profile is fully developed for all flow conditions tested. However, once the flow reaches the lobed nozzle this velocity profile becomes severely distorted.

The secondary air is forced to exit horizontally into the settling chamber through a wire screen at each inlet. The flow then passes through a 25% open perforated plate and two 51% open perforated plates to reduce the turbulent scales and flatten the velocity profiles. The contraction section is smoothly contoured (5th order polynomial) with a 7.44 to 1 area ratio and an exit diameter of 63.5 mm (2.5 in.). The end piece is two inches long and constructed out of Plexiglas.

2.3 NOZZLE DESIGN

Six nozzles have been designed, in addition to a circular baseline nozzle, to test different parameters of lobed mixers. Figure 2.4a,b show the baseline circular nozzle and the three six-lobed nozzles, designated N1, N2 and N3. The baseline nozzle is made from one inch stainless steel tubing, OD = 25.4 mm (1 in.) with an exit wall thickness of 0.75 mm (ID = 23.9 mm/0.94 in.). This thickness matches the thickness of the lobed nozzles, which was a design constraint. The piece was machined from thick wall stainless steel tubing and threads into the central tube. The inside surface was machined to produce the 0.75 mm wall thickness.

The lobed nozzles were manufactured from stainless steel bar stock by the (wire) electron discharge machining technique (EDM). The 0.75 mm wall thickness was the smallest thickness attainable. A thinner wall may be possible, but would require annealing of the bar stock prior to cutting to relieve internal stresses. The exit area of the baseline nozzle and that of the lobed nozzles is approximately 450 mm²

(0.70 in.²). The cross-sectional geometries of the lobed nozzles are constructed of circular arcs connected with straight lines that are directed along radii. The inward and outward ramp angles were adjusted to produce the same exit flow area as the 25.4 mm (1 in. nominal) diameter tube to which they were attached. Since the nozzles' inward and outward profiles are linear, the flow area through them remains constant.

The nozzle assemblies in Fig. 2.4 are 152.4 mm (6 in) long overall. The lobed nozzles themselves are either 25.4 mm (nozzle 3) or 50.8 mm (2 in) long (nozzle 1). Nozzle two is made up of a nozzle 3 and a 76.2 mm (3 in.) long straight section having the same cross-section. After being cut on the EDM machine, the nozzles were silver-soldered onto the stainless steel tube section and excess solder was filed smooth to the touch, both inside and out.

Pertinent geometric parameters of the nozzles are given in Table 2.1. A more complete geometric accounting is given later in Table 4.1. Nozzle 1 (N1) has inward and outward ramp angles of 10° . Nozzle 2 has the same cross-section as N1 but has a 0° ramp angle. The straight, yet convoluted section is used to damp out the streamwise vorticity (the circulation of the streamwise vorticity scales with ramp angle, Eqns. 1 and 2). The streamwise vorticity is substantially reduced although not fully dissipated [O'Sullivan et al., 1994]. Since the perimeter is a direct measure of the interfacial contact area, comparing N2 with the baseline nozzle shows the effect of increased interfacial contact area, since the exit perimeter is much greater for N2. Using N1 and N2, we can separate the effect of adding streamwise vorticity to the flow. Nozzle 3, with ramp angles of 20° , is designed to produce the highest level of streamwise vorticity

for the nozzles tested. These nozzles are, to some degree, the axisymmetric equivalent of the 2-D shapes studied by Manning [1991] and O'Sullivan et al. [1994].

Figure 2.5 shows the three four-lobed nozzles tested. All have ramp angles of 10° both inward and outward. Nozzle 4 has the same outlet cross-sectional area as the three six-lobed nozzles. The differences are that the nozzle has four lobes and the perimeter is approximately 30% less. Nozzle 5 is also four-lobed, but the lobes have the same geometric shape as the six-lobed nozzles therefore the cross-sectional area is 29% lower. The perimeter however, is only 4% less than N4. The last nozzle, N6, has lobes that have been squared off. This shape was tested to determine whether the corners on the lobes produce other secondary flows that may affect mixing.

Figure 2.6 shows a head-on scale view of the exit plane looking upstream. The central circle represents the central stainless steel tube/baseline jet. The flow through this tube is extruded into the shape of the nozzle, and then mixes with the coaxial outer flow, which has a 63.5 mm (2.5 in.) ID.

2.4 TEST CONDITIONS

Each nozzle was tested at five different flow conditions for the flow visualizations. Velocity data were taken at three different flow conditions for a single nozzle only. The conditions are summarized in Table 2.2. Similar velocity ratios were tested at two different velocity levels. This was done to explore any effect of velocity magnitude on mixing as, was noticed by Dahm et al. [1992] for coaxial jets.

Table 2.1 Nozzle Geometries

Nozzle	No. Lobes	Length	Ramp Angles inward/outward	Exit Flow Area	Exit Perimeter
1	6 lobes	50.8 mm	9.6°/10°	453mm ²	246 mm
2	6 lobes, straight	76.2	0/0	453	246
3	6 lobes	25.4	19/20	454	246
4	4 lobes	50.8	9.6/10	453	176
5	4 lobes	50.8	9.6/10	323	169
6	4 lobes, square	50.8	10/10	453	170

Table 2.2 Test Flow Conditions

Flow Condition	V _{primary} [m/sec]	V _{secondary} [m/sec]	V _{pri} :V _{sec}
FC1	30	10	3:1
FC2	30	30	1:1
FC3	30	90	1:3
FC4	90	30	3:1
FC5	90	90	1:1

Figure 2.1 Air supply schematic to Subsonic Coaxial Jet Facility.

Figure 2.2 Photograph of the Subsonic Coaxial Jet Facility.

Figure 2.3 Schematic of settling chamber and nozzle section.

Figure 2.4 Two views of the six-lobed nozzles and the baseline nozzle.

Figure 2.5 Four-lobed nozzles.

Figure 2.6 Scale drawing of exit cross-section.

CHAPTER III

EXPERIMENTAL TECHNIQUES

3.1 FLOW VISUALIZATION

Tobacco smoke was injected upstream of the stagnation chamber into the primary stream. The smoke patterns were illuminated using a Quanta Ray GCR-4, frequency doubled ($\lambda = 532$ nm) Nd:YAG laser. The Nd:YAG laser is capable of producing 600 mJ at 532 nm and has a pulse rate of 10 Hz with a 9 nsec pulse duration, effectively freezing the flow. A Princeton Instruments 14-bit intensified CCD camera, synchronized with the laser, was used to record the images, which were then stored on a PC. The optical setup is shown in Fig. 3.1. The laser beam is directed to the test section using prisms and focused into a laser sheet approximately 0.5 mm thick. The orientation shown in the figure is for cross-sectional views. The optics were also set up so that streamwise images could be recorded. Cross-sectional images were taken at x/D locations at 0,1,2,3,5,7 where $D = 25.4$ mm, the nominal tube diameter upstream of the nozzle.

3.2 VELOCITY MEASUREMENTS

A two component, coincident, laser Doppler velocimetry system (LDV) was used to collect velocity data. A schematic of the overall setup is shown in Fig. 3.2. The light source was a Spectra-Physics (model 2020-05) five watt argon ion laser. The green (514.5 nm) and blue (488 nm) beams were used to measure the two components of velocity. The laser beam was first separated into blue and green components. Each color was then split into two equal power beams, and then launched through the beam-coupler into fiberoptic cables attached to a fiberoptic probe. The back-scattered light was received by the same probe and transmitted through a fifth fiberoptic cable to a color separator. The color-separated scattered intensities could then be measured using photo multiplier tubes and converted to velocities by the TSI Inc. model IFA 750 signal analyzer. The process was computer controlled using the FIND software provided by TSI Inc. Photographs of some of the main components are shown in Fig. 3.3. The top photograph shows the optical setup, while the bottom photograph shows the alignment of the fiberoptic probe relative to the nozzle exit.

The fiberoptic probe used a lens with a 248.8 mm focal distance to focus the beams to a point, called the probe volume. The beam half-angle is 5.53° and based on standard calculation methods the probe volume dimensions are approximately 110 microns by 1100 microns. The fringe spacing is 2.532 microns for the blue beams and 2.669 microns for the green beams. To eliminate directional ambiguity, both beams were shifted by 40 MHz using TSI model 9182-3A acousto-optic Bragg cells.

Due to the time consuming and tedious nature of using an LDV system, and because of the several major and minor equipment failures during the research (most notably the argon ion laser and the fiberoptic probe), velocity data was only taken for nozzle 3, at three different flow conditions. In all cases, the blue beams were used to measure the axial velocity while the green beams were used to measure the cross stream components. Since three-dimensional measurements were desired, but only a two component system was available, each test had to be performed twice. The first time the nozzle was oriented with lobes aligned vertically as shown in Fig. 3.4a, where components u and w were measured. After these tests were performed, the stagnation chamber was rotated 90° and components u and v were measured as shown in Fig. 3.4b. Each time the stagnation chamber was moved, it had to be (painstakingly) realigned with the laser beams. This process took several hours, but from one data set to the next, the repositioning error was less than 0.4 mm. Setting the same operating conditions between runs was accomplished by performing the tests at similar storage tank pressures from run to run, thus requiring only minor adjustments to the control valves to maintain consistent flow rates.

The coupler unit which focused the laser beams onto the tip of the $3\ \mu\text{m}$ diameter fiberoptic cable, thus “launching” the beams into the cable, was found to be very sensitive to temperature changes. Since the equipment was set up in a large warehouse-sized room with no tight environmental control, the room temperature variation during the day required almost constant adjustment of the coupler to keep it aligned. As the room temperature rose or fell (only 3-4 degrees Fahrenheit were

necessary) the data collection rate would drop considerably as the system lost its alignment. This sensitivity was not noticed until late in the testing because several other problems were simultaneously appearing.

Once the problem was discovered, the optics were kept in alignment by alternately opening and closing a nearby access door. As the room heated up (either from the sun, electronic equipment, or space heaters in the room) the data rate would drop off and the door was then opened to let the cold outside air in. The system would cool down, realign, and data could be taken at an acceptable rate until the equipment cooled too much. At this point the door was closed and the cycle began again. This procedure worked very well (and kept the operator awake). It should be emphasized here that accuracy of the data is not affected by a slow data rate, unless only a few data points are collected in the time allotted. The low data rate simply increases the amount of time required to take data. When the system was operating properly, data rates in the 1000-3000 Hz range were easily attainable. When the optics fell out of alignment, the data rate would drop to 10-50 Hz, and frequently zero. Optimum optical alignment is essential when between 4k and 8k data points are taken at each location.

Figure 3.4a and b also shows the locations of the data points taken in relation to the nozzle. Radial separation between the points is 2.54 mm (0.1 in.) and angular separation is 5° . LDV data was taken at x/D locations of 0.25, 1, 2, 3, 4, 5, 6, and 7, where D is 25.4 mm. The angle between the beams prevented measuring velocities at the nozzle exit. A grid of 92 points was sufficient to cover the seeded flow area for the first two locations downstream. As data were collected further downstream, points

were added to the grid radially to cover the jet spread. At an x/D of 7, 134 points were necessary to cover the spread of the jet.

3.3 DATA ANALYSIS

3.3.1 Smoke Visualizations

Sets of 50 images were taken for the cross-sectional planes and 75 images for the axial plan views. The images were taken and stored in binary format on disk using Princeton Instruments' CSMA software. The cameras recorded each image on a 288x192 pixel array (the "bin by 2" option was set on the camera). The average image was then found by applying the relation

$$I_{i,j,avg} = \frac{1}{N} \sum_{k=1}^N I_{i,j} \quad (3)$$

where $I_{i,j,avg}$ is the intensity at pixel (i,j) and N is the number of images (50 or 75). The counters i and j run from 1 to 288 and 192, respectively. The standard deviation of the images is calculated from

$$\sigma_{i,j} = \sqrt{\frac{\sum_{k=1}^N (I_{i,j} - I_{i,j,avg})^2}{N - 1}} = \sqrt{\frac{[\sum_{k=1}^N (I_{i,j})^2] - N(I_{i,j,avg})^2}{N - 1}} \quad (4)$$

where $\sigma_{i,j}$ is the standard deviation at pixel (i,j) . The calculations were performed for all seven nozzles, for all the five flow rates, and at all measurement planes.

In an attempt to quantify the gross mixing of the inner jet with the outer jet, an estimate of the spread of the inner jet (smoke-marked area) was made. In essence, every pixel intensity above a certain threshold was counted as part of the expanded center jet, and those below the threshold were considered background. Plotting a histogram of the number of pixels vs pixel intensity for the average images was found to provide an adequate method for separating pixels representing smoke, from pixels representing background intensity. For the majority of images, the 'signal' was readily apparent, forming a 'hump' in the data at the higher end of the intensity scale. The other images (usually at the higher x/D values) did not have a readily discernible hump in the histogram, but exhibited a relatively flat portion followed by a drop off at the higher intensities. Determination of the cutoff threshold for these cases was more difficult, but there was usually a sharp change in slope in the histogram, which indicated a separation between the background pixels and the smoke image. A graph of a typical histogram is given in Fig. 3.5. More details about this method of estimating the jet spread will be given in the results section.

3.3.2 LDV Data

The TSI Inc. IFA 750 Digital Burst Correlator, in conjunction with the FIND software collects the data and calculates the flow parameters. The IFA 750 receives the electrical signals from the receiving optics/electronics and extracts the velocity data. The FIND software then analyzes this data by calculating the actual velocities and other variables, such as turbulence parameters.

There are many sources of error to be aware of when using the LDV technique. They are normally referred to as “bias” errors because they cause the measurements to be biased in some way. These sources can be in the physical setup, the optical setup, the electronics and/or the processing of the data. An example of a potential problem with the physical setup is the necessity of having to seed the flow with particles. Scattered light from the seed particles is used to measure velocity. Particle seeding for this project was accomplished by using a TSI Inc. Model 9306 six-jet atomizer with olive oil as the working fluid. Manufacturer’s data indicate that the bulk of the particles produced using olive oil are below 1 μm in diameter. Particles in this size range are generally regarded as being small enough to follow the flow, and thus lead to an accurate measurement of the flow velocity. A photograph of the seeding plumbing for the outer flow is shown in Fig. 3.6. The white tubing carries the particles to the back plate of the settling chamber where it is injected and mixed with the incoming main air flow (the one inch piping shown in Fig. 3.6). There are four injection locations on the back plate, of which only two are visible in the photograph. The flow path that the particles take through the tubing and associated fittings is very convoluted, and thus acts as another filter helping to ensure that only particles small enough to follow the flow will make it to the test section.

In addition to particle size, particle seeding density can affect the velocity measurements. Though the particles are small, having a high density of particles can begin to affect flow patterns. In the present experiment, the seeding density was too small to affect the flow. A nonuniform seed density in the measurement plane can also

cause seeding bias. Seeding bias in this study was tested by measuring the data rate at several locations within the area of Fig. 3.4 over which data was taken. There was no noticeable difference in data rate between the measurements.

Velocity biasing is another source of error that is probably the best known. This bias arises because the stationary probe volume can only measure the velocities of the particles that pass through it, which are not necessarily representative of the actual flow. These particles are traveling at various speeds (in turbulent flow), however, particles with high velocities are more likely to pass through the probe volume more often than slower particles. Consequently, more high velocity particles are measured than low velocity particles, and thus the average velocity is 'biased' toward the higher values. Essentially, the sampling of the velocity measurements is not random, but dependent on the velocity. The IFA 750 signal analyzer takes care of this bias effect by using the method called Transit Time Weighting, which is an acceptable method for correcting for this bias [Buchave et al., 1979; Edwards, 1987]. As each particle passes through the probe volume, the length of time it spends in the probe volume is recorded. This time is then used as a weight factor in calculating the average velocity. The average velocity, V_{avg} , is calculated by

$$V_{avg} = \frac{\sum_i^N V_i \Delta t_i}{\sum_i^N \Delta t_i} \quad (5)$$

where V_i is the measured (biased) velocity and Δt_i is the time spent in the probe volume for each measurement. The statistical moments are also based on this average velocity weighting, for example the standard deviation, σ_v is

$$\sigma_v = \sqrt{\frac{\sum_i^N V_i^2 \Delta t_i}{\sum_i^N \Delta t_i} - V_{avg}^2} \quad (6)$$

and so on for the higher moments.

Other biasing effects include filter bias, angle bias and gradient bias, among others. Filter bias can occur when the electronics cannot handle the highest and/or lowest frequencies of some of the particles' velocities, and thus some data is not recorded. The IFA 750 is capable of measuring frequencies from 300 Hz up to 100 MHz. For the present optical setup, a ± 10 m/sec velocity represents approximately a ± 4 MHz frequency change. Using a 40 MHz frequency shift for both beams (where a 40 MHz frequency measurement would represent zero velocity) a filter range of 20-60 MHz would enable velocity measurements to be made in the -50 m/sec to + 50 m/sec range. This range is much greater than what is expected for the cross stream velocities so it was used for all cases for the green beams. Since the axial flow varied between 10 and 90 m/sec, various filter ranges had to be used. The ranges found to work most efficiently were 30-70 MHz and 40-80 MHz. These filters permitted velocities in the range of -25 m/sec to +80 m/sec and 0 m/sec to 105 m/sec to be measured, respectively. Various test cases were run using a wider filter range of 10-100 MHz for several

individual locations and no difference in calculated velocity was found. The data rate for this wide range filter was very low, so it was not generally used for the experiments.

Angle bias occurs when a particle crosses the probe volume at such an angle that it does not register as a valid data point, and is not counted. The use of frequency shifting takes care of this bias effect. Gradient bias arises in flows with steep velocity gradients. Since the probe volume is of finite size, only velocity gradients of spatial extent greater than the probe volume can be resolved. This bias is not believed to be substantial in this experiment because the probe volume is small and the velocity gradients are not very steep over this distance.

Other sources of optical errors are, noncollimated beams, nonround beams, unequal beam intensities, distortion of the beams through the fiberoptic probe and others. Many of these problems arise from improper setup of the optical equipment, dirty optical surfaces and/or faulty optics. None of these effects are major concerns in the present study.

Since the LDV technique is a combination of many different types of electro-optical devices, and does not lend itself well to a standard error analysis, an overall rough estimate of error was made by comparing LDV measurements to a total head probe and a pitot-static probe, at two velocity levels. The velocity level was set at 90 m/sec using the Dwyer flow sensors. Measurements with the pitot and total head probes were 86.5 and 87.1 m/sec respectively, whereas the LDV system measured 85.2 m/sec. This leads to an accuracy of approximately 3%. Similar results were obtained at 30 m/sec. Statistical uncertainty is less than 2% since between 4k and 6k data points

were taken for most of the locations. Some sets have less than 3k points, but they are usually located in the outer mixing layer, which is not the focus of this study.

Figure 3.1 Optical setup for the smoke visualizations.

Figure 3.2 Schematic of LDV system setup.

Figure 3.3 Photographs of the optical setup showing a) the coupler, color separator and fiberoptic cables, and b) the nozzle exit with fiberoptic probe.

Figure 3.4 Sketch of nozzle and grid for which velocity data was taken; a) grid used for u and w components, b) grid used for u and v components.

Typical Histogram of Average Image

Figure 3.5 Typical histogram of intensity values for an averaged image from flow visualizations.

Figure 3.6 Photograph of stagnation chamber showing particle seeding plumbing.

CHAPTER IV

RESULTS AND DISCUSSION

As mentioned previously, preliminary experiments using a prototype nozzle showed a high degree of separation. Figure 4.1 shows instantaneous images recorded on videotape for a velocity ratio of 2:1 for the prototype nozzle at about $x/D = 1$. The images differ in time by approximately 1/30th of a second. Only about half the lobes are filled with smoke at any instant. This nozzle has an outward ramp angle of 20° and an inward ramp angle of 7.5° . Figure 4.2 shows successive instantaneous images (1/30th seconds apart) at the exit plane for a 3:1 velocity ratio, but with the outer flow seeded. Here it can be seen that the pressure in the lobes is low enough (due to flow separation inside the lobes) to immediately draw smoke from the outer stream into the lobes. It can also be seen that the separation is intermittent and switches between the lobes. Since this nozzle has ramp angles in the range previously used by other researchers who did not have separation, it was concluded that the center body used in early gas turbine model studies and the duct geometry play a major role in the flow dynamics. Thus, the nozzles were redesigned to keep a constant flow area to eliminate separation.

4.1 SMOKE VISUALIZATIONS

The flow visualizations for this study were performed by seeding the flow with tobacco smoke. Velocity ratios of 3:1 (30:10 and 90:30 m/sec), 1:1 (30:30 and 90:90 m/sec) and 1:3 (30:90 m/sec) were used when setting the flow conditions. Tables 4.1 and 4.2 list the geometric and flow parameters of the nozzles, and the Reynolds numbers for the various flow conditions. The Reynolds numbers are based on the hydraulic diameters for the primary and secondary streams. The visualization results for each nozzle at all three velocity ratios are presented first. Following the visualizations, the LDV results are presented.

4.1.1 Baseline Circular Nozzle (NB)

This subsection presents the results for the baseline circular nozzle for all flow conditions in Tables 2.2 and 4.2. Figures 4.3 and 4.4 show the cross-sectional average and standard deviation (RMS) images for the baseline nozzle at various locations downstream, for the 3:1 velocity ratios, i.e., flow conditions 1 and 4 (FC1 = 30:10 m/sec and FC4 = 90:30 m/sec). The 'scale' image shown in the figure displays circles of various diameters, taken so that a rough estimate of jet spread diameter can be made. The innermost circle has a diameter of 25.4 mm, the next larger circle has a diameter of 50.8 mm and so on. The small numbers in the image represent the diameter in inches. The circles appear somewhat elliptical because of the slight off-axis orientation (approximately 20°) of the ICCD camera. Sets of fifty instantaneous cross-sectional

images were taken for each of the downstream locations. The average images show the expected spreading of a round jet at various downstream locations. The parameter D is the nominal diameter of the baseline nozzle (25.4 mm OD, 23.9 mm ID) and this parameter is also used for the lobed nozzles. The spreading rate for both flow conditions is similar.

The lower halves of Figs. 4.3 and 4.4 show the standard deviations of the average images. It should be remembered that the absolute intensity (i.e., brightness) of the RMS images is not important, only the relative intensity within each image. Also, there is no correlation of intensity between the different images of any figure. The RMS is high (i.e., brighter) where the fluctuation in intensity (or smoke concentration) from the instantaneous images is high. A low RMS (i.e., darker regions) indicates areas where the smoke is either not mixed (e.g., the jet centerline), well mixed, or where there is no smoke at all. All of these areas would have a very low fluctuation in smoke concentration. The average images need to be kept in mind when interpreting the RMS data. Nevertheless, the regions of high RMS fluctuations can be used to define the intermittent smoke region, which is an approximation to the large-scale mixing region. Using this definition, we see that the circular nozzle forms a ring-shaped mixing region as expected. The mixing region grows radially outward and thicker as downstream distance increases.

Figure 4.5 and 4.6 show streamwise planar views of instantaneous, average and RMS images for the circular nozzle at flow conditions 1 and 4. The streamwise average and standard deviation images were calculated using 75 instantaneous images. The

laser sheet is oriented vertically and passes through the diameter of the nozzle. The flow is shown moving from left to right from approximately $x/D = 0$ to 9. The drop off in intensity at the downstream end of the images is due to the edge of the laser sheet. The instantaneous and average images show a typical jet spread with the large structures in the flow angled backward. A helical mode type of structure can be seen from approximately x/D of 3 to 6 in the instantaneous images of both figures. The RMS images show a growing and spreading mixing layer. The instantaneous and average images are extremely similar between figures 4.5 and 4.6, however the RMS image for Fig. 4.6 seems to show a thicker mixing layer, although this is not detectable in the cross-sectional views. Generally, the growth of the shear layer scales with velocity ratio for this type of flow. The different velocity levels, which would produce different jet initial conditions (through boundary layer thickness and turbulence level), could then affect the thickness of the intermittent region. However, considering the average image of Fig. 4.6 with the RMS image, it appears that the thicker mixing region for FC4 is most likely caused by insufficient smoke generation for this flow rate.

Figures 4.7 and 4.8 show the cross-sectional images for the 1:1 velocity ratios (flow conditions FC2 and FC5, 30:30 and 90:90 m/sec, respectively). For this velocity ratio the Kelvin-Helmholtz effect is minimized, but not completely eliminated because of the wake effect produced by the finite thickness nozzle wall, boundary layer growth on both the inner and outer surfaces of the nozzle and the general nonuniform (i.e., turbulent velocity profile) flow through the nozzle. For this case the jet still spreads radially, but at a lower rate than for the 3:1 velocity ratios. This is probably more easily

seen by comparing the average images of figures 4.3 and 4.4 with figures 4.7 and 4.8 at x/D of 7.

