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PRECESSING AND AXIAL FLOWS FOLLOWING A SUDDEN EXPANSION IN AN AXISYMMETRIC NOZZLE

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ABSTRACT

Earlier work has shown that the flow through an axi-symmetric abrupt expansion can produce an asymmetric reattachment when the expansion ratio is large. A nozzle which utilises this asymmetric flow in a cavity and with a second orifice at the nozzle exit plane generates a deflected jet which precesses about the nozzle axis. However an irregular switching between the precessing flow and a largely axial flow has also been observed to occur.

Fast response pressure measurements at four places within the cavity are recorded simultaneously using air as the working fluid. Together with flow visualisation conducted in water, they provide insight into the details of both flow modes. The use of either a single static pressure measured at the upstream part of the cavity or a single total pressure probe located near the jet exit gives a reliable indicator of the presence or absence of precession. Probability density functions indicate the time spent in each mode for a given geometry.

NOTATION

PJ	Precessing Jet
AJ	Axial Jet
Prob PJ	Probability of Precessing Jet occurring
f_p	Frequency of jet precession
u_1	Mean flow velocity through d_1 assuming incompressible flow
St_h	Strouhal number based on h
R_{d1}	Reynolds number based on d_1

INTRODUCTION

Investigations by Nathan (1988) on a nozzle within which the flow expands rapidly through an orifice into a cavity and then passes through a second orifice revealed the occurrence of a sharply deflected jet which precessed about the nozzle axis. This was found to generate very large scale mixing between the jet and the surrounding air downstream from the nozzle. A schematic of the Precessing Jet (PJ) nozzle is shown in figure 1.

One application of this newly discovered flow is in the field of combustion. A gaseous turbulent diffusion flame whose mixing is dominated by the jet precession has many desirable characteristics. The blow off velocity of an unconfined flame is increased by a factor of four and the stand off distance of the flame from the nozzle exit is reduced by an order of magnitude, when based on an equivalent exit diameter comparison with a simple turbulent jet flame (Nathan and Luxton 1988, 1991a,b). The high exit angle of the gas jet and the large scale mixing also results in a highly radiant bulbous flame.

The PJ burner has shown significant potential to reduce exhaust emissions. Trials at both laboratory and industrial scales have indicated reductions in NOx by up to 75% while maintaining low CO when compared to conventional burner technology (Nathan, Manias and Luxton 1991, Nathan, Luxton and Smart 1992).

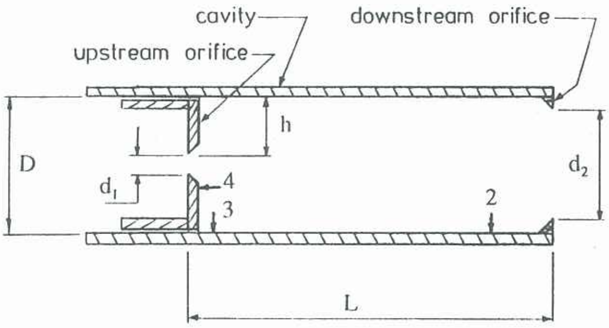

Figure 1: The PJ Nozzle. (2, 3 and 4 indicate static pressure measurement locations).

Hallett and Gunther (1984) and Dellenback, Metzger and Neitzel (1988) have independently reported the occurrence of a precessing jet through sudden expansions of about 2:1 when using weak upstream swirl. These researchers have not reported the spontaneous mode switching described in the present paper. A review of asymmetric reattachments downstream from sudden expansions is presented by Nathan and Luxton (1989).

The phenomenon of asymmetric flows in a symmetric geometry has been observed for other configurations. A study of a two dimensional jet which issues into a blind cavity (Sallam et al. 1980) has shown an asymmetric flow pattern which resembles that observed here, although no asymmetry was detected for the axi-symmetric configuration within the range of geometry tested.

Nathan and Luxton (1991c,d) have found that the frequency of the precessing jet flow (f_p) can be characterised by a constant Strouhal number (St), based on step height into the cavity from the inlet plane,

$$St = \frac{f_p\, h}{u_1} \approx 5\times10^{-3} \qquad (1)$$

though the precession was found to be somewhat irregular. They noted that the precessing flow field was occasionally interupted for a short time by a very different and predominantly axisymmetric axial jet (AJ), but did not investigate that flow in detail. Nathan (1988) describes techniques such as upstream swirl that can be used to stabilise the PJ flow field. In the present paper both the qualitative nature of the non-precessing flow field and a method of quantifying the proportion of time which the flow spends in each flow mode are described.

