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THE INFLUENCE OF THE EXIT ANGLE ON THE INITIAL TRAJECTORY OF A PRECESSING JET FLOW

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ABSTRACT

The 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 round jet inclined relative to the axis of rotation. The influence of the inclination of the jet to the axis of rotation on the path of the precessing jet is investigated here. Three dimensional laser Doppler anemometry is applied to obtain velocity data, phase-averaged at the frequency of precession at various distances from the nozzle exit. The conditional phase-averaging technique enables the local maxima of the velocity to be obtained. The effect of deflection angle on the velocity decay rates and the path of the local jet centreline are then determined. The characteristics of the precessing jet found here are compared with previous investigations of the same flow and with investigations of other turbulent jets.

INTRODUCTION

The precessing jet (PJ) has been the subject of detailed investigations at the University of Adelaide, Australia, since 1985. The precessing jet phenomenon can be generated naturally by a fluid mechanical instability that follows an orifice plate or a nozzle with a large abrupt axisymmetric expansion into a short chamber (Nathan, Hill and Luxton, 1998). It occurs over a wide range of flow conditions (Nathan and Luxton, 1991 and 1992). The emerging jet is deflected relative to the nozzle axis, leaving the nozzle chamber at an angle from the axis of between 30° and 60°, and the entire flow precesses about the axis of the chamber. This configuration is referred to as the "fluid mechanical" precessing jet nozzle.

The fluid mechanical precessing jet nozzle has been patented and is being commercialised as the "GYRO-THERM" burner. It has been retrofitted to a range of large scale rotary kilns in various industries both within and outside Australia (Manias and Nathan, 1993). Suction pyrometry measurements in a 2MW laboratory furnace have shown that the maximum time-averaged flame temperature of the PJ flame is typically 150°C lower than that of a comparable swirl burner, which is consistent with a reduction of NO_X emission by about 50%, while maintaining low CO emissions (Nathan et al. 1992). In the industrial kilns NO_X emissions are typically reduced by 30-60%, and specific fuel consumption is reduced by 3-10%. Thus the precessing jet flow has potential to contribute significantly to more efficient and cleaner industrial processes (Nathan and Manias, 1993).

To gain insight into the fundamental effect of precession on the mixing and combustion processes which result from the jet precession, a "deterministic" or "mechanical" nozzle has been developed (see Experimental Method and Fig.1). The mechanical nozzle produces a jet with known and well defined exit conditions (diameter, deflection angle, frequency of precession, velocity etc.) so that the flow can be compared with conventional jets. In addition, it allows easy conditional phase-averaging of the data and enables the Reynolds number at the origin, $Re=u_e d_e/\nu$ to be decoupled from the Strouhal number of precession, $St_p=f_p d_e/u_e$. Previously reported measurements in precessing jet flows have revealed that the mixing from the fluid mechanical nozzle is dominated by turbulent structures of a scale which is many times the nozzle dimensions (Nathan and Luxton, 1992). Also the entrainment rate of the fluid mechanical PJ nozzle in the first five exit diameters was found to be approximately five times greater than that of a simple turbulent jet (Ricou and Spalding, 1970) and the initial spread of both the mechanical and fluid mechanical precessing jets is significantly greater than that of either simple jets or swirled jets (Nathan and Luxton, 1992). Specifically for the mechanical nozzle previous investigations have found that in a "high" Strouhal number regime ($St_p>5x10^{-3}$) the phase-averaged Reynolds stresses throughout the first four exit diameters of the flow field are an order of magnitude larger than those in a simple jet (Schneider 1996). Also conditional measurements of velocity and pressure contours have revealed a low pressure zone between the jet and the spinning axis (Schneider 1996).

In the present paper a three dimensional Laser Doppler Anemometer (LDA) system is used to measure simultaneously all three velocity components in the jet. In their investigation of a turbulent precessing jet, Schneider et al. (1997) used a 3-dimensional LDA system and phase-averaging techniques to obtain structural information. They also provide a detailed analysis of the measurements errors. Similar techniques are applied here in the precessing jet with varying exit angles.

