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

9A-2

FLUID MECHANICS OF DEFLECTED JETS : EVALUATION OF NOZZLE THRUST VECTORS

S.S. VIDAKOVIC and R.E. LUXTON

Mechanical Engineering Department
University of Adelaide
GPO Box 498, Adelaide, SA 5001, AUSTRALIA

ABSTRACT

Deflecting a high speed jet at very large angle, without using deflector plates or targets, is now possible. A description of the large scale steady flow field in an asymmetric jet leaving an axisymmetric nozzle will be presented. The asymmetry is generated fluid mechanically within an axisymmetric cavity downstream of a convergent-divergent nozzle. The flow field within the cavity has been investigated using surface flow visualisation[1], smoke visualisation[2], pitot and static pressure probes and hot wire anemometry[3] and these data have been presented elsewhere.

The thrust capabilities of the novel nozzle have been studied and the experimental results are presented here. Measured velocity profiles and pressure distributions within and outside the cavity are used in the calculations of thrust and to assist in the interpretation of the flow. Comparisons are made of the thrust of a free turbulent jet issuing from a convergent nozzle, deflections of that jet by mechanical means, and the fluid mechanically deflected jet from the convergent-divergent nozzle/cavity system. The analyses include theoretical predictions as well as experimental measurements of the thrust over a range of Mach numbers based on the throat diameter of 10 mm. The possible uses of the controlled jet as a means of achieving high manoeuvrability of rockets and missiles and for V/S.T.O.L. aircraft are assessed.

NOTATION

A : Cross sectional area (mm)^2
C-D : Convergent-divergent
D_t : Throat diameter (mm)
T : Thrust (N)
T_o : Thrust based on throat Mach number
m : Mass flow rate (kg/s)
M : Mach number
P_a : Ambient static pressure (kPa)
P_e : Exit static pressure (kPa)
P_o : Stagnation pressure (kPa)
ρ : Density of air (kg/m^3)
U_e : Exit velocity (m/s)
R_e : Reynolds number based on throat diameter

INTRODUCTION

High speed jets can be deflected in a number of ways using mechanical[4,5] or acoustic means[6]. A novel way of deflecting a high speed jet of air through a convergent-divergent nozzle at a large angle by solely fluid mechanical means, by the addition of a final short cavity, has been discovered. The azimuthal location of the deflected jet can be controlled by a fluidic disturbance at the nozzle throat. In the present experiments this disturbance is achieved by injecting air through one of four pressure tappings at the throat of the nozzle to provoke separation of the main flow at the throat. The fluid is injected normally to the main flow. It behaves as a jet in a cross flow and creates turbulent mixing and a partial separation of the main flow from the divergent wall opposite from the control jet. The remaining flow remains attached so creating an asymmetric flow in the axisymmetric cavity downstream from the throat. The asymmetric flow which remains attached to the cavity wall expands laterally as it proceeds downstream, but is restricted by the physical presence of the solid wall. This forces the asymmetric jet "centre line" to move away from the wall as the jet proceeds downstream from the throat as shown in the interpretation of the flow inside the cavity in Fig.5. At the free surface of the asymmetric jet inside the cavity, the fluid is free to expand towards the cavity centre line and mix with the ambient fluid which is entrained into the cavity. The exiting jet does not occupy the whole of the exit plane of the cavity and the entrainment produces a sub-atmospheric pressure in the cavity so inducing the inflow of ambient fluid. Where the deflected jet exits the cavity and mixes with the ambient fluid, the transverse pressure gradient is remarkably large and is the prime reason for the high angle of deflection of the exiting jet.

The test nozzle, Fig.1 manufactured from an epoxy resin, consists of a convergent-divergent section with a smooth axisymmetric sinusoidal profile. To this is attached an optical quality perspex cavity to allow L.D.V. measurements of the velocity profiles within the cavity. At the downstream end of the cavity is a 45 degree chamfered orifice which augments the deflection of the flow away from the cavity axis to an angle of the order of 60 degrees, as determined by flow visualisation. A convergent nozzle has a profile up to the exit identical to the profile of the test nozzle up to the throat. At the exit of the convergent nozzle various attachments can be added and thrust performances evaluated. The configurations of the nozzles are shown in Fig.2. An evaluation of the nozzles as a means of producing vectored thrust is attempted from measurements of thrust, velocity profiles and pressure distributions. These measurements are also used in explaining the flow characteristics both inside and outside the cavity.