EXPERIMENTAL TECHNIQUES

Water Flow Visualisation

A perspex tank is used for the present water flow studies. The test nozzle cavity is made of perspex with an internal diameter, D, of 44mm and the length of the cavity can be varied. The PJ nozzle is mounted vertically in the test section to avoid trapping air in the cavity. The development length of straight pipe upstream from the nozzle is about 20 diameters which ensures that the flow is uniform at the first orifice.

Clean water is supplied to the nozzle by a centrifugal pump. Small air bubbles stabilised by the addition of a small amount of detergent are injected to visualise the flow. All flow rates are measured using a variable area Fisher and Porter float and tube meter calibrated by measuring the discharge volume for a known time period. Water flow visualisation has been conducted for Reynolds numbers up to about 50000.

$$R_{d_1} = \frac{u_1\, d_1}{\nu} \approx 50000 \qquad (2)$$

The nozzle and flow are illuminated by a 30mm thick sheet of white light formed through a slit and aligned along the axis of the nozzle. A standard video camera (25 frames per second) is used to record the image on VHS format tape from which still images are obtained.

Air Flow Pressure Measurement

A differential pressure transducer is used to measure cavity wall pressures, the records being digitised and stored on a PC. For the data presented here, four simultaneous pressure readings were logged. Care was taken to ensure that the pressure line connections had a negligible effect on the nominal 1000Hz response of the pressure transducer by keeping lines short (typically 40 to 150 mm), especially for the fast response measurements. Detailed cavity pressures are compared for the PJ and AJ flow occurring at different times in the one nozzle geometry. The total pressure probe has a longer tube and probe length and hence its response is reduced to about 200 Hz. Never-the-less this was found to be adequate for measuring the precession frequency which is typically less than 20 Hz in the present arrangement. The trace from an axial total pressure probe positioned about 1/6 of a cavity diameter away from the wall above static pressure tapping number 2 (see Figure 1), clearly detects the azimuthal motion of the jet past it.

The probability density function (pdf) of wall pressure measured upstream from the reattachment can be used to determine the proportion of total time which the jet spends in the PJ mode (Prob PJ), because the wall pressure is higher in the PJ mode than in the AJ mode (see Figure 6). High frequency pressure fluctuations are removed by a low pass filter with a cut off set at 10 Hz. This method has been used here to determine the probability of the preferred PJ mode of operation existing for a given configuration of the nozzle in a given operating environment.

RESULTS AND DISCUSSION

An image of the PJ mode of flow within the nozzle is shown in Figure 2(a). Figure 2(b) shows a schematic interpretation of the image developed after detailed observation of the video recording and highlights the main features of the flow. The instantaneous exit angle of the jet is estimated to vary between 45 and 70 degrees. A strong recirculation is observed in the exit region of the cavity.

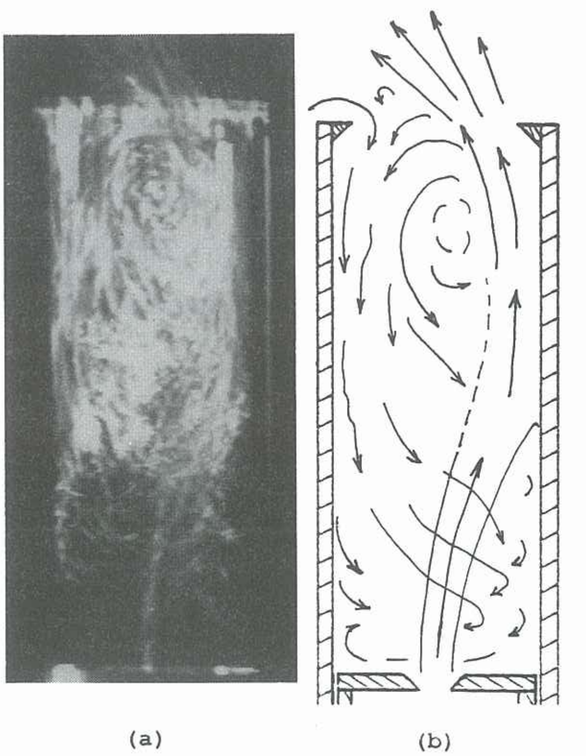

Figure 2: Water flow visualisation and schematic interpretation of instantaneous pathlines of the PJ flow mode. Note: Flow field rotates about the nozzle axis. R_{d1}= 15000, D=44mm, L=114mm, d_1=7.3mm, d_2=35mm.

