CHAPTER 3

ACTIVE TRIANGULAR NOZZLE STUDY

3.1 Background

3.1.1 Flow Control

Mixing in jet flows can be enhanced by two primary means, "passive" or "active". Passive control of jets consists of changes to the nozzle geometry to enhance mixing, such as using non-circular nozzles (Ho and Gutmark, 1986; Schadow, et al., 1988), and delta tabs as vortex generators (Zaman, Reeder, and Samimy, 1993; Grinstein, et al., 1993). These have been shown to affect the far flow field, but in a fixed manner; the manner in which the flowfield was affected could not be changed except by changing the nozzle geometry. Active control consists of introducing perturbations into the flow in order to influence the evolution of the jet flow. Active control has been shown to yield substantial control over the development of the near flow field, but, until recently, the effect did not seem to influence the far flow field (Cohen and Wygnanski, 1987; Corke and Kusek, 1993).

In several recent studies, C. Ding (1995) has shown that it is possible to control the evolution of jets in the near and far flow fields using spatial mode control. He applied spatial mode control to both a high turbulence level, fully developed flow issuing through a triangular nozzle (Vandsburger and Ding, 1995), and to a very low turbulence level, top-hat flow issuing through a round nozzle. The active triangular nozzle apparatus was chosen for this study due to the availability of momentum transfer data for comparison.

3.1.1.1 Spatial Mode Control

Spatial mode control takes advantage of the fact that jet flows have an additional dimension over the planar mixing layer, the jet diameter, which governs the evolution of the flow. The amplitude of excitation can be controlled along the azimuthal direction of the jet, exciting those azimuthal modes, or spatial modes, to which the flow may be unstable. The spatial modes can be defined by a mode number, m, which corresponds to the azimuthal wavenumber. The axisymmetric mode has no helical mode, and is thus m=0. The integer mode numbers, m=1, 2, etc., correspond to the first helical mode, second helical mode, and so

on. Double helical modes, or counter-propagating helical modes are those where helical mode pairs with equal but opposite azimuthal wavenumbers are superimposed, e.g. m=±1 corresponds to the pair of counterpropagating first helical modes. These different modes have been observed in the far field of a turbulent jet (Tso and Hussain, 1989; Yoda, 1992).

Excitation of these various modes began with Strange (1983), who studied a round, high Reynolds number jet excited at m=0, 1 and 2. This study showed that the growth rates of the axisymmetric and first helical modes in the near field were comparable. Later works by Cohen and Wygnanski (1987), and Corke and Kusek (1993) proved, both theoretically and experimentally, that many modes are equally unstable in the near field of circular jets. Of greater importance to this study, however, Cohen and Wygnanski (1987) showed that single, integer mode excitation had little effect over the jet, but standing wave excitation, another name for the counterrotating helical modes of the same mode number, can control the shape of the iso-velocity contours of the jet. For example, the iso-velocity contour shape generated by m=±1 excitation is elliptic, that of m=±1.5 excitation is triangular, and that of m=±2 excitation is square or cross-shaped.

3.1.1.2 Non-circular Nozzles

Non-circular nozzles have begun receiving more attention recently because they cause more efficient fluid entrainment than circular nozzles. Several non-circular geometries have been studied in unforced, cold flow studies, including elliptical (Ho and Gutmark, 1987; Hussain and Husain, 1989), square (Quinn and Militzer, 1988; Gutmark, Schadow, and Wilson, 1991; Grinstein, Gutmark, and Parr, 1995), rectangular (Sforza, Steiger, and Trentacoste, 1966), and triangular (Gutmark, et al., 1985; Gutmark, Schadow, and Wilson, 1991). These non-circular geometries have shown some advantages in changing the development of the far flow field with respect to a circular nozzle, but this change is fixed. Thus, the combination of external forcing combined with a non-circular nozzle might yield a controllable change in the far field of a jet. Examples of existing work in the area of excited non-circular nozzles are the cold flow studies of Wiltse and Glezer (1993) using a square nozzle, and Vandsburger and Ding (1995) using a triangular nozzle. One advantage to the sharp-edged non-circular geometries, such as the triangular nozzle, is that large-scale turbulence is generated along the sides of the nozzle, while small-scale turbulence is generated at the vertices.

3.1.2 Motivation

The motivations of this study were twofold: first, to develop flow visualization systems for the measurement of mixing in actively controlled free shear flows, and secondly, to examine the mass transfer characteristics of actively excited jets to compare with previous

experiments measuring momentum transfer. The active triangular jet apparatus was chosen as the platform for technique development because of the availability of hot-wire anemometry measurements of the effects of spatial mode excitation on the velocity field of the flow for comparison purposes with data collected using flow visualization (Vandsburger and Ding, 1995). Because the nozzle fluid and ambient fluid were both air, it was theorized that the mass and momentum transfer characteristics of the excited jet would be similar. In addition, insight into the development of the concentration field of the jet was needed in order to determine if the spatial mode control actually enhanced mass transfer in the same manner as it enhanced momentum transfer.