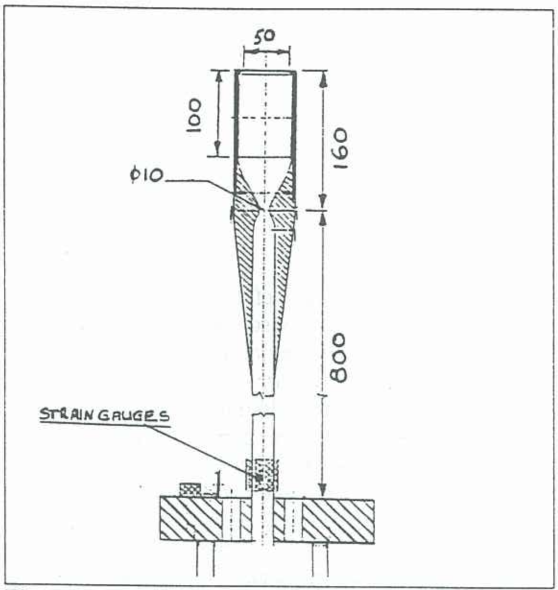

Figure 1.Test nozzle details

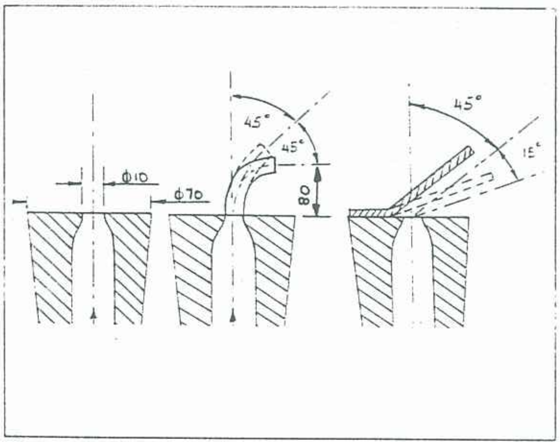

Figure 2. Convergent nozzle configurations.

DETAILS OF THE AXISYMMETRIC TEST NOZZLE AND MECHANICALLY DEFLECTED NOZZLES

To evaluate the thrust performance of the nozzle, the test nozzle and other mechanically deflected nozzles were mounted on a 25 mm I.D. brass air supply tube 900 mm in length with strain gauges at its base to measure the bending moments in 2 directions 90 degrees apart. The bending moments are generated by the deflected momentum leaving the nozzles. From these the magnitude of the side thrust generated at specific flow rates can be deduced. The strain gauges were calibrated by applying a known force at the nozzle exit plane in each of the 2 directions. The voltages varied linearly with the force applied up to 15 Newtons. Clean dry air is supplied from a storage vessel which is maintained at 700 kPa. A traverse table is mounted next to the rig so that the hot wire and the pitot-static probes can be traversed into and out from the cavity to determine the flow velocity profiles. A set of 16 equally spaced static pressure holes is located radially 60 mm upstream from the cavity exit. These pressure holes can be used to determine the static pressure distribution in the cavity for various flow conditions. A set of 7 equally spaced static pressure holes is located axially along the cavity wall to measure the axial static pressure distribution at different radial positions of the deflected jet.

EXPERIMENTAL RESULTS

The thrust efficiency is defined as the ratio of the deflected jet thrust at some angle theta from the nozzle axis and the thrust of the same mass flux through the convergent nozzle having the same outlet conditions. The side thrust data for various nozzle configurations was measured and the results then normalised to give the efficiencies of various thrust vectoring configurations as shown in Fig.4. A sample of the velocity profiles of a jet issuing from a convergent nozzle , using L.D.V., are shown in Fig.3a. A pitot probe and a hot wire were used to measure the velocity profiles in the jet outside the cavity of the test nozzle and other nozzle configurations. The two methods were used to check the accuracy of the velocity profile measurements. A sample of the velocity profiles outside the test nozzle taken at 45 degrees to the nozzle axis and in a plane perpendicular to the jet axis is shown in Fig.3b, and a sample of the velocity profiles taken at the edge of the 45 degree deflection plate are shown in Fig.3c. The free turbulent jet thrust was obtained from :

