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A RECIRCULATION ZONE IN A PRECESSING JET DETECTED WITH 3-DIMENSIONAL LDA

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ABSTRACT

The fully turbulent, three-dimensional and time-dependent flow field of a precessing jet is investigated. In the present case the jet precession is generated by mechanically rotating a circular jet inclined relative to the nozzle axis. The velocity data is obtained by three-dimensional Laser Doppler Anemometry. A conditional phase-averaging technique enables the display of phase-averaged velocity contours and vectors respectively, and reveals flow patterns and structures within the complicated flow field.

NOTATION

d_e	exit diameter of the spinning nozzle
α_e	exit angle of the spinning nozzle
f_p	frequency of precession
ν	kinematic viscosity
Re	Reynolds Number $u_e d_e/\nu$
St_p	Strouhal Number of precession $f_p d_e/u_e$
r,x,Φ	cylindrical coordinates (Fig.2)
	Φ pos. anti-clockwise, precession clockwise
u_e	exit velocity of the precessing jet
$\tilde{u}_x$	phase-averaged axial velocity
$\tilde{u}_r$	phase-averaged radial velocity
$\tilde{u}_\Phi$	phase-averaged tangential velocity

INTRODUCTION

The precessing jet (PJ) flow has been the subject of detailed investigations at the University of Adelaide, Australia, since 1985 (Nathan, 1988). The precessing jet phenomenon is a naturally occuring fluid mechanical instability that follows an abrupt axisymmetric expansion into a short cavity. Such an unsteady and asymmetric reattaching flow, when utilised in a precessing jet (PJ) nozzle, is augmented by placing a lip at the exit of the short cavity. The exiting jet is deflected, leaving the cavity at an angle of between 30^o and 60^o, and precesses about the geometric axis of the cavity (Hill et.al., 1992; Nathan and Luxton, 1991).

The precessing jet has proven to be an excellent mixing device and the 'fluid-mechanical' precessing jet nozzle has been patented and commercalised as a burner. The beneficial characteristics of the PJ burner, commercalised under the name GYRO-THERM, include reduction of NO_x emissions by up to 50%, maintenance of low CO emissions and reduction of specific fuel consumption (Nathan et.al., 1992; Nathan and Luxton, 1992).

To facilitate measurements of the complicated flow field a 'mechanical' nozzle has been designed (Fig.2) and a range of cold-flow investigations have been conducted and reported previously to gain insight into the effects of the precession on the mixing characteristics of the jet (Schneider et.al., 1992; Schneider et.al., 1993).

The present cold-flow investigation uses the non-intrusive laser Doppler anemometer measurement technique. This enables measurements of all three velocity components simultaneously over a wide velocity range in the precessing jet flow field.

EXPERIMENTAL TECHNIQUE

The Mechanical Nozzle

The mechanical nozzle (Fig.2), which is used in the present case to create the precessing jet flow field, has been tested in earlier investigations (Schneider et.al., 1992). When there is no rotation, $f_p = 0$, the jet has a typical top-hat velocity profile in the core region and displays self-similarity in the fully developed region as does a conventional turbulent jet (Wygnanski and Fiedler, 1969). In the precessing case the