3.2 Apparatus

The experiments were carried out using a triangular nozzle 12 mm on each side, yielding a hydraulic diameter of about 7 mm. Each of the flat sides of the nozzle consisted of an actuator made of 0.009" thick brass shim material and 0.03" bimorph piezoceramic material (Piezoelectric Products, Metuchen, NJ), as shown in Fig. 3.1. The actuators responded over a range from 30 Hz to 120 Hz, with a peak amplitude around 70 Hz. The actuators were driven by a PC-486 using a National Instruments AT-AO-10 D/A card. The amplitudes of the three output channels were controlled using audio amplifiers and transformers in order to match the amplitude of the vibration of each actuator at 80 Hz. Other channels of the output were used to trigger the CCD camera, and in the PLIF cases, to trigger the excimer laser. The trigger pulses were synchronized with the sine waves sent to the actuators, allowing for the collection of instantaneous phase-locked or phase-averaged images. The second and third actuator signal channels could be controlled in phase relative to the first channel, in order to generate a variety of spatial modes. The phase of the trigger pulses with respect to the first channel could also be varied in order to collect data at different points in the excitation cycle.

3.3 Experimental Conditions

The experiments were run using a jet of air, seeded with either oil smoke or acetone vapor, issuing into stagnant room air. The Reynolds number of the flow was 8000, based on the hydraulic diameter of the nozzle. A hot-wire anemometer was used to measure the initial conditions of the flow. The flow was fully sheared, with a turbulence level of about 10% at the vertices of the triangle. The velocity profile and turbulence level are shown in Fig. 3.2. The actuators were driven at 80 Hz, to match the conditions used in previous hot-wire studies of the same nozzle (Vandsburger and Ding, 1995).

3.4 Results
3.4.1 Planar Mie Scattering

The first set of experiments was run using the Planar Mie Scattering technique to visualize the flow, as detailed in Chapter 2. Five different excited cases were run, with spatial modes of m=0 (axisymmetric), m=1 (first helical mode), m=0.75 (fractional mode), m=±1 (counterrotating first helical mode), and m=±0.5 (counterrotating fractional mode). These were compared to a baseline case run without any actuation. The excited cases were all taken at phase=0° in the excitation cycle.

Shown in Fig. 3.3, A-F, are the two-dimensional iso-intensity contour I/Imax(z) = 0.5, or half intensity contour, at the station z/D = 30, for the unexcited jet and the five spatial modes listed above. Plot A shows the contour for the unexcited case, for comparison, showing that the initially triangular jet has returned to round by the time it reaches the far field. Plot B shows that excitation mode m=0 has very little effect on the far field contour of the flow. The contour has changed shape slightly, but there is little to no expansion. For mode m=1, plot C shows that there is some expansion of the contour in the far field over that of the unexcited case, but the contour is still basically round. Plots D-F, for modes m=0.75, m=±1, and m=±0.5, respectively, show that not only is the contour expanded over that of the unexcited case, but also that the contour shape has changed from circular to elliptical. Mode m=±1 shows the most pronounced elliptical shape. Thus, the size and shape of the far field contour can be controlled using the spatial mode control method.

Three-dimensional iso-intensity surfaces over the range of $0 \leq z/D \leq 30$, also of I/Imax(z) = 0.5, are shown in Fig. 3.4, A-F. These plots show the development of the jet into the contours shown in Fig. 3.3. In the four modes which show expansion (m=1, m=0.75, m=±1, and m=±0.5), there is evidence of coherent structures being formed in the flow, shown by bulges in the jet column.

For comparison, shown in Fig. 3.5 are the three-dimensional iso-velocity contours generated by C. Ding on the same experimental apparatus (Vandsburger and Ding, 1995). The only differences between the setups were the actuators and the air supply system upstream of the triangular nozzle. The actuators used by C. Ding were monomorph piezoceramic patches, 0.012" thick, bonded to brass shims, 0.009" thick with conducting epoxy. The actuators were tailored to have their resonant frequency near 80 Hz. However, the amplitude of vibration remained the same for both studies. The pipe length entering the triangular nozzle was reduced from 24" in the experiments by C. Ding to 18" in this study, though the 12" long triangular nozzle section remained the same. In addition, the smoke seeding system was added to the air supply system used by C. Ding.