$$T=\dot{m}U_e+(P_e-P_a)A_e \qquad (1)$$

where the exit and ambient pressures are the same for all cases except for the test nozzle. The test nozzle static pressure inside the cavity is sub-atmospheric and the difference increases with R_e. The momentum flux for the test nozzle and 45 degree deflector plate were calculated

$$T=\rho_e\int U_z^2 dz dy \qquad (2)$$

using equation 2. and the obtained velocity profiles. For the configuration (b) the calculated thrust at a Mach number of 0.382 was T=0.506 Newtons compared to the measured value of T=0.526 Newtons. For the configuration (c) the calculated thrust at a Mach number of 0.37 was T=0.691 Newtons compared to the measured value T=0.65 Newtons. These results indicate that the thrusts measured using strain gauges are reliable within 10% error and this is mainly due to the vibration of the rig. In Fig.4 the first set of data points (a) represents the measured side thrust using the test nozzle without air injection at the throat such that thrust varied in direction during the test. The magnitude of the side thrust was determined from the two force components and the instantaneous radial direction at any one time could then be calculated. The second set of results (b) represents the measured side thrust developed through the convergent-divergent nozzle and cavity with air injected at the throat to maintain radial position. The amount of air injected through the throat pressure tap can be adjusted by a fine adjustment valve to cause just enough disturbance to stabilise the radial position of the jet. If the amount of air through the throat pressure tap is increased, the main flow through the throat is distorted in a manner which reduces the amount of side thrust produced for a particular flow rate. The next set of configurations considered are a 100 mm square deflector plate inclined at (c) 45 degrees and (d) 60 degrees from the axis and placed at the exit of the convergent nozzle as shown in Fig.2. The next set of configurations were (e) 45 degrees and (f) 90 degree bends of 15 mm diameter pipe placed at the exit from the convergent nozzle, also shown in Fig.2. This configuration created an abrupt expansion from the 10 mm convergent nozzle to the 15 mm diameter tubes bent through 45 and 60 degrees to vector the thrust. The last set of configurations considered were (g) 45 degree and (h) 60 degree bends of 10 mm diameter placed at the exit of the convergent nozzle, as shown in Fig.2. From Fig.4 it can be seen that the thrust vectoring is most efficient for a 10 mm diameter 90 degree bend and least efficient for the test nozzle when there is no fluidic stimulation at the throat. For the range of Mach numbers considered, the thrust vectoring efficiency for (a) is an average of 30% compared to (b) an average of 35% . The thrust vectoring efficiency for (c) is an average of 48%, (d) an average of 44%, (e) an average of 68%, (f) an average of 64%, (g) and (h) an average of 90%.

CONCLUSIONS

From the results presented it can be concluded that the test nozzle investigated can be used for thrust vectoring in cold flow where the side thrust required does not exceed 35 % of the theoretical value. From Fig.4 it can be seen that the thrust efficiency for the controlled jet has a constant value of 35% for the range of Mach numbers considered. The deflected thrust measurements below M=0.3 were not considered due to the limitation of the strain gauge sensitivity. The test nozzle may have applications in the field of high manoeuvrability missiles and rockets where a system which can accommodate the severe environment of hot flows and higher pressure ratios is required.

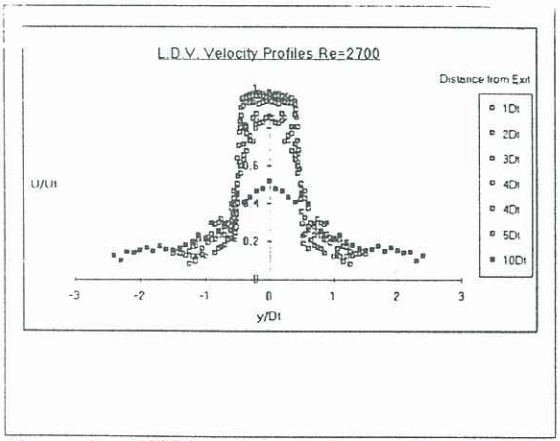

Figure 3a. L.D.V. axial velocity profiles from the simple convergent nozzle with Re=2700.

