*11th Australasian Fluid Mechanics Conference*
*University of Tasmania, Hobart, Australia*
*14-18 December 1992*

# AN EXPERIMENTAL STUDY OF A PRECESSING, DEFLECTED JET

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## Abstract

A conditional flow visualisation technique has been used to identify two characteristic flow types when a jet is caused to precess about an axis inclined to the jet centerline. Below a critical precessional Strouhal number of about $10^{-3}$, based on precession frequency, nozzle diameter and exit velocity, the Langrangian flow field appears to be analogous to a fully pulsed, axisymmetric jet. Above that value an entirely different flow field is observed with large scale recirculation of jet and entrained fluid. Previous investigations have described a geometrically simple symmetrical nozzle which generates a precessing jet flow naturally by means of a complicated fluid mechanical instability. The present paper describes an investigation of the flow with an asymmetric nozzle which is caused to precess by mechanical means. This allows each of the controlling parameters, frequency of precession, exit velocity and exit diameter, to be varied independently. The phase-averaged velocity profiles of the precessing jet flow in both flow regimes, obtained by hot-wire anemometry, are compared with measurements of the stationary jet and with published data for a fully pulsed axial jet.

## Notation

| | |
|---|---|
| $d$ | exit diameter of the nozzle |
| $f_p$ | frequency of precession |
| $r_{u0.5}$ | radial distance where the velocity is half the centerline velocity |
| $r$ | half the exit diameter of the nozzle |
| $Re$ | Reynolds number $= \frac{u_e \cdot d}{\nu}$ |
| $St$ | precessional Strouhal number $= \frac{f_p \cdot d}{u_e}$ |
| $u_m$ | mean centerline velocity of the jet |
| $u_e$ | mean exit velocity of the jet |
| $u$ | mean velocity in x-direction |
| $x$ | direction of the local nozzle exit |
| $y, z$ | direction normal to the jet exit |

## Introduction

The motivation to examine the complicated precessing jet flow field stems from a research programme at the University of Adelaide which aims to reduce nitrogen oxide emissions from turbulent jet flames. A Precessing Jet (PJ) nozzle described by Nathan and Luxton (1989,1991,1992), uses an abrupt expansion into a short cavity to generate naturally an asymmetric reattachment which in turn produces a jet which exits the nozzle at an angle of between 45° and 65°, and precesses. The largest scale of the mixing is many times that of a simple turbulent jet and, when used as a burner, this achieves large reductions in $NO_x$ emissions while maintaining low CO emissions (Nathan et.al.1992).

Bremhorst et.al. (1978, 1981, 1987 and 1990) have shown that the Reynolds stresses in a fully pulsed, axial jet are significantly larger than for a simple turbulent jet. They are considered to be the cause of the much higher rates of entrainment which have been observed. The rate of decay of the centerline velocity is increased, while measurements over the first ten nozzle diameters show that momentum flux is increased. While analogies between this flow and a precessing jet can be found in some conditions, detailed measurements of a precessing jet flow do not appear to have been made.

Various investigations of a jet in cross flow (Birch et.al. 1989, Catalano et.al.1989, Crabb et.al.1981, Kamotami et.al.1972 and Pratte et.al.1967) identified the deformation of its cross section into a kidney-shape and the deflection of its axis. The pair of axial vortices so formed grow with the distance from the jet exit and increase jet asymmetry until self-similarity is obliterated. The relative tangential velocity between the precessing jet and the ambient fluid can be expected to produce comparable flows under some conditions although measurements to verify this postulate are yet to be conducted.

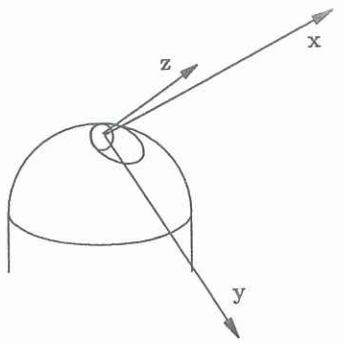

Figure 1: Coordinate System

## Experimental Technique

The mechanically rotated nozzle shown in Figure 1 is used in the present isothermal investigation. It is possible to vary the exit diameter and the exit angle relative to the spinning axis by changing nozzle tips. Although in the present investigation a constant exit diameter of 10mm and exit angle of 45° are used. The constant Reynolds number, $2.5 \times 10^4$ in these experiments, corresponds to an exit velocity of 40m/s.