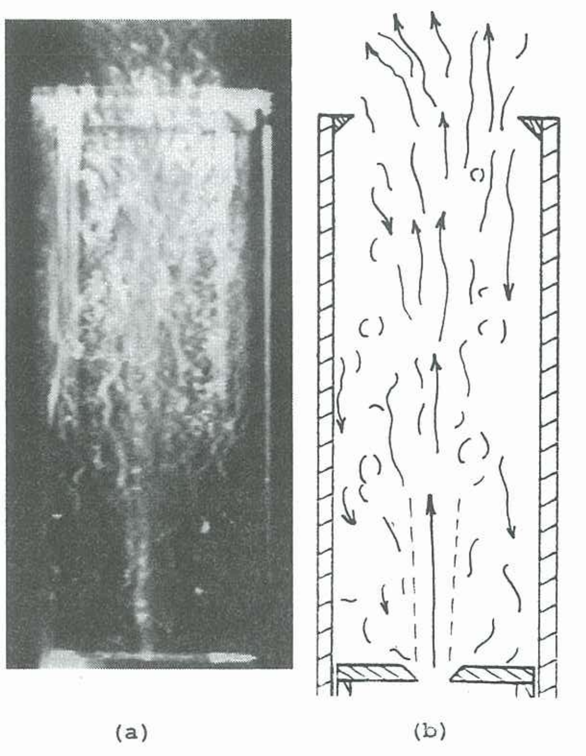

Figure 3: Water flow visualisation and schematic interpretation of instantaneous pathlines of the AJ flow mode. (Conditions as for Fig. 2).

The combination of the recirculated fluid and ambient fluid induced into the cavity generates a strong swirling motion at the upstream end of the cavity in the opposite direction to that of the precession consistent with previous investigations (Nathan 1988, Nathan and Luxton 1991c,d). Figure 3 shows the same nozzle operating in the AJ mode for comparison to the PJ mode. The jet does not reattach to the cavity wall but is seen to flick around the exit plane of the nozzle as ambient fluid is entrained into the cavity approximately uniformly around the circumference of the jet. The AJ mode ressembles the flow observed using a similar technique for a turbulent jet confined in an axisymmetric duct by Barchilon and Curtet (1964).

Pressure traces within the cavity are plotted in Figure 4 for the PJ mode and Figure 5 for the AJ mode within the same nozzle. This record highlights the differences between the two modes. A large radial pressure gradient exists at the inlet end of the cavity as may be seen by comparing traces for positions 3 and 4 for the PJ mode. This is consistent with the observed strong curvature of the streamlines of the swirling reverse flow. By contrast, Figure 5 indicates that there is only a very small radial pressure gradient in the AJ mode.

The pressure signal obtained from an off axis total pressure probe (shown in Figure 4 as line 1) is consistent with the azimuthal motion of an asymmetric jet past the probe as postulated previously by Nathan and Luxton (1991c,d). The large variation in the period of successive cycles can be seen in this example. For the axial jet the total pressure is less than the static pressure at this location, indicating a continuous flow in the negative x-direction which is consistent with visual observation (see Figure 3).

<u>Probability of Jet Precession (Prob PJ)</u>

The double peaked p.d.f. of the wall pressure derived from Figure 6 and shown in Figure 7 indicates that the nozzle operates in either of the two modes, but rarely in transition between the modes. The proportion of time that the flow spends in the PJ flow mode for a given geometric configuration can be determined from the area under the right hand peak in the pdf in Figure 7 and plotted in Figure 8.

Alternatively, a total pressure probe located on the nozzle axis, just inside the exit plane of the cavity, can be used to distinguish the flow modes. The PJ mode is indicated by a negative pressure and the AJ mode by a positive pressure due to the jet impingement on to the probe. The majority of points plotted in Figure 8 are calculated from this centreline pressure measurement and are in good agreement with the wall pressure technique also shown in Figure 8.