The images of Figure 4.7 have a somewhat distorted shape. Since this is not evident in the other images, the distortion was most likely caused by a speck of dirt (tobacco tar) adhering to the inner surface of the nozzle. Even with this local flow disturbance, it is still noticeable that the intermittent region forms a slightly thinner ring than for the 3:1 velocity ratios. This effect, however, is more readily seen in the RMS images at $x/D = 5$ and 7, where the total spread is greater and the differences between the two flow condition are more obvious. Thus, the 1:1 flow condition not only spreads less, but has a smaller region of interaction as well.

The streamwise views for these flow conditions are shown in Figs. 4.9 and 4.10. The instantaneous images show a noticeable difference in spreading rate for this flow compared with FC1 and FC4. With the Kelvin-Helmholtz roll-up at a minimum, the jet width spreads slowly. There is still some degree of interface roll-up noticeable in the individual flow structures but this is due to the boundary layers on the inner and outer nozzle surfaces. The instantaneous images also show helical mode structures from approximately x/D of 3-6. The average streamwise image also shows a jet with much less spread. The RMS images show an intermittent region that is growing thicker with downstream distance, as well as spreading radially outward. Unlike the 3:1 flow condition, this case appears to have an inward growth toward the jet centerline. Comparing the bright intermittent regions of Figs. 4.9 and 4.10 with the corresponding regions in Fig. 4.5, they are roughly equal in size and thickness. Therefore, the

apparent inward growth of the intermittent region for this case is because the overall spread of the jet is less. And, as the intermittent region grows thicker, the inward growth is more noticeable.

The results of the last flow condition, FC3 (30:90 m/sec), are shown in Figs. 4.11 and 4.12. The spread of the jet looks comparable to the 1:1 flow conditions. The mixing region growth is also similar, but is distinctly thicker at the further downstream locations. The streamwise instantaneous view of Fig. 4.12 shows forward slanted structures, as expected for a faster outer flow. Some of the structures are so large that they have penetrated to the centerline of the jet. Since the outer flow is faster, the preferred direction of the interface roll-up is inward, toward the jet axis. The flow characteristics for this condition are thus comparable to a wake flow. Tennekes and Lumley [1972] show that the average spreading rate of a wake flow is lower than a jet flow. The inward roll-up of the large-scale structures, is the main reason for the low spreading rate and the much thicker mixing region for this flow rate, which can be seen in both the cross-sectional images, and especially the streamwise views.

4.1.2 Nozzle Two (N2)

The results for nozzle 2 are displayed in Figs. 4.13-4.22. This is the nozzle with the convoluted straight section added to damp out the streamwise vorticity (see Fig. 2.4). The exit area is the same as the circular nozzle, however, the interfacial contact area (i.e., perimeter) is much larger. Since the flow is exiting with little or no streamwise vorticity, comparisons between the results of this nozzle and the baseline

circular nozzle will provide information on the effect of adding interfacial contact area to the mixing process.

Cross-sectional visualizations for FC1 and FC4 are shown in Figs. 4.13-4.14. In Fig. 4.13, an initial observation is that the average images show no sign of flow separation, as all six lobes are filled with smoke at the exit plane. At $x/D = 1$, all six lobes are distinctly visible but have grown slightly thicker. At $x/D = 2$ the lobes are still separated but are beginning to merge, such that by $x/D = 3$ they are mostly merged and by $x/D = 5$ only the overall hexagonal pattern is noticeable. The average image at $x/D = 7$ shows the smoke pattern approaching the rounded shape of a circular jet. The RMS images for Fig. 4.13 display a convoluted mixing region following the contour of the average image. The area of the mixing layer roughly straddles the border of the average image. In other words, the outer border of the mixing region is slightly larger than the border of the average image, whereas the inner border of the mixing region is slightly within the border of the average image. This mixing region spreads out radially and becomes thicker as distance downstream increases. The results for the velocity ratio of 90:30 m/sec shown in Fig. 4.14 are qualitatively similar. However, at this higher flow rate, and at the locations further downstream (i.e., $x/D=5, 7$), there is a slightly lower overall radial jet spread, yet a thicker mixing region.

The thicker mixing region for N2 at the higher flow rate is due to streamwise vorticity. Many coaxial jet studies (e.g., Champagne and Wygnanski, [1970], Ko and Kwan [1976], Ko and Au [1985]) have shown that velocity profiles and other flow parameters scale well with the velocity difference between the two streams. Ko and

Kwan [1976] even found little difference in velocity profiles between two different velocity levels. Thus one would not expect the mixing region thickness to depend on absolute velocity. The cross-sectional RMS smoke visualizations of the baseline nozzle confirm this. One need only compare the RMS images of Figs. 4.3 and 4.4 and Figs 4.7 and 4.8, to see that the intermittent regions, which are representative of the large-scale interactions due to the velocity gradients, are comparable in size and thickness. This implies that the velocity ratio, independent of absolute velocity, is the proper scaling factor.

With nozzle two, on the other hand, the thickness of the intermittent region does seem to be dependent upon absolute velocity. This is because the streamwise vorticity is not damped out completely by the straight section of the nozzle (O'Sullivan et al. [1994]), and the streamwise vorticity is dependent on the axial velocity, through the magnitude of the cross stream velocity component. Therefore, the thicker intermittent regions for the higher velocity level images are due to the streamwise vorticity.

The streamwise views for the 3:1 velocity ratio for N2 are shown in Figs. 4.15 and 4.16. For these images the laser sheet is aligned through the lobe tips of the nozzle. The instantaneous images show flow structures with a backward angle alignment similar to the baseline nozzle instantaneous images for these velocity ratios. The image at the higher flow rate of Fig. 4.16 shows a slight helical mode type structure from approximately $x/D = 3$ to 7. The average images display a similar spreading angle to the baseline nozzle for this flow rate. The standard deviation images show an intermittent region that is spreading radially outward and growing thicker with increasing distance

downstream. The mixing region for the higher flow rate, FC4, is thicker, as was seen in the cross-sectional images. This feature is more difficult to see in the streamwise views because the laser sheet is much more spread and thus less energy is available for any individual particle to scatter.

Figures 4.17-4.20 display the results for the 1:1 velocity ratios (FC2 and FC3, 30:30 and 90:90 m/sec, respectively). For these cases the Kelvin-Helmholtz effect is minimized and this is easily seen in the images. The smoke in Figs. 4.17 and 4.18 can be seen to spread radially outward, but at a reduced rate relative to the 3:1 velocity ratio. The individual lobes are also spreading azimuthally, but also at a much reduced rate. So much reduced, that six individual lobe traces are still visible, even at $x/D = 7$. Figure 4.18, at the higher flow rate, shows average smoke patterns that are very similar to the lower speed images, with the individual lobes still separate and distinguishable. The RMS images for both velocity levels show a well defined mixing region up to $x/D = 5$. At seven diameters downstream, the mixing region is still a distorted, six-lobed shape, but it has grown noticeably thicker and is starting to smooth out. As previously seen for the 3:1 cases, the higher flow velocity produces a thicker mixing layer, which is related to the higher level of streamwise vorticity.

The streamwise views for the 1:1 velocity ratios are shown in Figs. 4.19 and 4.20. The instantaneous images show that the smoke is spreading less than the 3:1 flow rates. At the 90:90 velocities (Fig. 4.20) there is a definite helical mode type of structure beginning at about $x/D = 3$. The same type of structure is visible in Fig. 4.19, however it is essentially confined to the central core region and is much less prominent.

The average images show much less spread of the smoke compared to the 3:1 velocity ratio, and they are very similar to each other. At the higher flow rate, the smoke is dissipating by $x/D = 7$, possibly due to insufficient smoke generation. The RMS images have dark streaks along the flow axis which show that very little mixing is taking place in that region. This is corroborated in the average images, which show steady streams of smoke along the jet axis and in the instantaneous images which show that very few flow structures are large enough to carry unseeded air into the center. The RMS image also shows that the intermittent region is thicker for the 90:90 case than the 30:30 case.

Figure 4.20 shows that the helical mode could also be at least partially responsible for the thicker intermittent region seen in the RMS images, because it causes at least some intermittency close to the jet axis. However, helical structures do develop at both flow rates.

The results for the last flow rate, 1:3 (FC3, 30:90 m/sec), for this nozzle are given in Figs. 4.21 - 4.22. The spatial extent of the smoke is the lowest of all the flow rates, but the smoke pattern is more diffuse than for the 1:1 case. The six individual lobes are distinguishable through $x/D = 3$, however, by $x/D = 5$, the image has lost its lobe-shaped appearance. The RMS images exhibit a well defined mixing region outlining the nozzle shape until $x/D = 3$ also. By $x/D = 5$, the intermittent region has a hexagonal shape and is also surrounded by a less intense intermittent region. The dark region in the center is representative of unmixed smoke. This is confirmed in the streamwise instantaneous image of Fig. 4.22, which shows very little penetration of unseeded air to the centerline. This image also displays a helical mode structure

beyond $x/D = 3$ which could be partially responsible for the outer region's relatively high intermittency seen in the cross-sectional images at $x/D = 5$ and 7. The streamwise RMS image displays the inward growth of the mixing region also seen in the results of the circular nozzle for this flow rate. The effect of adding Kelvin-Helmholtz roll-up where the outer flow is faster has mixed the central smoke stream but has not spread the smoke radially outward because of the inward roll of the interface. Note how the intermittent region begins to thicken at approximately $x/D = 3$, however it is not nearly as strong as the 'main' intermittent region that remains fairly straight with an inward growth.

4.1.3 Nozzle One (N1)

The results for nozzle 1, with the ten degree inward and outward ramp angles, are shown in Figs 4.23 - 4.32. The 3:1 flow rate results are displayed in Figs. 4.23 - 4.26. Unlike the first two nozzles, N1 adds streamwise vorticity to the flow. The visualizations at the exit plane ($x/D \approx 0$) show that there is no separation in the lobes. At $x/D = 1$ (Figs. 4.23 and 4.24), six individual lobes are distinctly visible, but the pattern has a greater radial extent than N2 and the individual lobes are spreading in the azimuthal direction (i.e., growing thicker) as well. At $x/D = 2$, the smoke continues to spread such that by $x/D = 3$ the smoke from the individual lobes is merging. The smoke in the lobe tips shows a distinct bulge at $x/D = 2$, which is due to the streamwise vorticity. The streamwise vorticity is initiated because of the outwardly travelling smoke and the inwardly rushing secondary air, as the flow follows the outward and

inward ramp angles, respectively. As the smoke at the lobe tips ejects into the secondary air, it is forced back inward toward the centerline by the secondary air, forming the mushroom-shaped bulges at the lobe tip regions. Further downstream the lobes fully merge and a growing, hexagonal smoke pattern develops. This pattern extends through $x/D = 7$, where it appears that part of the top and bottom of the image may have been clipped by the laser beam and/or the camera field of view.

The RMS images show a growing mixing region that appears to be of comparable thickness for both flow rates for the first several locations downstream. But by $x/D = 7$ it is distinctly thicker for FC4. As with nozzle 2, the complexity of the flow field, in particular the addition of streamwise vorticity, causes a much thicker intermittent region.

Streamwise views of N1 for the 3:1 velocity ratios are shown in Figs. 4.25 and 4.26. The spread of the jet is much greater than either the baseline nozzle or N2. The smoke, for both flow conditions, is following the outward angle of the nozzle initially, but does appear to increase its spreading rate slightly beyond $x/D = 1$. This increase in spreading rate downstream of the exit plane can also be seen in the visualizations for the circular nozzle and N2, but much less prominently. There are several plausible explanations for this behavior. The first is that it is caused by the typical ring type instability found in circular jets. Flow visualizations by Liepmann and Gharib [1992] on a single, water jet at low Reynolds number revealed that the jet was fairly stable for axial distances less than $x/D = 2$. Their Fig. 5 shows instabilities starting to grow at $x/D = 1$ and pairing by $x/D = 2$. The entrainment by the axisymmetric structures, and the

growth of the structures due to the pairing process causes a distinct increase in jet spreading rate. Similar behavior was found in the coaxial studies of Dahm et al. [1992] and Wicker and Eaton [1994]. Dahm et al. [1992] found the outer jet displaying this behavior while Wicker and Eaton [1994] discovered this for both the inner and outer jets. Dahm et al., found substantial coupling between both jets with the outer jet generally dominating the inner jet. This was possibly caused by the relatively narrow geometry of their annular jet. The outer to inner jet area ratio for their system was 0.94 compared to approximately 8 for Wicker and Eaton's system and 5.6 for the present study. However, the geometry of the lobed mixer is such that, near the lobe tips, the annular thickness is roughly 1.0 cm, which may produce similar results to the study of Dahm et al. in those regions.

A second possible explanation for the increase in spreading rate is interaction with the ambient air. The streamwise laser sheet was aligned with the lobe tips which is also the thinnest annular section. Studies by Champagne and Wygnanski [1971] and Ko and Au [1985] both showed that the length of the outer potential core is relatively constant for different velocity ratios. As the outer core decays, the relative shear between the inner jet and outer ambient air increases, causing greater instabilities in the mixing region which could lead to a higher growth. Ko and Au determined that the length of the outer potential core was approximately 3.4 inner diameters. The concept of a potential core is not as meaningful for a lobed mixer because of the convoluted exit area. However, if the hydraulic diameter is used for nozzle 1 ($D_{hN1} = 0.74 \text{ cm}/0.29 \text{ in.}$,

which is the same for nozzles 2 and 3), the location where the smoke begins to spread ($x/D = 1$) is approximately 3.4 hydraulic diameters.

Yet another explanation for the change in growth is that it is more likely the result of the streamwise vorticity. The vorticity generated by the nozzle essentially adds large three-dimensional disturbances to the two streams. This could cause the mixing layer to develop sooner since the natural, existing, flow instabilities do not have to grow and amplify as much because of the 'head start' from the nozzle. Essentially the shear layer is going through transition sooner, as seen in planar shear layers (Chandrsuda et al. [1978], Browand and Troutt [1985]). This idea also explains why the effect is less prominent in the cross-sectional images for N2, and not at all detectable for the circular nozzle.

The average images also show a drop off in intensity at the downstream side. This is mainly due to the drop in intensity of the laser sheet and the dilution of the smoke.

The RMS images of Figs. 4.25 and 4.26 show that the area of highest intermittency is along the outer reaches of the expanding smoke. The central dark stripe in Fig. 4.25 shows that the smoke issuing from the center of the nozzle is not being mixed until further downstream. In contrast, the central area of Fig. 4.26 is mixing more evenly in the center because the intensity levels show a less sharp contrast. This is the effect of the streamwise vorticity producing a thicker mixing region as discussed earlier for the cross-sectional images.

The results of the 1:1 velocity ratios (FC2 and FC5) for N1 are shown in Figs. 4.27-4.30. For these flow rates, the Kelvin-Helmholtz effect is minimized and thus the streamwise vorticity is relatively more prominent. The cross-sectional average images of Figs. 4.27 and 4.28 demonstrate the effect of negating the interface roll-up. The smoke pattern grows radially downstream, however, through $x/D = 5$ there is very little interaction between the lobes. The images at $x/D = 2$ show a concentration of smoke at the lobe tips and at $x/D=3$, the streamwise vorticity is noticeable as the smoke is turning back toward the jet axis due to the inwardly rushing secondary air. Even at $x/D = 7$, the central core is still recognizable as a bright spot, indicating that it is still not fully mixed without the help of the Kelvin-Helmholtz effect.

The cross-sectional RMS images highlight the locations of the mixing due to streamwise vorticity. The images at $x/D = 1$ for FC2 show a mixing region outlining the shape of the nozzle, however, the other RMS images at $x/D = 2$ and 3 generally show a mixing region surrounding the nozzle tips and a central, ring-shaped mixing region. This is caused because the fast moving, smoke-filled core flow exiting the center of the nozzle is mixing with the inwardly rushing, non-smoke-filled, secondary air, forming a circular mixing region. This circular region persists in the RMS images up to $x/D = 5$ and it is even recognizable at $x/D = 7$.

The streamwise views of Figs. 4.29 and 4.30 show a much different smoke pattern than the previous flow conditions and nozzles. Three separate jets of smoke issuing from the nozzle are visible, one from the central core and one each from the lobe tips, with very little action between them. The dark streaks are caused by the

inwardly rushing secondary air diluting the smoke in this region because of the thinness of the lobes (i.e., flow area) near the center of the nozzle. In addition, because of the outward radial velocity component of the central jet, the smoke is concentrating in the lobe tip region. This process is more visible for these flow conditions (1:1) because of the near absence of the Kelvin-Helmholtz roll-up. Without the interface roll-up effect, the streamwise vorticity is not sufficient to induce the separate streaks to interact with each other. These dark streaks are not as prominent in the images for N2 because of the small amount of streamwise vorticity generated.

The streamwise images for the 1:1 velocity ratio cases also show a change in jet growth, like the 3:1 flow cases, only it is delayed until approximately $x/D = 3$ where change is much more drastic, especially for the 90:90 velocity. The jump in jet growth is delayed until $x/D = 3$ because of the reduced shear between the central jet and its surroundings. Champagne and Wygnanski [1971], Ko and Kwan [1976], and Wicker and Eaton [1994] noticed an increase in the central potential core length as the outer stream velocity increased.

The large jump in spreading rate is caused by a combination of two factors. The first is the growth of the natural instabilities in the shear layer, as discussed previously for the 3:1 velocity ratio. The second is the break down of the streamwise vortices. As will be presented and discussed later, the LDV results for N3 show a strong streamwise vortex pattern through $x/D = 2$ for the 30:30 flow rate, but a less well-defined pattern by $x/D = 3$ where they are beginning to break down. Assuming a similar process is happening for N1, the vortex break down is probably initiated by the pinch off effect of

McCormick [1992], but the flow visualizations of this study cannot confirm this because the visualization methods are different. McCormick seeded the boundary layer in his experiments whereas the whole inner flow was seeded for the present study, and thus detailed flow structures near the interface are not highlighted. The 3:1 velocity ratio does not produce a large jump in the smoke spread because the Kelvin-Helmholtz roll-up is already spreading the smoke to a greater degree than the 1:1 ratio. In addition, on a relative basis, the streamwise vorticity is stronger for the 1:1 than for the 3:1 flow rates so it would be expected to have a larger relative effect.

The RMS images also give further evidence of the vortex break down. The bright, outer intermittent regions, initiating from the lobe tips, begin as fairly narrow straight regions, following the contour of the average image. At the same location ($x/D = 3$) where the average images experience the discontinuity in jet growth, the RMS regions for both flow rates increase in thickness and blend into a fairly thick region further downstream. This effect is more clear in Fig. 4.30. Contrast this with the RMS images of Fig. 4.25 and 4.26 (3:1 ratio) where the brightest intermittent regions initiate at the lobe tips, spread gradually as the smoke in the average image does, yet remain relatively thin and strong throughout the axial distance shown. The blending of the RMS regions in the 1:1 images is what one would expect as large-scale vortices stretch and deform into smaller scale turbulence.

The RMS image of Fig. 4.29 has a central dark streak showing that relatively little mixing is taking place along the jet axis. Adjacent to this central streak (on either side) are brighter regions that correspond roughly to the dark regions of the average

image. The streaks are dark in the average image because there is very little smoke there, and bright in the RMS image because it is intermittently filled with smoke due to the streamwise vorticity. The streaks are not as noticeable for the 3:1 velocity ratio because of the added mixing benefit of interface roll-up. At the 90:90 flow rate, Fig. 4.30 shows similar behavior to the 30:30 case.

The results for the last flow rate examined for N1, FC3 (1:3 velocity ratio), are shown in Figs. 4.31-4.32. With interface roll-up again being a factor in the mixing, the cross-sectional views have similar qualities to the 3:1 velocity ratio case. In other words, the intermittent region traces the outline of the nozzle, which is also the pattern of the interface roll-up. This flow condition is similar to a wake flow so the interface is essentially rolling inward, from outer to inner jet. Thus the smoke spread is much less for this case. The smoke spreads slightly downstream and the individual lobes spread azimuthally as well. The individual lobes are more distinct at $x/D = 3$ than at the same location for the 3:1 velocity ratio. This is because the unseeded secondary flow is rolling inward toward the jet axis and hindering the smoke from spreading outwardly.

The streamwise views are displayed in Fig. 4.32. The instantaneous image shows a relatively straight smoke pattern with large-scale, smoke-filled structures beginning to penetrate into the secondary flow at approximately $x/D = 2 - 3$, which is a similar location as the 1:1 velocity ratio. The average image also shows a large jump in spreading rate in this region, indicating that the genesis of these large structures is a stable process. The jump, and subsequent spread of the smoke is less than for the 1:1 velocity ratio because of the wake effect. Similar behavior can also be seen in the

images of Wicker and Eaton [1994]. Although they did not present average images, the instantaneous ones do show that the inner stream spreads less when the velocity of the inner stream is faster and/or equal to the outer flow. They also mention that the transformation from a small wavelength to a large wavelength structure is delayed as the velocity of the outer jet increases.

The jump in the smoke spread of Fig. 4.32 is partly due to the pinch off effect of McCormick [1992] and subsequent break down of the streamwise vorticity as in the 1:1 velocity ratio. However, the RMS image does *not* show as strong a change in the intermittent region as did the RMS images for the 1:1 flow case. Rather the main intermittent region for the 1:3 flow is fairly strong and narrow for the full length of the image. There is no smoothing or blending into a thicker region. It is also growing slightly inward toward the centerline. There is an increase in thickness over the same region where the average image increases in thickness, however, this region is not nearly as bright as the 'main' intermittent region. In addition, the LDV data (for nozzle 3) to be presented later, does not show that strong, stable, streamwise vortices have developed, for this velocity ratio. Consequently, the strength of the Kelvin-Helmholtz roll-up is overpowering the streamwise vorticity and the outer jet is controlling the behavior of the inner jet. Dahm et al., [1992] and Wicker and Eaton [1994] have both witnessed that the outer annular flow can dominate the behavior of the inner jet, especially when the outer flow is faster. Thus, the discontinuity in growth is a result of the dominance of the outer jet and its interaction with the ambient air.

4.1.4 Nozzle Three (N3)

Nozzle 3 has the highest outward ramp angle of all the nozzles explored so it is expected to produce the highest streamwise vorticity. The cross-sectional and streamwise visualizations for FC1 and FC4 are shown in Figs. 4.33-4.36. Even with the 20° ramp angles, the average images of Figs. 4.33 and 4.34 at the nozzle exit show no sign of separation. At $x/D = 1$, the smoke in the lobe tips is rapidly expanding radially outward and also being turned inward by the secondary flow, thereby forming a bulge in the smoke pattern. The smoke in the individual lobes is starting to merge by $x/D = 2$ and is fully merged by $x/D = 3$. The images are similar to nozzle 1, but the overall jet spread is much greater. Further downstream the smoke pattern still has a hexagonal shape although it has expanded beyond the camera's field of view.

The RMS images of Figs. 4.33-4.34 show a mixing region surrounding the outline of the average image at $x/D = 1$. The RMS images at $x/D = 2$ show intermittent regions mostly confined to the outer border of the smoke even though there are dark regions between the lobes of the average images. Further downstream the mixing region spreads into a hexagonal shape. The mixing region for the 90:30 flow rate is thicker and more spatially uniform at the furthest location downstream, which was seen in the previous results for the 3:1 flow conditions for N2 and N1. This is due to the addition of streamwise vorticity by the nozzle.

The streamwise views for this velocity ratio are shown in Figs. 4.35-4.36. The instantaneous images show a strong stream of smoke issuing from the center of the nozzle and two streams on either side originating from the lobe tip region. The central

jet of smoke exhibits helical mode type structures for both flow rates. The average images show the smoke spreading at approximately the ramp angle initially, but there is a slight discontinuity at approximately $x/D = 1$, similar to N1, where the spreading rate increases. The change in spreading rate is due to the shear layer instabilities and streamwise vorticity and has been discussed previously. Comparing Figs. 4.35-4.36 with 4.25-4.26, N3 is seen to be spreading the smoke at a larger angle than N1.

The RMS images show that the regions of high intermittency are located at the boundary of the smoke. The dark streak along the jet axis is indicative of low mixing in the region where the central core of smoke is issuing from the nozzle. Along side this dark central streak are regions of intermittency (more prominent in the 90:30 image of Fig. 4.36) which form the circular ring shape at the center of the RMS cross-sectional images at $x/D = 2$ and 3. The ring shaped region of intermittency is caused by the interaction between the core jet of smoke and the inwardly rushing secondary air. The intermittency caused by this interaction however is not nearly as strong as the outer regions.