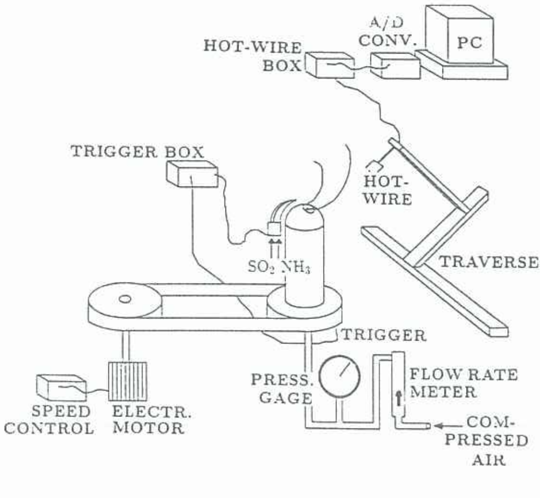

Figure 2: Apparatus

The apparatus is shown in Figure 2. A standard 5μm Tungsten constant temperature hot-wire with an active length of 1mm was used to measure velocity. The unfiltered signal from the anemometer was converted to a digital signal and stored on a PC. For the stationary jet 1000 samples were collected at a sampling frequency of 200Hz. Sixteen thousand data points were collected in the precessing jet flow at 1500Hz for $f_p = 3$Hz and at 20000Hz for $f_p = 40$Hz. The velocity profiles are then phase-averaged over 32 cycles. The traverse can be positioned to within ±0.025mm. A 370W variable frequency electric motor, used to rotate the nozzle, is controlled by a TASC Speedstar II (415 Volts, 50Hz) unit to a selectable constant speed with an accuracy of ±0.25Hz at the 60Hz maximum speed. Flow visualisation is achieved by injecting $SO_2$ and $NH_3$ through separate tubes. These components react to produce a high density smoke. The smoke is injected at about the same velocity as the jet to minimise the influence of the technique on the jet flow. The injection was triggered by a sensor which produces a signal at a fixed phase in the precession. In this way conditional visualisation is achieved with the smoke injected tangentially to the instantaneous jet. The duration of each injection pulse can also be controlled. Images were recorded with a KODAK Ektra Pro 1000 high speed video camera at speed of up to 1000 frames/second.

## Results

Two types of flow field have been identified using flow visualisation. These appear to depend upon the Strouhal number, $St = \frac{f_p d}{u_e}$, where $u_e$ is the exit velocity of the jet, d the exit diameter and $f_p$ the frequency of precession.

To confirm that the inlet conditions of the mechanical nozzle do not seriously perturb the turbulent jet, velocity profiles were first measured with the stationary jet ($f_p = 0$). In Figures 3 and 4 it can be seen that the small initial asymmetry produced by the nozzle plane decays

