CHAPTER 4

SWIRL NOZZLE STUDY

4.1 Background
4.1.1 Swirl flows

Swirling jet flows continue to be an important area of research in the combustion community because of the added flame stability provided by the swirl and because it is also the primary means currently employed for fuel - air mixing. This is especially critical in modern combustors designed to operate in the lean premixed mode in order to minimize pollutant formation. The issue for combustion research in the field of lean, premixed combustors is, therefore, the enhancement of mixing between fuel and oxidizer. Enhanced mixing can lead to lower pollutant emissions and greater efficiency as well as providing more stable combustion. A review of early studies into combustion in swirling flows was presented by Syred and Beer (1974). More recent studies have been conducted on swirl combustors to show the effect of swirl on NO_X formation (Claypole and Syred, 1981), stability limits (Rawe and Kramer, 1981), blowout limits (Feikema, Chen, and Driscoll, 1990), and flame stabilization (Hillemanns, Lenze, and Leuckel, 1986). An interesting apparatus is the variable geometry swirl combustor at the University of Maryland, which has six concentric annuli for the study of stability and emissions characteristics in complex swirling flows (see Gupta, et al., 1991, and references therein). A study by St John and Samuelsen (1994) applied active control techniques to a swirl combustor, using swirl intensity and excess air as control variables to optimize burner operation with respect to NOx emissions and combustion efficiency.

The two primary types of swirl combustors are the swirl burner and the cyclone combustion chamber. In the swirl burner, swirling air and coflowing fuel exit into a furnace or the atmosphere, where combustion occurs. In the cyclone burner, air is injected tangentially into the combustion chamber, where it is mixed with the fuel and combustion occurs (Syred and Beer, 1974). The tangential momentum imparted by the swirling air seems to help stabilize and enhance mixing in the nonpremixed flame (Rawe and Kremer, 1981). For comparison purposes, the geometric swirl number, Sg as defined by Claypole and Syred (1981), can be used as a non-dimensional measure of the angular momentum added to the flow. The swirl number is given by:

$$Sg = (r_o \pi r_e) / A_t \text{ [Tangential Flow / Total Flow]}^2$$

where r_o = the radius of the swirl generator jets (SGJs) from the center of the combustor
r_e = the radius of the tangential inlets
A_t = the total area of the SGJ inlets

Most of the swirl combustion studies conducted have used very high swirl numbers, generally on the order of Sg = 1. This is to ensure the formation of a recirculation zone at the main jet exit, which greatly enhances mixing and causes the stabilization of the flame. The effect of this recirculation zone was studied by Chen and Driscoll (1988). They showed that as swirl is increased, a jet flame can be reduced in length by a factor of five. However, in another study, Tangirala and Driscoll (1988) showed that the reaction aids in the recirculation vortex formation, since a cold flow test with Sg = 1.0 did not show a recirculation vortex. A later study by Feikema, Chen, and Driscoll (1990) studied some swirl flames with low enough swirl numbers that the recirculation vortex did not form. They found that these low swirl conditions can have a beneficial effect on the stability and blowout limits of these co-flowing fuel and air flames. They also verified that lean flames need to have a lower swirl number in order to be stable, because the swirl velocity can subject the reaction zone to flame strain which results in the quenching of the reaction.

4.1.2 Objectives

The objective for this study was to determine what effect pulsing swirl generator jets would have on the development of a swirling flow. Pulsed jets have been used in boundary layer control by McManus, Legner, and Davis (1994). The pulsing jets promoted mixing between the high velocity fluid in the free stream with the low velocity fluid in the boundary layer by generating streamwise vorticity in the flow. Their data suggested that the mass flow for separation control was greatly reduced by using pulsed jets instead of continuous jets. It was thought that it might be possible to make additional gains in swirl flow mixing through the use of pulsed swirl generator jets to create controlled large scale structures in the flow. Using pulsed jets, it would also be possible to apply the spatial mode control described in Chapter 3 to swirling jet flows, and to study the effect of spatial mode control using pulsed jets rather than vibrating actuators.