The 1:1 velocity ratio results for N3 are displayed in Figs. 4.37-4.40. This flow condition minimizes the Kelvin-Helmholtz instability, but cannot eliminate it completely because of the inner and outer boundary layers at the lobe peaks/troughs, and the nonparallel flow at the exit plane due to the ramp angles. Nevertheless, as with the N1 visualizations, the cross-sectional average images show that interface roll-up is essentially eliminated because there is very little interaction between the lobes. In particular, the images at x/D locations of 1, 2 and 3 clearly show the existence of

streamwise vortices, which were not distinctly visible in the 3:1 images because of the added mixing of the Kelvin-Helmholtz effect.

At $x/D = 1$ the smoke begins to concentrate in the outer tips of the lobes because of its initial radial velocity component. At $x/D = 2$, it is turning back radially inward toward the centerline due to the inwardly rushing secondary air. The clearly identifiable, smoke-filled, U-shaped regions at each lobe tip are indicative of two counter-rotating streamwise vortex pairs. The dark regions between the lobe peaks, and between the peaks and the center of the nozzle, show that without interface roll-up, the streamwise vorticity by itself is not enough to cause the lobes to interact at this distance downstream. In these dark regions the unseeded air is rushing inward just as the smoke is rushing outward, which effectively dilutes the smoke. At $x/D = 3$, the smoke has diffused more, but especially at the lobe tips. This could be due to the small Kelvin-Helmholtz effect at the lobe tips and also to the pumping action of the streamwise vorticity. The images at x/D locations 5 and 7 show that the smoke has diffused more and dispersed radially outward, however there are several regions of high concentration, especially at the jet centerline.

The standard deviation images confirm the mixing characteristics of the average images. Without the interface roll-up effect, the mixing region is no longer continuous but is confined to the lobe tips where the streamwise vorticity is active. The sides of the lobes no longer form a border to the mixing region. There is a dark spot on the jet axis that indicates a region of low intermittency. This coincides with the strong jet of smoke issuing from the centerline of the nozzle. Surrounding this dark spot is a ring of higher

intermittency, especially at $x/D = 3, 5$ and 7 . This is the region where the outer, unseeded flow is flowing radially inward along the 20° inward ramp and interacting with the strong central jet of smoke. Outside of this ring is a dark region of low mixing that matches with the dark regions of the average images. These effects are best seen in the images at $x/D = 3$, but are still recognizable in the other images. Beyond this region, the RMS images show the mixing region of the streamwise vortices in various stages of development as they evolve and break down. The limaçon-shaped mixing regions at the lobe tips of the images at $x/D = 1, 2$ and 3 encompass the U-shaped vortex pairs of the average images.

The views for the 90:90 flow rate in Fig. 4.38 are very similar to 30:30, but slightly less well-defined. As previously seen for nozzles 2 and 1, the intermittent region is thicker for the higher velocity case. However, the RMS images between the two flow rates are so similar that this is only noticeable at $x/D = 7$. In Fig. 4.37, the image at $x/D = 7$ shows a central ring-shaped intermittent region, a slightly darker (lower intermittency) region surrounding the ring, and an outer region of slightly higher intermittency that is partially clipped on the top and bottom. The corresponding image in Fig. 4.38 does not show the ring-shaped intermittent region or the darker region surrounding it. Rather, this image shows an intermittent region that roughly encompasses the whole smoke pattern. This is further evidence that the higher flow rates produce a thicker intermittent region due to the higher streamwise vorticity. The images at $x/D=5$ and 7 appear to have been clipped somewhat by the laser beam and the camera.

The streamwise results for FC2 and FC5 are given in Figs. 4.39 and 4.40. The instantaneous images show three separate streams of smoke issuing from the nozzle center and each lobe. There is interaction between the streams through flow structures of various size, however, they are mostly distinct. The average images appear dark between the streams, which is the region where the secondary unseeded air is diluting the smoke, as was seen in the cross-sectional images. As with N1, there is also a jump in jet growth for N3 for these 1:1 flow conditions. Comparing Figs. 4.39 and 4.40 with Figs. 4.29 and 4.30, the discontinuity in jet growth begins approximately $0.5D$ further upstream for N3. The actual location being approximately $2.5D$ for N3 and $3D$ for N1. The higher streamwise vorticity produced by nozzle 3 induces a higher degree of instability in the flow, which causes the shear layer to transition sooner.

The streamwise RMS images exhibit a narrow, well defined intermittent region at the outer boundary of the smoke until $x/D = 2.5$ where the jet spread is discontinuous. The intermittent region then expands rapidly and blends into a thicker, less well defined region between $x/D = 3 - 5$. This is also the axial distance over which the streamwise vorticity is breaking down (confirmed by the LDV data), which is the major reason for the discontinuity in growth. The RMS images also show a dark streak, along the jet axis, implying that the primary stream potential core interacts very little with the outer stream. The streamwise vorticity is located further out (radially) from the jet axis and without the Kelvin-Helmholtz roll-up, the center core is expanding similarly to a single jet.

The results for the last flow condition for this nozzle, FC3, are presented in Figs. 4.41 and 4.42. With the addition of the Kelvin-Helmholtz effect, the individual streamwise vortices are no longer distinct in the cross-sectional views, however their effects are still visible through the large-smoke-filled regions at the lobe tips. The overall radial spread of the jet is much less than the 3:1 case and even less than the 1:1 case, with only streamwise vorticity. The average image at $x/D = 2$ in Fig. 4.41 shows six separate smoke-filled regions from the lobe tips and a seventh central smoke-filled region. By $x/D = 3$, these regions have grown enough to substantially merge together, except for a slightly darker region surrounding the central core. At the lobe tips there is a distinct diffusion of smoke into the secondary stream. This is partially due to the previously mentioned boundary layer effect at the lobe tips and/or the pumping action of the streamwise vorticity. Another more likely explanation is that, even though the predominant roll-up direction is radially inward, there is still smoke being entrained into the outer flow because of the large-scale structures from the outer shear layer. The outer layer is in effect controlling the ejection of the smoke. The image at $x/D = 5$ shows the smoke spreading into a more even circular pattern although the center still shows a dark ring. By $x/D = 7$, the smoke pattern is made up of a bright core region surrounded by a darker region representing smoke that has been ejected from the central core.

The RMS cross-sectional images show intermittent regions surrounding the lobe tips that are slightly thicker than the corresponding mixing regions at the 3:1 velocity ratio, but they are much more centrally confined. The RMS image at $x/D = 3$ shows a

large, but less dynamic mixing region to the outside of the lobe tips. This is the same location as the light smoke trails of the corresponding average image. The images at $x/D = 5$ and 7 display a mostly round, ring-shaped mixing region. The slightly darker region in the center of the ring could indicate a region where the jet of smoke issuing from the nozzle center is just beginning, or where the mixing is mostly complete.

The streamwise views of Fig. 4.42 confirm the cross-sectional images. The instantaneous image shows three mostly separate streams of smoke exiting the nozzle that merge at about $x/D = 5-7$. These streams form a central core that does not spread. Surrounding this core is a much darker region of smoke beginning at approximately $x/D = 3$, which is where the discontinuity in spreading rate begins. This location is approximately the same for N1, indicating that for this 1:3 flow rate, the jump in spreading rate may not be related to streamwise vorticity as for the 1:1 velocity ratios. The intermittent region grows thicker as the jet expands, but it does not blend into a single, thick intermittent region as for the 1:1 velocity ratios. Instead, though the intermittent region has dissipated somewhat, it is still recognizable through the length of the RMS image. It also has an inward growth which is to be expected for a wake flow and a shear layer that is still fairly strong. The spread for this case, therefore, is more dependent upon coupling between the inner and outer flows through the dominance of the outer flow and its interaction with the ambient air. Similar behavior was witnessed in studies by Dahm et al. [1992] and Wicker and Eaton [1994].

4.1.5 Nozzle Four (N4)

The first of the four-lobed nozzles is designated nozzle four (N4). The flow visualization results for this nozzle are displayed in Figs. 4.43-4.52. This nozzle has the same exit area as the previous nozzles. Since there are only four lobes, the lobes are slightly larger than the six-lobed counterparts. The ramp angles for this nozzle and the two to follow are similar to nozzle one: 10° inward and outward. Thus, the streamwise vorticity produced should be comparable to N1. The cross-sectional images for the 3:1 flow rates in Figs. 4.43-4.44, show that there is no separation visible at the exit plane. Further downstream the smoke is concentrating in the lobe tips, as for N1, and spreading radially as well. By $x/D = 5$, the smoke from the lobes is beginning to merge together. At $x/D = 7$, the smoke has significantly diffused into the secondary flow, but there are still five distinct areas of smoke concentration. The smoke seems to be spreading as much as it did for N1, however, the spread is not as uniform. The RMS images show the same characteristics as for previous nozzles. The mixing regions essentially outline the smoke patterns of the average images, and grow thicker and outward with distance downstream. The intermittent region at $x/D = 7$ for the 90:30 flow rate is slightly thicker than at 30:10, as seen in the previous results for the other nozzles.

The streamwise images of Figs. 4.45 and 4.46 show a spreading angle similar to that for N1. The average images for both flow rates show a slight discontinuity at approximately $x/D = 1$, similar to previous nozzles and indicating that the same mixing processes are taking place at this velocity ratio. The RMS images show that the highest

intensity mixing is taking place at the outer edge of the smoke-filled region. There is also a central dark streak representative of the low intermittency along the jet centerline. The image for the 90:30 flow rate also has a dark streak along the jet axis, but it is much less pronounced.

The results for the 1:1 velocity ratios are displayed in Figs. 4.47-4.50. As with the six-lobed nozzles, the cross-sectional images of Figs. 4.47 and 4.48 show much less lobe interaction when the Kelvin-Helmholtz effect is minimized. The images at $x/D = 2$ and 3 show the U-shaped, counter rotating, streamwise vortex pairs forming in the lobe tips. They are not quite as well defined as in the N3 images, but they are still distinct. Also at $x/D = 3$, there is a small amount of smoke trailing off the lobe tips. This effect is more noticeable in the corresponding RMS image below, where it can be seen that there is a relatively weaker intermittent region extending into the secondary flow. The average images at $x/D = 5$ and 7 show a more diffuse smoke pattern, but there is still a central core region connected to four distinct outer regions of smoke. The open spaces between the lobes do not fill up with smoke as well as for the 3:1 cases without the Kelvin-Helmholtz effect. The standard deviation at $x/D = 5$ shows relatively thick intermittency regions surrounding the streamwise vortices, which then narrow significantly along the long dimension of the lobe. This shows that most of the mixing is caused by the streamwise vorticity for this flow condition. The RMS image of Fig. 4.47, at $x/D = 7$, shows a fairly even mixing region with a dark spot along the jet axis. The images for the 90:90 flow rate generally show similar characteristics to the 30:30 images. The RMS regions are not as well defined at 90:90 however, because the higher

level of streamwise vorticity is causing a more even intermittency pattern and more uniform mixing. This effect is more prominent at $x/D = 3$ and beyond. The images at $x/D = 5$ and 7 are obviously clipped by the laser sheet at the top of the image, but still show the same basic mixing characteristics.

The streamwise views for the 1:1 ratio, Figs. 4.49-4.50, display the effect of minimizing the Kelvin-Helmholtz instability. There is much less interaction between the three streams of smoke. The images also show a jump in the jet spread approximately three diameters downstream, which is the same distance as for N1. Nozzle 1, it may be recalled, has similar ramp angles, and thus produces similar streamwise vorticity. The standard deviation image shows the usual region of high intermittency trailing from the lobe tips, which spreads slightly radially and grows thicker until approximately $x/D = 4-5$. This distance is further downstream than N1, but the behavior of the intermittent region is the same. The delay is probably related to the slightly different magnitude and/or scale of the streamwise vortices generated by N4. As the streamwise vortices break down, the intermittent region dissipates and blends into a larger region such that by $x/D = 6$ there is no strong mixing region that can be traced from the exit plane at the lobe tips through the length of the image, like there is for the 3:1 and 1:3 velocity ratios.

The 1:3 velocity ratio results, displayed in Figs. 4.51 and 4.52, show a much less expanded smoke pattern than the 3:1 case. From the cross-sectional views, it appears that the overall smoke spread is similar to the 1:1 case. At $x/D = 3$, the smoke at the lobe tips shows a slightly diffused pattern, similar to the previous nozzles at this

velocity ratio. The inward roll-up of the interface (i.e., wake effect) helps to keep the individual lobes from interacting with each other and the smoke more centrally confined. By $x/D = 5$, the Kelvin-Helmholtz effect produces a bright, smoke-filled, lobed pattern surrounded by a much more diffuse, somewhat circular pattern. This pattern is similar to the six-lobed nozzles for the 1:3 flow rates except that the nozzle shape is still noticeable for N4, which is to be expected since there are fewer lobes and they are farther apart.

The 1:3 velocity ratio, for all the nozzles presented so far, produces this typical pattern: a bright centrally located smoke pattern, which may or may not still resemble the nozzle shape, surrounded by a much darker smoke pattern. This is what would be expected if the outer jet were entraining ambient air through large-scale structures and then engulfing the smoke from the primary stream and 'rolling' it into the ambient flow. The low intensity of the outer smoke-filled region suggests larger scale structures because there would be fewer of them and thus the average image would produce a darker intensity. The thickness of this dim region also suggests large-scale structures because of the distance the smoke has traveled.

The RMS images exhibit the usual mixing region outlining the nozzle shape near the exit, and growing thicker with downstream distance. The nozzle shape is still noticeable at $x/D = 5$, but is barely recognizable at $x/D = 7$.

The streamwise views of Fig. 4.52 are similar to previous results. The discontinuity in spreading rate begins at approximately $x/D = 2.5$. The average image shows that the bulk of the smoke has an inward slant as it travels downstream, thereby

producing the bright central region seen in the cross-sectional images. The expanded region is noticeably dimmer. The RMS image shows the intermittent region having a slight inward slant. The intensity of the region is reduced as the jet expands, however it is still distinguishable for the full length of the image, unlike the mixing regions of the 1:1 flow conditions, which blend into the expanded smoke pattern as the vortices break down. This once again shows that the mixing process for this velocity ratio is different from the other velocity ratios. The interaction of the outer stream with the ambient air and the dominance of the outer stream over the inner stream is what is controlling the mixing for the 1:3 flow condition.

4.1.6 Nozzle Five (N5)

Nozzle five is a four-lobed nozzle designed to have a lobe size and geometry the same as the six-lobed nozzles, thus the exit flow area is less than the other nozzles, and there is a flow area decrease through the nozzle. Because of the area decrease, separation was not expected to be a problem with this nozzle. The ramp angles are also 10° so the streamwise vorticity is still expected to be of similar strength to nozzles 1 and 4.

The results for this nozzle are presented in Figs. 4.53-4.62. The smoke patterns for the 3:1 flow cases, Figs. 4.53 and 4.54, are noticeably thinner near the nozzle exit, but have similar spreading characteristics to N4. The smoke pattern gradually spreads radially and the individual lobes spread azimuthally as well. The smoke from the lobes

does not fully merge even by $x/D = 7$, which shows five distinct regions of smoke concentration in the image, but the pattern is nevertheless very much spread out.

The RMS images display similar patterns to N4 for these flow conditions, The intermittent regions generally follow a path encircling the smoke-filled area of the corresponding average images. Whereas with N1 the intermittent region formed a hexagonal shape at $x/D = 7$ with only inward protrusions where the secondary air flowed, the four-lobed nozzles show a distinct four-lobed outline. The overall spread of the jet still appears to be fairly high because the RMS image at $x/D = 7$ is slightly clipped by the laser sheet on the top and bottom. The images for the 90:30 flow rate are almost carbon copies of the 30:10 flow rate except for the RMS image at $x/D = 5$. This image does not display the expected lobe-shaped intermittent region, but rather an almost 'inverse' of what is expected. The thickness of the corresponding average image above suggest that the flow rate of the smoke might not have been high enough to give a good representation of the mixing.

The streamwise views of Figs. 4.55 and 4.56 show a jet spreading outward as witnessed for previous nozzles. Even with the Kelvin-Helmholtz effect present at this velocity ratio, the average images show two darker regions in the streamwise views on either side of the central streak. These dark regions are caused because the lobes are much thinner relative to the size of the unseeded air region and thus there is a relatively larger amount of unseeded air rushing inward and diluting the smoke. The average images again show a slight discontinuity in the spreading rate of the jet, but this time it appears to be close to $x/D = 2$. The RMS images show a dark streak along the jet axis

indicating the low level of mixing taking place there and the usual high degree of intermittency at the outer boundary of the smoke.

The 1:1 velocity ratio results are displayed in Figs. 4.57-4.60. As previously seen, without interfacial roll-up, the streamwise vorticity is more prominent and readily visualized. The counter rotating streamwise vortices can be seen at the lobe tips in the images at $x/D = 2$ and 3 of Figs 4.57 and 4.58. The size of the streamwise vortices for this nozzle are noticeably smaller than for the other nozzles. Both flow rates exhibit a tremendous jump in total smoke area between 3 and 5 diameters downstream which is generally confined to the lobe tip regions. The break down of the streamwise vorticity produces a relatively large increase in mixing for this nozzle. The streamwise vortices do not extend to the center of the nozzle, however, and thus the core nozzle flow is not mixed by $x/D = 7$.

The RMS images display brighter regions near the streamwise vortices indicating a high degree of intermittency in these areas. The images for the 30:10 case at the locations $x/D = 5$ and 7 show well-mixed regions surrounding the lobe tips, but well-defined strips of mixing areas connecting the tip areas. The dark center spot represents the jet of smoke issuing from the center of the nozzle that has not mixed at all. The RMS images for the 90:90 flow rate at $x/D = 5$ and 7 have both been clipped by the laser sheet, but similar patterns are still recognizable overall. The mixing regions in the lobe tips at $x/D = 5$ (90:90) are more evenly distributed than for the 30:30 flow rate, which show a faint circular outline around the lobe tip regions. It is difficult to tell

for this nozzle, but it does appear that the intermittent regions for 90:90 are thicker ($x/D = 5$ and 7) than for 30:30.

The streamwise views of Figs. 4.59 and 4.60 show a jet with a moderate outward spread until approximately $x/D = 3$ where there is a significant increase in the spreading rate. This coincides with the sudden dispersion of the smoke in the lobe tip areas seen in the cross-sectional images between $x/D = 3$ and $x/D = 5$ and is indicative of the vortex breakdown discussed earlier for the 1:1 flow rates. The RMS images for both flow rates show the usual strong intermittent regions beginning at the lobe tips, which then increase in thickness and decreases in intensity at the location where the growth rate is discontinuous. These images are very consistent with previous results for the 1:1 velocity ratios and is one of the better examples of the effect of vortex break down.

The visualizations for the last flow rate, FC3 (30:90), can be seen in Figs. 4.61 and 4.62. As has normally been the case for this flow condition, the radial spread of the jet is significantly reduced although there is a relatively high mixing region at the tip of the lobes. These regions can be seen in the streamwise views of Fig. 4.62 as a sudden increase in the jet spread at approximately $x/D = 3$. The cross-sectional average image at $x/D = 7$ shows a faint vertical stripe on the right side of the smoke outline. This is a reflection from some object in the background. It is also noticeable in the image at $x/D = 5$, although to a lesser degree. Since this is a constant reflection, it does not affect the calculation of the standard deviation. An interesting feature of this flow condition is that even though the average cross-sectional image at $x/D = 7$ shows five bright regions

of smoke surrounded by a dimmer smoke-filled region, the corresponding RMS image shows a circular core region with significant mixing activity, which is typical of the nozzles for this velocity ratio. Nozzle 4 showed similar behavior but not as distinctive as for N5. The average images at $x/D = 5$ and 7 show the same general patterns for the 1:3 velocity ratio: a bright, centrally located, smoke pattern representing the basic nozzle shape around which is a much light region of smoke.

The streamwise views show similar behavior to other images at this 1:3 velocity ratio. The jump in jet spread begins at about $x/D = 2.5$. The RMS image shows a region of high intermittency with a slight inward slant. The intermittent region grows slightly thicker at the axial location where the jet growth changes. However, here the thicker area has a lower intensity than the 'main' intermittent region. This is unlike the 1:1 velocity ratios where the intermittent region blended into a thicker, more uniform pattern. This is indicative of the large-scale interaction between the outer flow and the ambient air, and the effect this interaction has on the mixing processes for both streams. Instead of streamwise vorticity being mainly responsible for the mixing, as it is for the 1:1 velocity ratios, or the combination of streamwise vorticity and the Kelvin-Helmholtz roll-up being the cause for the large-spread for the 3:1 ratios, it is essentially the outer flow that is responsible for the mixing for the 1:3 ratio. As the outer potential core decays, the large-scale eddies that interact between the secondary stream and the ambient air entrain the smoke from the primary stream and transport it radially outward into the surrounding air. The wake effect is still strong because the RMS image of Fig. 4.62 shows a distinct inward slant to the intermittent region, which limits the overall

spread of the jet. This is why this flow rate generally produces a bright central region of smoke, whereas the lighter region of smoke surrounding the bright core is caused by the entrainment and subsequent passing of the large-scale outer structures. Thus, the process governing the jet growth for the 1:3 velocity ratio is not directly caused by the streamwise vorticity as for the 1:1 cases, but rather by interaction with the outer jet and the ambient air.

4.1.7 Nozzle Six (N6)

The last nozzle to review is nozzle 6, which has square-shaped lobes. These results are displayed in Figs. 4.63-4.72. Nozzle six has lobes with parallel side walls, so the lobe does not become wider further away from the centerline. Because of the constant thickness, the square lobe is wider near the jet axis than the other nozzles but slightly thinner at the tip than N4 and comparable in thickness to the six-lobed nozzles.

The 3:1 velocity ratio results are given in Figs. 4.63-4.66. The effect of having thicker lobes is noticeable in that the smoke pattern is thicker issuing from the nozzle. There are still concentrations of smoke in the lobe tips, but they are less prominent, and do not spread as quickly downstream. By $x/D = 7$, the overall spread of the smoke is visibly less than nozzles 4 and 5, however, the smoke concentration does appear to be more uniform throughout the mixed region than for the other four-lobed nozzles. Both FC1 (Fig. 4.63) and FC4 (Fig. 4.64) produce similar results for the average images and the standard deviations. The mixing region for FC4 is again thicker than the lower speed flow of FC1. This effect is noticeable in the images at both $x/D = 5$ and 7.

The streamwise views, shown in Figs. 4.65 and 4.66, show the jet spreading at approximately the nozzle angle, similar to previous nozzles. The instantaneous and average images do not show three streaks of smoke as prominently as for the other nozzles. The thickness of the lobes near the base allows a relatively larger amount of smoke to exit near the jet axis and thus it is not as readily diluted by the outer air. The RMS views show that the high intensity intermittency is at the outskirts of the smoke-filled area while a darker streak along the jet axis shows the relatively lower mixing in that region.

The 1:1 velocity ratio results are shown in Figs. 4.67-4.70. The cross-sectional images of Figs. 4.67 and 4.68 show lobes of smoke that are slightly thinner than for the 3:1 velocity ratio, but the concentration of smoke in the lobe tips, due to the streamwise vorticity, is still present. The smoke-filled areas at the tips of the lobes spread out rapidly between $x/D = 3$ and 5, even though the areas along the length of the lobes do not spread quickly. Unlike the results for the other nozzles, the streamwise vorticity for N6 does not display as clearly. There are no U-shaped regions of smoke concentrating at the lobe tips, just the usual mushroom shaped bulges which are slightly more prominent than in the 3:1 images.

The RMS images show a generally well-defined intermittent region through $x/D = 3$. Beyond that point, the smoke disperses more rapidly, especially at the lobe tips, and the mixing region grows with it. The images at the 90:90 flow rate (Fig. 4.68) exhibit similar behavior to the 30:30 flow rate, just slightly less well-defined. The average images at $x/D = 3, 5$ and 7 have a background reflection to the right of the

smoke pattern. Also, the image at $x/D = 7$, and possibly the one at $x/D = 5$, is clipped on the top by the laser beam.

The streamwise views in Figs. 4.69 and 4.70 display the dual spreading rate also. The discontinuity is located at approximately $x/D = 3$, where the spreading rate increases to an angle that is approximately equal to the angle for the 3:1 velocity ratio. As noted previously for the other nozzles at this velocity ratio, this phenomena is related to vortex break down. Evidence of vortex break down is seen in the RMS images. The well defined mixing regions initiating from the lobe tips expand and blend into thicker, less intense regions between $x/D = 3$ and 5, similar to the other nozzles for FC2 and FC4. The dark streak along the jet axis shows the usual region of low mixing which coincides with the dark central spot in the RMS cross-sectional images. The streamwise image of Fig. 4.70 for the 90:90 flow rate appears to have an even steeper jump in jet growth. This jump begins slightly further downstream of the jump for the 30:30 flow rate, and it is more of a step change than an increase in angle. The beginning of the discontinuity is not detectable because the smoke dissipates too rapidly in this region, due to the much higher flow rate. This is confirmed in the RMS image. The discontinuity in the RMS image of Fig. 4.70 begins approximately one full diameter upstream of the step change in the average image. Since the RMS images of the previous streamwise views track the average images very closely, it is likely that the smoke in Fig. 4.70 has been diluted by the much higher flow outer stream.

