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THE MEAN FLOW FIELD OF A PRECESSING JET[1]

J. Mi, R. E. Luxton and G. J. Nathan

Department of Mechanical Engineering
University of Adelaide, SA 5005, AUSTRALIA

ABSTRACT

Precession of a jet can be generated from a rotating nozzle whose axis is inclined at a non-zero angle to the axis of rotation. There is growing evidence suggesting that, in comparison with its non-precessing counterpart, the large-scale globally coherent motions in a precessing jet may significantly modify turbulent mixing. This paper describes an investigation, in which a hot-wire probe was used for anemometry, in a mechanically precessing jet (MPJ) with $\alpha = 45°$ and Strouhal numbers of precession $St_p \approx 0.005$, 0.01 and 0.02. The results show that the characteristics of mean flow are determined predominately by St_p. The flow with any St_p has a regime of globally coherent precession at $x/d \leq 10$. The data, together with those of Schneider (1996), indicate that the critical Strouhal number, below which the mean flow never behaves like a simple jet, is $St_p \approx 0.01$. At higher Strouhal numbers, the far-field mean flow eventually becomes similar to that of a simple free jet. The flow for $St_p = 0.02$ becomes fully-developed at $x/d \approx 20$. For $St_p \geq 0.01$, the precession promotes large-scale mixing at the expense of the suppressed generation of fine-scale turbulence.

INTRODUCTION

Turbulent mixing has been extensively investigated both experimentally and theoretically for many decades. The understanding of mixing in turbulent free jets has long been a central objective of fundamental research because these relatively simple flows are a basic component in many practical systems. In an effort to alter mixing characteristics, many practical systems have become far more complex and include such features as swirl, bluff-bodies and multiple jets. There is now growing evidence that modifying the turbulent mixing characteristics of a simple jet can introduce benefits such as increased flame emissivity and reduced NO_x emissions. A typical example of this is the use of a naturally occurring jet precession (Luxton & Nathan 1987), which has found application in industrial burners. Full-scale installations of commercial precessing jet (PJ) burner systems in rotary kilns (15~120 MW) have consistently demonstrated that, relative to the flames from the burners they replaced, NO_x emissions are reduced by 50% to 70% while the fuel savings of 5% are typical (Manias *et al.* 1995 and Manias & Nathan 1993,1994).

Whilst the efficacy of the precessing jet (PJ) flow is proven in practice, it is a flow which is extraordinarily difficult to study at the fundamental level. Primarily this is due to its continuous instability, and it is this very instability which appears to be the source of the beneficial effects. As a step towards dissecting the natural PJ flow into its component features, the Turbulence, Energy & Combustion Research Group of the University of Adelaide is undertaking a fundamental investigation of the effects of precession on jet mixing. Using a mechanically rotating nozzle, it is possible to generate a PJ flow which has its origin at the nozzle exit. Unlike the flow from the fluidic nozzle, the mechanically precessing jet (MPJ) has well-defined initial conditions, each of which can be varied independently. Nathan *et al.* (1996) have conducted a fundamental investigation of combustion in turbulent diffusion flames. By changing the initial conditions of a mechanical PJ flow they produced a wide range of turbulent mixing characteristics. During the experiments, the nozzle exit diameter (d), jet exit velocity (U_e), heat output and fuel type remained nominally unchanged. They found that, relative to a conventional jet diffusion flame, the precession can increase the radiant fraction and reduce the NO_x emissions of small open natural gas flames by up to 15% and 25% respectively.