4.2 Apparatus

In order to study the effects of pulsed swirl generator jets on a jet flow, and thus possible applicability to swirl combustors, this study was conducted using a round nozzle. The nozzle consisted of a round jet of 12.5 mm diameter, with four tangential injection ports of 1.75 mm diameter. The nozzle geometry is shown in Fig. 4.1. The tangential air was supplied through four externally controlled solenoid valves, which could be pulsed at a rate of up to 35 Hz, at varying pulse duration, or held continuously open. By using a PC-486 with a D/A board, the frequency, pulse duration, and sequence of valve openings were controlled. Trigger pulses were also generated by the PC for the camera (PMS and PLIF) and the excimer laser (PLIF only), to allow for phase-locked data sampling.

4.3 Experimental Conditions

The experiments were run using a jet of air issuing into stagnant room air. The main jet was seeded with either oil smoke or acetone vapor, while the air in the SGJs was not seeded. The mass flow rate of air through the main jet was 1.5×10^{-3} kg/s, and the maximum velocity of the main jet was 13 m/s. The Reynolds number of the flow was 8300, based on the nozzle diameter and average velocity. The initial conditions of the main jet flow were measured using a hot-wire anemometer. The main flow was neither top hat nor fully sheared, and had a turbulence level of about 5%. The velocity profile and turbulence level are shown in Fig. 4.2. The valves were driven at 10, 20, and 30 Hz, to see how frequency variations affect the flow. The constant flow side jets were operated at momentum ratios (MR) of 0.02, 0.08, and 0.18 with respect to the main jet, yielding geometric swirl numbers of 0.04, 0.13, and 0.26 respectively. The swirl numbers for the pulsed tangential jet cases depended on the pulse duration used as well as the momentum ratio. For the present study, the pulse duration was half a cycle on each valve, yielding swirl numbers of 0.01, 0.04, and 0.08 for MRs of 0.02, 0.08, and 0.18 respectively.

4.4 Application of Spatial Mode Excitation

In the active triangular nozzle study, the actuators used were able to respond to a sine wave source with a sinusoidal vibration. In the present study, the valves used were of an on/off type, which would only respond to a square wave excitation. Thus, modification of the control scheme was necessary to attempt to apply the spatial mode control technique to the pulsed SGJ system. This was done by varying the order in which the valves were opened. For the axisymmetric mode, m=0, all the valves opened together and closed together. To generate the first helical mode, the four valves were opened sequentially, clockwise, one quarter cycle apart. Similarly, to generate the fractional mode used, in this case m=0.5, the valves were opened in order, clockwise, one eighth cycle apart. For the counter-rotating modes, the waveforms for clockwise and counter-clockwise were superimposed and the result sent to the valves. For mode $m=\pm1$, this yielded the first two valves (0 and 1) opening together, and the opposite two valves (2 and 3) opening together one half cycle later. The result for mode $m=\pm0.5$ was to have three valves (1, 2, and 3) open one quarter cycle after the initial valve opened (0).

4.5 Results
4.5.1 Planar Mie Scattering

The initial phase of this study consisted of a broad range of tests on the swirl flow facility, using the Planar Mie Scattering technique to visualize the development of the flow. The parameters varied were the momentum ratio between the main and side jets, pulsation frequency, and the spatial mode generated by the pulsating jets. The momentum ratios studied were 0.02, 0.08, and 0.18, for side jet maximum velocities of 13 m/s, 25 m/s, and 38 m/s respectively. For comparison purposes, the flowfield was studied with the side jets running continuously. The spatial modes run were m=0, m=1, m=0.5, m=±1, and m=±0.5. For a single mode case, m=1, the effects of pulsation frequencies of 10, 20, and 30 Hz were studied.

Figure 4.3, A-F, shows the two-dimensional iso-intensity contours, I/Imax(z) = 0.5, or half intensity contours in the far field, at z/D = 15, and the three-dimensional iso-intensity contours, I/Imax(z) = 0.5, over a range of $0 \leq z/D \leq 15$, for MR = 0.02, 10 Hz excitation, for several spatial modes. Plot A shows the case of constant swirl, for comparison. The area inside the far field contour, z/D = 15, is 940 mm^2. Plot B shows the contours for m=0. This plot shows that there is some evidence of structure in the flow, and the area inside the far field contour has expanded slightly over that of the constant swirl jet case, to 1162 mm^2, a 25% increase, but still appears to be circular. The contour for m=1, Plot C, shows more evidence of structure in the flow. The shape of the far field contour is still round, but has expanded to 1593 mm^2, or 70% larger than the constant flow case. Plot D, the contour of the m=0.5 case, again shows some signs of coherent structures in the flow and appears to have a far field contour similar to that of m=0, with an area of 1326 mm^2, a 40% increase. Plot E, showing the contours for m=±1 shows very little effect from the excitation. There is some slight evidence of structure in the jet column, but the far field area is only 1032 mm^2., an increase of only 10%. The contours for m=±0.5, Plot F, show little evidence of structure, but the area of the far field contour expanded to 1384 mm^2, an increase of 45%.