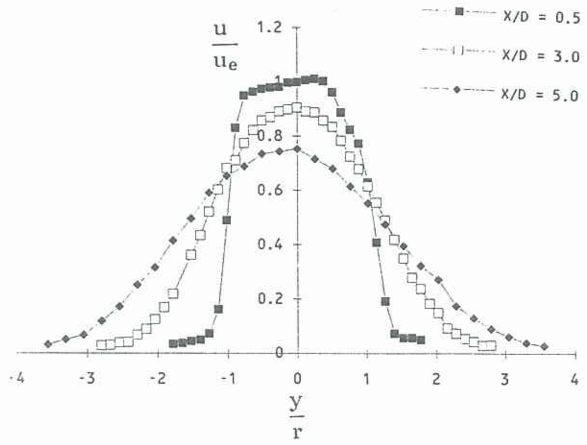

Figure 3: Velocity profiles in y-direction

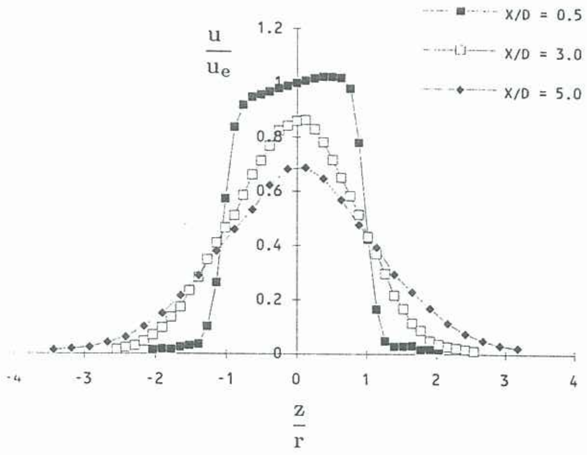

Figure 4: Velocity profiles in z-direction

rapidly and reasonable similarity is displayed beyond 3 exit diameters (Figure 5 and 6). The maximum asymmetry $\Delta u/u$ in the jet beyond this station is 8%. Figures 3-6 show good agreement with various investigations of a simple, turbulent jet (Abramovich 1963, Crow and Champagne 1971, Wyganski and Fiedler 1969). The centerline velocity decay follows a linear relationship downstream of the potential core which terminates between x/d=3 and 4.

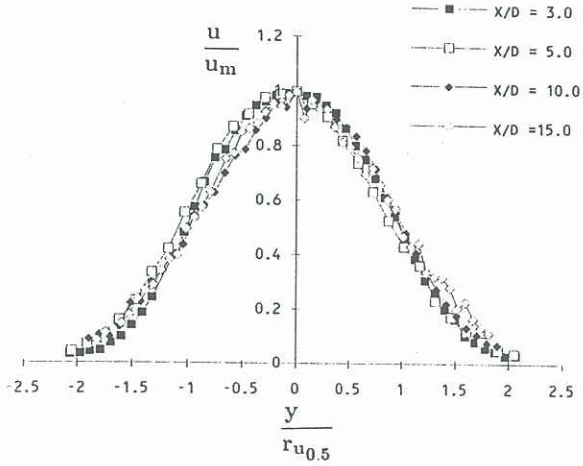

Figure 5: Self-similarity in y-direction

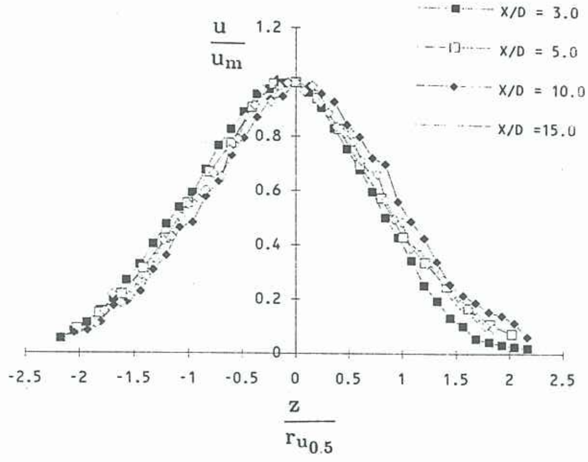

Figure 6: Self-similarity in z-direction

The character of the precessing jet flow below a critical value of the Strouhal number, $St_{crit} \approx 10^{-3}$, is illustrated in Figure 7, while the flow above $St_{crit}$ can be seen in Figure 8. The flow visualisation technique reveals an apparent analogy between the turbulent flow fields of the fully pulsed axial jet investigated by Bremhorst et.al.(1978, 1981, 1987 and 1990) and the sub-critical precessing jet (Figure 7). A typical vortex puff similar to that of a fully pulsed jet can be seen. The deflection of the jet from the x-direction is negligible and the flow field seems to combine features of the jet in a small cross flow and the fully pulsed jet.