To explain better the observed combustion characteristics of a MPJ flame, Schneider (1996) and Schneider *et al.* (1997a,b) have investigated the near field of the flow using both the LDA technique and a miniature four-hole "Cobra" pitot probe. By employing phase-averaging scheme, they revealed flow patterns and structures within the flow field. For the case of St_p ($\equiv f_p d/U_e$) ≈ 0.015 and the Reynolds number Re_d ($\equiv U_e d/\nu$) = 26600 (where f_p is the frequency of precession and ν is the kinematic viscosity), they have shown that the jet spirals out from the nozzle around a recirculation flow zone and the entire flow at $x/d \leq 6$ precesses. Under the same experimental conditions, Nobes *et al.* (1996, 1998) have measured the concentration field using the Mie scattering technique. These studies have improved our knowledge about the MPJ flow but, due to its extraordinary complexity, our understanding of turbulent mixing in the flow is still in infancy. Recent velocity measurements with a hot-wire probe in both the MPJ flow and a non-precessing jet were motivated by a desire to improve this situation. Our previous papers (Mi *et al.* 1997; Nathan *et al.* 1997) have reported spectral data for St_p =

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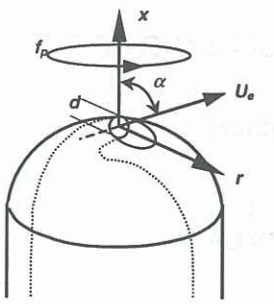

Figure 1: A sketch of a rotating nozzle and the associated coordinate system.

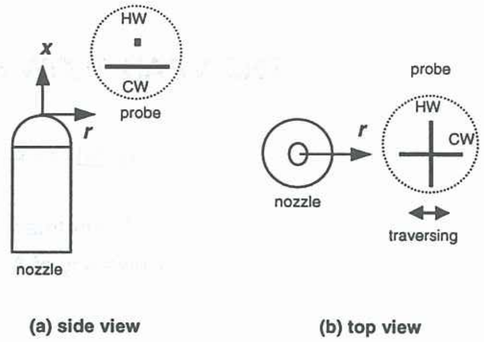

Figure 2: The measuring probe and it versus the nozzle. HW and CW denote 'hot-wire' and 'cold-wire', respectively.

0.02. The aim of this paper is to examine the effect of St_p on the mean and phase-averaged flow of the jet into the far field.

EXPERIMENTAL DETAILS

A precessing jet flow was produced by the rotating nozzle shown in Fig. 1. The nozzle was supplied with filtered and compressed air (whose maximum pressure is 500 kPa at the temperature of 20°C). The parameters which characterise the flow field of the jet are the frequency of precession f_p, the exit diameter d, the exit angle α, the exit mean velocity U_e and the jet exit eccentricity (see Fig. 1). For the present case, d = 10 mm, $\alpha = 45°$, $U_e \approx 21$ m/s and the jet exit is centred on the axis of rotation. The corresponding Reynolds number Re_d is approximately 14000. The variation in Strouhal number ($St_p \approx 0.005$, 0.01 and 0.02) was produced by changing only the precession frequency (f_p = 10, 20, 40 Hz). The mean exit velocity U_e was measured by a variable area flow-rate meter with an accuracy of ±2%. Nozzle rotation was made by a 300 W variable-speed electric motor and the rotation frequency f_p were measured with an uncertainty of ±0.1 Hz.

Hot-wire anemometry was used for the velocity measurements. The measuring probe (Fig. 2) combines a 5 µm tungsten "hot" wire (to measure velocity) with a 2.5 µm tungsten "cold" wire. The cold wire detects possible flow reversal by sensing the presence of the thermal wake of the hot-wire. In the coordinate system of the nozzle, the axis of cold-wire filament was aligned in the radial direction and the hot-wire filament was aligned in the tangential direction (Fig. 2). During the experiments, the probe was traversed radially at several x-locations. The hot-wire measures $U = (V_x^2+V_r^2)^{1/2}$, where V_x and V_r are the axial and radial components of the velocity vector. The configuration of the probe enables the cold-wire to identify reversed flow for which $V_x < 0$.

The hot-wire was operated at an overheat ratio of 0.5 by an in-house constant temperature circuit, while the cold-wire was operated at 0.1 mA with an in-house constant current anemometer. The sign of the velocity component V_x is determined from the cold-wire signal when processing the data. Voltage signals from both wires were offset before being amplified, low-pass filtered at 2.8 kHz to eliminate high frequency noise, and digitised at 5.6 kHz using a 12-bit A/D converter on a personal computer. The data record duration is about 30 seconds, a time that is sufficient for both large-scale and small-scale motions to be adequately resolved in the spectrum. Calibrations of the hot-wire probe were carried out using a standard Pitot tube at the exit plane of a round smoothly contracting nozzle.