EXPERIMENTAL METHOD

The Mechanical Nozzle

The significant parameters in a precessing jet flow are the exit angle, exit velocity, frequency of precession, eccentricity of the jet exit and the exit diameter of the jet. The mechanical nozzle (Fig 1) provides means by which to define precisely and to vary each of these parameters independently. Here the exit of the jet is centred on the spinning axis. When the nozzle is not rotating (f_p=0) the

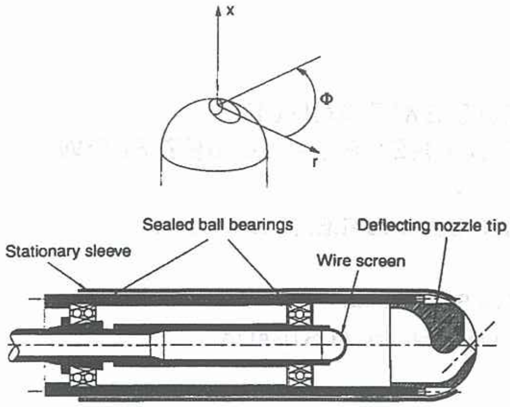

Figure 1: The mechanical nozzle and the coordinate system

cold flow of the emergent jet exhibits all the well established characteristics of a symmetric turbulent jet. The exit angle relative to the spinning axis of the nozzle has been varied here from 0°, 15°, 45° to 60° by means of interchangeable nozzle tips, leaving the exit diameter of the jet constant at 10mm.

The results presented in this paper all relate to an exit diameter d_e=10mm, a mean exit velocity of u_e=40m/s and a frequency of f_p=40Hz. This corresponds to a Reynolds number Re=26,600 and a precessional Strouhal number St_p=0.01. A 300W variable frequency electric motor, connected to a speed control unit, allows the frequency of precession to be controlled within <±1%.

Laser Doppler Anemometer System

Phase-averaged, three dimensional velocity measurements were conducted at the University of Wales, Cardiff. A schematic of the experimental arrangement is shown in Fig 2. The LDA system is a DANTEC three-component backscatter system using a COHERENT Inova 70 series 5 Watt Argon-Ion laser.

Optics

To remove directional ambiguity, all three colours were frequency shifted by Bragg cells. After the colour separation and beam splitting, the six beams are optically coupled into two fibre optic probe heads. The two heads are set at 90 degree to each other and arranged so that the six beams are crossed at 600 mm away from the heads. With this arrangement, direct measurements of each of the three velocity components are possible. The tangential, axial and the radial velocities in the present experiments were measured using wavelengths of 514.5, 488.0, and 476.5 nm respectively. The lengths of the control volumes for each of the beams, calculated from the 600mm focal length of the lenses, the beam diameter, the wavelength and the incidence angle are: for the green beam dr=4.9mm; for the blue beam dr=4.6mm; and for the violet beam dΦ=4.5mm. The diameter of each of the control volumes is about 0.16mm.

Signal Processing and Data Acquisition

The signals from the three beams were sent to separate Burst Spectrum Analysers and the resulting frequencies were stored on the PC with their associated arrival times. In addition to the velocity signals, a fourth trigger signal, to reference the angular position of the spinning nozzle, was collected simultaneously. The data was then phase-averaged relative to that reference signal, which identifies Φ_0 (Φ=tangential direction at the exit plane), over multiple cycles of precession with a chosen resolution of 360 parts for each cycle (1 degree segments). A total of 14,000 data points were recorded on each of the channels, allowing more than 35 cycles of the precessing jet to be recorded and phase-averaged for each radial position. The software used for the averaging was developed by the University of Wales specifically for the present experiments.

Seeding

To maintain a high data rate in the jet region and in the external flow, both the jet and the ambient fluids were seeded. A ROSCO 4500 fog machine was used to produce "HAZE", sub micron glycol particles which are found to have no influence on the dominant flow patterns, and which have very good scattering characteristics. To ensure uniform seeding of the surrounding fluid and the jet fluid with one fog machine, different hose diameter ratios have been assessed.

Traversing

The optical heads carrying the laser beams were mounted on an automatic DANTEC traverse system which locates accurately to within ±0.05mm. The beams were traversed radially (along the green and blue beams) from the nozzle axis, r=0mm, to r=120mm in 5mm steps, thus collecting 25 radial positions for each plane. Six r-Φ planes at the distances x/d_e=2,4,6,8,10 and 12 were measured.