The increase in the stability of the PJ mode (Prob PJ) with increase in Reynolds number for various nozzle geometries is shown in Figure 8. The dependence is strongest when the diameter of the downstream orifice departs from its optimum value of 0.88D. This technique has been used to optimise the geometry of the nozzle in terms of Prob PJ by Hill (1992).

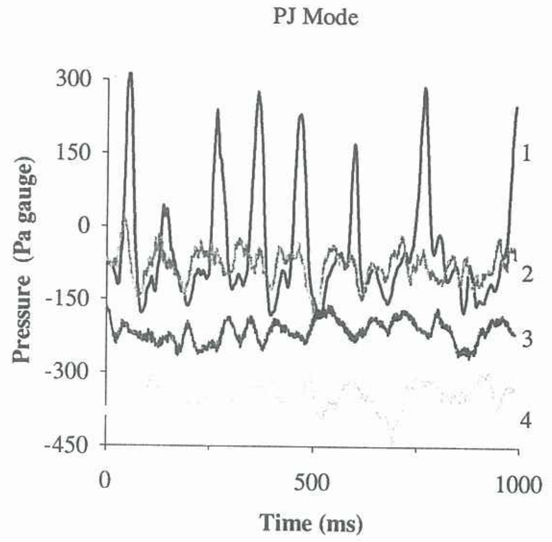

Figure 4: Pressure traces of PJ mode. Locations of measuring points 1,2,3 & 4 are as marked on Figure 1. R_{d1}=74000, D=91mm, L=242mm, d_1=14.1mm, d_2=80mm.

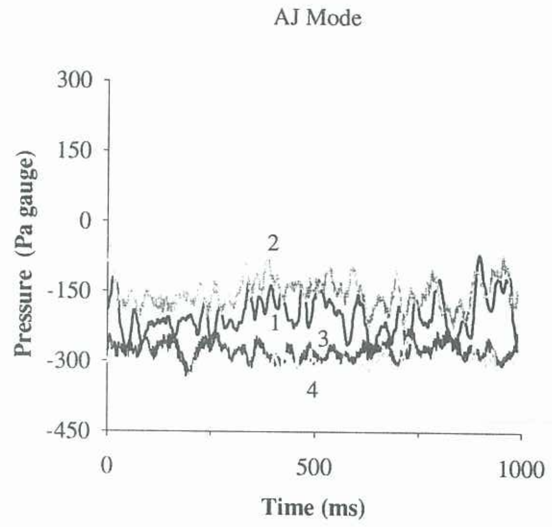

Figure 5: Pressure traces of AJ mode. (Conditions as for Fig. 4).

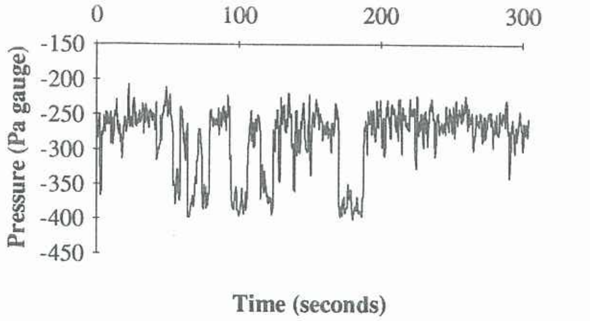

Figure 6: Pressure trace for position 3 showing mode switching. R_{d1}=74000, D=91mm, L=244mm, d_1=14.1mm, d_2=70mm.

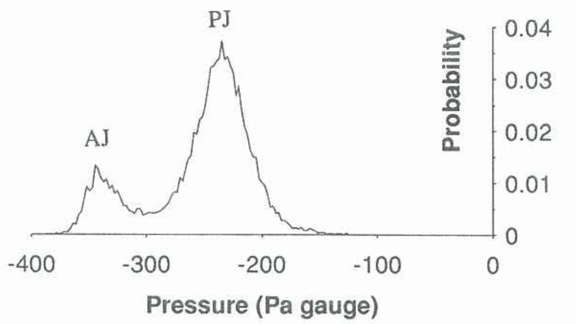

Figure 7: Cavity Wall Pressure pdf. (Conditions as for figure 6).