The results for the last flow rate for this nozzle, the 1:3 case, are displayed in Figs. 4.71 and 4.72. The cross-sectional views show a more confined smoke image at

all locations downstream. The smoke pattern along the lobes is of similar thickness to the 3:1 velocity ratio cases. The smoke in the lobe tips accelerates its radial spread at approximately $x/D = 3$, such that the smoke pattern at $x/D = 5$ is of comparable size to its counterpart for the 3:1 velocity ratio. The intensity of the smoke pattern, however, is much less uniform due to the fact that the spread is caused by structures in the outer flow entraining smoke and not by the jet as a whole. At $x/D = 7$, the pattern has a fairly rounded shape, similar to what one would expect for a circular jet profile. As is typical for the 1:3 velocity ratio, the intensity within the center of the image shows a much higher concentration of smoke near the jet axis, which is surrounded by a region of lower intensity smoke. This is due to the dilution of the smoke by the secondary air and the ambient air as the secondary jet interacts with the ambient air. The RMS images show a mixing region roughly tracing the outline of the nozzle through $x/D = 3$, where the flow interaction at the lobe tips distorts the mixing region. The mixing layer at $x/D = 7$ is a fairly circular, ring-shaped region, much different from the other flow conditions. There is a centrally located dark spot in all the RMS images indicating that little mixing is taking place along the jet axis.

The streamwise images are displayed in Fig. 4.72. The instantaneous image shows the influence of the large-scale structures. Large streaks of smoke can be seen tearing away from the main smoke trail extending into the outer flow. The average image also shows a sudden jump in jet spread at approximately $x/D = 2.5$. The three separate streams of smoke issuing from the nozzle merge further downstream, even as the rest of the jet is expanding. The RMS image displays a central dark streak

emphasizing the unmixed central jet of smoke. The outer region of high intermittency has a jump in growth at approximately $x/D = 2.5$, but does not dissipate and blend into the expanded region as is the case for the 1:1 velocity ratios. Instead, the main intermittent region is still traceable further downstream and has a slight inward slant. There is some dissipation at approximately $x/D = 4 - 5$ but it is still recognizable for most of the image.

4.1.8 Jet Spread Results

In an attempt to quantify the gross mixing of the inner jet with the outer jet, an estimate of the spread of the inner jet (smoke-marked area) was performed. In essence, every pixel whose intensity was above a certain threshold was counted as part of the spread center jet. Pixels below the threshold were considered background. Since every set of images had a different intensity level, it was not possible to set a single threshold for all the images. Consequently each set of images had to be examined separately. Plotting a histogram of the number of pixels versus pixel intensity for the average image of each set was found to provide an adequate method for delineating between pixels representing smoke and pixels representing background. For the majority of the images, the "signal" was readily apparent, forming a 'hump' in the data at the higher end of the intensity scale. The other images, usually at x/D locations 5 and 7, did not have a readily discernible hump in the histogram, but exhibited a relatively flat portion followed by a drop off at the higher intensities. Separating the pixels representing smoke was more difficult for these cases but it was still possible to obtain consistent

results because the histograms contained sharp changes in slope at locations where the threshold would likely be. The results on the whole are consistent with what one would perceive when viewing the individual average images. In the figures to follow, the smoke-filled area is normalized by the exit area of the nozzles, which is approximately 750 pixels for nozzle five and 1050 pixels for the others.

Figure 4.73 shows the spread of the smoke for the baseline circular nozzle for all the flow conditions examined. The plots show a general trend of increasing smoke spread with increasing distance downstream, as in the average images. The 3:1 velocity ratios show higher jet spread than the other flow conditions, expanding to approximately five times the nozzle exit area. As was seen in the visualizations, the 3:1 velocity ratios generally produced the greatest spread of the smoke. The 30:10 and 90:30 flow rates produce similar results because of the similar mixing processes taking place. Likewise the 30:30 and 90:90 flow rates produce similar growth. The 1:3 velocity ratio has comparable spread to the 1:1 ratios. The same general trends of Fig. 4.73 can also be seen in the average images of Figs. 4.3-4.4, 4.7-4.8 and 4.11. Since this technique involves some subjectivity in determining the smoke-filled area, these graphs should be used for comparison purposes between the different nozzles and flow rates, not as measurable quantities.

The growth rates for nozzle two are presented in Fig. 4.74. Again, the 3:1 velocity ratios provide the greatest growth rates, while the other three cases have similar spreading rates. The effect of adding interfacial area is easily seen since the spread for

this nozzle is generally higher than the baseline nozzle. Again, similar velocity ratios produce similar growth.

The nozzle one results are shown in Fig. 4.75. The spread for the 3:1 velocity ratios is much greater than for the other flow conditions. The 1:1 cases show the jump between x/D of 3 and 5, and appear to level off between $x/D = 5$ and 7, especially for the 90:90 flow rate. Reviewing the average cross-sectional images of Fig. 4.28 at these two locations, there appears to be a 'few' less pixels highlighted with smoke at $x/D = 7$. This slight drop off is most likely due to insufficient smoke generation when these images were taken, because the streamwise view doesn't show any decrease in jet growth. Nevertheless, the images show that the growth is similar of both 1:1 flow rates. The 30:90 flow rate produces the smallest spread of the smoke. As was seen in the visualizations, this flow rate is similar to a wake flow which has slower growth in general. With the addition of streamwise vorticity for N1, the growth of the inner jet is greater than the corresponding velocity ratios of N2.

The N3 results in Fig. 4.76 show even greater growth, as expected from the average images. The 3:1 flow rates produce the highest growth. Recall that the cross-sectional images at $x/D = 7$, and possibly $x/D = 5$ for the 3:1 velocity ratios were partially clipped by the laser sheet and/or camera lens, so the total growth could be higher. The plots for the 3:1 ratios even show the discontinuity in spread between x/D of 1 and 2. The 1:1 velocity ratios produce the next highest spread of the smoke, followed by the 1:3 case. The 90:90 flow rate produces slightly greater growth than the 30:30 flow rate. This is consistent with the expectation of the higher

strength streamwise vortices produced under the higher speed flows. This subtle difference is not discernible in the cross-sectional views but can be seen in the streamwise views (Figs. 4.39 and 4.40). On the other hand, the 3:1 velocity ratios show the opposite behavior. Reviewing the cross-sectional and streamwise visualizations for this case (Figs. 4.33-4.36) reveals that the spread appears to be even more than the graph would suggest. The cross-sectional images (from which the growth rates are calculated) for the 90:30 flow rate are slightly dimmer than their 30:30 counterparts, which would make a less sharp cutoff threshold in the histogram plots, and possibly lead to some of the 'signal' pixels being counted with the background. This shows some of the limitations with this method. Nevertheless, the results are still consistent for each flow rate for any nozzle, and also when comparing between nozzles.

The jet growth results for nozzle four are shown in Fig. 4.77. These plots confirm the general trends observed in the average images of Figs. 4.43-4.44, 4.47-4.48 and 4.51. The growth for the 3:1 ratios is generally higher than the other flow rates. At $x/D = 5$, the jet growth is greater for the 1:3 velocity ratio than for the 1:1 cases. Reexamining the cross-sectional views shows that while the overall lobe-tip to lobe-tip spread of the smoke is similar for the three cases, the lack of interaction between the lobes for the 1:1 velocity ratios produces a less area-filling smoke pattern, and smaller total area. By $x/D = 7$ however, the 1:3 case shows the least growth.

The growth trends for nozzle five are displayed in Fig. 4.78. The spread of the smoke-filled area for this nozzle appears to be as great as the spread for nozzle three, with both nozzles spreading to approximately 30 times their respective exit areas for the

3:1 velocity ratios. The cross-sectional images for the 3:1 cases show that N3 produces a more spread out jet of smoke than N5, but since the exit area of N5 is less than N3, the magnitudes of the normalized spreads are similar. It appears that there is probably some overlapping of smoke in the images of the six-lobed nozzles, and possibly the others. Nozzle five has lobes of the same shape and size as the six-lobed nozzles, so the lobes of the six-lobed nozzles have the potential to spread the same as in N5. Since the lobes are much closer together in the six-lobed nozzles, there is less secondary flow area into which the smoke can disperse, thus there may be some overlapping and the estimates of jet spread could be conservative. Similar behavior was witnessed by Zaman et. al. [1994] who studied vortex generators (tabs) placed at the exit of subsonic and supersonic jets. The tabs were found to produce streamwise vorticity in the shear layer. When six tabs were placed equally spaced around the exit, through interaction between the streamwise vortices, a flow pattern developed that was extremely similar to the flow pattern developed when only three tabs were used. This indicated that there is interaction between the vortices and that the flow was more stable with three tabs rather than six. The researchers also discovered that four tabs seemed to be the optimum number for increasing the jet entrainment, i.e., growth. Nozzle 5 could be exhibiting similar behavior in that the four, small lobes could be optimum for this system since it appears that the normalized jet growth is roughly equal to N3.

The individual plots of Fig. 4.78 show the same trends as the average images of Figs. 4.53-4.54, 4.57-4.58 and 4.61. The curves for the 1:1 and 1:3 velocity ratios show

a sharp jump in jet spread between x/D of 3 and 5 whereas the 3:1 cases show a more gradual spread. These trends are also noticeable in the cross-sectional images.

The nozzle six jet spread results are presented in Fig. 4.79. The overall spread is generally less for this cross-shaped nozzle than for the other four-lobed nozzles. The 3:1 velocity ratios generally spread greater than the other ratios. The 1:3 case shows a distinct decrease in spreading rate between x/D of 5 and 7. This was seen in the average images of Fig. 4.71 where the smoke has a clear cross-shaped pattern at $x/D = 5$, but attains a much more compact and rounded shape at $x/D = 7$. As was mentioned previously, since this flow condition is similar to a wake flow, the primary roll-up direction is inward which helps to keep the smoke confined. In addition, since the outer flow rate is so much greater than the inner flow rate, the smoke that does disperse into the secondary stream is too diluted to show brightly and may not be counted in the area.

The plot for the 90:90 flow rate shows a large jump in area from x/D of 5 to 7. From Fig. 4.68 it appears that this jump should be even greater since part of the image at $x/D = 7$ has been clipped by the laser sheet. Since this great a jump is not evident in the images for the 30:30 flow rate in Fig. 4.67, a possible explanation for this discrepancy is that not enough smoke was being generated for the images taken at $x/D = 5$ for the 90:90 flow rate.

4.1.9 Growth Comparisons Between Nozzles

Figures 4.80 a-e show plots of jet spread for the six-lobed nozzles compared to the baseline nozzle for all five flow rates. These graphs show the effect of adding interfacial area and streamwise vorticity to the flow downstream of the nozzle. In all five figures, N3 (20° ramp) produces a greater spread of the smoke than N1 (10° ramp). Likewise, N1 spreads more than N2 (no ramp) which spreads more than the circular nozzle. The 3:1 velocity ratio also produces a higher overall growth than the 1:1 velocity ratio which in turn has a higher jet growth than the 1:3 velocity ratio. These results show that adding streamwise vorticity is important for mixing, but the Kelvin-Helmholtz instability is also important. In addition, for an axisymmetric geometry the direction of the Kelvin-Helmholtz roll-up makes a major difference. The graphs show that the overall jet growth is generally lower for the 1:3 velocity ratio, however, the cross-sectional images generally show a higher intermittency region within the confined area.

Figures 4.81 a-e compare the four-lobed nozzles to each other and to the baseline nozzle. The streamwise vorticity is of the same order of magnitude for each nozzle since the ramp angles are the same. The differences in growth are therefore mainly attributable to the lobe shape and also possible interference/interaction between the individual vortices. The plots show that the smoke from N5 spread more than N4, which spreads more than N6. The squared off lobes of N6 do not produce the high level of mixing of the other nozzles, although in several cases it is comparable to N4. This could be related to boundary layers building up in the corners of the nozzle that may be

hindering the formation of the streamwise vortices. These corners also tend to generate small scale streamwise vortices, or secondary flows (Daily and Harleman [1966]), which may be counteracting the large-scale streamwise vortices generated by the nozzle. Additionally, the small horseshoe vortices that are known to exist in the lobe tips (Patterson, [1982, 1984]; McCormick [1992]; McCormick and Bennett, [1993]) and oppose the direction of rotation of the larger scale streamwise vortices, may be stronger for this lobe shape.

One of the objectives of the present study is to separate the contributions to overall mixing due to the increase in interfacial area and the streamwise vorticity generated by the lobed nozzles. The difference in the inner jet growth between N2 and the baseline nozzle provides the contribution to total mixing due to the increase in interfacial area. The difference in inner jet growth between N1 and the baseline nozzle provides the contribution to total mixing due to both interfacial area and streamwise vorticity. The contribution due to the streamwise vorticity alone is found by subtracting the nozzle two area from nozzle one. Using Figs. 4.80 a-c, the various contributions to mixing can be calculated. Table 4.3 shows the results of calculating the mixing contributions for x/D locations 1, 2 and 3. The data for locations 5 and 7 are not shown because they have the most uncertainty due to clipping of some of the images by the laser sheet. The data in the table are calculated using the baseline nozzle, N2, and N1.

At $x/D = 1$, and a velocity ratio of 3:1, the contribution to overall mixing due to streamwise vorticity is greater than the contribution of the interfacial area. Moving downstream, the contribution from the interfacial area decreases slightly while the

streamwise vorticity enhancement increases. This is consistent with previous work (Werle, et. al., 1987; Eckerle, et al., 1991) showing that the streamwise vortices grow first and break down downstream, thereby increasing turbulence levels and mixing. As the vortices evolve through the processes of stretching, pairing and tearing, mixing increases. For the velocity ratio of 1:1, we see the interfacial area provides a much larger fraction of the mixing than the streamwise vorticity at $x/D = 1$. The same trends as for the 3:1 velocity ratio are evident moving downstream. However, the fractional contribution due to interfacial area decreases--hence, that due to streamwise vorticity increases--at a much faster rate. Since the Kelvin-Helmholtz effect is minimized for the 1:1 velocity ratio, the streamwise vortices are the dominant structures in the flow, as was seen in the visualizations. As they interact downstream, their mixing effects are more prevalent. The results for the 1:3 velocity ratio are similar to the previous two cases. The relative contributions to mixing at $x/D = 1$ are in approximately the same proportions as for the 1:1 case, but the change in proportions moving downstream is about the same as the 3:1 case.

Figure 4.82 shows the data of Figs. 4.80 a-c and Table 4.3 plotted differently. The bar graphs show the total mixing for nozzle one at three different locations downstream, but with the interfacial area and streamwise vorticity contributions shaded differently. A point not obvious in the table is that even though the fraction of mixing due to the interfacial area decreases as velocity ratio increases, the total amount of mixing due to interfacial area still increases with downstream distance. Comparing different velocity ratios for each x/D location, there is a distinct increase in total mixing

as velocity ratio increases and the percentage of enhancement due to streamwise vorticity increases. This is in agreement with Manning's results (1991) except Manning did not discuss any effect due to downstream distance.

4.2 LDV RESULTS

To compliment the smoke visualizations, velocity data were taken using a laser Doppler velocimeter (LDV). Due to the time-consuming and tedious nature of taking LDV data, and because of the many equipment problems that arose during the testing, only data for nozzle three were taken. Since this nozzle produces the highest streamwise vorticity of the nozzles tested, it presents the best case for following the evolution of the streamwise vortices. Since the LDV system was only capable of measuring two components of velocity at a time, each set of data had to be taken twice. The first time through, the u and w velocity components were measured. Afterwards, the settling chamber and nozzle were rotated 90° and the u and v components were measured (as mentioned in chapter 3). To ensure setting consistent flow rates from run to run, the experiments were performed at the same pressure in the storage tanks, thus requiring only minimal adjustments to the valves to attain the same flow rates.

A grid of data covering a 30° circular sector was taken for the 30:10, 30:30 and 30:90 flow rates. The full grid is shown in Fig. 4.83. At the locations near the nozzle exit, data were taken out to a radius of 31.75 mm (1.25in.), whereas further downstream, as the jet expanded, points further out were taken. The data from this

sector was then mapped to a full 360° circle to give a full view of the flow patterns. The radii along which data were taken are spaced at 5° intervals beginning with the radius along the lobe centerline (0°) and ending along a radius between two adjacent lobes (30°). These are designated the 'peak' and 'trough' radii, respectively. Note that the radius at 10° is along the edge of the lobe, but is shown slightly off center here for clarity.

For free shears/mixing layers, the velocity data is generally scaled using the velocity difference between the two streams. Ko and Au [1981] showed similarity of velocity profiles for the mixing regions of coaxial jets using this difference for several different velocity ratios. Similarity for the outer mixing layer, however, was attained using the ratio of local velocity to average velocity that is normally used for single jets. The 1:1 velocity ratio case for this study presents a scaling problem when using the velocity difference. The 1:1 flow condition however, is similar to a single jet of diameter equal to the outer diameter, if both coaxial jets were circular. Thus, the average velocity could be used to scale the data. In the results to follow, the 30:10 flow condition data is scaled using 20 m/sec, the 30:90 flow condition is scaled using 60 m/sec, and the 30:30 flow condition is scaled using 30 m/sec. Alternatively, one could consider this as using the average velocity of the two stream for all cases, which, for these chosen velocity ratios, is equivalent.

The results to be presented first are the axial and cross stream velocities to show the overall flow patterns that develop downstream of an axisymmetric lobed mixer. Subsequently, other flow parameters such as turbulence kinetic energy and Reynolds

stresses will be presented. Results for the 30:10 velocity ratio will be given first, followed by the 30:30 and 30:90 flow conditions.

4.2.1 Flow Condition 1: 30:10

4.2.1.1 Mean Velocity Results (30:10) Figures 4.84 a and b show a three-dimensional surface plot perspective of the axial velocity and a vector plot of the cross stream velocity, respectively, at $x/D = 0.25$. The 3:1 velocity ratio produces a steep gradient between the fairly flat outer jet velocity profile and the highly peaked nozzle profile. The nozzle produces a very sharp central peak and six separate secondary peaks in the lobe regions. The vector plot shows that the flow is indeed radially outward in the lobes and inward in the trough regions. The midpoints of the vectors in Fig. 4.85b are located at the points of measurement and the maximum cross stream velocity is labeled in the figure. At the lobe tips, the outward flow does penetrate slightly into the secondary flow, but is quickly turned inward toward the centerline and thus the streamwise vorticity begins to develop. The oppositely directed inward and outward flow is what induces the streamwise vortices to form. And because of the inward flow on either side of the lobes, the streamwise vortices form into counter rotating vortex pairs. The center region of the nozzle shows very little cross stream flow as well as the region near the outer jet wall.

Figures 4.85a and b show the same velocity results for $x/D = 1$. The surface plot shows a slightly more rounded profile over the nozzle region. There are still seven well defined peaks, but they are starting to blend with the outer flow. They are also starting

to expand radially into the outer flow region. The vector plot shows distinct, counter rotating, streamwise vortex pairs approximately located on either side of the lobe peaks. This location matches very well with the bulge in the smoke pattern at the lobe tips of Fig. 4.33. Note the 'scale' image in the lower half of Fig. 4.33. The numbers in the scale image represent the diameters of the circles in inches. The streamwise vorticity is spreading the smoke into the mushroom shaped pattern at the lobe tip, reaching out to a radius of approximately D . From Fig. 4.85b, D is approximately the outer extent of the streamwise vortices. The streamwise vorticity is expanding the area over which mixing takes place in this region. However, from the RMS images of Fig. 4.33 at $x/D = 1$, it is the velocity gradients of the axial velocity (through the Kelvin-Helmholtz effect) that form the intense mixing region surrounding the nozzle. The bright, intermittent region outlining the nozzle is of similar thickness in areas both with and without streamwise vorticity. Thus, while the bulge caused by the streamwise vorticity is spreading the mixing region at the lobe tips over a larger area, it is not as large an effect as the Kelvin-Helmholtz roll-up.

Figures 4.86a and b show similar results for $x/D = 2$. The axial velocity plot shows a well rounded profile that is expanding radially outward. The vector plot also shows that the streamwise vortices have spread outward. The extent of the vortices is slightly beyond the area over which data were taken, but still mostly visible. The cross stream velocities within the boundary of the nozzle have slowed down considerably but there is now a strong outward flow along the peak radii beyond the lobe. Because the jet is not confined, the air is free to flow radially outward without any hindrance. This

is a major difference between the present study and the previous, confined flow studies. The streamwise vortices of this study are spiraling outward as they travel downstream, whereas they generally remain within the lateral range of the lobe mixer when confined (Eckerle et al. [1990], McCormick [1992]).

Comparing again to the smoke image of Fig. 4.33 at $x/D = 2$, the outer extent of the smoke is approximately within the 3 inch diameter circle. This is roughly where the outer extent of the streamwise vorticity is located. The standard deviation image again shows that the highest intermittency is located where the axial velocity gradients are steepest. It also roughly outlines the streamwise vortices.

Figures 4.87a and b presents the flow patterns for a downstream distance of 3 diameters. The axial velocity profile still shows distinct humps representing the nozzle core and lobe regions but they have become more rounded. The outer air flow near the jet axis has sped up, but now the bulk of the outer flow being entrained at this axial location is the zero-velocity ambient air. The steep gradients seen at the outer edges of the lobe tip regions are an artifact of not taking data far enough out. During the first round of taking data, the laser plasma tube and the fiberoptic probe were (gradually) failing and the as yet undiscovered temperature sensitivity problem with the coupler were all occurring at the same time. The result of all these problems was low laser beam power in the probe volume. Low laser power causes a low data rate, and in the outer region of the flow where the seeding density is low and the velocities are small, the overall data rate was so low that taking the u and w data was not feasible in this

region. When most of the problems were corrected and the u and v velocity components were taken, the same grid was used to be consistent.

The vector plot of Fig. 4.87b shows that the cross stream components have generally decreased within the border of the outer jet, but still have a strong outward flow along the lobe axes. Note that the scale of the vector lengths has changed. The maximum cross stream velocity component has decreased substantially, but the length of the vectors has increased. The streamwise vorticity has moved substantially outward and just the 'edge' of the vortices can be seen at the furthest extent of the data. The center of the vortices is approximately near the outer jet wall, which is approximately where one would expect it to be from the smoke images. The first several rings of vectors surrounding the jet axis show that the flow is essentially outward, indicating that the strong central peak is behaving much like a single jet.

The velocity results for $x/D = 4$ are shown in Fig. 4.88a and b. The axial velocity surface plot shows that the jet has spread more and the surface has become more rounded. The vector plot reveals that most of the flow within the outer jet boundary has slowed considerably. The central core has now spread to a radius of approximately $0.5D$ since most of the vectors within the first five radii are pointing outward. The highest velocities, as in the previous plots, are located radially out from the lobes. Since there are higher velocities in this region, it appears that the streamwise vorticity is still active, and still beyond the range of the data. The sharp gradients seen in the surface plot confirms this. The overall jet has more than doubled its area and the outer jet is entraining the ambient air.

Figures 4.89a,b - 4.91 a,b show the axial velocity surface plots and the cross stream vector plots for $x/D = 5, 6$ and 7 , respectively. The change in appearance of the surface plot between $x/D = 4$ and 5 is slight. However, the changes between x/D of 5 and 6 , and 6 and 7 appear to be larger. The velocity profile is much more flattened out although small regions of higher velocity are still noticeable at $x/D = 7$.

The vector plots for these three figures have also been plotted with an enlarged scale for the vector length to enhance the details of the flow field. (Note that the labeled maximum velocity is smaller than previous graphs but has comparable length vectors.) The enlarged vectors show that the streamwise vortices are still active and spiraling outward. There is a strong radially outward flow beyond the border of the outer jet, in a sector surrounding the peak radii. This is in the location of the 'humps' in the velocity profiles of Fig. 4.89a. The initial peaks in the velocity profile are not only smoothing over, but they are also still moving outward because of the initial radial velocity component. Since the jet is not confined, the inward flow from the streamwise vortices is not as strong and they are beginning to die off, probably due to interaction with the ambient air. The vector plot at $x/D = 6$ (Fig. 4.90b) displays a similar pattern to the previous plot although the flow within the outer jet boundary is less uniform, more indicative of smaller scale mixing taking place. The high speed flow from the center core of the nozzle is still the highest peak in the velocity profile. The vector plot shows that it has now spread to a radius of roughly $0.5 - 0.6D$ since the vectors within this radius are generally pointing outward. The velocity profile and vector plot at $x/D =$

7 (Fig. 4.91a and b) are very similar to $x/D = 6$ except that the velocities are somewhat lower.