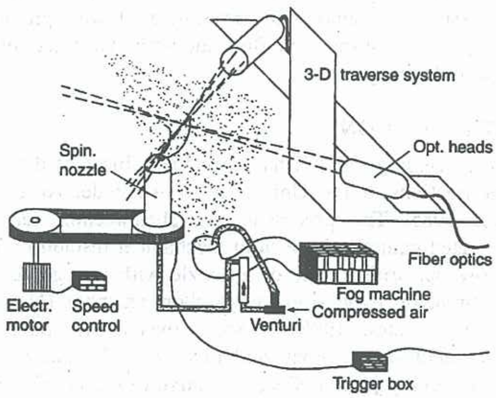

Figure 2: The apparatus

Discussion of Errors:

The most significant error in the LDA technique used here is the inability to resolve large velocity gradients accurately. This is due to the length of the control volume and limited radial (5mm traversing steps) and angular (1° ≈ 2mm at r_{max} =120mm) resolution, resulting in broadening of the mean velocity. It was not possible to estimate the errors a priori, since the velocity gradients in a precessing jet were not known. Based on measurements for a comparable simple turbulent jet by Komori and Ueda (1985), the limitations of spatial resolution would be insignificant (<±0.4%). Based on the maximum gradients determined in the present measurements of the precessing jet, the errors are in the order of 2%.

Other potential sources of bias in LDA systems have been eliminated or found insignificant here. The velocity bias towards higher velocities (McLaughlin and Tiederman 1973) was reduced to insignificant levels by ensuring that both the surrounding fluid and the jet fluid were uniformly seeded with a high particle density, following Edwards (1981), and a controlled processor was used as shown by Winter et al. (1991). The fringe bias or angle bias was reduced to a minimum by applying a frequency shift of 40 MHz. The clock-induced error, produced by the frequency shift of 40 MHz was corrected following Graham et al. (1989). Particle lag effects can be neglected when using particles of HAZE with a typical diameter $d_p < 1\mu m$ and a density ratio relative to air of $\sigma = 800$. Calculating the frequency response (Durst et al. 1981) of the HAZE particles yields approximately 7.5 kHz, which is much larger than the maximum turbulence frequency measured in the jet. From the dimensions of the control volume, the velocity of the flow and the number of bursts per second, a density of the scattering particles of $N=3.5x10^{10}$ particles/m^3 can be calculated. This concentration is sufficient to resolve velocity fluctuations in excess of 200kHz which is about two orders of magnitude higher than the fluctuation frequency in the turbulent jet so that the particle arrival rate is adequate (Durst et al. 1981). In the present case the statistical error in a randomly sampled data set, calculated by Winter et al. (1991) is negligible.

RESULTS

The results of the LDA measurements in six planes downstream from the nozzle exit, x/d_e=2, 4, 6, 8, 10 and 12 are presented here. To identify the effect of the exit angle of the precessing jet on the phase-averaged trajectory of the jet, the local centreline of the precessing jet is plotted in Figs. 3 and 4. The local centreline is defined here as the location of the maximum phase-averaged velocity at each plane of measurement. In all Figures in this section the jet with 0° exit angle represents an axial round jet (spun at the same frequency as the other jets) for comparison. Previous investigations (Schneider 1996 and Schneider et al. 1997) show that the present jet exiting from the spinning mechanical nozzle with 0° exit angle is similar to a conventional non-precessing turbulent round jet (Wygnanski and Fiedler, 1969).

Figure 3 shows the local jet centreline of the precessing jet plotted in the x-r plane. Three regions of the flow can be identified. In the first region, to the end of the potential core, the emerging precessing jet follows the initial exit angle. Downstream from the potential core, in the second region, the local jet centreline is deflected sharply towards the axis of rotation due to a low pressure region between the jet and its spinning axis (Schneider 1996). Sufficiently downstream, in the third region, the radial position of the phase-averaged velocity is approximately constant within the range of data. Scalar measurements by Nobes (1998) suggest that in the far field the mixing characteristics of a precessing jet are broadly comparable with those of a non-precessing jet, suggesting that the local jet centreline is deflected back towards r/d_e=0 in the far field of the precessing jet (x/d_e>30) .

Figure 4 shows that there is initially no deflection of the jet centreline in the r-Φ plane (region I). It is also apparent that with increasing exit angle the azimuthal deflection increases. Thus the pitch of the "spiral" of the local jet centrelines is smaller in radial extent with a small exit angle and is widened with increased angle.

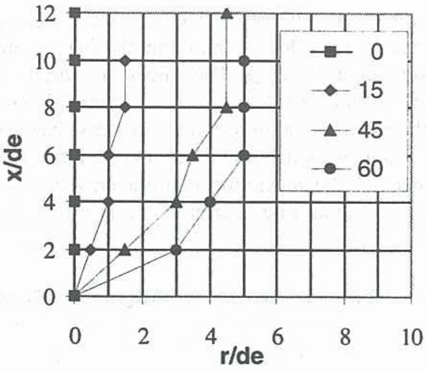

Figure 3: The trajectory of the local , phase-averaged jet centreline for different exit angles in the x-r plane