Figure 4.4, A-F, shows the same types of iso-contours for the case of MR = 0.08, and 10 Hz excitation for several spatial modes. For the m=0 case, shown in Plot B, structures are clearly visible in the flow. However, there is little expansion in the far flow field contour from the constant flow side jets case, only 10%, from 1044 mm^2 to 1142 mm^2. In Plot C, the contour for the m=1 case indicates that large structures are being generated in the flow. The far flow field contour expanded dramatically, to 1809 mm^2, an increase of 75%, though the contour still appears to be roughly circular in shape. The last three cases, m=0.5, m=±1, and m=±0.5, shown in Plots D, E, and F, respectively, all exhibit clear evidence of structures being formed in the flow and large expansions compared to the constant flow case. The far field contour for m=0.5 is slightly elliptical and has an area of 2142 mm^2, a 105% increase. The plot of the far field contour for m=±1 is round in shape and the area increased 85%, to

1939 mm^2. Finally, the far field contour for the m=±0.5 case is roughly triangular in shape, and doubled in area, to 2076 mm^2.

The contours for the last case of momentum ratio examined, MR = 0.18, are shown in Fig. 4.5. The contour for m=0, Plot B, shows a development slightly different from that of the constant side jet case, but the far field contour still appears to be circular. However, the area increased to 1979 mm^2, up 25% from 1580 mm^2 in the constant flow case. The mode m=1 case, shown in Plot C, shows the jet column moving in a helical motion, appears to have a slightly elliptical far field contour shape, and expanded 45%, to 2312 mm^2. The m=0.5 and m=±1 contours, shown in Plots D and E, show the swirling nature of the flow also, and both appear to have slightly elliptical far flow field contours as well. The area within the far field contour for m=0.5 was 1815 mm^2, a 15% increase, and for the m=±1 case, the area increased 25%, to 1972 mm^2. Plot F, showing the contours for m=±0.5, shows very little motion in the jet column and the far field contour is circular. However, the area inside the contour increased 50%, to 2368 mm^2.

The effect of the excitation frequency on the development of the flow was studied next. Tests were performed using all three momentum ratios, 0.02, 0.08, and 0.18, at excitation frequencies of 10, 20, and 30 Hz, for one spatial mode, m=1. This mode was chosen because it consistently showed a dramatic increase in far field contour area and clear structures in the jet column during the previous tests. The results are shown in Fig. 4.6, 4.7, and 4.8 for momentum ratios of 0.02, 0.08, and 0.18, respectively. For a momentum ratio of 0.02, the plots of Fig. 4.6 show very little change with changing frequency. However, the area inside the far field contour increased with increasing frequency, from 1593 mm^2 at 10 Hz to 1724 mm^2 at 20 Hz and 1861 mm^2 at 30 Hz. The plots in Fig. 4.7, for a momentum ratio of 0.08, show a smoothing of the three-dimensional contour with increasing frequency, as expected. Higher frequencies of excitation are desirable in order to smooth the transients in the flow caused by the excitation. The 10 Hz contour, Fig. 4.7, Plot A, shows the best detail of the flow structure under excitation. At 10 Hz, the area inside the far field contour was 1809 mm^2, which decreased to 1600 mm^2 for 20 Hz, but increased to 2031 mm^2 for 30 Hz. For a momentum ratio of 0.18, the plots in Fig. 4.8 also show a smoothing of the contour. They also showed an increase in far field contour area, from 2312 mm^2 at 10 Hz to 2932 mm^2 at 20 Hz and 3187 mm^2 at 30 Hz.