Axial velocity profiles along a radius aligned with the lobe peaks are given in Fig. 4.92. These velocities are also scaled using the values mentioned previously. For clarity the data along the radii are mirrored across the jet axis and plotted over a full diameter. The individual plots represent velocity profiles at various locations downstream. The location $x/D = 0.25$ was the closest attainable to the nozzle exit and is therefore the most representative of the nozzle exit profile. The first point to note is that the flow exiting the nozzle is not uniform. The magnitude of the central peak velocity is more apparent in these profiles. The maximum calculated velocity of the turbulent flow in the upstream piping is approximately 35 m/sec (White, 1986), so some acceleration has occurred through the nozzle along the jet centerline, even though the flow area is constant. This implies that there are boundary layers within the nozzle restricting the flow. Slightly away from the centerline the velocity drops off as the flow is caught up in the boundary layers near the narrowest section of the lobe (the second radial point away from the jet axis, beginning with the center point as point zero, see Fig. 4.83). Further out, as the lobe becomes wider, the velocity rises slightly to a secondary peak, not as high as at the centerline. At the nozzle lobe tip, the velocity drops off again due to the boundary layer in the peak region and interaction with the outer flow.

This behavior is quite different from previous two-dimensional lobed mixer studies where the axial velocity profiles were much more uniform at the exit planes

(Eckerle et al., 1990, Yu et al., 1995, Barber et al., 1988, McCormick, 1992). The difference is probably due to two effects. First, the dimensions of the present setup are smaller than the other studies. Consequently, any boundary layers that develop will have a relatively larger effect on the flow patterns. A second, and probably more important, difference is due to the axisymmetric geometry. Axisymmetric lobes do not have a constant width, but rather a constant spread angle. The sides of the lobes follow radial lines, therefore, the lobe grows wider away from the jet axis. This is opposite to two-dimensional lobed mixers where the widest section of the lobe is usually at the base. The two-dimensional lobed mixer runs the risk of developing boundary layers, and even separation in the lobe tip regions, whereas the axisymmetric lobed nozzle can have these problems as well as flow disturbances caused by boundary layers near the jet axis where the lobe is thinnest. This is illustrated in the double peak of the velocity profiles in Fig. 4.92.

The last several points in the plot at $x/D = 0.25$ show a relatively constant velocity section representing the outer flow. The last point in the profile is located at the wall of the outer jet and is in the wake region resulting from the boundary layer along this wall. The velocity is nonzero because the profile has been taken at $x/D = 0.25$ and the flow has had a chance to accelerate from the no slip condition. Further downstream, at $x/D = 1$, the velocity profile is similar. It still shows a high speed centerline velocity, a dip on either side, and then a higher speed hump further out, which represents the fluid from the middle to the lobe. Due to the nozzle's 20° outward ramp angle, these axial velocities also have outward radial components as seen in the

vector plots. The effect of this radial component can be seen in the significant outward movement of the hump. Taking into account the downstream distance of the velocity profile, the length of the nozzle and the diameter of the central tube, the jet is spreading at approximately 17° - 19° for the first three profiles, showing that the flow, at least initially, is spreading at the angle of the nozzle. Further downstream, as the inner and outer streams interact, it is more difficult to track the spread in this manner, especially since data was not taken far enough away from the jet axis.

Generally speaking, the plots of fig. 4.92 show a typical velocity decay with downstream distance. The central peak decays and spreads with downstream distance. At $x/D = 4$, the peak is slightly flattened. The slower secondary air is being entrained into the central core, slowing down the average velocity in that region. The effect is very small because of the strong core flow. At first it might appear that the streamwise vorticity is causing this aberration by sweeping the slower secondary flow toward the centerline. However, a reexamination of Fig. 4.88b shows that the streamwise vortices have moved substantially away from the jet axis. Additionally, the core flow is behaving similar to a single jet by this location, i.e., the cross stream vectors near the centerline are all pointing outward.

A more plausible explanation for the flattened profile is that the shear layer formed at the lobe troughs, due to the Kelvin-Helmholtz roll-up, is causing the outer air to be entrained into the center region. The mixing region exists along the whole perimeter of the nozzle (recall the RMS smoke images) and entrains fluid perpendicular to the perimeter. By this downstream location, there may be enough entrainment of the

slower outer air to slow down (slightly) the centerline velocity. There is also the possibility that the system was slightly out of alignment when this data was taken. However, if this were the case, we would expect more irregularities for other velocity profiles, which is not the case.

The spread of the fast moving core flow can also be seen in the evolution of the fourth point (counting the center point as zero) from the centerline. This is the location of the secondary peak in the velocity profile at $x/D = 0.25$. Due to the secondary flow and the outward velocity in the lobe region, the velocity of this point decays rapidly by $x/D = 1$. The decay shows down at $X/D = 2$ and 3 until $x/D = 4$, where the velocity increases slightly and then starts to decay again downstream. Reviewing Fig. 4.88b, the central core can be seen to be behaving like a single jet out to a radius of approximately $0.35D$, which is the radius at which the fourth point is located. Thus, the initial decay in the velocity for this point occurs because of the steep gradients caused by the mixing layer and the streamwise vorticity. The spread of the central core causes the velocity to speed up where it then decays normally. The profiles are approaching similarity by $x/D = 7$.

Figure 4.93 presents velocity profiles across the 'trough' radius. The central peak is much more well defined along this diameter. The profile at $x/D = 0.25$ shows the relatively constant velocity of the outer jet. The slight drop off near the center (at approximately $0.25D$) shows the effect of the outer jet boundary layer in the trough region. At $x/D = 4$ and 5 there is a slight depression of the velocity profile at the jet axis which is more prominent than the dip in Fig. 4.92. Since the centerline velocities

are equal for both graphs (Figs. 4.92 and 4.93), it must be the case that the adjacent point velocities are greater in Fig. 4.93 than in Fig. 4.92. Referring to Fig. 4.83 and considering the location of this first point on the trough radius, we can see that it is directly between two adjacent lobes. The first point along the peak radius, on the other hand, is directly between two adjacent troughs. Therefore, the point along the trough radius is 'surrounded' by faster moving air and would tend to have a higher velocity. The peak point, being surrounded by two troughs that contain slower moving air, would tend to have a lower velocity. At $x/D = 1$, there is a point at $0.95D$ that seems to have no connection with the rest of the data and is probably an errant data point.

At $x/D = 2$, the flow furthest away from the jet axis has substantially slowed down. This is due to the combined effects of the wake produced by the outer jet wall and interaction with the ambient air. The plots for $x/D = 3$ and 4, in the region from $r = 0.85D$ to $1.15D$, show a flat section indicating an increase in velocity. Since the core has not yet penetrated this far, the faster fluid must be coming from the lobe region through the action of streamwise vorticity. Referring to Fig. 4.87b, there is inward flow in this area which is at the inner boundary of the streamwise vortices, thus carrying faster moving air to this region.

The profiles for $x/D = 6$ and 7 are very similar in appearance, especially away from the jet axis. Ambient air is being entrained in this region and thus the velocity profile of the outer jet is approaching similarity, as is typical of single jets.

Figures 4.94 and 4.95 display the magnitude of the cross stream velocity along the peak and trough radii, respectively. These are the same values as seen in the vector

plots, except that only magnitude is plotted, without regard for direction except through the sign of the velocity. The sign convention used for these two plots is a positive velocity indicates flow away from the centerline and a negative velocity indicates flow toward the centerline. Consequently, one would expect most of the velocities along the peak radius to be positive while the trough velocities should be negative. The largest radial velocity in Fig. 4.94 is approximately half of the average velocity. This is much greater than would be expected from geometrical considerations, e.g., $U_{\text{avg,pri}} \sin(20^\circ) = 10 \text{ m/sec}$. This maximum velocity, however, is only acting over a small area and rapidly decays to much smaller values. The plots show that the cross stream flow is generally away from the jet axis, as has been seen in the vector plots. The maximum magnitude decays with distance downstream as well as moving outward as the jet expands. The values at the lobe tip at $x/D = 0.25$ are slightly negative, indicating that secondary flow is drawn toward the centerline as the faster nozzle flow expands outward.

Figure 4.95, at $x/D = 0.25$, shows much lower velocities in the secondary stream, but still higher than would be expected, based upon similar geometric arguments to above. The inward flow velocities decrease with downstream distance. Despite the fact that these profiles are taken along the trough radius, near the jet centerline the flow is generally away from the center. This is to be expected since the fast moving core flow is expanding and dominating the slower outer jet. Many of the plots at the farther downstream locations look like broken lines because the magnitudes

are very small and the trough region is where the flow is more likely to be angled in many different directions.

Axial velocity decay plots, normalized as before, are shown in Fig. 4.96. The three graphs show the decay of the centerline velocity for N3 and the circular nozzle, and for the fourth point from the centerline (along the peak radius), for N3. For comparison purposes, Ko and Au [1981] give the length of the potential core for a single jet as $4.7D$, which agrees with Liepmann and Gharib's [1992] value of less than $5D$. For coaxial jets where the primary velocity is greater than the secondary velocity, Forstall and Shapiro [1950] suggest that the length of the primary stream potential core is $L_{pc} = 4 + 12\lambda$, where $\lambda = U_{sec}/U_{pri}$ and $L = x/D_i$. Their equation is an empirical formula based on their data. Using their equation, the length of the potential core for the present velocity ratio would be approximately $8D$ (for the baseline nozzle), which is in the range of the data of Champagne and Wygnanski [1971]. The data of Fig. 4.96 would thus be considered to be in the near-field of the jet(s).

The plot for the baseline nozzle in Fig. 4.96, while relatively flat, still has a distinct decay to it, even though the data is within what is normally the potential core. The difference between this plot and data of previous studies is that the velocity profile of the present study is a fully developed turbulent profile, whereas the previous studies used converging nozzles to attain flat exit profiles. In effect, the baseline nozzle of this study does not have a potential core since the exit velocity profile is not uniform.

The velocity exiting N3 leaves with an initially higher velocity than the circular nozzle, but rapidly decays to values lower than the circular nozzle. The curvature of

this graph is more like what one would expect from a velocity decay plot, indicating that the streamwise vorticity is mixing the two streams well enough to make them act like a single jet. The lower centerline velocity for N3 shows that the lobed nozzle improves the mixing between the two streams.

The plot for the fourth point from the centerline (along the peak radius) illustrates the effect of the decay and spread of the center core. As the central core flow spreads, it raises the velocity of this point slightly before it begins to decay again.

4.2.1.2 Turbulence Results (30:10). Figures 4.97-4.104 display contours of the turbulence kinetic energy (TKE) normalized by the square of the scale velocity. At $x/D = 0.25$ the TKE profiles essentially outline the nozzle, indicating the mixing regions between the inner and outer flows. The contours show regions of high TKE located near the center of the nozzle and slightly further out along the nozzle peaks. This is more easily seen in the contour at $x/D = 1$ (Fig. 4.98) where the turbulence near the lobe tips is spreading because of the streamwise vorticity. The center region of the nozzle is already starting to spread like a round jet. The regions of highest TKE are near the jet axis and over the lobes, spreading with the flow. The plot at $x/D = 2$ shows that the areas of high TKE have separated into a central region and six lobe regions. This is an indication that the "pinch off" effect of McCormick [1992] has already occurred. McCormick found this happened by 1.75 lobe heights downstream for a two-dimensional system with a velocity ratio of 1.75. For the axisymmetric nozzles, this distance would be at approximately $x/D = 1.3$. The axisymmetric geometry has all the

lobe troughs close to the centerline and thus the flow doesn't have far to travel before vortex interaction can take place.

Recall from the vector plots that $x/D = 2$ is the axial location where the streamwise vorticity extended beyond the range of the data. Since the data range is limited, the regions of high TKE from the lobe tips appear to have steep gradients on their outer borders, which is not necessarily the case. These regions are probably more rounded on the border than displayed. The outer periphery of the TKE contour compares very well with the intermittent zone of the RMS image in Fig. 4.33.

By $x/D = 3$, Fig. 4.100, the central and outer regions are spreading such that the general level of TKE is higher between them. This is also the axial location where the cross-sectional image (fig. 4.33) shows trough regions filled with smoke. The six outer regions of high TKE now have a distinct horseshoe shape, however, because of the limitations of the data range it is difficult to tell the full shape.

The contours at $x/D = 4$ and 5 (Figs. 4.101 and 4.102) show that the core flow is spreading as well as the streamwise vortices. The maximum magnitude of the TKE is approximately half of what it was at $x/D = 0.25$. The horseshoe shaped regions contain two distinct regions of high TKE which could roughly define the center of the counter rotating vortices. The vector plot shows that this is approximately true. At $x/D = 5$, these regions are separated, indicating that the intensity of the vortices is weakening and/or that they are breaking up.

Figures 4.103 and 4.104 show the contours of TKE for $x/D = 6$ and 7. The level of turbulence at these locations is decreasing and becoming more uniform and circular.

There is still a noticeable hexagonal pattern to the contours just as seen in the smoke images of Fig. 4.33.

Plots of TKE along peak and trough radii are presented in figures 4.105 and 4.106, respectively. The data along the peak radius shows low TKE at the centerline, but a very high jump in turbulence at the adjacent point. The maximum at $x/D = 0.25$ occurs at the second and third points from the center (counting the center as point zero). This peak in TKE is adjacent to the peak in the velocity profile, which occurred at point four (Fig. 4.92). It appears that there is mixing with the secondary stream at this radial location, which is another reason--in addition to boundary layers inside the nozzle--why the velocity profile has a dip in this region. Referring to Fig. 4.84b again, it can be seen that points along the first three radii from the center show interference from the outer stream. The plots at $x/D = 0.25$ for both figures shows a very low turbulence level in the outer flow. Further downstream, the plots along the peak radius show that the peak in TKE is lessening and moving outward. It is also evident at $x/D = 2, 3$, and 4 that data was not taken far enough out because of the rise in TKE away from the jet axis. By $x/D = 5$ the TKE profiles are beginning to flatten out.

The data in Fig. 4.106 along the trough radius show generally lower levels of TKE than the peak radius. The peaks in the profile at $x/D = 0.25$ are at the radial location where the inwardly flowing secondary air is interacting with the high speed core flow. At $x/D = 3$ and 4, as the streamwise vorticity spreads the flow from the lobe tip region into the trough region, the level of TKE rises at a radius of approximately 1-

1.25D. The data point at $r = 0.95D$ at $x/D = 1$ is an errant data point, mentioned earlier during the velocity profile discussion. The profiles are becoming similar by $x/D = 6$.

Profiles of the turbulence kinetic energy of the cross stream components $(\overline{v'^2} + \overline{w'^2})$ are given in figures 4.107 and 4.108. The levels of TKE contained in these components, which are normalized as before, are roughly half that of the axial component. The trends for the cross stream components are also similar to the full TKE profiles for both the peak and trough radii. As with the total TKE profiles, the cross stream TKE profiles at $x/D = 6$ and 7 are flattening out, indicating that the axial velocity fluctuations are leveling off at the same distance as the cross stream component fluctuations.

Profiles of $\overline{uw}$ and $\overline{uv}$ Reynolds stresses, normalized by the initial velocity difference, along the peak radius are presented in figures 4.109-4.110, respectively. Because of the alignment of the LDV system and the nozzle (see Fig. 4.83), along the peak radius *only*, $\overline{uw}$ is essentially a correlation between axial and radial velocities, and $\overline{uv}$ is a correlation between axial and tangential velocity. Since the data for the w and v components were taken at separate times, proper Reynolds stresses along polar axes cannot be constructed for other radii because the associated time histories are not known.

The plot for $x/D = 0.25$ in Fig. 4.109 shows high Reynolds stress near the jet axis $r \leq 0.35D$. This is the region of the highest velocity and velocity gradients, which is where the largest flow structures are expected to be. The larger and more organized the structure the larger would be its associated correlation between its fluctuations and

thus the higher the Reynolds stress. The magnitudes of the Reynolds stresses decrease with downstream distance as the flow evolves into smaller scale turbulence. Similar to the velocity profiles, the peaks in the $\overline{uw}$ stress spread radially outward through $x/D = 2$, though not at the same rate.

The normalized $\overline{uv}$ Reynolds stresses of Fig. 4.110 are of lower magnitude than the $\overline{uw}$ stresses. This is to be expected since the v velocity is negligible along the peak radius. The sharp peaks near the core flow for $x/d = 0.25$ show that there is a significant v -component of shear stress in this region.

Figure 4.111 shows profiles of the $\overline{uv}$ stress along the 10° radius. The flow structures caused by the Kelvin-Helmholtz effect, being perpendicular to the lobe side wall, is causing significant organized interaction between the two streams in this area. The shear stress presented in the plots does not contain a velocity component that is perpendicular to the lobe side wall, however, it is only 10° off and still represents a good approximation to the component normal to the wall. As expected, the plots show a much higher magnitude $\overline{uv}$ shear stress than along the 10° radius, and the highest stress acts over a larger section of the lobe, not just confined to localized peaks.

4.2.2 Flow Condition 2: 30:30

This flow condition, because of the equal average velocities, minimizes the Kelvin-Helmholtz effect. Because of the boundary layers on the inner and outer surfaces of the nozzle, and also the circumferential variation of the velocity at the interface between the two streams, the effect cannot be eliminated completely. Note

that the data are normalized by the average velocity of the two streams, 30m/sec. since using the velocity difference would be undefined. Alternatively, since both streams have the same velocity, this can be thought of as using the average velocity of a single jet.

4.2.2.1 Mean Velocity Results (30:30). The axial and cross stream velocity results for this flow condition are presented in figures 4.112-4.118. At $x/D = 0.25$ (Fig. 4.112a) the surface plot of the axial velocity is much more even than the previous case. The strong peak velocity along the jet axis is still visible, although not as prominent due to the higher level of velocity over the rest of the flow area. It is difficult to tell from the vector plot, but the cross stream velocities in the trough region are generally higher than for the 30:10 flow rate. This combination of higher cross stream velocities (hence higher streamwise vorticity) and a minimized interface roll-up is what contributed to the well-defined intermittent regions in the smoke visualizations.

The axial velocity results at $x/D = 1$, shown in Fig. 4.113a, show a more smooth profile. The vector plot shows pockets of streamwise vorticity developing on the outside of the lobe tips. Comparing with the visualizations of Fig. 4.37, the streamwise vortices line up with the mushroom shaped bulges at the lobe tips of the average and standard deviation images. The streamwise vortices are not spreading radially as far as for FC1 (see Fig. 4.85b). The higher speed outer flow essentially eliminates the outwardly rolling Kelvin-Helmholtz instability, and it is acting as a barrier to the nozzle flow, keeping the streamwise vortices more confined.

Figure 4.114a and b display the results for the $x/D = 2$ location. The axial velocity surface plot is essentially a central peak surrounded by a flat shoulder region. The vector plot shows streamwise vortices that have moved slightly further out radially and have developed into well-defined patterns. These well-defined vortices cause the smoke to curl up into the U-shaped structures in Fig. 4.37. Note that for the 30:10 flow condition at this axial distance, the streamwise vortices were partially beyond the reach of the data. Here, they are still well within the boundary of the outer jet. The central core flow has expanded to approximately the first three radii of data ($r/D = 0.25$), essentially acting like a single jet in this region.

At $x/D = 3$, Fig. 4.15, the axial velocity exhibits slight depressions in the trough regions which shows the effect of entraining the ambient air. It appears that for this flow condition, as well, data was not taken at a large enough radius. However, as the vector plot shows, the streamwise vorticity is still confined to the data range. It can be seen from Fig. 4.115B that the streamwise vortices are beginning to exhibit signs of breaking down. The vortices are well defined on the inside, i.e., the half closest to the jet axis, however, the cross stream vectors toward the outside of the vortices have a relatively lower magnitude. The outward flow along the lobe centerline does not seem to be affected much by the streamwise vorticity since the vectors show very little components in off-radial directions. The break down of the vortices near their outer boundary could be due to interaction with the outer flow and/or the ambient flow. It is also possible that the wake region from outer jet side wall can be contributing to this effect but this is probably secondary. The mixing effect of this vortex break down is

demonstrated in the 'fuzzy' regions in the smoke visualizations at $x/D = 3$ in Fig. 4.37. The smoke filled, U-shaped regions at $x/D = 2$ have evolved into a slightly blurred region where most of the blurring is on the outside of the streamwise vortices.

Another interesting point to be made deals with the central core. In Fig. 4.114 ($x/D = 2$) it was shown that the vectors along the first three radii were generally pointed outward, and thus it was concluded that the central core was behaving like a single jet as in the 3:1 flow rate. At $x/D = 3$, however, the vectors along these first three radii are no longer as uniform, indicating that there is more mixing going on. This can also be seen in the standard deviation smoke image of Fig. 4.37. There is a bright ring of high intermittency surrounding the dark central core, comparing well with the location of the vectors.

The results for $x/D = 4$ are shown in Fig. 4.116a and b. The velocity surface is beginning to show well rounded humps representing the air from the nozzle lobes, and slight depressions in the trough regions representing the effect of the ambient air on the overall flow pattern. The rounded slope of the surface on the outside of the profile indicates that the range of the data is probably adequate through this downstream location. The vector plot shows that the streamwise vorticity has decreased considerably, on both the outside and inside regions. Many of the vectors in the outer flow region appear to be of similar magnitude. There is still noticeable inward flow in the trough regions, which is causing the depressions seen in the surface plot in the trough regions. The outward flow along the lobe centerline is keeping the radial velocity high in those regions.

The axial and cross stream velocity results at $x/D = 5$ are given in Fig. 4.117a and b. The surface plot shows that the velocity humps are decreasing as the jet spreads radially. The steep gradients at the boundary of the profile indicates that the jet extends slightly beyond the range of the data. The vector plot does not show signs of well defined, large-scale, streamwise vorticity, however there is still strong inflow in the trough regions and outflow in the peak regions with numerous vectors having tangential velocity components between these regions. The large-scale vortices have broken down into smaller scale vortices and/or turbulence. This explains the jump in jet growth in Fig. 4.37 between $x/D = 3$ and 5 and for the other nozzles.

As seen previously in the streamwise flow visualizations, there is a discontinuity, or jump, in jet growth for all the 1:1 and 1:3 velocity ratios in the range of $x/D = 3 - 5$. The 3:1 ratio displayed a less dramatic discontinuity further upstream, but that was more related to transition of the shear layer. The LDV data for the 1:1 case shows the streamwise vortices becoming less coherent and even breaking down over the same range as the jump in jet growth. The streamwise RMS image of Fig. 4.39 shows the intermittent zone blending into a thicker area over this downstream region. It is the streamwise vortices that are mostly responsible for the growth of the jet at this velocity ratio. The 3:1 case spread because of the interaction of the streamwise vorticity with the ring-type vortices due to the Kelvin-Helmholtz instability. The 1:3 case has a similar jump in jet growth which was attributed to the dominance of the outer jet. This will be seen when the LDV results are presented for that ratio.

For the 3:1 flow condition at $x/D = 5$, the vector plot showed the central core having expanded to the first 5 or 6 radii outward. For this 1:1 case, Fig. 4.117b shows the inner core is more confined, which is due to the fact that the relative strength of the core is much lower for this flow. The outer boundary of the data shows a fairly uniform outward flow indicating that the flow is behaving like a single jet there. Between the jet axis and the outer boundary, the streamwise vorticity has mixed the flow substantially.

The last location downstream, $x/D = 6$, is displayed in Fig. 4.118a and b. The velocity surface plot exhibits a broken pattern in the trough regions. This is probably a problem with the plotting software because there is no evidence of this in velocity profiles plotted along radii. The vector plot has been drawn with the vectors scaled larger than in the previous figures. There is still a strong outward flow in the lobe tips, but the otherwise erratic pattern of arrows is indicative of lack of any streamwise vortices.

Velocity profiles along peak and trough radii are plotted in figures 4.119-4.120. As with the 3:1 flow condition, the profile along the peak radius at $x/D = 0.25$ exhibits a central peak and two lower peaks on either side. The dip in the velocity at the ninth point from the center represents the wake region formed from the nozzle tip.

Because the outer flow is faster than the previous velocity ratio, it is more difficult to follow the spread of the peaks from the lobe flow, however, it is still possible to tell that the nozzle flow is spreading at a slightly smaller angle than the 3:1 case. The velocity also appears to be leveling off more quickly. By $x/D = 4$, the

profiles along the peak radius are approaching similarity which is unlike the behavior of the 3:1 case along the peak radius.