RESULTS AND DISCUSSION

A. Mean Flow Field

Figs. 3(a) and (b) show the axial evolution of the radial distribution of the time-averaged velocity, $\overline{U}$, and the rms velocity fluctuation $u' \equiv \overline{u^2}^{1/2}$ in the region 1.5 ≤ x/d ≤ 20 for St_p = 0.005, 0.01 and 0.02. From these plots, the following observations may be made:

(1) At all three Strouhal numbers St_p, there is a recirculation zone present around the axis of rotation in the region $0<x/d<8$. As St_p decreases, the zone becomes larger in size and the average speed of the reversed flow increases.

(2) The radial distribution of mean velocity has two off-axis peaks in the near-field region. As the flow proceeds downstream, the peaks become less distinct. The radial location $R_m(r)$ of the peak is significantly influenced by the magnitude of St_p. While R_m increases monotonically with x for St_p = 0.005, it increases and then decreases, eventually becoming zero, for St_p = 0.01 and 0.02. Fig. 4 shows the axial variation of R_m. Included in the figure are also those data obtained by Schneider (1996), who used LDA, for St_p = 0.002, 0.01 and 0.015 at Re_d = 26600. The present and Schneider's measurements for St_p = 0.01 are clearly in close agreement. Fig. 4 suggests that St_p = 0.01 may be a critical Strouhal number; below it the mean flow never behaves like a simple jet, whereas above it the far-field mean flow eventually becomes similar to the far field of a simple jet. For example, as shown in Fig. 5, when $x/d \geq 20$ the mean and rms profiles for the PJ flow of St_p = 0.02 is somewhat like those of a simple round jet.

(3) With increasing axial distance from the nozzle, the flow speed, U, initially decays at a much higher rate in the PJ flow than in a non-precessing, simple jet. This is demonstrated in Fig. 6 by comparing the assemble average, $\langle U\rangle_{max}$, of local maxima of U (which occur once a cycle of precession) for the PJ with the centreline $\overline{U}$ for a round jet (Mi & Nathan 1998). In