During the previous tests of three momentum ratios excited by several spatial modes, it was observed that for most excitation modes used, a momentum ratio of 0.08 yielded the greatest increases in the area of the far field contour. It was also observed that the excitation frequency did affect the development of the jet and the far field cross-section. Thus, it was decided to follow up these PMS tests with PLIF experiments using a momentum ratio of 0.08, since this was the momentum ratio where pulsation showed the greatest effect. MR = 0.08 had a greater effect on the flowfield than MR = 0.02 due to the increased momentum in the swirl generator jets. For MR = 0.18, the momentum in the swirl generator jets probably dominated the development of the flowfield. Thus the pulsation was able to have a greater influence on flowfield development for MR = 0.08 than for MR = 0.18.

4.5.2 Planar Laser-Induced Fluorescence

An additional set of tests were run on the swirl jet facility using the PLIF technique, since the previous study demonstrated that the PLIF technique yielded much greater detail of the flow structures than the PMS technique. The tests were run using the momentum ratio of 0.08, or a maximum velocity of 25 m/s through the side jets. During the PMS experiments, it was observed that MR = 0.08 had the greatest effect on the three-dimensional flowfield and the far field cross-sectional area. Again, the tests included a constant side jet case, and spatial mode excitations of m=0, m=1, m=0.5, m=±1, and m=±0.5. Pulsation frequencies of 10 Hz and 30 Hz were tested over the range of spatial modes.

Figure 4.9, A-F, shows the two- and three-dimensional contours for the 10 Hz experiment. For the mode m=0 case, Plot B shows a large scale structure at about z/D=7 and an expanded circular contour at z/D = 15. The area inside the far field contour increased to 1087 mm^2, a 25% increase from the constant jet case area of 869 mm^2. In Plot C, the m=1 case, also exhibits an expanded, circular far field contour with an area of 1235 mm^2, a 45% increase, but exhibits a twisting jet column, which is indicative of a three-dimensional vortical structure. For the m=0.5, m=±1, and m=±0.5 cases, shown in Plots D through F, roughly circular far field shapes are observed, with areas of 1394 mm^2, 1404 mm^2, and 1275 mm^2, respectively, yielding increases of 60%, 60%, and 50%, respectively. In Plot E, the m=±1 case, again exhibits evidence of a single large structure about halfway up the jet, and an expanded circular far field profile.

In comparing the results from the PLIF and PMS studies, it was noted that the jet column for m=0 looked very different. A single large structure was observed in the PLIF test, while several smaller structures are evident in the PMS test. It is believed that the PLIF test shows the actual flow structure, however. The wavelength of the excitation for the 10 Hz case is approximately 1.3 m. It is not possible that the pulsation is the source of the structures observed in the m=0 case in the PMS study, since the range of observation only extended to 0.18 m downstream of the nozzle exit. The structures seen in the PMS figures have a wavelength of about 50 mm, which corresponds to an excitation frequency of about 250 Hz. The only part of the system which has any correspondence to this value is the response time of the valves used, which was about 5 ms ± 2 ms, or about 200 Hz. However, it seems unlikely that the phenomena seen is caused by the PMS technique itself. One possible explanation is that the PMS and PLIF images were taken at slightly different times -- the PMS just before the valves opened and the PLIF just after. This is possible because the delay in the camera gate is very small, on the order of 100 ns from receiving a trigger pulse, while the delay in the excimer laser firing is on the order of 5 μs. Since the trigger pulse to the camera and laser was sent at the same time as the signal to open the reference (0) valve, the camera gate opened before the valve opened but the laser could have fired before or during the opening of the valve, depending on the exact response time of the laser and the valve. The camera gate time controlled the image acquisition time in the PMS experiments, while the laser pulse time determined the image acquisition time in the PLIF experiments. This would account for the fact that a large structure is seen in the PLIF images and no similar structure is seen in the PMS images. If the valves were starting to open in the PLIF case, it would also account for the base of the jet, z/D = 0, and the far field contour area, z/D = 15, being larger in the PLIF case. Furthermore, if the valves were closed during the PMS sampling time, the bumps in the jet column could be attributed to slight vibrations of the valve solenoid. It becomes apparent that when using square waves as the excitation signal rather than a sine wave, the point of sampling becomes extremely critical.