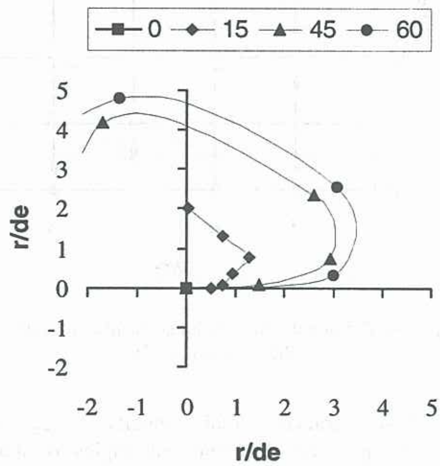

Figure 4: The trajectory of the local , phase-averaged jet centreline for different exit angles in the r-Φ plane

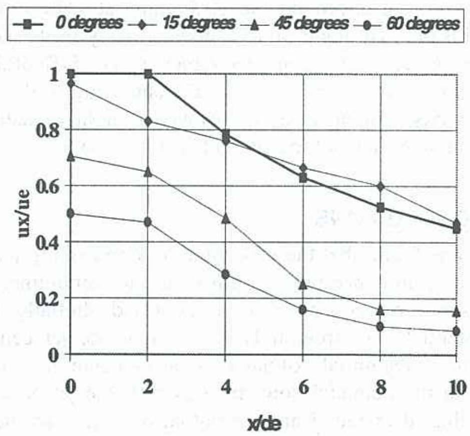

Figure 5: The axial , phase-averaged centreline velocity for different exit angles

The axial velocity decay of the precessing jet with different exit angles is shown in Figure 5. The velocities are normalised on the total exit velocity, hence the u_X/u_e at x/d_e=0 show different initial values for the different exit angles. The jet with exit angle of 15° has a velocity decay comparable with the round turbulent jet of 0° exit angle. However, for the larger exit angles Φ=45° and Φ=60° the velocity decays more rapidly than for the non-precessing jet at $4 \le x/d_e \le 8$. The values of u_x/u_e at $x/d_e=10$ are 10.5% of the exit velocity (at 45°) and 7.2% (at 60°). Since the radial velocity at $x/d_e=10$ is less than half that of the axial velocity for these exit angles the total component of the maximum phase-averaged velocity at this point is about one quarter of the non-precessing jet flow.

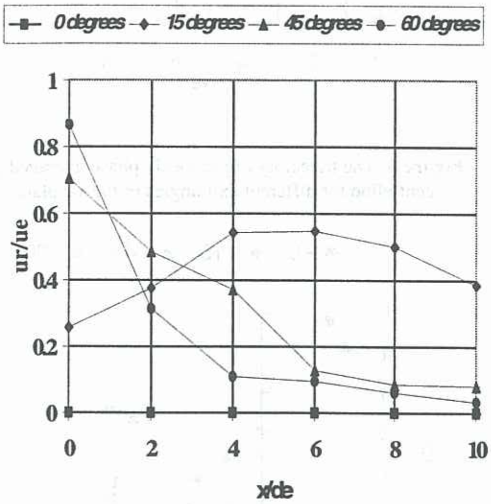

Figure 6: The radial , phase-averaged centreline velocity for different exit angles

The phase-averaged radial velocity decay of the precessing jet with different exit angles is shown in Figure 6. At exit angles of 45° and 60° the precessing jet shows an rapid decrease of the radial velocity component. At 60° the radial component has decayed to under 10% of the exit velocity at $x/d_e \ge 4$. For the 45° jet the radial component is around the 10% value at $x/d_e=6$. The jet with the exit angle of 15° shows a delay in the velocity decay. The radial component increases to 54% of the exit velocity at $x/d_e=4$ and 6. Beyond $x/d_e=6$ the radial velocity component decreases with a slightly smaller rate than identified at the exit angles of 45° and 60°.

CONCLUSIONS

It was found that the exit angle of a precessing jet has a strong influence on the path of the jet centreline. Three distinct regions have been identified. Initially in the potential core (region I) the path of the jet centreline follows the initial exit angle in the x-r plane. Downstream from the potential core, in region II, the jet is strongly deflected in radial and azimuthal direction. In the third region the path of the jet centreline assumes a constant radial position in the near field.

The axial velocity decay showed that for small exit angles the velocity decay is similar to a turbulent round jet. However, with increasing exit angles the decay of the velocity increases dramatically. The phase-averaged radial velocity decay showed that for a small exit angle the velocity initially increases, while at distances of $x/d_e>4$ and for the large exit angles the radial velocity decays rapidly and becomes insignificant for $x/d_e>6$.

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