The plots in Fig. 3.5 are of the contour U/Umax(x) = 0.5 over the range of $0 \leq x/D \leq 30$. It is evident that the plots show similar trends: expansions of the iso-surface are seen for m=1, m=0.75, m=±1, and m=±0.5, and elliptical far-field contours are seen for m=0.75, m=±1, and m=±0.5. The motion of the jet column in the near to intermediate fields, from the nozzle exit to about z/D = 10, is also very similar. However, the experimental results show differences in the rate of expansion for all cases, including the unexcited. There are several possibilities as to why this might be seen. First, the differences in initial conditions may have contributed. The shorter length of pipe upstream of the nozzle and the seeding system may have changed the velocity profile of the jet such that the jet column would not respond to the excitation in quite the same manner. Second, the high Schmidt number of the smoke particles may have limited their transport, and thus the particles may not have followed the mass transfer of nozzle air molecules completely. It is clear, though, that the spatial mode control technique enhances the mass transfer in the jet as well as the velocity transfer.

3.4.2 Planar Laser-Induced Fluorescence

There was some concern that the PMS technique might mask some details of the flow evolution due to the high Schmidt number of the smoke particles. Therefore a new set of experiments were run using Planar Laser-Induced Fluorescence of acetone vapor. The same six conditions were run: unexcited, m=0, m=1, m=0.75, m=±1, and m=±0.5. All five excitation modes were measured at phase=0° in the excitation cycle. In addition, for m=±1, measurements were taken at phase=0°, 60°, 120°, 180°, 240°, and 300° in the excitation cycle in order to study how the flow evolves temporally as well as spatially.

The two-dimensional iso-intensity contours, I/Imax(z)=0.5, for z/D=30, are shown in Fig. 3.6, A-F. Again, Plot A shows the contour of the unexcited case, for comparison. The area enclosed by the contour at z/D = 30 is 648 mm^2. As seen in Fig. 3.3 earlier, the contour for m=0 in Plot B is still roughly circular in shape, like the unexcited jet. However, the area enclosed by the contour has increased by about 30%, to 844 mm^2. The contour for m=1 in Plot C shows a more dramatic expansion than that seen in Fig. 3.3, but still circular in shape. The area enclosed by the half intensity contour for m=1 is 1080 mm^2, which is more than 65% greater than the size of the unexcited case. The contours for m=0.75, m=±1, and m=±0.5 all show expansions and elliptical shapes, as seen previously in Fig. 3.3. The areas of the half intensity contours are 1355 mm^2, 1414 mm^2, and 1146 mm^2 respectively. Again, in these plots, the contour for m=±1 is definitely the largest of the three, increasing almost 120% in area, and the elliptical shape is even more pronounced than previously.

Shown in Fig. 3.7 is the increase in the area enclosed by the half intensity contour, plotted versus downstream location. In the near field, z/D < 10, there appears to be very little difference between the rates of expansion of the excited an unexcited jets. However, the

excitation appears to generate a dramatic increase in cross-sectional area at about z/D = 13 for m=1 and m=±1, z/D = 15 for m=±0.5, and m=17 for m=0.75. It also appears that the rate of growth of the area within the half intensity contour is greater with excitation, with the greatest rate of growth for the m=±1 excitation. The point in the flowfield where the dramatic expansion begins in this study contrasts with that seen in Fig. 3.5, the results of the experiments by C. Ding. Again, it is hypothesized that the differences in the apparatus upstream of the nozzle exit caused difference in the onset of the expansion of the jet.

Though there were some measurable and visible changes in the two-dimensional iso-contours shown in Fig. 3.6, there are even more significant differences in the three-dimensional iso-intensity contours. These are shown in Fig. 3.8, A-F, for I/Imax(z) = 0.5, over the range of $0 \leq z/D \leq 30$. Plot A shows the unexcited jet, which can be used as a baseline for comparison. For the jet excited with mode m=0, the jet develops to a very similar contour, but the jet column shows evidence of the axisymmetric forcing in the shape of the jet column. These details were completely masked in the PMS images. Plot C, showing the jet exited with mode m=1, shows strong evidence of the helical mode in the shape of the jet column. Again, this was hardly evident in the data from the PMS experiment. The increased level of detail seen in the jet columns of the m=0 and m=1 cases in the PLIF experiment are most probably due to the molecular rather than particulate seed. The inertia of the acetone molecules is much lower than that of the smoke particles, and thus could better reflect the subtle changes in the flowfield for these modes. Thus, the acetone molecules follow the nozzle air, while the smoke particles continued on their previous course with little disturbance. The development of the last three cases, m=0.75, m=±1, and m=±0.5, were very similar to those seen in the PMS cases. The movement of the jet column appears to be much better defined in the PLIF images, but it was still evident in the PMS images. The increased definition is also due to the molecular rather than particulate tracer. However, the particles were still able to follow the primary characteristics of the flowfield.