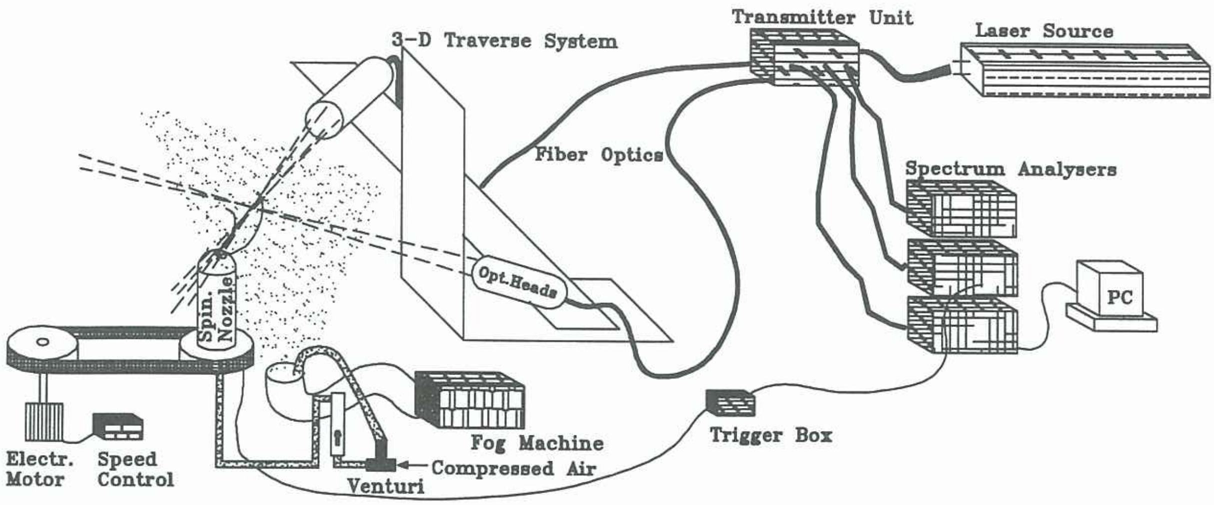

FIG.1: APPARATUS

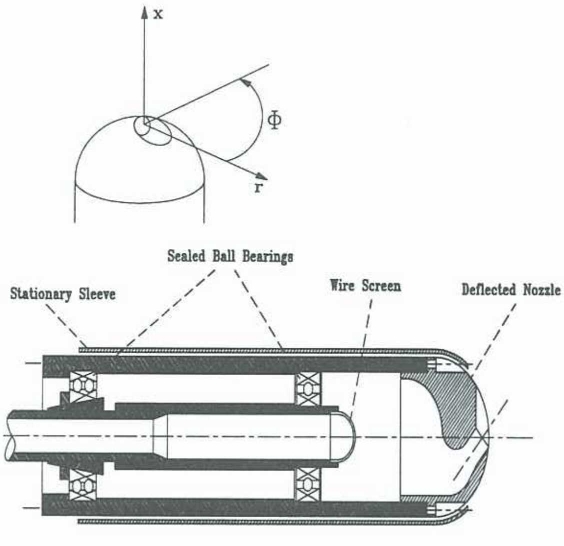

FIG.2: MECHANICAL NOZZLE AND COORDINATE SYSTEM

nozzle establishes well defined initial conditions for the jet (exit diameter d_e, exit angle α_e, frequency of precession f_p, exit velocity u_e and a jet exit on the centreline). These well defined conditions allow data to be conditionally phase-averaged. In addition, the Reynolds number at the origin can be varied independently from the Strouhal number of precession.

The initial conditions selected for this investigation are an exit velocity $u_e = 39$ m/s, corresponding to an exit Reynolds number Re=26,000, measured by a flow rate meter with an accuracy of ±2%. The frequency of precession is set, via a speed controlled electric motor, to $f_p = 59.1 \pm 0.5$ Hz, which corresponds to a Strouhal number of precession $St_p = 15.2 \times 10^{-3}$. The tip of the mechanical nozzle has an exit diameter d_e = 10mm and an exit angle $\alpha_e = 45^o$ with the origin of the exiting jet on the spinning axis.

A stationary sleeve (Fig.2) is placed around the spinning nozzle during the experiments to reduce the influence of the external boundary layer on the flow field to be measured.

The LDA System

The 5W Argon-Ion laser at the University of Cardiff/Wales is used as a light source to conduct the LDA measurements. The light from this laser source is passed through a Bragg cell to create the required frequency shift and a transmitter unit to separate the beams into three components (green, blue and violet). The beams are focused through separate fibre optic cables and passed to two optical heads. These heads contain the transmitting and receiving optics so that the unit operates in backscatter mode. The beams are arranged at 90° to each other, to enable each velocity component to be measured separately (Fig.1). Alignment is such that the green beam measures the tangential velocity, the blue beam the axial velocity and the violet beam the radial velocity. The control volumes (calculated from the focal length of the lenses (600mm), the beam diameter (1.3mm), the wavelength (green=514nm, blue=488nm, violet=476.5nm) and the incidence angle) are approximately 4.6mm long and 0.15mm wide. To ensure high focal accuracy in the mutual control volume the three beams are focused through a 50μm pinhole. The received signals, passing through separate Burst Spectrum Analysers, are transformed to velocity data and stored on a PC. In addition to the three velocity signals (plus their arrival times), a trigger signal is collected simultaneously. The trigger signal is produced from a Hall effect sensor serving as a reference signal for the nozzle position to enable phase-averaging of the data. A total number of 42,000 (3× 14,000) points are recorded on each of the channels, allowing over 100 cycles of the precessing jet to be recorded and phase-averaged for each radial position. The software used for the averaging has been specially developed by the University of Wales (Froud, 1993). To maintain a high data rate in the jet region and in the external flow both the jet and the ambient fluids are seeded. A "fog" machine is used to vapourise a glycol based fluid to produce sub micron particles