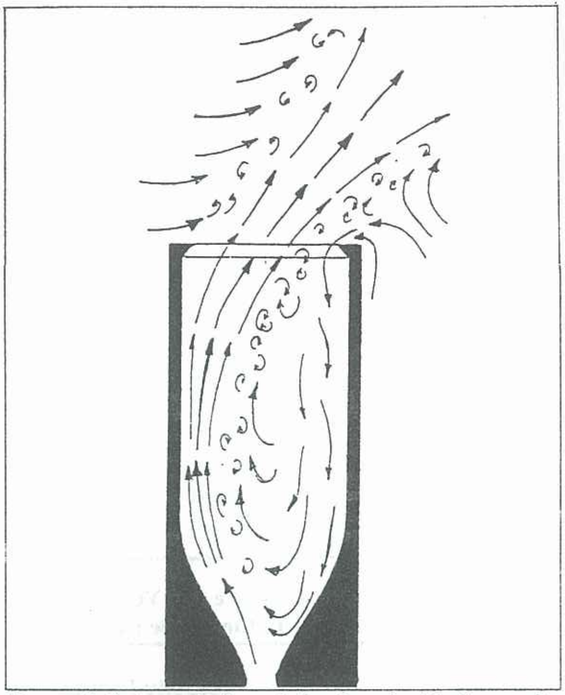

Figure 5. Interpretation of the flow inside the cavity along the plane of symmetry.

REFERENCES

1) Nathan,G.J. and Luxton,R.E. "The flow field within an axi-symmetric nozzle utilising a large abrupt expansion" ASME, Fluids Engineering, Canada. 1990.

2) Vidakovic,S.S. and Luxton,R.E. "Fluid mechanics of vectored jets : Flow visualisation within the nozzle" International Symposium of Transport Phenomena 4, pp 50-61, Sydney, Australia, July 14-18 1991.

3) Vidakovic,S.S. and Luxton.R.E. "Fluid mechanics of vectored jets : Velocity flow fields within the cavity" International Aerospace Congress 1991, pp 675-684, Melbourne, Australia, May 12-16 1991.

4) Badri Narayanan,M.A. and Platzer,M.A. "Jet excitation by a bivane system and its application to an ejector for thrust augmentation". Naval Postgraduate School, Monterey, California, U.S.A.

5) Bradbury.L.J.S. and Khadem.A.H. "The distortion of jet by tabs"J. Fluid Mech. 1975, Vol. 70, part 4, pp. 801-813.

6) Jungowski.W.M. "Some self induced supersonic flow oscillations"Prog. Aerospace Science 1978. Vol 18, pp 151-175.

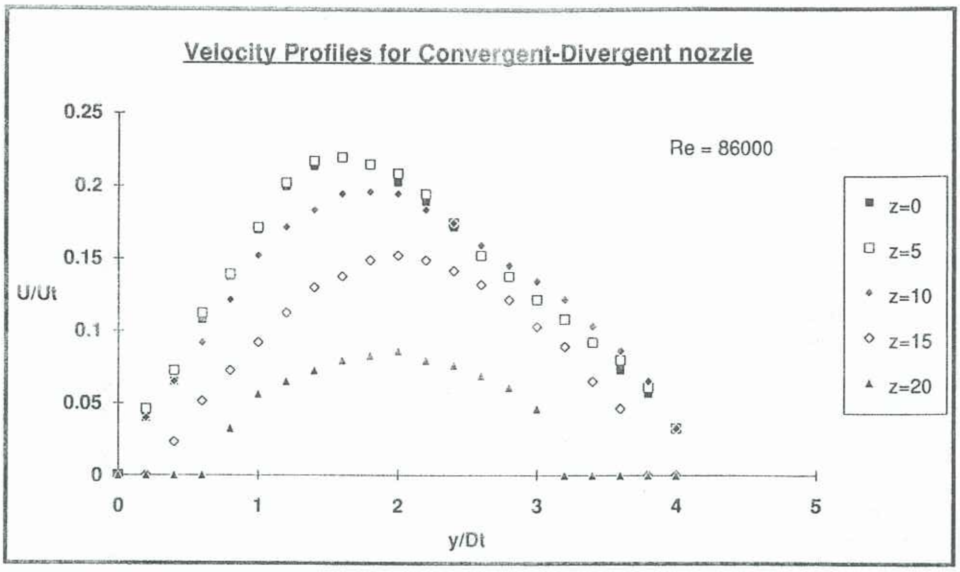

Figure 3b. Velocity profiles measured at 45 degrees to the nozzle axis along a plane of symmetry.