The results collected using PLIF should also be compared to those collected using the hot-wire, shown in Fig. 3.5. Again, the rate of expansion of the contours is not as great in the PLIF experiments, even in the unexcited case. Also, the detail of the axisymmetric (m=0) and helical (m=1) excitation effects on the flow are visible in the PLIF experiment, which they are not in the hot-wire experiment. The question arises again as to why there are differences between the hot-wire and flow visualization results. The two theories remaining after the PMS experiments were that the differences were due to either the initial conditions or the high Schmidt number of the smoke. The latter seems to be unlikely given the PLIF results because the acetone was a molecular rather than a particulate tracer, and thus should have accurately followed the nozzle fluid. Dimotakis (1989) noted that the far field behavior of turbulent free shear layers is dependent on the initial conditions. Thus it seems most likely that the differences seen can probably be attributed to the differences in initial conditions between the experiments. It is still evident, though, that the mass transfer of the jet, whether measured using PLIF or PMS, is enhanced through the use of spatial mode excitation.

Figure 3.9, A-F, shows results for the mode m=±1 case taken at phase= 0°, 60°, 120°, 180°, 240°, and 300° in the excitation cycle. By closely studying the lower section of the jet, in the range of $0 \leq z/D \leq 15$, motion is evident in the jet column. This motion is the formation and movement downstream of large scale structures in the flow. These structures are being formed due to the excitation being applied to the flow. Very little change is seen in the upper half of the images, due to the phase decorrelation in the flow. This matches well with similar tests run by C. Ding (Vandsburger and Ding, 1995), where control over the jet evolution in the far field was attributed to the three-dimensional motion of the jet column in the near field. The large directional expansion seen by C. Ding is also evident, which has been attributed to the asymmetric movement of the jet column in the near field. This test also serves as a validation of the phase-locking of the imaging because the structures observed would not be moving downstream with increasing phase angle if the images were not being taken sequentially in the excitation cycle.

To verify the repeatability of the results, the 2-D and 3-D iso-intensity contours for tests run at the same conditions but various times and days were compared. These contours indicated that the behavior of the flowfield was the same. There was some variation in the contours, but the general characteristics of the jet column motion, contour shape, and contour area increase were repeatable from experiment to experiment. In order to quantify the variations seen in the area enclosed by the iso-intensity contour, a statisitical analysis was performed. The standard deviation was consistently found to be about 5% of the average area, regardless of downstream position and spatial mode. This yields a 95% confidence band of ±10% for the area enclosed by the iso-intensity contour.

3.5 Summary and Conclusions

The first goal of this study, to develop techniques for the measurement of the concentration field in forced flows, was realized. Both visualization techniques, Planar Mie Scattering from oil smoke particles and Planar Laser-Induced Fluorescence of acetone vapor, were able to yield information on the concentration field of the triangular jet. The techniques can also yield temporal data by changing the sampling phase with respect to the excitation. There were visible differences in the results of the visualization experiments compared with the hot-wire experiments, though these were most likely due to differences in the initial conditions of the two experiments, such as the velocity profiles of the jets, and not a result of the high Schmidt number of the smoke particles. It is evident that the PLIF visualization technique can yield detail of the flow structure superior to that of the hot-wire measurements, especially in the cases of m=0 and m=1.

It was shown that the PMS technique is capable of showing the major effects of the spatial mode control on the jet development, but the PLIF technique provides a more accurate picture of the jet development. This is probably due to the large inertia of the smoke particles

used in the PMS technique which had to be overcome by the bulk fluid motion in order for the particles to follow the nozzle fluid, but the acetone molecules acted as part of the nozzle fluid and thus were transported by smaller scale structures and diffusion, as well as by the large scale structures. The PMS technique is still valid for use in flows where bulk fluid motion is the most important transport mechanism and can still yield useful, though not completely detailed, pictures of the flow field in excited turbulent jets.

The second goal of this study was to study the mass transfer characteristics of an actively controlled triangular jet. The development of the flow from the actively excited triangular jet was observed for the spatial modes m=0, m=1, m=0.75, m=±1, and m=±0.5, using both the PMS and PLIF techniques. Though the mass transfer could not be quantified, the dramatic expansion of the far field contours indicates that m=1, m=0.75, m=±1, and m=±0.5 excitations all enhance the mass transfer from the jet by generating three-dimensional motion in the jet column. In addition, m=0.75, m=±1, and m=±0.5 excitations all yield elliptical contours in the far flow field of the jet, due to the axisymmetric directional movement of the jet column in the near field. This elliptical expansion, which is fixed in orientation for a given zero reference actuator, could lead to techniques to actively control the concentration field in the far flow field of jet flows. The mode m=±1, the counterrotating helical mode, shows the greatest improvement to mixing and the most pronounced elliptical contour, and therefore is the most promising for further studies in spatial mode control.