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# CONTROL OF INITIAL GROWTH RATE OF A JET BY COMBINED PRECESSING AND AXIAL JET FLOWS

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## ABSTRACT

A semi-quantitative flow visualisation technique, based on laser-induced fluorescence in water, was used to characterise the mixing which occurs when a precessing jet and a central axial shaping jet interact. The momentum ratio between the central axial jet and the precessing jet was found to be the controlling parameter in determining the growth rate and structure of the combined jet flow field. For all ratios, the results demonstrate that the two jets interact strongly, generating large coherent structures which span the entire width of the flow from the exit plane. The spreading angle and hence the size of the large-scale structures of the combined jets was found to depend directly upon the momentum ratio.

## INTRODUCTION

Jet spreading rates from a nozzle are a measure of the mixing rate of the jet fluid with the surrounding medium. Its significance has stimulated many investigators to use acoustic, mechanical and fluidic excitation to alter or control the rate of mixing. Such techniques typically excite and hence alter the large-scale structures present in a flow. For example, Parekh *et al.* (1987) used dual-mode acoustic excitation to produce a bifurcating jet with a half-spread angle of up to 35°. Badri Narayanan *et al.* (1987) used oscillating lips on either side of a plane jet to increase spread angles to 33°. However, acoustic and mechanical excitation methods are restricted to limited operating ranges or planar geometry. They also have practical limitations for industrial application.

The fluidic precessing jet (PJ) nozzle utilises a fluid dynamical instability following a large sudden expansion into an axisymmetric chamber. Fluid-mechanic excitation of the jet causes it to deflect and precess. The nozzle creates a flow field immediately downstream from it, which is dominated by turbulence of a scale, many times that of the nozzle, resulting in very large scale mixing and a half-spread angle of 40°-60°. Nathan *et al.* (1998) and Luxton *et al.* (1991) give an extensive description of the PJ flow and the conditions under which it arises.

The PJ burner has been shown to have beneficial combustion characteristics in rotary kiln applications due to the unique mixing field generated by the flow. It has been found to improve the stability of natural gas flames significantly, to reduce $NO_x$ emissions by 40 to 70% (Manias and Nathan, 1993, 1994) and to increase the radiation from the flame relative to conventional burner flames (Nathan and Luxton, 1992; Nathan *et al.* 1993).

In a rotary kiln, the control of jet spread and flame heat transfer characteristics is important because the process requirements of a rotary kiln can vary significantly from day to day and plant to plant, with a consequent change in the optimum heat flux requirements. The flame must also be shaped so that it does not impinge upon the product. By combining a PJ flow with an axial jet flow, good control of the heat flux distribution in a cement kiln is possible (Rapson, Stokes, and Hill, 1995). However the details of how these two jets interact has not been investigated previously. This paper presents the results of a semi-quantitative examination of the interaction between a PJ flow and a Central Axial Jet (CAJ) flow and demonstrates that the mixing characteristics and hence the spreading rate of the combined flow can be controlled. A schematic diagram of the fluidic PJ combined with a CAJ for flame shaping is shown in Figure 1.

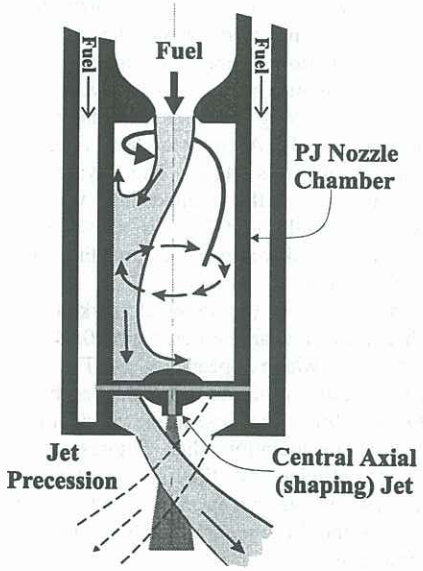


**Figure 1** : Schematic of the fluidic Precessing Jet (PJ) nozzle with a central axial jet (CAJ) for flame shaping.

Since mixing largely determines the combustion characteristics of most industrial diffusion flames, a mixing study has been undertaken to investigate the interaction between a CAJ and a PJ, and its effect upon the mixing and spread angle of the combined flow. As the technical requirements to investigate the mixing in flames are very difficult to overcome, it is easier to conduct the analysis in cold flow conditions. The results from cold-flow studies of mixing within the region corresponding to

the onset of flame stabilisation can be applied to flames in a semi-quantitative manner to assess flame stabilisation and shape (Nathan *et al.*, 1997). Gutmark (1990) has also concluded that the similarity of flow dynamics in flames and cold flows implies that methods used to control mixing in cold flows can also control a combustion process.

## EXPERIMENTAL METHOD

The mixing investigation was conducted using a Laser-Induced Fluorescence (LIF) technique in a large water tank. The use of a LIF technique enabled two different dyes, which fluoresce at different wavelengths, to be used to differentiate between the shaping and precessing jets so that their interaction can be examined in a semi-quantitative manner.