In similar fashion to the first flow condition, the profile across the center core flow exhibits a flattened shape for x/D of 4 or greater. As discussed previously, this effect is probably caused by the Kelvin-Helmholtz roll-up at the six trough interfaces. Though this 1:1 flow condition minimizes the interface roll-up, the profile along the trough radius in Fig. 4.120 at $x/D = 0.25$ shows that there is a steep velocity gradient in the near vicinity of the core flow. The depression of the velocity profile at the center is more pronounced along the trough radii due to the fact that the velocity at the first few points from the jet axis have a tendency to be accelerated by the flow from the adjacent lobes. The profiles along the trough radius also appear to be approaching similarity by $x/D = 4$, which is similar to the 3:1 flow ratio. The profiles generally have a smooth slope for most of the locations downstream. Since these profiles are constructed from the same data set used for the axial velocity surface plots, the brokenness observed in the plot of Fig. 4.118a must be an artifact of the plotting routine.

Cross stream velocities along peak and trough radii are plotted in Figures 4.121 and 4.122. As before, just the magnitudes of the velocities are plotted, without regard for direction. However, since most of the velocities along these two radii are generally in the direction of the radii, this should not cause confusion. The maximum radial velocity exiting the lobe (i.e., along the peak radius) is approximately 17 m/sec, very similar to the maximum for the 3:1 flow condition. This maximum decreases and moves outward as the jet spread downstream. At locations further downstream, the

outward velocity is fairly constant and near zero close to the jet axis, but then accelerates slightly farther away from the centerline. This higher speed at the boundary is due to the spread of the jet into the ambient air.

The velocities along the trough radius (Fig. 4.122) are generally toward the centerline. The maximum value of approximately 8.5 m/sec is roughly what one would expect from the relation $30\sin(20^\circ)$. The trends here are similar to the first flow condition. Near the centerline, the flow is away from the jet axis due to the strength of the core flow. Further away from the axis, the flow is generally inward toward the centerline.

Figure 4.123 displays plots of the centerline velocity decay for N3 and the circular nozzle. As with the 3:1 velocity ratio, the circular jet does not show a potential core because the exit velocity profile is not flat. Thus, the jet centerline velocity begins to decay at the exit plane. The nozzle flow, on the other hand, shows a small potential core until $x/D = 1$ and then begins to decay. Due to the mixing abilities of the streamwise vorticity, the decay rate of the nozzle flow is greater than the jet, although both decay much slower than the 3:1 case because of the faster outer flow.

4.2.2.2 Turbulence Results (30:30). Contours of TKE are presented in figures 4.124-4.130. The contours at $x/D = 0.25$ for this flow rate are very similar to those for the previous case. Many of the contours outline the nozzle shape, which is basically marking the mixing region around the nozzle caused by the various boundary layers. The magnitudes of the TKE contours are substantially lower than for the 30:10 flow

rate, which is to be expected since the velocities are closely matched. Evidence of the higher secondary flow can be seen in the circular contours surrounding the flow field that are marking the outer shear layer. The TKE contour plot of Fig. 4.97 does not have the bordering ring contours. This plot does, however, because the secondary velocity is higher. The small, odd-shaped contours within the outer ring are an artifact of the plotting software. The software is using a rectangular grid interpolation scheme whereas the data are arranged on a polar grid.

The TKE contours at $x/D = 1$, in Fig. 4.124, show the core region starting to develop and the lobe regions spreading. The contours in the lobe tip regions do not have pronounced mushroom shapes like the smoke patterns of Fig. 4.37, but are still expanding nonetheless.

The TKE contours at $x/D = 2$ are shown in Fig. 4.126. Here the individual streamwise vortices are visible and line up very well with the smoke image of Fig. 4.37 and the vector plot of Fig. 4.114b. The magnitudes of the contours are much less than for the 3:1 case indicating that the level of turbulence is decreasing.

Figure 4.127 gives the TKE profiles at $x/D = 3$. Recall that this is the distance where the vector plots showed a slight break down of the streamwise vortices toward their outside edge. The contours of TKE still outline the streamwise vortices, however they are much smaller and it appears that it is the inner regions of the vortices that are outlined. Further downstream, the TKE contours at $x/D = 4$ in Fig. 4.128 show a faint streamwise vorticity pattern about $1.1D$ from the centerline in the vicinity where the

vector plot showed only a slight vortical pattern. Several of the other contours of the plot display a broken pattern indicative of vortex break down.

At $x/D = 5$, Fig. 4.129, the contours still display a pattern reminiscent of the streamwise vortices, however the vector plot showed a very erratic flow pattern, with possibly many different vortices interacting. The contours of Fig. 4.130, $x/D = 6$, are similar in pattern to the previous figure, but are much more broken. This compares well with the vector plot at this distance.

Profiles of turbulence kinetic energy along peak and trough radii are given in figures 4.131 and 4.132, respectively. As with the previous flow rate, both figures show a peak in TKE near the center and a drop toward the outside at $x/D = 0.25$. The magnitudes of the peaks are much lower than the 3:1 flow rate. The central peaks in Fig. 4.131 decrease quickly with downstream distance and move outward as the inner jet spreads. At the outer edge of the data, the TKE rises in the outer shear layer as the streams interact with the ambient air. The reduced shear between the two streams is evident in the fact that the values of TKE in the outer shear layer are generally higher than the values within the shear layer. As with the velocity profiles, both graphs show similarity beyond $x/D = 4$.

Profiles of the cross stream TKE (i.e., v and w components) are given in figures 4.133 and 4.134. The magnitude of the cross stream TKE is roughly greater than half the total TKE, unlike the 3:1 flow case where the cross stream components made up less than half of the total TKE. Since the Kelvin-Helmholtz instability is minimized, the streamwise vorticity has a relatively larger effect and the TKE of the cross stream

components would be expected to be relatively higher for this flow rate. The plots exhibit similar behavior to the total TKE. The peaks near the jet axis dissipate quickly and the TKE levels within the primary stream region soon become lower than those in the outer shear layer. The plots for both peak and trough radii are beginning to show similarity by $x/D = 5$.

Figures 4.135-4.136 present the $\overline{uw}$ and $\overline{uv}$ Reynolds stresses along the peak radius, respectively. As with the previous flow condition, the bulk of the values are within a very tight range. The 1:1 velocity ratio does not produce the large-scale structures of the previous flow condition, so the Reynolds stresses are much lower. The main difference is that the 30:30 flow condition has fewer peaks in the plots. The largest $\overline{uw}$ stress is in the outer shear layer between the secondary flow and the ambient air at $x/D = 6$. It shows a large negative value consistent with outwardly rolling, large organized structures. The plot of the $\overline{uv}$ stress also shows that many of the values fall between a very tight band and the magnitudes are much lower than the 3:1 velocity ratio. As witnessed in the mean velocity results, the main contributor to interface roll-up is due to boundary layer development on the inner and outer nozzle surfaces and this is not enough to affect the tangential flow along the peak radius.

Figure 4.137 shows ' $\overline{uv}$ ' Reynolds stresses along the 10^0 radius. As expected, the correlation, at least for the first location downstream, is much higher because it is along the border between the inner and outer streams. The bulk of the data are still within a very narrow band, however the magnitudes of the values at $x/D = 0.25$, which are the most likely to be affected, show a definite increase.

4.2.3 Flow Condition 3: 30:90

The last flow condition for which detailed LDV measurements were collected was the 1:3 velocity ratio, with the inner flow at 30 m/sec average velocity and the outer flow at 90 m/sec. The much higher speed of the outer flow for this case, induces a much higher, inward, cross stream velocity in the trough regions, and therefore increases the magnitude of the streamwise vorticity over the 30:10 and 30:30 cases. Also, because the geometry is axisymmetric, we would expect this case to generate a wake-like rather than a mixing-layer-like flow field, especially further downstream.

4.2.3.1 Mean Velocity Results (30:90) The axial velocity surface and vector plots for this condition are presented in Figs. 4.138-4.145. The results at $x/D = 0.25$ are shown in Figs. 4.138a and b. The nozzle flow appears as a depression in the surface plot because the outer velocity is so much greater and therefore not much detail of the inner stream is visible. The vector plot displays similar patterns to the previous flow rates with radially outward flow in the nozzle lobe regions and inward flow in the rough regions. The inward flow is much greater than previously seen for the other flow rates. Another difference can be seen in the vectors along the side walls of the lobes. They are all generally perpendicular to the lobe surface, pointing toward the outer flow. The outer flow, being faster, has a slightly lower static pressure and it is drawing the primary flow outward.

At $x/D = 1$ (Fig. 4.139a), the surface plot reveals that the velocity depression of the nozzle flow is beginning to fill, especially near the centerline. The strong outer

flow has almost isolated the individual lobe tip regions. The vector plot shows the nozzle flow is substantially overcome by the outer flow. Only a small region of the lobe section has a large outward component and this component has not escaped into the outer flow at the lobe tips like the previous flow rates. The interface roll-up direction is inward, perpendicular to the nozzle surface, and this is effectively limiting the penetration of the outer flow. A small streamwise vortex pair can be identified in the lobe tip regions, within the outline of the lobe. This is a significant difference from the previous flow conditions where larger vortex pairs were easily discernible and spread out further radially and azimuthally.

The strong inward flow near the jet axis shows that the velocity deficit at the centerline still exists. The average smoke image at this distance, Fig. 4.41, shows that the smoke is confined to the lobe tip regions and has minimal spread. Since the streamwise vorticity does not appear to have developed as uniformly as the previous velocity ratios, it is likely that most of the jet spread was due to the shear layer mixing processes and not the streamwise vorticity. Especially since the streamwise vorticity that is visible is well within the lobe dimensions. The secondary flow in the trough regions, at a radius of roughly $r/D = 1$, is traveling toward the lobe regions, "filling" the velocity deficit.

Figure 4.140 presents the velocity results for $x/D = 2$. The surface plot shows the velocity profile becoming flatter although there are still noticeable depressions from the lobes and the centerline. These depressions almost extend to the outer limits of the data. The vector plot shows a strong inward flow in the secondary stream, but a much

more subdued outward flow in the nozzle region. Streamwise vortices are no longer visible, however, if data were taken on a finer grid they might still be found to exist because partial vortices are visible within the lobe boundary at a radius of $0.5D$. The previous two flow conditions exhibited distinct streamwise vorticity at this distance. The average smoke image of Fig. 4.41 for this location shows that the smoke has spread radially to the outer boundary of the lobe tips. The largest three radii at which data were taken in Fig. 4.140b exhibit a mostly radially outward flow, marking the outer shear layer. This outer shear layer has not yet penetrated the inner flow region.

In the lobe trough region, at a radius of approximately $1D$, the vector plot displays vectors pointing toward the lobe tip regions. As can be seen in the surface plot, the velocity depressions have expanded radially and azimuthally and have set up velocity gradients in the azimuthal direction. The outer flow is thus rushing toward the lobe tip regions to fill the void.

Figure 4.141a and b present the results for $x/D = 3$. The velocity surface plot shows a central depression representing the velocity deficit of the core flow and six surrounding depressions representing the deficits from the lobe regions. The outer shear layer and the nozzle flow now overlap because depressions in the velocity profile along the lobe radii are now visible at the outer edge of the data, in the outer shear layer. Data from Ko and Au [1985] show that the outer potential core length is approximately $1.7D$, which would be $x/D = 4.25$ for this geometry. The increased mixing of the lobed nozzle is causing the streams to interact sooner.

This is also the axial location ($x/D = 3$) where the streamwise instantaneous image (Fig. 4.42) showed large-scale structures developing and where the average image displayed the large jump in growth rate. As was stated during the discussion of the flow visualizations, for this flow condition, the discontinuity in jet growth is caused mainly by the interaction of the outer jet with the ambient air and the dominance of the outer jet over the inner jet. Control of the inner jet by the flow conditions of the outer jet has been witnessed before by Wicker and Eaton [1994] and Dahm et al., [1992].

The results at $x/D = 4$ are given in Fig. 4.142. The surface plot still shows the velocity defects from the nozzle flow, although they are decreasing. The vector plot shows a fairly strong flow toward the jet axis as the outer flow is still working to fill the velocity defect in the center. The vectors at the outer boundary of the data are showing the growth of the outer shear layer. Since the velocity defect from the nozzle lobes is extending into this shear layer, the vectors are pointing toward these depressions so they do not have an exact radial direction. There is still a strong inward flow within the nozzle region because the velocity deficit still exists there.

Figure 4.143 presents the results for $x/D = 5$. The surface plot shows the velocity is approaching the rounded profile of a single jet, although slight depressions are still visible. The steep gradients at the border of the data show that the jet extends beyond the range of the data. The vector plot is very similar to the previous axial location. The outer shear layer has grown slightly and the inward flow near the center has decreased in magnitude.

The results for the final two locations, $x/D = 6$ and 7 , are given in Figs. 4.144 and 4.145, respectively. There are still slight depressions in the surface plots, so it appears that the flow is not quite uniform, however, the magnitudes of the cross stream velocities are extremely small. The vector plots show the same type of behavior seen at the previous axial stations. Figure 4.144b shows that vectors along two radii ($0.65D$ and $0.75D$) are somewhat haphazardly oriented and could be evidence of vortex break down. A small difference between these two plots is that the vectors of Fig. 4.145b show a third radius of randomly oriented vectors on the inside of the two radii in the previous plot. This further evolution of the mixing region probably explains the increased intermittency in the center of the average smoke image at $x/D = 7$ compared to $x/D = 5$, of Fig. 4.41.

Axial velocity profiles along the peak and trough radii are given in Figs. 4.146-4.147. An initial observation is that the profiles have the basic appearance of a wake flow but with much more variation. The profile at $x/D = 0.25$ of Fig. 4.146 shows that the nozzle flow is much slower than the outer flow. The center point, having a negative velocity, indicates the presence of a recirculation zone just downstream of the nozzle along the axis. This recirculation zone has been mapped and will be discussed after the velocity profiles. The centerline velocity accelerates quickly downstream because of the influence of the inwardly rushing air from the six trough regions.

The spread of the central jet can be tracked in Fig. 4.146 by following the data points at the tip of the lobe. Unlike the velocity peaks of the previous flow conditions, the velocity deficits of this flow case do not migrate radially outward or inward. The

depression in the center of the flow exists for the full range of data, indicating that a uniform, or similarity flow condition has not been obtained. Despite that fact, the last two velocity profiles ($x/D = 6$ and 7) match very closely to each other.

The velocity profiles at $x/D = 0.25$ along the trough radius (Fig. 4.147) show the negative peak in the center and a fairly uniform velocity in the outer flow. The velocity profiles are generally accelerating in the center and slowing down in the outer stream as the flow develops downstream. There is one small depression in the velocity profile of $x/D = 2$ at $r/D = 0.5$. This is the location where the velocity depressions from the lobe regions have expanded enough to finally merge. The effect is also observable in the surface plot of Fig. 4.140a. The average smoke image of Fig. 4.41 shows that the smoke has not yet merged which is probably because there is no streamwise vorticity to carry the smoke to this point. The depression is still noticeable at $x/D = 3$, but it is much less dramatic. This is also the axial location where the smoke has merged together, demonstrating that it is the Kelvin-Helmholtz effect that is promoting most of the mixing for this flow condition, not the streamwise vorticity.

The recirculation zone for this flow rate is plotted in Fig. 4.148. Data were taken along the jet axis from approximately $0.1D$ to $1.0D$ downstream. A total of 8192 points were taken at each location to ensure a representative sample. From the velocity profiles at $x/D = 0.25$, it appears that the recirculation zone is very narrow, with a six-pointed star shaped cross-section. The centerline has the greatest negative velocity, but the adjacent point along the peak radius is also slightly negative, whereas the adjacent point along the trough radius is positive. Figure 4.148 shows the extent of the

recirculation zone to be from $x/D = 0.22$ to 0.5 . The high velocity outer flow causes a local low pressure region strong enough to reverse the axial flow. Evidence of this was seen in the vector plot of Fig. 4.138b, where the vectors at the lobe sidewalls were pointing roughly perpendicular to the wall. This indicates a net mass flow from the primary stream to the secondary stream. To make up for this loss of mass, the flow along the centerline reverses direction to satisfy continuity. The plot of the standard deviation of the axial velocity shows that the higher value is the stagnation point.

Decay of the centerline velocity for this flow rate is shown in Fig. 4.149. There is no baseline nozzle data to compare with because the equipment failures occurred before the data was taken and it was decided to take the nozzle three data once the repairs were made. The plot shows that by $x/D = 3$, the velocity has accelerated to a fairly constant value, and is not decaying by $x/D = 7$. Data from Champagne and Wygnanski [1971] for a velocity ratio of 1:5, shows that the inner flow accelerates over a distance of approximately twelve inner diameters. The quick acceleration of the primary flow for N3 shows the effect of the higher mixing this nozzle produces. The higher mixing is mostly due to the higher interfacial area compared to the baseline nozzle.

Cross stream velocities along peak and trough radii are given in Fig. 4.150 and 4.151. The profile along the peak radius at $x/D = 0.25$ reveals a very large outward velocity. The peak is almost twice the value for the first two cases, even though the inner stream flow rates are approximately equal. The low pressure region created by the outer flow is accelerating the radial flow of the inner stream. This is further

evidence of why the recirculation zone formed. The higher radial velocity, in addition to the velocities being perpendicular to the lobe side walls, essentially increases the radial (outward) mass flow of the primary stream for this case, relative to the other flow conditions. Since the mass exiting the nozzle is approximately the same as the other flow rates, the 'extra' mass needed to make up the difference comes from the reverse flow. The plots show that the velocity at the first data point from the center is positive, indicating flow away from the jet axis along both radii, which is consistent with a recirculation zone in this area. The flow along the peak radius is generally outward until $x/D = 2$, where the flow begins to turn inward toward the velocity deficit at the center of the jet, and remains outward to the outer shear layer. The cross stream velocity direction along the trough radius is generally inward toward the centerline for the inner points, but also flows outward for the points within the outer shear layer.

4.2.3.2. Turbulence Results (30:90). Contours of turbulence kinetic energy are presented in Figures 4.152 - 4.159. The contours of Fig. 4.152 follow a rough outline of the nozzle and the outer shear layer, essentially marking the steep gradients in those regions. The contours at $x/D = 1$, of Fig. 4.153 shows that the outer shear layer has grown and the lobe regions have become more rounded, much like the smoke image of Fig. 4.41. The central core region does not show a well defined circular pattern like the previous flow conditions did at this axial location.

Figure 4.154 displays the contours for $x/D = 2$. The vector plot for this location showed partial streamwise vortex pairs located within the lobe at approximately $r/D =$

0.5. The TKE contours mark this region very well. There are also pockets of lower TKE in the trough regions where the velocity deficits exist.

At $x/D = 3$, Fig. 4.155, the contours show that the streamwise vorticity, if it existed, is decaying, as was seen in the vector plot. The main features of this plot are contours that seem to be marking an outline of the trough regions where one would still expect the Kelvin-Helmholtz instability to exist because of the velocity depressions. However, these regions do not show TKE levels as high as in the outer shear layer region, where the velocity gradients are steeper. The central contour outlines the center dip in the velocity profile.

At $x/D = 4$, Fig 4.156, the TKE contours show a fairly smooth pattern overall. The central contours are slightly broken which effectively marks the region where the cross stream vectors had a somewhat erratic pattern. This is the region that would most likely contain the decaying streamwise vorticity.

The next three locations downstream, $x/D = 5, 6$, and 7 , in Figs. 4.157-4.159 mirror what has already been seen in the velocity surface and vector plots. As the nozzle flow interacts with the outer flow, the streamwise vorticity and the interface roll-up between the two flows is leveling off and the main region of interaction now is in the outer shear layer. Even though depressions in the velocity profile are still noticeable at these downstream locations, the level of turbulence has significantly decreased.

The detailed TKE profiles along peak and trough radii are displayed in figures 4.160 and 4.161. The familiar peaks in TKE near the nozzle centerline are visible in both graphs and exhibit the level of interaction between the inwardly rushing outer air

and the core nozzle flow. The difference between this 1:3 flow condition and the previous two can be seen in the profiles at $x/D = 0.25$. Near the centerline, the profiles are flatter, i.e., the core region is more broad for the 1:3 case. This shows the effect of the recirculation zone. The recirculating fluid is stable enough to effectively keep the high speed flow from interacting at the centerline. Also, the decay in the TKE along the jet axis is steady, whereas the 1:1 and 3:1 flow rates exhibited an initially low value at $x/D = 0.25$ that rose for the next several locations downstream, after which it decayed.

The plots at the locations further downstream show similar behavior to the previous velocity ratios. Unlike the velocity profiles, the TKE profiles along the peak radius do appear to show some spreading of the central peaks with downstream distance. The profiles level off downstream with the central region becoming less turbulent as the flow develops and the outer region of the flow developing into a shear layer containing higher levels of turbulence. The profiles at $x/D = 6$ and 7 are nearly identical to each other. It is interesting to note that the range of the data does generally encompass the region of the shear layer containing the highest level of turbulence, which is located at approximately $r/D = 1.5$.

Both figures also show that the outer shear layer does not begin affecting the inner jet until $x/D = 3$. The profiles for $x/D = 0.25, 1$ and 2 show a local minimum at $r/D = 1.05$ which represents the low general turbulence level in the outer flow. This essentially shows a separation between the two streams. Not until $x/D = 3$ do the plots begin to display the U-shaped profile typical of the downstream plots. This supports the claim that it is the outer flow that is controlling the mixing for this flow condition.

The TKE of the cross stream components (i.e., v and w) is shown in Figs. 4.162 and 4.163. These plots show similar behavior to previous cross stream TKE plots. The main difference is that the magnitude of the cross stream TKE along the peak radius is a much greater percentage of the total TKE than for the other flow rates. The cross stream TKE along the peak radius also shows some spreading with downstream distance.

The next three figures, 4.164-4.166, present the $\overline{uw}$ and $\overline{uv}$ Reynolds stress profiles. The $\overline{uw}$ stress profiles show generally low correlation over most of the flow region. For the first several locations downstream, the correlation is higher near the lobe tips, indicating that the flow structures are more organized there. The sign of the stress is opposite to the 3:1 flow condition indicating that the predominant roll-up direction is inward in this region. Further downstream in the outer shear layer, the sign of the $\overline{uw}$ stress changes to negative.

The $\overline{uv}$ stress plots of fig. 4.165 exhibit much lower magnitudes. As with the first two flow rates, the cross stream velocity component is not very strong along the lobe centerline. Along the 10^0 radius, where the Kelvin-Helmholtz instability is strongest, the $\overline{uv}$ stress of Fig. 4.166 shows a definite increase along the length of the lobe for the first two locations downstream. Elsewhere in the flow the $\overline{uv}$ stress is low, indicating that the organization of the structures decreases quickly. This is consistent with what has been seen in the vector plots. There was essentially no tangential (y-direction) component of velocity along the peak radius so the $\overline{uv}$ stress is low. Along

the lobe wall, near the exit plane, the vectors were essentially pointing toward the secondary flow which would lead to a much higher correlation along the 10^0 radius.

4.3 SUMMARY OF RESULTS

Due to the large number of nozzles and flow conditions explored, and the large number of different images presented, a brief summary of the main results will be presented here which are then followed by the conclusions in the next chapter.

Figure 4.167 displays average images for the baseline circular nozzle and the six-lobed nozzles, taken from previous figures in chapter four. By combining the images on a single figure, it is much easier to distinguish the differences between them. The images are arranged in order of increasing streamwise vorticity, from top to bottom, and increasing distance downstream from left to right.

The baseline nozzle shows the expected spreading of a jet downstream. The lobed nozzles show similar behavior, but at a higher rate. The spread of the smoke for nozzle 2 is greater than the baseline nozzle, predominantly due to the increased interfacial contact area. With the addition of streamwise vorticity from N1, the smoke spread is even greater. Not only do the individual lobes spread more rapidly, but the entire smoke pattern spreads radially as well. Nozzle 3, which produces the highest streamwise vorticity, shows even more dramatic changes. The images for N1 and N3, even at $x/D = 1$, show the existence of counter-rotating streamwise vortices in the form of mushroom-shaped smoke concentrations at the lobe tips.

The same nozzles and downstream locations are represented in Fig. 4.168 for the 30:30 velocity ratio. This flow condition minimizes the Kelvin-Helmholtz instability between the two streams, but cannot eliminate it completely because of the boundary layers on the inner and outer lobe surfaces, especially in the trough and peak regions, and the nonparallel flow at the exit due to the ramp angles. Nevertheless, the images do show that interface roll-up is essentially eliminated. In all cases, the smoke from the individual lobes has not yet merged, and thus the spread of the central jet is significantly reduced. There is still growth of the individual lobes and overall radial spread of the smoke but no lobe interaction. The negligible roll-up of the interface between the two streams enables the streamwise vorticity to be visualized. The smoke-filled, U-shaped regions at $x/D = 2$ for N3 at the lobe tips are indicative of two counter-rotating, streamwise vortex pairs. These streamwise vortices were also visible in the 3:1 velocity ratio images, but they were not as well defined because of the Kelvin-Helmholtz instability.