Shown in Fig. 4.10 is a plot of the area enclosed by the half intensity contour versus downstream location. In this test, it appears that the rate of expansion for all cases are very similar until about z/D = 7. At this point, the rate of expansion appears to increase for all cases, but the excitation cases appear to have a greater increase in the rate of expansion than the constant flow case. There appears to be a much greater variability in the rate of expansion for the m=±1 case than for the constant flow case. Though the overall rate of expansion appears similar to the other modes, the expansion appears to increase almost stepwise, followed by a leveling off. This could be indicative of large scale structures being formed in the flow. This variability also appears in the other excited cases, though not to as great an extent.

The array of tests were also run for 30 Hz excitations, and the results are shown in Fig. 4.11, A-F. These show similar behavior to those of the 10 Hz case, with a few exceptions. First, in the m=0 case, shown in Plot B, the bulge halfway up the jet column is much smaller, though still present. This is thought to be due to the fact that not as much mass is being injected into each structure, because the time the valve is open is one third that of the 10 Hz case. The area inside the far field contour increased 45%, from 806 mm^2 in the constant side jet case to 1187 mm^2. Plot C, for the m=1 case, shows similar behavior to the 10 Hz case, but the cycle appears more pronounced, probably due to a wavelength of about 0.4 meters. Thus, a larger portion of the wave is shown in the 0.18 m observation zone. The area inside the far field contour increased to 1344 mm^2, a 65% increase. Plots D and F show similar results to their 10 Hz counterparts, including the roughly circular contour in the far field and the area inside, which were 1355 mm^2 and 1280 mm^2, or increases of 70% and 60% respectively, for the 30 Hz test. The mode m=±1 case, shown in Plot E, again has a large bulge halfway up the column, but the structure appears to spread into an elliptical contour rather than returning to a circular contour as the 10 Hz case did. The area inside the far field contour increased 90%, to 1548 mm^2. It is suspected that the higher frequency causes the flow to respond more accurately to the m=±1 mode rather than to a m=0 mode at twice the frequency.

Shown in Fig. 4.12 is a plot of the area enclosed by the half intensity contour versus downstream location. In this test, it appears that the rate of expansion for all cases are very similar until about z/D = 5, which is very similar to the results for the 10 Hz excitation test above. At this point, the rate of expansion appears to gradually increase for all cases, but the excitation cases appear to have a greater increase in the rate of expansion than the constant flow case. The curves for the excited cases appear to be much smoother than those in the previous test. This is expected, since the 30 Hz excitation would naturally lead to a larger number of smaller structures. It was easier to discern which modes had the greatest effect on the rate of expansion for the 30 Hz case as well. The m=0 case has the least benefit, with m=1 slightly better. The m=0.5 and m=±0.5 cases appear to be about the same, slightly better than m=1, and m=±1 has the greatest effect.

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 7% of the average area, regardless of downstream position and spatial mode. This yields a 95% confidence band of ±15% for the area enclosed by the iso-intensity contour.

4.6 Summary and Conclusions

The primary goal of this study, to observe the effects of pulsating swirl generator jets on a swirling jet flow, was met. The pulsating jets did have a noticeable effect on the development of the jet when compared with constant swirl jets. The area inside the half intensity contour was seen to increase up to 100% due to the excitation. The most promising set of conditions appeared to be a momentum ratio of 0.08 and an excitation frequency of 30 Hz. The momentum ratio of 0.08 was chosen because the excitation caused greater expansions in the far field relative to the constant flow cases than the other two momentum ratios studied. The frequency of 30 Hz appeared to be the most promising because the flow appeared to respond to the spatial mode excitation more accurately at the higher frequency. It is possible that still higher frequencies would have an additional benefit. At these conditions, the mode m=±1 appeared to be the most beneficial, with an expanded elliptical far field contour, 90% greater than the constant side jet case, and a greater rate of expansion than the other excited cases.

In addition, these tests revealed that the PMS experiment and the PLIF experiment, under identical flow and forcing conditions, can yield different results. The observed differences probably resulted from a very slight difference in the sampling time between the two techniques. It is suggested that the slight difference became critical because of the on/off nature of the excitation used in this experiment. Had the excitation been continuous, such as the sine wave excitation used in the active triangular nozzle study, this difference in sampling time probably would not have been noticed.