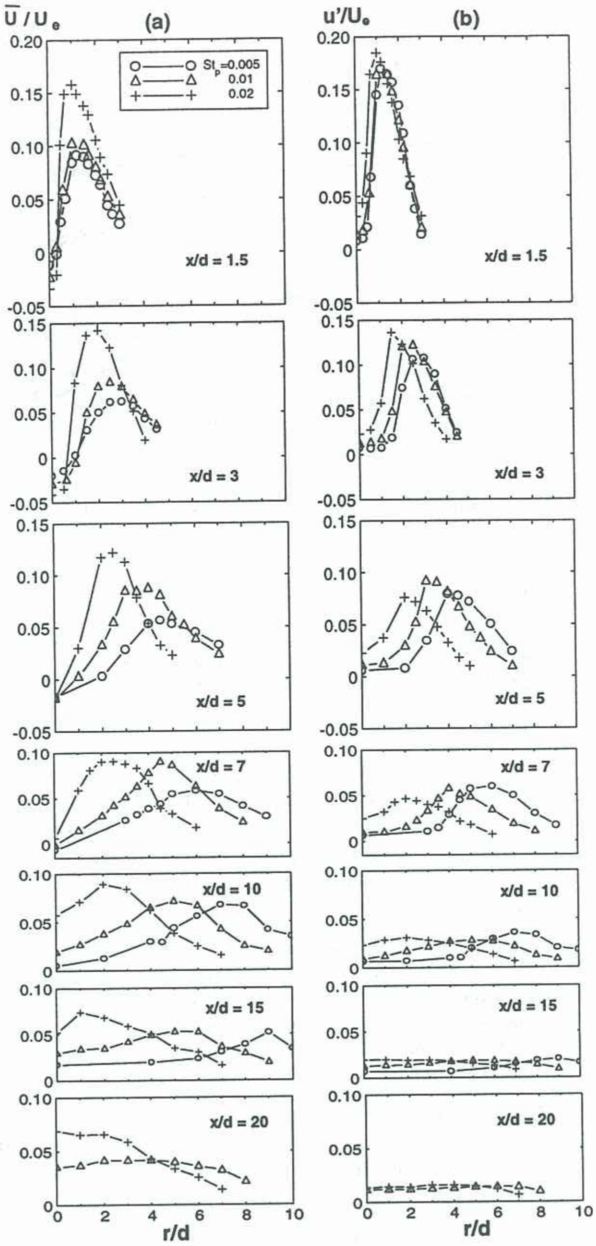

Figure 3: Effect of St_p on the velocity mean and rms field in a precessing jet flow.

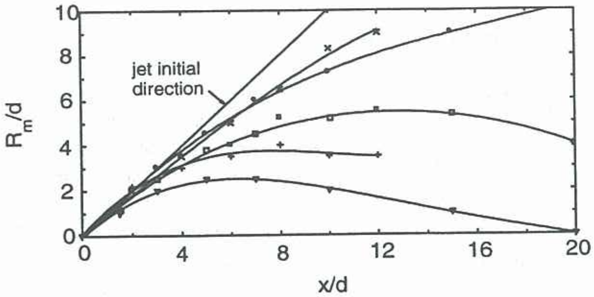

Figure 4: Effect of St_p on the radial location at which the maximum of $\overline{U}$ occurs. Present: ●, St_p = 0.005; ◻, 0.01; ∇, 0.02. Schneider (1996): ×, 0.002; ■, 0.01; +, 0.015.

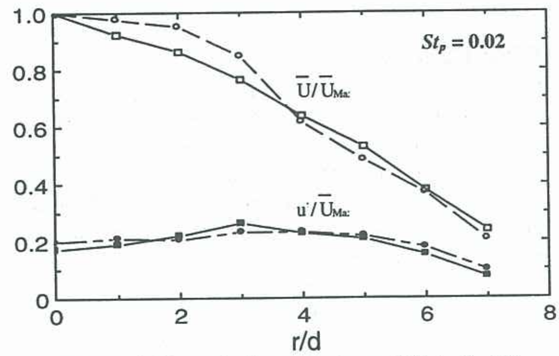

Figure 5: Normalised mean and rms of U at x/d = 20 (○,●) and 30 (◻,■) in the PJ flow of St_p = 0.02.

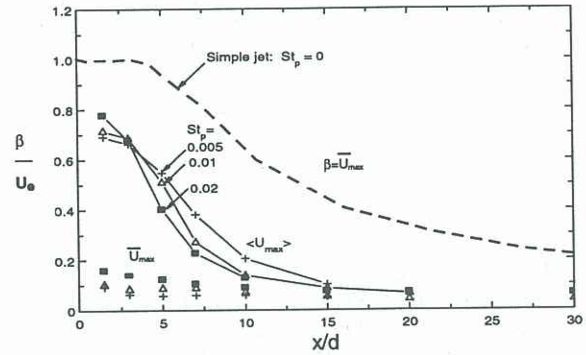

Figure 6: Effect of St_p on local maxima $<U>_{max}$ and $\overline{U}_{Max}$. +, St_p = 0.005; Δ, 0.01; ■, 0.02.

the figure, the local maximum $\overline{U}_{Max}$ is also included for reference, although its magnitude is influenced strongly by the intemmitency of the jet and entrained ambient flow due to the precession. The influence of St_p on the decay rate of $<U>_{max}$ is clear: i.e. the greater the Strouhal number (St_p), the higher the decay rate.