The results for the last velocity ratio, 30:90, are summarized in Fig. 4.169. Generally speaking, there is still a definite jet spread with distance downstream and with added streamwise vorticity. However, compared to the previous flow conditions the smoke spread is reduced. The effect of adding streamwise vorticity is more apparent in terms of spreading the individual lobes, but that does not appear to be enough to increase the overall spread.

Figures 4.170 and 4.171 show the effect of velocity level on mixing for the 3:1 and 1:1 velocity ratios, respectively. The figures show the intermittent region at $x/D =$

7. For the baseline nozzle, the effect is negligible. This is in agreement with coaxial jet studies where velocity ratio has been found to be the proper scaling parameter for these simple flows. Nozzle 2 has a small effect due to the small amount of streamwise vorticity generated. Nozzles 1 and 3 show much thicker intermittent regions for the higher velocity case because of the increased streamwise vorticity. The thickening of the intermittent regions was generally more prominent at the further downstream locations, where the intermittent region has grown to an appreciable size. The effect is also more noticeable for the 3:1 case than for the 1:1 case, although different images from the various nozzles show the effect to a greater or lesser degree.

The effect of velocity ratio on the overall jet spread can be seen in the cross-sectional average images at $x/D = 7$ for nozzle 1, shown in Fig. 4.172. The 3:1 velocity ratios produce the largest spread. The 1:1 ratios also spread the jet, however, the interaction between the lobes is greatly reduced without the Kelvin-Helmholtz instability. The last velocity ratio, 1:3, produces what appears to be a more compact jet. There is a bright, centrally located region of smoke, surrounded by a much darker region. This dual-intensity image is typical of the 1:3 velocity ratio.

Figures 4.173 and 4.174 display streamwise views for N1 for the average and standard deviation images, respectively. The average images of Fig. 4.173 show an essentially monotonic spread of the jet for the 3:1 velocity ratio. There is a slight change in growth rate at $x/D = 1$ related to transition as previously discussed, but overall the growth rate is basically constant. The 1:1 ratios show less interaction

between the lobes, but also have a jump in jet growth at approximately $x/D = 3$. There is a similar discontinuity for the 1:3 velocity ratio.

The RMS images of Fig. 4.174, in addition to the velocity data, help to explain the mixing processes occurring for the different flow cases. The 3:1 cases show a region of high intermittency that follows the spread of the smoke in the average image. The LDV data showed that distinct, streamwise vortices formed for this velocity ratio, and that they spiraled outward with downstream distance.

The 1:1 velocity ratios exhibit slightly different behavior. The LDV data for N3 showed that the Kelvin-Helmholtz roll-up is significantly reduced and that the streamwise vortices did not spread as much radially as for the 3:1 velocity ratio. It also showed that the vortices started breaking down at the same downstream location where the discontinuity in jet growth appears. The RMS images show a bright intermittent region that initiates from the nozzle lobe tips, similarly to the 3:1 case, but does not spread at as great an angle initially as the 3:1 case. Also unlike the 3:1 case, the intermittent region blends into a much broader, more uniform area at the location where the discontinuity exists, whereas the intermittent region for the 3:1 case remains relatively strong and well defined along the outer edge of the smoke.

For the last velocity ratio, 1:3, the LDV data for N3 showed that any streamwise vorticity that did develop, dissipated by $x/D = 3$, if not sooner, so it is unlikely that the jump in jet growth for this case could be caused by the streamwise vorticity. In addition, though the intermittent region of Fig. 4.174 does show a slightly thicker region at the location where the discontinuity begins, there is still a strong narrow

region that has an inward slant. There is no blending into a thicker, more uniform intermittent region, as in the 1:1 case.

Quantitative information on the spread of the inner jet for the six-lobed nozzles was obtained through a pixel counting technique. Separating the effects of interfacial surface area between the streams versus streamwise vorticity revealed that the effect of the Kelvin-Helmholtz instability on mixing is important, even in the presence of strong streamwise vorticity. The fraction of mixing enhancement due to streamwise vorticity, relative to mixing enhancement due to increased interfacial area, was found to increase as velocity ratio increased.

Table 4.1 Geometric and Flow Parameters of Nozzles.

Nozzle	NB	N1, N2, N3	N4	N5	N6
Flow Area	448 mm ²	454	454	323	454
Perimeter	74.9 mm	246	176	169	170
D _h (primary)	23.9 mm	7.37	10.3	7.65	10.7
Blockage Area	506 mm ²	639	587	452	581
D _h (secondary)	32.3 mm	18.6	22.7	26	23.1

Table 4.2 Reynolds Numbers for Different Flow Conditions Based on Hydraulic Diameter.

Nozzle	Baseline Nozzle		N1, N2, N3	
	Prim. Flow	Sec. Flow	Prim. Flow	Sec. Flow
FC1 (30:10)	57,000	29,600	16,500	17,600
FC2 (30:30)	57,000	88,800	16,500	53,000
FC3 (30:90)	57,000	266,000	16,500	15,900
FC4 (90:30)	171,000	88,800	49,500	53,000
FC5 (90:90)	171,000	266,000	49,500	159,000

Table 4.2 continued.

Nozzle	Nozzle 4		Nozzle 5		Nozzle 6	
	Prim. Flow	Sec. Flow	Prim. Flow	Sec. Flow	Prim. Flow	Sec. Flow
FC1	23,000	21,000	17,000	22,900	24,000	21,800
FC2	23,000	63,900	17,000	68,700	24,000	65,400
FC3	23,000	192,000	17,000	206,000	24,000	196,000
FC4	69,000	63,900	51,000	68,700	72,000	65,400
FC5	69,000	192,000	51,000	206,000	72,000	196,000

Table 4.3 Contributions to Mixing by Interfacial Area and Streamwise Vorticity

Velocity Ratio	Contribution of:	$x/D = 1$	$x/D = 2$	$x/D = 3$
3:1	Interfacial Area	40%	39%	32%
	Streamwise Vorticity	60%	61%	68%
1:1	Interfacial Area	73%	58%	37%
	Streamwise Vorticity	27%	42%	63%
1:3	Interfacial Area	72%	63%	52%
	Streamwise Vorticity	28%	37%	48%

Figure 4.1 Instantaneous images showing separation in lobes of prototype lobed nozzle.

Figure 4.2 Instantaneous images of prototype at exit plane with outer flow seeded. Separation causes outer flow to be drawn into the lobes immediately downstream.

Average Images 30:10 (m/sec) **$x/D = 0$** **$x/D = 1$** **$x/D = 2$** **$x/D = 3$** **$x/D = 5$** **$x/D = 7$** **Standard Deviation****SCALE** **$x/D = 1$** **$x/D = 2$** **$x/D = 3$** **$x/D = 5$** **$x/D = 7$**

Figure 4.3 Baseline nozzle cross-sectional, average and standard deviation images, 30:10 flow rate.

Figure 4.4 Baseline nozzle cross-sectional, average and standard deviation images, 90:30 flow rate.

30:10 (m/sec)

Instantaneous

Average

Standard Deviation

$x/D = 1 \quad 2 \quad 3 \quad 5 \quad 7$

Figure 4.5 Baseline nozzle streamwise views: instantaneous, average and standard deviation, 30:10 flow rate.

90:30 (m/sec)

Instantaneous

Average

Standard Deviation

$x/D = 1 \quad 2 \quad 3 \quad 5 \quad 7$

Figure 4.6 Baseline nozzle streamwise views: instantaneous, average and standard deviation, 90:30 flow rate.

Figure 4.7 Baseline nozzle cross-sectional, average and standard deviation images, 30:30 flow rate.

Figure 4.8 Baseline nozzle cross-sectional, average and standard deviation images, 90:90 flow rate.

30:30 (m/sec)

Instantaneous

Average

Standard Deviation

$x/D = 1 \quad 2 \quad 3 \quad 5 \quad 7$

Figure 4.9 Baseline nozzle streamwise views: instantaneous, average and standard deviation, 30:30 flow rate.

90:90 (m/sec)

Instantaneous

Average

Standard Deviation

$x/D = 1 \quad 2 \quad 3 \quad 5 \quad 7$

Figure 4.10 Baseline nozzle streamwise views: instantaneous, average and standard deviation, 90:90 flow rate.

Figure 4.11 Baseline nozzle cross-sectional, average and standard deviation images, 30:90 flow rate.

30:90 (m/sec)

Instantaneous

Average

Standard Deviation

$x/D = 1 \quad 2 \quad 3 \quad 5 \quad 7$

Figure 4.12 Baseline nozzle streamwise views: instantaneous, average and standard deviation, 30:90 flow rate.

Average Images 30:10 (m/sec)

Standard Deviation

Figure 4.13 Nozzle 2 (0° ramp) cross-sectional, average and standard deviation images, 30:10 flow rate.

Figure 4.14 Nozzle 2 (0° ramp) cross-sectional, average and standard deviation images, 90:30 flow rate.

30:10 (m/sec)

Instantaneous

Average

Standard Deviation

$x/D = 1 \quad 2 \quad 3 \quad 5 \quad 7$
Figure 4.15 Nozzle 2 (0° ramp) streamwise views: instantaneous, average and standard deviation, 30:10 flow rate.

90:30 (m/sec)

Instantaneous

Average

Standard Deviation

$x/D = 1 \quad 2 \quad 3 \quad 5 \quad 7$

Figure 4.16 Nozzle 2 (0° ramp) streamwise views: instantaneous, average and standard deviation, 90:30 flow rate.

Figure 4.17 Nozzle 2 (0° ramp) cross-sectional, average and standard deviation images, 30:30 flow rate.

Average Images 90:90 (m/sec) **$x/D = 0$** **$x/D = 1$** **$x/D = 2$** **$x/D = 3$** **$x/D = 5$** **$x/D = 7$** **Standard Deviation****SCALE** **$x/D = 1$** **$x/D = 2$** **$x/D = 3$** **$x/D = 5$** **$x/D = 7$**

Figure 4.18 Nozzle 2 (00 ramp) cross-sectional, average and standard deviation images, 90:90 flow rate.

30:10 (m/sec)

Instantaneous

Average

Standard Deviation

$x/D = 1 \quad 2 \quad 3 \quad 5 \quad 7$
Figure 4.19 Nozzle 2 (0° ramp) streamwise views: instantaneous, average and standard deviation, 30:30 flow rate.

90:90 (m/sec)

Instantaneous

Average

Standard Deviation

$x/D = 1 \quad 2 \quad 3 \quad 5 \quad 7$

Figure 4.20 Nozzle 2 (0° ramp) streamwise views: instantaneous, average and standard deviation, 90:90 flow rate.

Average Images 30:90 (m/sec)

$x/D = 0$

$x/D = 1$

$x/D = 2$

$x/D = 3$

$x/D = 5$

$x/D = 7$

Standard Deviation

SCALE

$x/D = 1$

$x/D = 2$

$x/D = 3$

$x/D = 5$

$x/D = 7$

Figure 4.21 Nozzle 2 (0° ramp) cross-sectional, average and standard deviation images, 30:90 flow rate.

30:90 (m/sec)

Instantaneous

Average

Standard Deviation

$x/D = 1 \quad 2 \quad 3 \quad 5 \quad 7$

Figure 4.22 Nozzle 2 (0° ramp) streamwise views: instantaneous, average and standard deviation, 30:90 flow rate.

Average Images 30:10 (m/sec)

 $x/D = 0$

 $x/D = 1$

 $x/D = 2$

 $x/D = 3$

 $x/D = 5$

 $x/D = 7$

Standard Deviation

SCALE

 $x/D = 1$

 $x/D = 2$

 $x/D = 3$

 $x/D = 5$

 $x/D = 7$

Figure 4.23 Nozzle 1 (10^0 ramp) cross-sectional, average and standard deviation images, 30:10 flow rate.

Average Images 90:30 (m/sec)

$x/D = 0$

$x/D = 1$

$x/D = 2$

$x/D = 3$

$x/D = 5$

$x/D = 7$

Standard Deviation

SCALE

$x/D = 1$

$x/D = 2$

$x/D = 3$

$x/D = 5$

$x/D = 7$

Figure 4.24 Nozzle 1 (10^0 ramp) cross-sectional, average and standard deviation images, 90:30 flow rate.

30:10 (m/sec)

Instantaneous

Average

Standard Deviation

$x/D = 1 \quad 2 \quad 3 \quad 5 \quad 7$
Figure 4.25 Nozzle 1 (10° ramp) streamwise views: instantaneous, average and standard deviation, 30:10 flow rate.

90:30 (m/sec)

Instantaneous

Average

Standard Deviation

$x/D = 1 \quad 2 \quad 3 \quad 5 \quad 7$

Figure 4.26 Nozzle 1 (10^0 ramp) streamwise views: instantaneous, average and standard deviation, 90:30 flow rate.

Figure 4.27 Nozzle 1 (10^0 ramp) cross-sectional, average and standard deviation images, 30:30 flow rate.

Average Images 90:90 (m/sec)

$x/D = 0$

$x/D = 1$

$x/D = 2$

$x/D = 3$

$x/D = 5$

$x/D = 7$

Standard Deviation

SCALE

$x/D = 1$

$x/D = 2$

$x/D = 3$

$x/D = 5$

$x/D = 7$

Figure 4.28 Nozzle 1 (10^0 ramp) cross-sectional, average and standard deviation images, 90:90 flow rate.

30:30 (m/sec)

Instantaneous

Average

Standard Deviation

$x/D = 1 \quad 2 \quad 3 \quad 5 \quad 7$

Figure 4.29 Nozzle 1 (10° ramp) streamwise views: instantaneous, average and standard deviation, 30:30 flow rate.

90:90 (m/sec)

Instantaneous

Average

Standard Deviation

$x/D = 1 \quad 2 \quad 3 \quad 5 \quad 7$

Figure 4.30 Nozzle 1 (10^0 ramp) streamwise views: instantaneous, average and standard deviation, 90:90 flow rate.

Figure 4.31 Nozzle 1 (10^0 ramp) cross-sectional, average and standard deviation images, 30:90 flow rate.

30:90 (m/sec)

Instantaneous

Average

Standard Deviation

$x/D = 1 \quad 2 \quad 3 \quad 5 \quad 7$
Figure 4.32 Nozzle 1 (10^0 ramp) streamwise views: instantaneous, average and standard deviation, 30:90 flow rate.

Figure 4.33 Nozzle 3 (20° ramp) cross-sectional, average and standard deviation images, 30:10 flow rate.

Figure 4.34 Nozzle 3 (20° ramp) cross-sectional, average and standard deviation images, 90:30 flow rate.

30:10 (m/sec)

Instantaneous

Average

Standard Deviation

$x/D = 1 \quad 2 \quad 3 \quad 5 \quad 7$

Figure 4.35 Nozzle 3 (20° ramp) streamwise views: instantaneous, average and standard deviation, 30:10 flow rate.

90:30 (m/sec)

Instantaneous

Average

Standard Deviation

$x/D = 1 \quad 2 \quad 3 \quad 5 \quad 7$

Figure 4.36 Nozzle 3 (20° ramp) streamwise views: instantaneous, average and standard deviation, 90:30 flow rate.

Figure 4.37 Nozzle 3 (20° ramp) cross-sectional, average and standard deviation images, 30:30 flow rate.

Figure 4.38 Nozzle 3 (20° ramp) cross-sectional, average and standard deviation images, 90:90 flow rate.

30:30 (m/sec)

Instantaneous

Average

Standard Deviation

$x/D = 1 \quad 2 \quad 3 \quad 5 \quad 7$

Figure 4.39 Nozzle 3 (20° ramp) streamwise views: instantaneous, average and standard deviation, 30:30 flow rate.

90:90 (m/sec)

Instantaneous

Average

Standard Deviation

$x/D = 1 \quad 2 \quad 3 \quad 5 \quad 7$

Figure 4.40 Nozzle 3 (20° ramp) streamwise views: instantaneous, average and standard deviation, 90:90 flow rate.

Figure 4.41 Nozzle 3 (20° ramp) cross-sectional, average and standard deviation images, 30:90 flow rate.

30:90 (m/sec)

Instantaneous

Average

Standard Deviation

$x/D = 1 \quad 2 \quad 3 \quad 5 \quad 7$

Figure 4.42 Nozzle 3 (20° ramp) streamwise views: instantaneous, average and standard deviation, 30:90 flow rate.

Average Images 30:10 (m/sec)

$x/D = 0$

$x/D = 1$

$x/D = 2$

$x/D = 3$

$x/D = 5$

$x/D = 7$

Standard Deviation

SCALE

$x/D = 1$

$x/D = 2$

$x/D = 3$

$x/D = 5$

$x/D = 7$

Figure 4.43 Nozzle 4 (10^0 ramp) cross-sectional, average and standard deviation images, 30:10 flow rate.

Figure 4.44 Nozzle 4 (10^0 ramp) cross-sectional, average and standard deviation images, 90:30 flow rate.

30:10 (m/sec)

Instantaneous

Average

Standard Deviation

$x/D = 1 \quad 2 \quad 3 \quad 5 \quad 7$

Figure 4.45 Nozzle 4 (10^0 ramp) streamwise views: instantaneous, average and standard deviation, 30:10 flow rate.

90:30 (m/sec)

Instantaneous

Average

Standard Deviation

$x/D = 1 \quad 2 \quad 3 \quad 5 \quad 7$

Figure 4.46 Nozzle 4 (10^0 ramp) streamwise views: instantaneous, average and standard deviation, 90:30 flow rate.

Average Images 30:30 (m/sec)

$x/D = 0$

$x/D = 1$

$x/D = 2$

$x/D = 3$

$x/D = 5$

$x/D = 7$

Standard Deviation

SCALE

$x/D = 1$

$x/D = 2$

$x/D = 3$

$x/D = 5$

$x/D = 7$

Figure 4.47 Nozzle 4 (10^0 ramp) cross-sectional, average and standard deviation images, 3030 flow rate.

Average Images 90:90 (m/sec)

$x/D = 0$

$x/D = 1$

$x/D = 2$

$x/D = 3$

$x/D = 5$

$x/D = 7$

Standard Deviation

SCALE

$x/D = 1$

$x/D = 2$

$x/D = 3$

$x/D = 5$

$x/D = 7$

Figure 4.48 Nozzle 4 (10^0 ramp) cross-sectional, average and standard deviation images, 90:90 flow rate.

30:30 (m/sec)

Instantaneous

Average

Standard Deviation

$x/D = 1 \quad 2 \quad 3 \quad 5 \quad 7$

Figure 4.49 Nozzle 4 (10^0 ramp) streamwise views: instantaneous, average and standard deviation, 30:30 flow rate.

90:90 (m/sec)

Instantaneous

Average

Standard Deviation

$x/D = 1 \quad 2 \quad 3 \quad 5 \quad 7$

Figure 4.50 Nozzle 4 (10^0 ramp) streamwise views: instantaneous, average and standard deviation, 90:90 flow rate.

Average Images 30:90 (m/sec)

$x/D = 0$

$x/D = 1$

$x/D = 2$

$x/D = 3$

$x/D = 5$

$x/D = 7$

Standard Deviation

SCALE

$x/D = 1$

$x/D = 2$

$x/D = 3$

$x/D = 5$

$x/D = 7$

Figure 4.51 Nozzle 4 (10^0 ramp) cross-sectional, average and standard deviation images, 30:90 flow rate.

30:90 (m/sec)

Instantaneous

Average

Standard Deviation

$x/D = 1 \quad 2 \quad 3 \quad 5 \quad 7$

Figure 4.52 Nozzle 4 (10^0 ramp) streamwise views: instantaneous, average and standard deviation, 30:90 flow rate.

Average Images 30:10 (m/sec) **$x/D = 0$** **$x/D = 1$** **$x/D = 2$** **$x/D = 3$** **$x/D = 5$** **$x/D = 7$** **Standard Deviation****SCALE** **$x/D = 1$** **$x/D = 2$** **$x/D = 3$** **$x/D = 5$** **$x/D = 7$**

Figure 4.53 Nozzle 5 (10^0 ramp) cross-sectional, average and standard deviation images, 30:10 flow rate.

Average Images 90:30 (m/sec)

 $x/D = 0$

 $x/D = 1$

 $x/D = 2$

 $x/D = 3$

 $x/D = 5$

 $x/D = 7$

Standard Deviation

SCALE

 $x/D = 1$

 $x/D = 2$

 $x/D = 3$

 $x/D = 5$

 $x/D = 7$

Figure 4.54 Nozzle 5 (10^0 ramp) cross-sectional, average and standard deviation images, 90:30 flow rate.

30:10 (m/sec)

Instantaneous

Average

Standard Deviation

$x/D = 1 \quad 2 \quad 3 \quad 5 \quad 7$

Figure 4.55 Nozzle 5 (10^0 ramp) streamwise views: instantaneous, average and standard deviation, 30:10 flow rate.

90:30 (m/sec)

Instantaneous

Average

Standard Deviation

$x/D = 1 \quad 2 \quad 3 \quad 5 \quad 7$
Figure 4.56 Nozzle 5 (10^0 ramp) streamwise views: instantaneous, average and standard deviation, 90:30 flow rate.

Figure 4.57 Nozzle 5 (10^0 ramp) cross-sectional, average and standard deviation images, 30:30 flow rate.

Average Images 90:90 (m/sec)

$x/D = 0$

$x/D = 1$

$x/D = 2$

$x/D = 3$

$x/D = 5$

$x/D = 7$

Standard Deviation

SCALE

$x/D = 1$

$x/D = 2$

$x/D = 3$

$x/D = 5$

$x/D = 7$

Figure 4.58 Nozzle 5 (10^0 ramp) cross-sectional, average and standard deviation images, 90:90 flow rate.

30:30 (m/sec)

Instantaneous

Average

Standard Deviation

$x/D = 1 \quad 2 \quad 3 \quad 5 \quad 7$

Figure 4.59 Nozzle 5 (10° ramp) streamwise views: instantaneous, average and standard deviation, 30:30 flow rate.

90:90 (m/sec)

Instantaneous

Average

Standard Deviation

$x/D = 1 \quad 2 \quad 3 \quad 5 \quad 7$

Figure 4.60 Nozzle 5 (10^0 ramp) streamwise views: instantaneous, average and standard deviation, 90:90 flow rate.

Figure 4.61 Nozzle 5 (10^0 ramp) cross-sectional, average and standard deviation images, 30:90 flow rate.

30:90 (m/sec)

Instantaneous

Average

Standard Deviation

$x/D = 1 \quad 2 \quad 3 \quad 5 \quad 7$

Figure 4.62 Nozzle 5 (10° ramp) streamwise views: instantaneous, average and standard deviation, 30:90 flow rate.

Average Images 30:10 (m/sec)

$x/D = 0$

$x/D = 1$

$x/D = 2$

$x/D = 3$

$x/D = 5$

$x/D = 7$

Standard Deviation

SCALE

$x/D = 1$

$x/D = 2$

$x/D = 3$

$x/D = 5$

$x/D = 7$

Figure 4.63 Nozzle 6 (10^0 ramp) cross-sectional, average and standard deviation images, 30:10 flow rate.

Average Images 90:30 (m/sec)

$x/D = 0$

$x/D = 1$

$x/D = 2$

$x/D = 3$

$x/D = 5$

$x/D = 7$

Standard Deviation

SCALE

$x/D = 1$

$x/D = 2$

$x/D = 3$

$x/D = 5$

$x/D = 7$

Figure 4.64 Nozzle 6 (10^0 ramp) cross-sectional, average and standard deviation images, 90:30 flow rate.

30:10 (m/sec)

Instantaneous

Average

Standard Deviation

$x/D = 1 \quad 2 \quad 3 \quad 5 \quad 7$
Figure 4.65 Nozzle 6 (10^0 ramp) streamwise views: instantaneous, average and standard deviation, 30:10 flow rate.

90:30 (m/sec)

Instantaneous

Average

Standard Deviation

$x/D = 1 \quad 2 \quad 3 \quad 5 \quad 7$
Figure 4.66 Nozzle 6 (10^0 ramp) streamwise views: instantaneous, average and standard deviation, 90:30 flow rate.

Average Images 30:30 (m/sec)

$x/D = 0$

$x/D = 1$

$x/D = 2$

$x/D = 3$

$x/D = 5$

$x/D = 7$

Standard Deviation

SCALE

$x/D = 1$

$x/D = 2$

$x/D = 3$

$x/D = 5$

$x/D = 7$

Figure 4.67 Nozzle 6 (10^0 ramp) cross-sectional, average and standard deviation images, 30:30 flow rate.