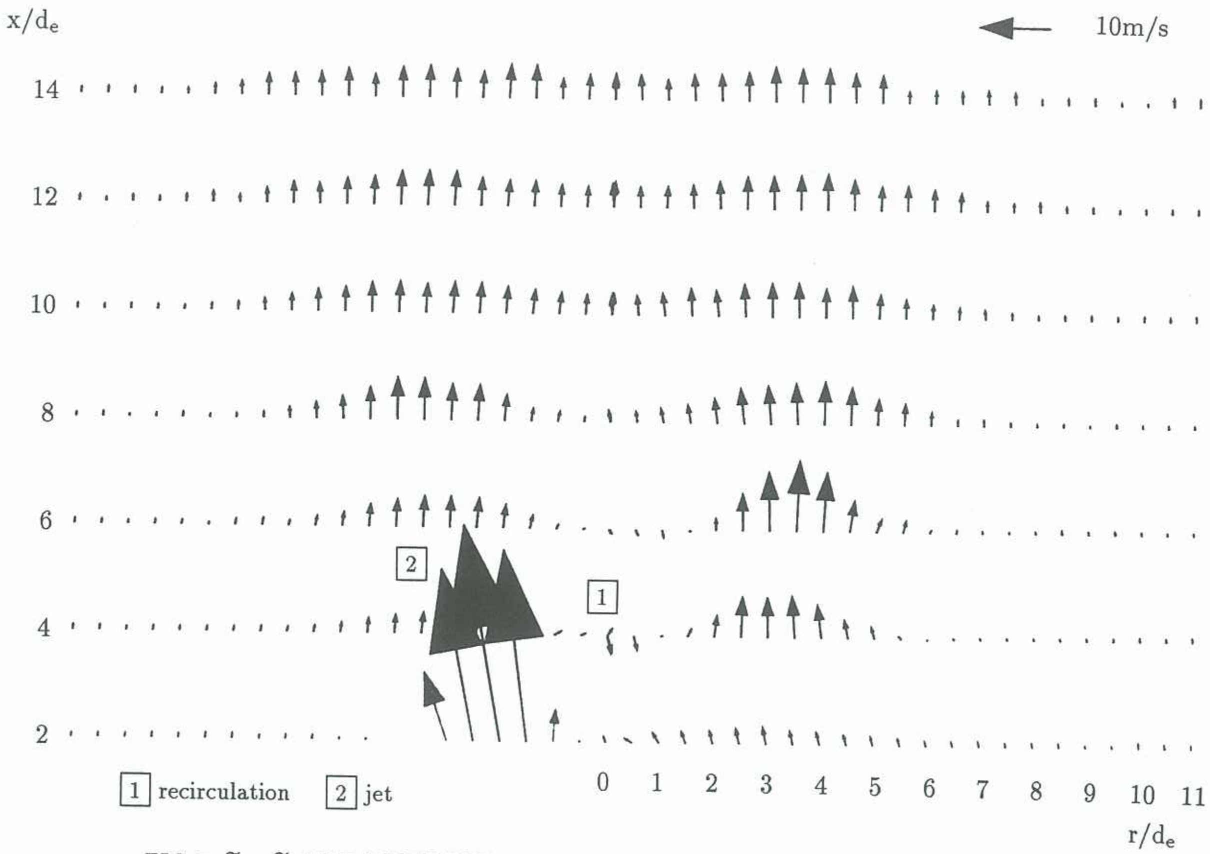

FIG.3: $\tilde{u}_x$ -$\tilde{u}_r$ VELOCITY VECTORS IN A SLIZE THROUGH THE r–x PLANE

('HAZE'). These can be shown to follow the flow very well under the present conditions and to have very good scattering characteristics. The beams are traversed radially from the nozzle axis, r=0mm, to r=120mm in 5mm steps, thus collecting 25 radial positions for each plane. Seven planes at the distances x/d_e=2,4,6,8,10,12 and 14 are measured.

The limitations of using the LDA system in the precessing jet flow come from the the inability to resolve large velocity gradients accurately due the length of the control volume (Durst et.al., 1981). Fringe or angle bias can be reduced to a minimum by applying a frequency shift of 40MHz (Durst et.al., 1993). The sub–micron particles used as seeding ensure that particle lag effects are negligible (Melling and Whitelaw, 1975). An adequate particle arrival rate is achieved to resolve velocity fluctuations which are an order of magnitude higher than the expected fluctuation frequency in the precessing jet (Durst et.al., 1981).

RESULTS

Figure 3 shows a slice of phase–averaged velocity vectors through an r–x plane which spans $2 \leq x/d_e \leq 14$ and $0 \leq r/d_e \leq 12$. One representative contour of the phase-averaged axial velocity is shown in Figure 4. The corresponding radial and tangential flow patterns at x/d_e=4 are presented in Figure 5. A distinct reverse flow region is measured between the jet and the spinning axis. Its presence is observed for x/d_e=2,x/d_e=4 and x/d_e=6 (Fig.3).