(4) The measurements of the rms velocity fluctuation u' in the near-field region do not adequately express the turbulence intensity of the jet flow because of the high intermitency of the induced non-turbulent ambient flow. This is illustrated by observing that $u' > \overline{U}$ at x/d = 1.5 for all values of St_p. However, as the flow develops downstream, globally coherent motion at the frequency of the precession tends to disappear and consequently u' can then be regarded as a measure of turbulence intensity of the flow (Schneider 1996).

B. Power Spectra of Velocity

Fig. 7 shows the power spectra (Φ_u) of the velocity fluctuation u, which are obtained at the radial locations of the mean velocity peaks (R_m). The spectra are normalised such that $\int \Phi_u(f^*)df^* = 1$ and $f^* \equiv fd / U_e$. In the near-field region, the periodic precession determines the motion of the whole flow field. As a result, in the region $x/d \leq 10$, Φ_u has a primary peak at $f^* \approx St_p$, followed by a number of harmonics. Since the precession initially dominates the velocity fluctuations u, the local relative rms $u'/\overline{U}$ is much higher than that of the non-precessing round jet at $x/d \leq 10$. As x increases, the mixing between the precessing jet and the ambient flow becomes more irregular and consequently the peaks associated with the precession becomes less prominent. At *x/d* = 15, the lack of discrete spectral peaks indicates an absence of globally coherent precession, the end of the precessing-flow regime, and the onset of a 'simple jet'-like flow regime. For St_p = 0.02, the new regime flow appears to be "fully" developed in the mean from $x/d \approx 20$ where $\overline{U}_{Max}$ is located on the axis (see Figs. 3-5). This is supported by the collapse of the centreline spectra normalised by x and $\overline{U}_{Max}$ for *x/d* = 20 and 30, see Fig. 3 of Mi *et al.* (1997). Applying the same normalisation scheme to the spectra for St_p = 0.01, the result is not as good (not presented here). Therefore, we are confident in concluding that, as St_p increases from the critical value, the axial distance required for the development of 'simple jet'-like flow decreases.

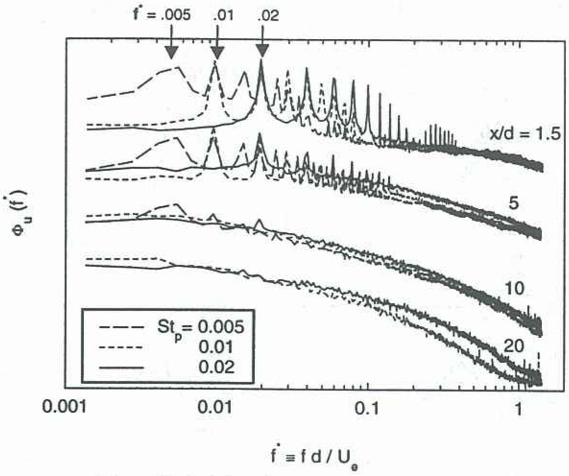

Figure 7: Axial evolution of spectra of the velocity fluctuation u at the radial locations of $\overline{U}_{Max}$.

CONCLUSIONS

The mean and rms velocity of the flow field produced by a mechanically precessing jet (MPJ) has been measured by a combined hot/cold-wire probe. The emerging jet was inclined at an angle of 45° from the axis of rotation of the nozzle. Data were obtained for three values of the Strouhal number of precession, i.e. $St_p \approx 0.005$, 0.01 and 0.02. The results have demonstrated that the Strouhal number of precession has a primary effect on the mean flow field. The flow has a regime of globally coherent precession in the region $0 < x/d \leq 10$ for all values of St_p. The present data and those of Schneider (1996) have together suggested that the critical Strouhal number is $St_p \approx 0.01$. At lower values of St_p the mean flow never behaves like a simple axisymmetric jet, whereas at higher values it eventually develops into a 'simple jet'-like regime in the far field. The flow for St_p = 0.02 becomes fully-developed at $x/d \geq 20$. When St_p is reduced, the fully-developed state is attained at larger downstream distances. For $St_p \geq 0.01$ (the critical value), the precession increases large-scale mixing of the flow at the expense of a reduction of the generation of fine-scale turbulence.

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