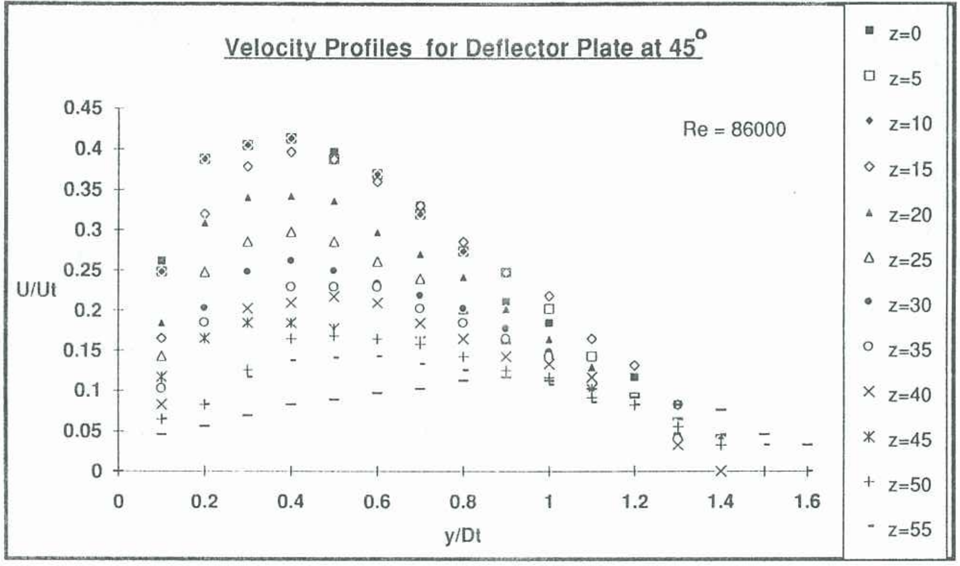

Figure 3c. Velocity profiles measured at 45 degrees to the nozzle axis along a plane of symmetry.

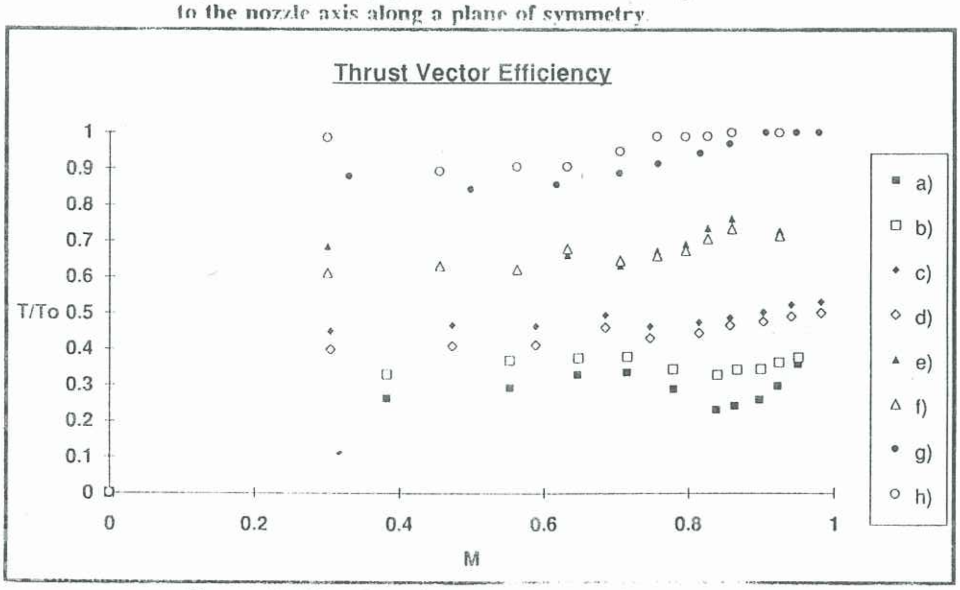

Figure 4. Thrust vectoring efficiencies for various configurations of nozzles