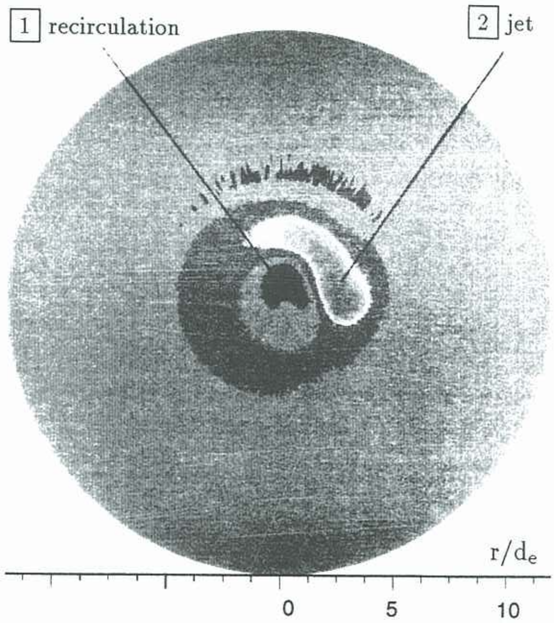

FIG.4: $\tilde{u}_x$ VELOCITY CONTOUR AT x/d_e=4

The maximum negative phase-averaged velocity is measured to be -3.5m/s at x/d_e=4 and r/d_e=1.5. The overall size of the phase-averaged recirculation region is approximately two to three nozzle diameters in width (r–direction) and six nozzle diameters in length (x–direction). Figure 5 also shows a strong inflow towards the recirculating region near the center of rotation. A bifurcation is apparent tangentially just ahead of the jet. This flow probably consists of

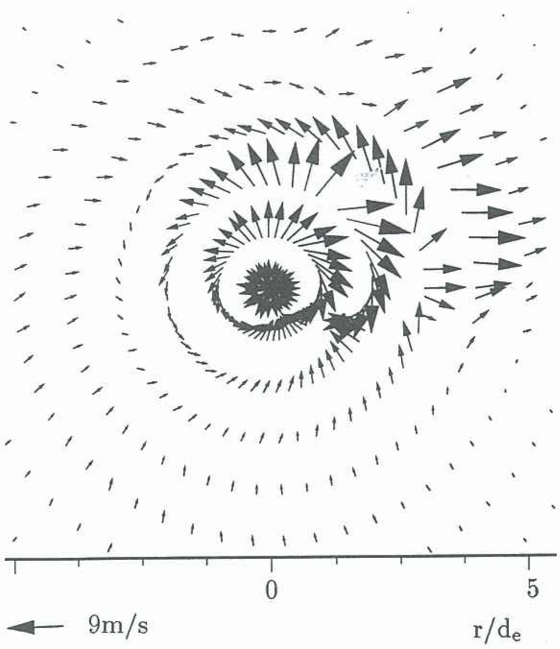

FIG.5: $\tilde{u}_r - \tilde{u}_\Phi$ VELOCITY VECTORS AT $x/d_e=4$

both jet and ambient fluid. The bifurcation signifies inflow into the recirculation zone. Part of this fluid seems to be re-entrained tangentially behind the jet. On the 'outer' side of the phase-averaged jet only small positive radial components are found and there is an almost imperceptible inflow into the 'wake' of the jet.

While the jet spreads rapidly from the origin, its radial extent remains approximately constant from $x/d_e=4$ to $x/d_e=14$ and the radial velocity component decays rapidly, so that at $x/d_e=4$ (Fig.3) it is already less than half the axial component there, reminiscent of a limit cycle.

The rate of nozzle centerline velocity decay is much higher than for other turbulent jets and in the planes of the strong reverse flow ($x/d_e=2$, 4 and 6), the decay rate is even more marked. A significant linear correlation (R=0.712) exists between the magnitude of the reverse flow and the decay of the phase-averaged axial velocity. Further downstream these features are no longer present. There is no clear flow structure when phase-averaged at the frequency of precession and the flow is almost axisymmetric (Fig.3).

CONCLUSIONS

Phase-averaged measurements of the velocity components within a precessing jet reveal organised large-scale motion and distinctive flow characteristics. A reverse flow region between the jet and its spinning axis has been detected, contributing to an overall increase in the decay of the jet velocity. The phase-averaged stream lines of the jet are observed to curve both radially towards the nozzle axis, and tangentially in the direction opposite from that of the jet precession. Meanwhile flow is drawn in toward the recirculation zone from the region not occupied by the instantaneous jet.

In the region $x/d_e \geq 8$, the mean velocity profiles become more uniform and the velocity components of the precessing jet are dramatically reduced. The phase-averaged radial and tangential velocity vectors show inflow in the upstream region of the flow induced by the recirculation zone. They become insignificant with increasing distance from the jet exit.

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