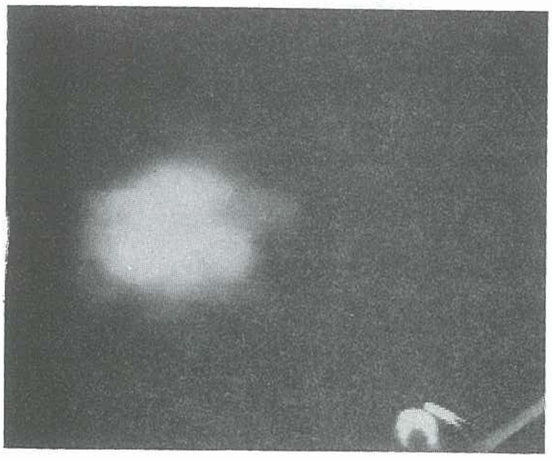

Figure 7: Smoke visualisation at $St=0.8 \times 10^{-3}$

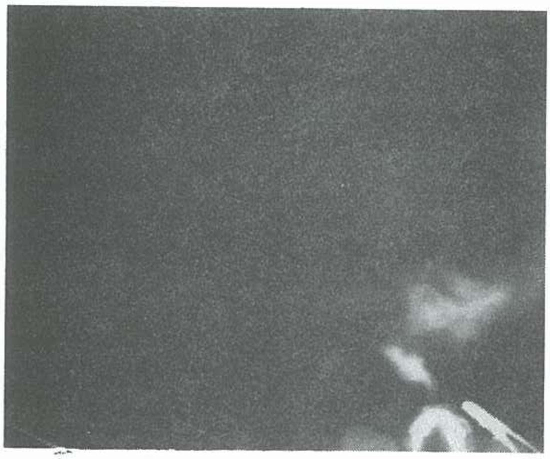

Figure 8: Smoke visualisation at $St=5 \times 10^{-3}$

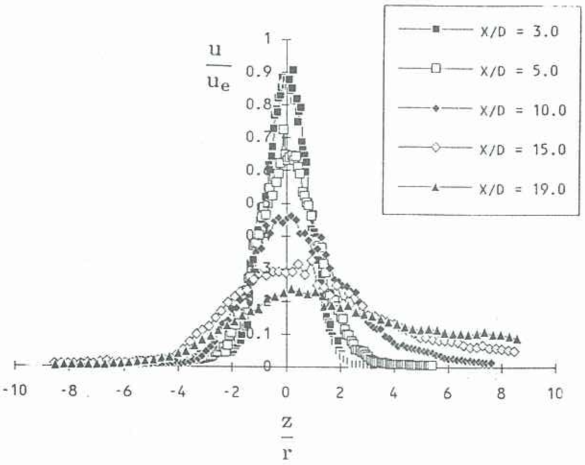

Figure 9: Velocity profiles at $St = 0.75 \times 10^{-3}$

The velocity profiles of the sub-critical Strouhal number flow at the same axial location as those for the stationary jet (x/d=3.0, 5.0, 10.0, 15.0, 19.0) are shown in Figure 9. A slight increase in asymmetry with distance in the x-direction can be seen and a slight departure from self-similarity occurs. The velocity decay of the centerline is in the range of that of the fully pulsed jet (Bremhorst 1990).

By contrast the super-critical Strouhal number flow is dramatically different. Recirculation of a scale much larger than the diameter of the comparable steady jet is observed (Figure 4) and the decay rate of the jet centerline velocity is much higher than in the other flow fields. A comparison of Figures 9 and 10 shows that at x/d=5, the centerline velocity of the sub-critical flow has decayed to about 65% of its exit value, while that of the super-critical flow has decayed to about 45%. At 10 nozzle diameters no significant velocity can be detected in the super-critical flow while the centerline velocity of the sub-critical flow is still nearly half of its initial value. The asymmetry of the velocity profiles is also greatly increased.

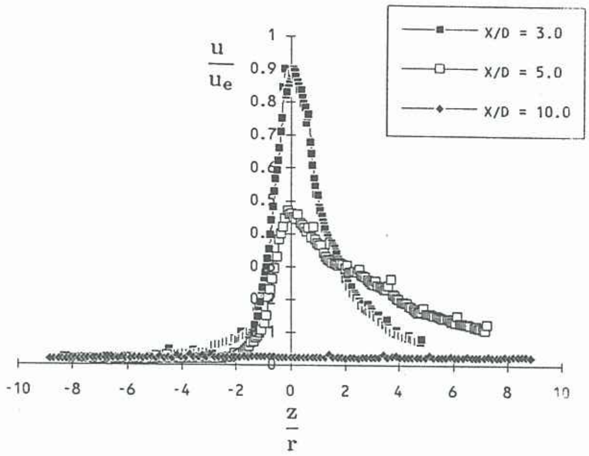

Figure 10: Velocity profiles at St $= 10 \times 10^{-3}$

## Conclusions

Two classes of precessing jet flow have been identified using a mechanically rotated nozzle, apparently seperated by a critical Strouhal number. The visualisation and measurements in both regimes show dramatically different flow characteristics. In the sub-critical Strouhal number flow, the flow appears to be analogous to that of a fully pulsed axial jet and the rate of decay of the centerline velocity is comparable with that of a steady jet. In the super-critical flow the centerline velocity decay is increased drastically and large departures from symmetry of the local jet is observed. Flow visualisation reveals recirculation on a scale much larger than that of the equivalent steady jet. Further investigations will seek to define the exact $St_{crit}$ and detailed measurements of the two flow field modes will be made to determine the reason for these phenomena.

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