Figure 4.68 Nozzle 6 (10^0 ramp) cross-sectional, average and standard deviation images, 90:90 flow rate.

30:30 (m/sec)

Instantaneous

Average

Standard Deviation

$x/D = 1 \quad 2 \quad 3 \quad 5 \quad 7$

Figure 4.69 Nozzle 6 (10^0 ramp) streamwise views: instantaneous, average and standard deviation, 30:30 flow rate.

90:90 (m/sec)

Instantaneous

Average

Standard Deviation

$x/D = 1 \quad 2 \quad 3 \quad 5 \quad 7$

Figure 4.70 Nozzle 6 (10^0 ramp) streamwise views: instantaneous, average and standard deviation, 90:90 flow rate.

Average Images 30:90 (m/sec)

$x/D = 0$

$x/D = 1$

$x/D = 2$

$x/D = 3$

$x/D = 5$

$x/D = 7$

Standard Deviation

SCALE

$x/D = 1$

$x/D = 2$

$x/D = 3$

$x/D = 5$

$x/D = 7$

Figure 4.71 Nozzle 6 (10^0 ramp) cross-sectional, average and standard deviation images, 30:90 flow rate.

30:90 (m/sec)

Instantaneous

Average

Standard Deviation

$x/D = 1 \quad 2 \quad 3 \quad 5 \quad 7$

Figure 4.72 Nozzle 6 (100 ramp) streamwise views: instantaneous, average and standard deviation, 30:90 flow rate.

Normalized Inner Jet Growth

Figure 4.73 Growth of the inner jet for the Baseline circular nozzle for all five flow conditions.

Normalized Inner Jet Growth

Figure 4.74 Growth of the inner jet for Nozzle 2 (0° ramp) for all five flow conditions.

Normalized Inner Jet Growth

Figure 4.75 Growth of inner jet for Nozzle 1 (10^0 ramp) for all five flow conditions.

Normalized Inner Jet Growth

Figure 4.76 Growth of inner jet for Nozzle 3 (20^0 ramp) for all five flow conditions.

Normalized Inner Jet Growth

Figure 4.77 Growth of the inner jet for Nozzle 4 (10^0 ramp, four lobes) for all five flow conditions.

Normalized Inner Jet Growth

Figure 4.78 Growth of the inner jet for Nozzle 5 (10^0 ramp, four lobes, small) for all five flow conditions.

Figure 4.79 Growth of the inner jet for Nozzle 6 (10^0 ramp, square lobes) for all five flow conditions.

a)

Comparison of Six-Lobed Nozzles with Baseline

b)

Comparison of Six-Lobed Nozzles with Baseline

Figure 4.80a-e Comparisons between the six-lobed nozzles and the baseline circular nozzle for all flow conditions.

Figure 4.80 continued.

c) Comparison of Six-Lobed Nozzles
with Baseline

d) Comparison of Six-Lobed Nozzles
with Baseline

Figure 4.80 continued.

e) Comparison of Six-Lobed Nozzles
with Baseline

a)

Comparison of Four-Lobed Nozzles with Baseline

b)

Comparison of Four-Lobed Nozzles with Baseline

Figure 4.81 Comparison between the four-lobed nozzles and the baseline circular nozzle for all flow conditions.

Figure 4.81 continued.

c) Comparison of Four-Lobed Nozzles with Baseline

d) Comparison of Four-Lobed Nozzles with Baseline

Figure 4.81 continued.
e) Comparison of Four-Lobed Nozzles
with Baseline

Figure 4.82 Comparison of absolute contributions of interfacial contact area and streamwise vorticity to total mixing, for Nozzle 1 (10^0 ramp) at three locations downstream.

Figure 4.83 Sketch of nozzle with corresponding grid for LDV data showing radial and angular dimensions; a) grid used for u and w components, b) grid used for u and v components.

Figure 4.84 a) Axial and b) cross stream velocity plots for the 30:10 (m/sec) flow condition at $x/D = 0.25$.

Figure 4.85 a) Axial and b) cross stream velocity plots for the 30:10 (m/sec) flow condition at $x/D = 1$.

Figure 4.86 a) Axial and b) cross stream velocity plots for the 30:10 (m/sec) flow condition at $x/D = 2$.

Figure 4.87 a) Axial and b) cross stream velocity plots for the 30:10 (m/sec) flow condition at $x/D = 3$.

Figure 4.88 a) Axial and b) cross stream velocity plots for the 30:10 (m/sec) flow condition at $x/D = 4$.

Figure 4.89 a) Axial and b) cross stream velocity plots for the 30:10 (m/sec) flow condition at $x/D = 5$.

Figure 4.90 a) Axial and b) cross stream velocity plots for the 30:10 (m/sec) flow condition at $x/D = 6$.

Figure 4.91 a) Axial and b) cross stream velocity plots for the 30:10 (m/sec) flow condition at $x/D = 7$.

Figure 4.92 Axial velocity profiles along the peak radius for the 30:10 flow condition.

Velocity Profiles Across Troughs **Nozzle 3, 30:10 m/sec**

Figure 4.93 Axial velocity profiles along the trough radius for the 30:10 flow condition.

Cross Stream Velocity Profile: Across Peaks **Nozzle 3, 30:10 m/sec**

Figure 4.94 Cross stream velocity profiles along the peak radius for the 30:10 flow condition. A positive velocity indicates flow away from the jet axis.

Cross Stream Velocity Profile: Across Troughs **Nozzle 3, 30:10 m/sec**

Figure 4.95 Cross stream velocity profiles along the trough radius for the 30:10 flow condition. A negative velocity indicates flow toward the jet axis.

**Axial Velocity Decay 30:10 m/sec
Nozzle 3 and Baseline Circular Nozzle**

Figure 4.96 Axial velocity decay along the centerline for the circular jet and the lobed nozzle for the 30:10 flow condition.

Turbulence Kinetic Energy

Figure 4.97 Contour plot of turbulence kinetic energy at $x/D = 0.25$ for the 30:10 flow condition.

Turbulence Kinetic Energy

Figure 4.98 Contour plot of turbulence kinetic energy at $x/D = 1$ for the 30:10 flow condition.

Turbulence Kinetic Energy

Figure 4.99 Contour plot of turbulence kinetic energy at $x/D = 2$ for the 30:10 flow condition.

Turbulence Kinetic Energy

Figure 4.100 Contour plot of turbulence kinetic energy at $x/D = 3$ for the 30:10 flow condition.

Turbulence Kinetic Energy

Figure 4.101 Contour plot of turbulence kinetic energy at $x/D = 4$ for the 30:10 flow condition.

Turbulence Kinetic Energy

Figure 4.102 Contour plot of turbulence kinetic energy at $x/D = 5$ for the 30:10 flow condition.

Turbulence Kinetic Energy

Figure 4.103 Contour plot of turbulence kinetic energy at $x/D = 6$ for the 30:10 flow condition.

Turbulence Kinetic Energy

Figure 4.104 Contour plot of turbulence kinetic energy at $x/D = 7$ for the 30:10 flow condition.

Figure 4.105 Profiles of turbulence kinetic energy along the peak radius for the 30:10 flow condition.

Turbulence Kinetic Energy Profiles Across Troughs **Nozzle 3, 30:10 m/sec**

Figure 4.106 Profiles of turbulence kinetic energy along the trough radius for the 30:10 flow condition.

Cross Stream Turbulence Kinetic Energy Across Peaks **Nozzle 3, 30:10 m/sec**

Figure 4.107 Profiles of the turbulence kinetic energy of the cross stream components along a peak radius for the 30:10 flow condition.

Cross Stream Turbulence Kinetic Energy Across Troughs **Nozzle 3, 30:10 m/sec**

Figure 4.108 Profiles of the turbulence kinetic energy of the cross stream components along a trough radius for the 30:10 flow condition.

Reynolds Stress-UW Profiles Across Peaks Nozzle 3, 30:10 m/sec

Figure 4.109 UW-Reynolds stress profiles along the peak radius for the 30:10 flow condition.

Figure 4.110 UV-Reynolds stress profiles along the peak radius for the 30:10 flow condition.

Reynolds Stress-UV Profiles (10 Degrees) Nozzle 3, 30:10 m/sec

Figure 4.111 UV-Reynolds stress profiles along the radius 10^0 from the peak radius for the 30:10 flow condition.

Figure 4.112 a) Axial and b) cross stream velocity plots for the 30:30 (m/sec) flow condition at $x/D = 0.25$.

Figure 4.113 a) Axial and b) cross stream velocity plots for the 30:30 (m/sec) flow condition at $x/D = 1$.

Figure 4.114 a) Axial and b) cross stream velocity plots for the 30:30 (m/sec) flow condition at $x/D = 2$.

Figure 4.115 a) Axial and b) cross stream velocity plots for the 30:30 (m/sec) flow condition at $x/D = 3$.

Figure 4.116 a) Axial and b) cross stream velocity plots for the 30:30 (m/sec) flow condition at $x/D = 4$.

Figure 4.117 a) Axial and b) cross stream velocity plots for the 30:30 (m/sec) flow condition at $x/D = 5$.

Figure 4.118 a) Axial and b) cross stream velocity plots for the 30:30 (m/sec) flow condition at $x/D = 6$.

Figure 4.119 Axial velocity profiles along the peak radius for the 30:30 flow condition.

Velocity Profiles Across Troughs Nozzle 3, 30:30 m/sec

Figure 4.120 Axial velocity profiles along the trough radius for the 30:30 flow condition.

Cross Stream Velocity Profile: Across Peaks **Nozzle 3, 30:30 m/sec**

Figure 4.121 Cross stream velocity profiles along a peak radius for the 30:30 flow condition. A positive velocity indicates flow away from the jet axis.

Cross Stream Velocity Profile: Across Troughs **Nozzle 3, 30:30 m/sec**

Figure 4.122 Cross stream velocity profiles along a trough radius for the 30:30 flow condition. A negative velocity indicates flow toward the jet axis.

Axial Velocity Decay 30:30 m/sec
Nozzle 3 and Baseline Circular Jet

Figure 4.123 Centerline velocity decay for the baseline circular nozzle and the lobed nozzle for the 30:30 flow condition.

Turbulence Kinetic Energy

Figure 4.124 Contour plot of turbulence kinetic energy at $x/D = 0.25$ for the 30:30 flow condition.

Turbulence Kinetic Energy

Turbulence Kinetic Energy

Figure 4.126 Contour plot of turbulence kinetic energy at $x/D = 2$ for the 30:30 flow condition.

Turbulence Kinetic Energy

Figure 4.127 Contour plot of turbulence kinetic energy at $x/D = 3$ for the 30:30 flow condition.

Turbulence Kinetic Energy

Turbulence Kinetic Energy

Figure 4.130 Contour plot of turbulence kinetic energy at $x/D = 6$ for the 30:30 flow condition.

Figure 4.131 Turbulence kinetic energy profiles along a peak radius for the 30:30 flow condition.

Turbulence Kinetic Energy Profiles Across Troughs **Nozzle 3, 30:30 m/sec**

Figure 4.132 Turbulence kinetic energy profiles along a trough radius for the 30:30 flow condition.

Cross Stream Turbulence Kinetic Energy Across Peaks **Nozzle 3, 30:30 m/sec**

Figure 4.133 Turbulence kinetic energy of the cross stream components along a peak radius for the 30:30 flow condition.

Cross Stream Turbulence Kinetic Energy Across Troughs **Nozzle 3, 30:30 m/sec**

Figure 4.134 Turbulence kinetic energy of the cross stream components along a trough radius for the 30:30 flow condition.

Reynolds Stress-UW Profiles Across Peaks Nozzle 3, 30:30 m/sec

Figure 4.135 UW-Reynolds stress profiles along the peak radius for the 30:30 flow condition.

Reynolds Stress-UV Profiles Across Peaks Nozzle 3, 30:30 m/sec

Figure 4.136 UV-Reynolds stress profiles along the peak radius for the 30:30 flow condition.

Figure 4.137 UV-Reynolds stress profiles along the radius 10^0 from the peak radius, for the 30:30 flow condition.

Figure 4.138 a) Axial and b) cross stream velocity plots for the 30:90 (m/sec) flow condition at $x/D = 0.25$.

Figure 4.139 a) Axial and b) cross stream velocity plots for the 30:90 (m/sec) flow condition at $x/D = 1$.

Figure 4.140 a) Axial and b) cross stream velocity plots for the 30:90 (m/sec) flow condition at $x/D = 2$.

Figure 4.141 a) Axial and b) cross stream velocity plots for the 30:90 (m/sec) flow condition at $x/D = 3$.

Figure 4.142 a) Axial and b) cross stream velocity plots for the 30:90 (m/sec) flow condition at $x/D = 4$.

Figure 4.143 a) Axial and b) cross stream velocity plots for the 30:90 flow condition at $x/D = 5$.

Figure 4.144 a) Axial and b) cross stream velocity plots for the 30:90 (m/sec) flow condition at $x/D = 6$.

Figure 4.145 a) Axial and b) cross stream velocity plots for the 30:90 (m/sec) flow condition at $x/D = 7$.

Velocity Profiles Across Peaks **Nozzle 3, 30:90 m/sec**

Figure 4.146 Axial velocity profiles along the peak radius for the 30:90 flow condition.

Velocity Profiles Across Troughs Nozzle 3, 30:90 m/sec

Figure 4.147 Axial velocity profiles along a trough radius for the 30:90 flow condition.

Extent of Recirculation Zone Nozzle 3, 30:90 m/sec

Figure 4.148 Centerline velocity plot for the lobed nozzle showing the recirculation zone induced by the 30:90 flow condition.

**Axial Velocity Decay 30:90 m/sec
Nozzle 3**

Figure 4.149 Centerline axial velocity decay for the 30:90 flow condition.

Cross Stream Velocity Profile: Across Peaks **Nozzle 3, 30:90 m/sec**

Figure 4.150 Cross stream velocity profiles along a peak radius for the 30:90 flow condition. A positive velocity indicates flow away from the jet axis.

Cross Stream Velocity Profile: Across Troughs **Nozzle 3, 30:90 m/sec**

Figure 4.151 Cross stream velocity profiles along a trough radius for the 30:90 flow condition. A negative velocity indicates flow toward the jet axis.

Turbulence Kinetic Energy

Figure 4.152 Contour plot of turbulence kinetic energy at $x/D = 0.25$ for the 30:90 flow condition.

Turbulence Kinetic Energy

Figure 4.153 Contour plot of turbulence kinetic energy at $x/D = 1$ for the 30:90 flow condition.

Turbulence Kinetic Energy

Figure 4.154 Contour plot of turbulence kinetic energy at $x/D = 2$ for the 30:90 flow condition.

Turbulence Kinetic Energy

Figure 4.155 Contour plot of turbulence kinetic energy at $x/D = 3$ for the 30:90 flow condition.

Turbulence Kinetic Energy

Figure 4.156 Contour plot of turbulence kinetic energy at $x/D = 4$ for the 30:90 flow condition.

Turbulence Kinetic Energy

Figure 4.157 Contour plot of turbulence kinetic energy at $x/D = 5$ for the 30:90 flow condition.

Turbulence Kinetic Energy

Figure 4.158 Contour plot of turbulence kinetic energy at $x/D = 6$ for the 30:90 flow condition.

Turbulence Kinetic Energy

Figure 4.159 Contour plot of turbulence kinetic energy at $x/D = 7$ for the 30:90 flow condition.

Figure 4.160 Turbulence kinetic energy profiles along a peak radius for the 30:90 flow condition.

Turbulence Kinetic Energy Profiles Across Troughs **Nozzle 3, 30:90 m/sec**

Figure 4.161 Turbulence kinetic energy profiles along a trough radius for the 30:90 flow condition.

Cross Stream Turbulence Kinetic Energy Across Peaks **Nozzle 3, 30:90 m/sec**

Figure 4.162 Turbulence kinetic energy of cross stream components along a peak radius for the 30:90 flow condition.

Cross Stream Turbulence Kinetic Energy Across Troughs Nozzle 3, 30:90 m/sec

Figure 4.163 Turbulence kinetic energy of the cross stream components along a trough radius for the 30:90 flow condition.

Figure 4.164 UW-Reynolds stress profiles along the peak radius for the 30:90 flow condition.

Figure 4.165 UV-Reynolds stress profiles along the peak radius for the 30:90 flow condition.

Figure 4.166 UV-Reynolds stress profiles along the radius 10^0 from the peak radius, for the 30:90 flow condition.

Baseline Nozzle (circular)

Nozzle 2 (straight)

Nozzle1(10 degree ramp)

Nozzle 3 (20 degree ramp)

Figure 4.167 Effect of adding streamwise vorticity for a velocity ratio of 30:10.

Baseline Nozzle (circular)

Nozzle 2 (straight)

Nozzle 1 (10 degree ramp)

Nozzle 3 (20 degree ramp)

Figure 4.168 Effect of adding streamwise vorticity at a velocity ratio of 30:30.

Baseline Nozzle (circular)

Nozzle 2 (straight)

Nozzle 1 (10 degree ramp)

Nozzle 3 (20 degree ramp)

Figure 4.169 Effect of streamwise vorticity for a velocity ratio of 30:90.

Figure 4.170 Effect of velocity level on the thickness of the intermittent regions for the 3:1 velocity ratio at $x/D = 7$.

Figure 4.171 Effect of velocity level on the thickness of the intermittent regions for the 1:1 velocity ratio at $x/D = 7$.

Figure 4.172 Comparison of cross-sectional average images at $x/D = 7$ for the different velocity ratios for nozzle 1.

Figure 4.173 Comparison of streamwise average images for the different velocity ratios for nozzle 1. Downstream scale is the same as for Fig. 4.25.

Figure 4.174 Comparison of streamwise RMS images for the different velocity ratios for nozzle 1. Downstream scale is the same as for Fig. 4.25.

CHAPTER V

SUMMARY AND CONCLUSIONS

Flow visualizations using a passive scalar (tobacco smoke) have been performed to explore mixing processes and enhancement in a dual stream axisymmetric geometry where the inner jet is a lobed mixer nozzle. Seven different nozzle geometries were studied: a circular nozzle, three six-lobed nozzles, and three four-lobed nozzles. The six-lobed nozzles were designed to investigate three different mixing mechanisms. They are, the increased interfacial contact area of the lobed nozzles over the circular nozzle for a given area, the streamwise vorticity produced by the lobed nozzle, and the inner:outer velocity ratio, through the Kelvin-Helmholtz instability. Three different velocity ratios were tested, two of them at two velocity levels, for a total of five flow conditions.

To complement the qualitative visualizations, quantitative velocity measurements were obtained using a two-component, coincident, laser Doppler velocimeter. Measurements for nozzle 3, which produces the highest level of streamwise vorticity, were taken for the 30:10 m/sec (inner:outer), 30:30 and 30:90 flow conditions.

Qualitatively, the streamwise visualizations showed little difference in jet spread (average images) for different velocity levels (e.g., Fig. 4.173). There are, however, noticeable differences in the cross-sectional average images for the different velocity levels. These differences can generally be attributed to lower smoke seeding at the higher flow rates. The gross smoke patterns are the same, just the details at the outer reaches of the images are not as visible, due to insufficient smoke.

The spread of the inner jet was generally the greatest for the 3:1 velocity ratios, followed by the 1:1 ratios, and finally the 1:3 velocity ratio. The spread for the 1:3 ratio, however, was frequently comparable to the 1:1 cases (see also, Fig. 4.172). Without the Kelvin-Helmholtz instability, the 1:1 velocity ratios do not produce as much interaction between the individual lobes.

On the other hand the intermittent regions, exhibited in the RMS images, did show a difference between the different velocity levels. The intermittent regions were generally thicker for the higher velocities, which was attributed to the higher level of streamwise vorticity produced when the axial velocity is higher. A thicker intermittent region was not witnessed for the baseline circular nozzle because no streamwise vorticity is produced. A moderate thickening of the intermittent region was visible for nozzle 2 because of the small amount of streamwise vorticity still present after the damping effect of the straight section (see Fig. 4.170).

Streamwise views of the spread of the inner jet showed a generally constant growth rate for the 3:1 velocity ratios. The 1:1 and 1:3 ratios also show a constant,

although lower, growth rate for several diameters downstream, after which a discontinuity, or jump, in jet spread is seen (see e.g., Fig. 4.173).

The different spreading characteristics of the inner jet for the different velocity ratios is due to different mixing processes. The jet spread for the 3:1 velocity ratios, with an outward roll to the interface, is a combination of the Kelvin-Helmholtz instability (as is typical of round jets) with the streamwise vorticity. The LDV data for N3 (Figs. 4.84 - 4.91) showed that strong streamwise vortices developed for this velocity ratio and spiraled radially outward as the jet expanded. Though LDV data were only taken for N3, the flow visualizations show that similar processes are occurring at this velocity ratio for all the nozzles. Comparing the streamwise RMS images for N1 (e.g., Fig. 4.174) with the LDV data, it was concluded that the mixing for the 3:1 velocity ratios is governed by the interface roll up, in combination with the streamwise vorticity.

The LDV data for the 1:1 velocity ratio (Figs. 4.112 - 4.118) also showed strong streamwise vortices, but unlike the 3:1 case, they did not travel radially outward. They were also found to break down near $x/D = 3$. Again, using the LDV data in combination with the streamwise RMS images (e.g. Fig. 4.174), it can be concluded that the mixing for this case is much more dependent upon the streamwise vorticity generated by the nozzle.

The mixing processes for the 1:3 velocity ratio are different than the previous two cases. The LDV data (Figs. 4.138 - 4.145) showed that little or no streamwise vorticity was generated, as the outer stream appeared to completely dominate the inner

stream. A representative streamwise RMS image for this velocity ratio (Fig. 4.174) shows a slightly inward slant to the 'main' intermittent region, with a darker, ancillary mixing region surrounding it, which forms the region of the jump in the jet growth. This behavior shows that the outer flow for the 1:3 case is interacting strongly with the ambient air and controlling the mixing of the inner stream. Thus, the three different velocity ratios tested are governed by three different mixing processes.

Quantitative estimates of the spread of the inner jet were made based on a pixel counting technique. The technique contains some subjectivity in determining the area of the smoke-filled regions, however, consistent results were obtained for all the nozzles and flow rates. Overall jet spread, normalized by the nozzle exit area (which is equal for all nozzles except N5) was highest for N3 and N5. Nozzle three induces the greatest streamwise vorticity and produced the highest area-filling smoke pattern (Fig. 4.33 - 4.34). The smoke pattern for N5 did not cover as large an area as N3, but due to N5's lower exit area, the relative spreads are comparable. This is because of possible overlapping of the smoke for the six-lobed nozzle which may not be present to the same degree in N5. Also, previous researchers, using tabs to generate streamwise vortices, have found that a higher number of tabs produced interactions between the streamwise vortices that tended to combine them.

When the mixing enhancement effects of interfacial surface area and streamwise vorticity were separated, it was found that the relative effect of streamwise vorticity increased from the 1:1 case to the 3:1 case, at $x/D = 1$. This is in agreement with previous researchers. The relative effect of streamwise vorticity also increased with

downstream distance, but to varying degrees. The 1:1 case showed the largest relative increase with downstream distance since interface roll up is at a minimum.

The lobed mixer does appear to mix two streams more quickly than a circular jet. The increased interfacial surface area of the lobed nozzle (i.e., perimeter) enhances mixing because the two streams have a greater region of interaction. The streamwise vorticity produced by the lobed nozzle also enhances mixing because the pumping action of the streamwise vorticity sweeps the outer fluid into the inner stream and the inner fluid into the outer stream.

Previous research for two-dimensional, confined flows found that the streamwise vortices remained within the projected area of the lobed mixer as they advected downstream. The unconfined, axisymmetric flow of the present study showed that, depending on velocity ratio, the streamwise vortices may or may not spiral radially outward, or even exist. It was also seen that one of the streams can completely dominate the mixing processes. A designer, contemplating using a lobed nozzle to enhance the interaction between two flows streams, would need to be aware of the different mixing mechanisms involved.

Recommendations for future work would include performing simultaneous flow visualizations for both inner and outer streams to explore their interaction in more detail. Also, it would be instructive to design a nozzle that produces streamwise vorticity but does not impart a *net* radial (cross-stream) velocity in either direction. A nozzle that produces swirl might be a logical choice, but it would need to have the requisite commingling of the streams that the lobed mixer produces at the exit plane.

Another area that should be addressed is the 'cost' of mixing. It generally requires some amount of energy to mix two fluids and this is usually in the form of pressure drop. Exploring the relationship between pressure drop and mixing would be a worthwhile endeavor. This would entail devising a definition for mixedness however, which is a project in itself.

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