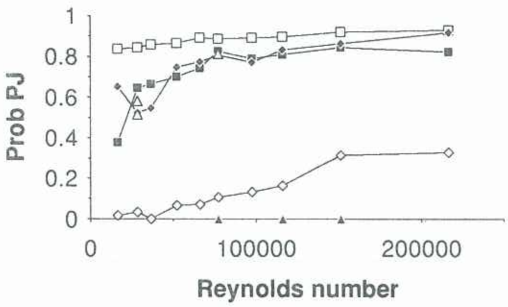

Figure 8: Probability of PJ vs Reynolds Number determined from total pressure pdf measurement. D=91mm, L=242mm, d_1=14.1mm, d_2=(■ ,91mm; □,80mm; ◆ ,70mm; ◇ ,60mm; ▲ ,50; △ ,70mm using wall static pressure).

CONCLUSION

The present paper has demonstrated the presence of two alternate modes of flow within the axi-symmetric "Precessing Jet" (PJ) nozzle configuration. The PJ mode is characterised by the precession of a highly asymmetric flow. The other mode, the Axial jet retains a significant axial velocity through the nozzle cavity. The pressure upstream of the reattachment has been shown to provide a means of determining which flow mode is instantaneously occuring and has enabled a quantitative measure of the flow conditions that generate this novel type of flow.

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REFERENCES

BARCHILON,M. AND CURTET,R. (1964) "Some Details of the Structure of an Axisymmetric Confined Jet with Backflow", ASME Journal of Basic Engineering, Vol 86, pp 777-787.

DELLENBACK,P.A., METZGER,D.E. AND NEITZEL,G.P. (1988) "Measurements in Turbulent Swirling Flow Through an Abrupt Axi-Symmetric Expansion", AIAA Journal, **26**, (6), 669-681.

HALLETT,W.L.H. AND GUNTHER,R. (1984) "Flow and Mixing in Swirling Flow in a Sudden Expansion", Canadian J. Chem. Eng., **62**, 149-155.

HILL,S.J. (1992) "A Precessing Jet from an Axi-symmetric Nozzle", Internal Progress Report, Dept. Mech. Eng., University of Adelaide, Australia.

LUXTON,R.E. AND NATHAN,G.J. (1989) "A Precessing Asymmetric Flow Field in an Abruptly Expanding Axi-symmetric Duct", Tenth Australasian Fluid Mechanics Conference, Dec 11-15, 1989, Melbourne, Australia, Vol 2, pp 11.29-33

NATHAN,G.J. (1988) "The Enhanced Mixing Burner", PhD. Thesis. Dept. Mech. Eng., The University of Adelaide.

NATHAN,G.J. AND LUXTON,R.E. (1991a) "Flame Stability and Emission Characteristics of the Enhanced Mixing Burner", 2nd European Conference on Industrial Furnaces and Boilers, April 2-5, Algrave, Portugal.

NATHAN,G.J. AND LUXTON,R.E. (1991b) "The Entrainment and Combustion Characteristics of an Axi-symmetric, self exciting, Enhanced Mixing Nozzle", Third ASME-JSME Thermal Engineering Joint Conference, March 17-22, 1991, Reno, Nevada.

NATHAN,G.J. AND LUXTON,R.E. (1991c) "The Flow Field within an Axi-symmetric Nozzle Utilising a Large Abrupt Expansion", the International Conference on Experimental Fluid Mechanics, Chengdu, China, June 17-21, 1991

NATHAN,G.J. AND LUXTON,R.E. (1991d) "Mixing Enhancement by a Self-Exciting, Asymmetric Precessing Flow-Field", The Fourth International Symposium on Transport Phenomena, Sydney, Australia, July 14-18, 1991.

NATHAN,G.J., LUXTON,R.E., AND SMART,J.P. (1992) "Reduced NOx Emissions and Enhanced Large Scale Turbulence from a Self Exciting Burner", 24th International Symposium on Combustion, University of Sydney, Australia, 5-10 July, 1992.

NATHAN,G.J., MANIAS,C.G. AND LUXTON,R.E. (1991) "Potential Increases in Efficiency of a Rotary Kiln using an Enhanced Mixing Burner", IEAust International Mech Eng Congress, Sydney, Aust, July '91, Conference 4, pp 58-61.

SALLAM,T.M., KAJI,M., NAKANISHI,S., ISHIGAI,S. AND MATSUMOTO,S. (1980) "Characteristics of Reversed Flow Due to Jet Issuing to Dead-End Channel", Technology Reports of the Osaka University, Japan, Vol 30, pp 217-224