A 1mm thick light sheet was produced from an Argon-Ion (Spectra Physics) laser. The laser was operated in multi-line mode and the output power was estimated to be 2.3W. The light sheet was aligned to pass through the axis of the nozzle, which is directed downwards into a water tank of dimensions 750×750×1500mm, see Figure 2. The PJ nozzle chamber diameter is 44mm so the confinement is very low. The design of the PJ nozzle conforms to the optimal geometry as determined by Hill (1998). The CAJ exit consists of an interchangeable insert that allows the diameter of the jet to be varied so that the momentum can be changed independent of the flowrate.

The flows to the PJ and to the CAJ were controlled using Fischer and Porter flowmeters of size 1" and ½" respectively. The nominal accuracy of the flowmeters is ±2% of the maximum capacity. The flowrate through the CAJ was maintained as nearly constant as possible within the range of flow ratios investigated. The Reynolds Number, calculated at the CAJ exit was $10{,}500 < Re_{CAJ} < 16{,}000$. By varying the mass flowrate through the PJ, the proportion of CAJ to total flow rate, and thus the momentum ratio was altered. The Reynolds Number, of the PJ calculated at the chamber inlet was $20{,}000 < Re_{PJ} < 61{,}000$. Newbold (1997a) has shown that Reynolds Number only weakly affects the spreading angle of the PJ flow in this range.

Rhodamine B, (0.045mg/L) marked the PJ fluid, which appears red and Fluorescein (0.04mg/L) marked the CAJ fluid, which appears yellow. The concentrations used are within the limits recommended by Arcoumanis (1990) for a linear response to the incident light and also take into consideration that Fluorescein is a more fluorescent efficient dye than the Rhodamine-B. Hence, as the laser attenuation is minimal, the recorded signal intensity of the fluorescence is a direct measure of the jet concentration.

To minimise spurious illumination, data acquisition was performed with the room darkened. Since the tank has no co-flow, the run time is limited to about two minutes. Background noise becomes significant with longer run times. A shutter speed of t=1/1000s was required for both video and photographic images to adequately freeze the motion of the exiting jets. A "lipstick" video camera was used to record time-resolved images onto Hi-8 digital videotape. The precessional frequency is ≈1Hz, sufficiently slow for the framing rate of the camera (25 frames per second) to capture multiple images during each precessional cycle. A Pentax SLR camera using ISO-800 film was used to capture high quality still images of the flow field. Both cameras were positioned normal to the laser sheet, as close as possible together so that their imaging windows were almost identical. The imaging area is about 240×180mm.

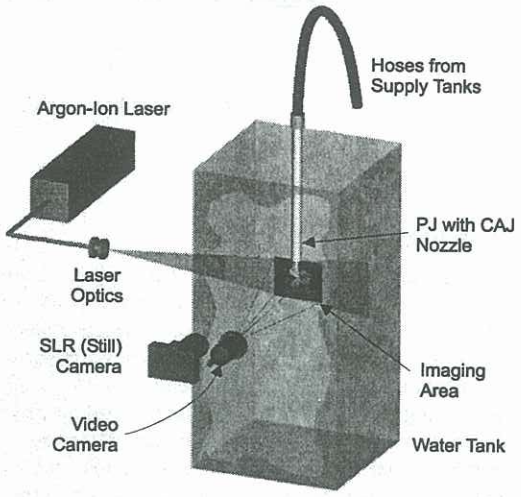


**Figure 2** : Schematic diagram of experimental set-up for flow visualisation of the interaction between a Central Axial Jet (CAJ) and Precessing Jet (PJ) by laser-induced fluorescence.

## RESULTS AND DISUCSSION

High quality colour still images and video sequences of the flow visualisation experiments are presented in Parham *et al.* (1998a, 1998b). The results demonstrate that two broad classes of flow regime can be generated, depending on the proportion of CAJ flow to the total flowrate and hence the momentum ratio of CAJ (calculated at the jet exit) to PJ (calculated at the inlet to the chamber), $G_{CAJ}$:$G_{PJ}$. At low proportions of CAJ flow (0-25% of the total, Figure 3a) the mixing field is dominated by the large-scale flow structures generated by jet precession, consistent with the observations of Newbold *et al.* (1997b) and Nathan and Luxton (1997). The CAJ flow merges with the PJ fluid so that the combined jet precesses about the nozzle axis. The spreading of the combined jet flow is smaller than that of a "PJ only" flow. Large structures of precessing jet fluid exit at a wide angle, spanning the full extent of the flow from the exit plane. These structures move out of the plane of the laser, entraining large amounts of ambient fluid onto the axis of the nozzle.

At higher proportions of central axial jet flow (greater than 30% of total, Figure 3b), the CAJ dominates the mixing field. In this condition, although the two jets still interact strongly, the CAJ tends to "punch through" the PJ flow and does not exhibit significant precession within the near-field. However, some precession is evident in toward the bottom of the viewing frame. The size of the large-scale flow structures is diminished, and the spread of the jet tends toward that of an axisymmetric simple jet flow. The PJ flow still has a wide spreading angle very close to the nozzle exit but its spread is reduced by the CAJ, which rapidly entrains some of the PJ fluid. Larger PJ flow structures remain independent of the CAJ. The transition from precessing jet to axial jet

dominated regimes corresponds to a momentum ratio, $G_{CAJ}$:$G_{PJ}$, of about 0.3.

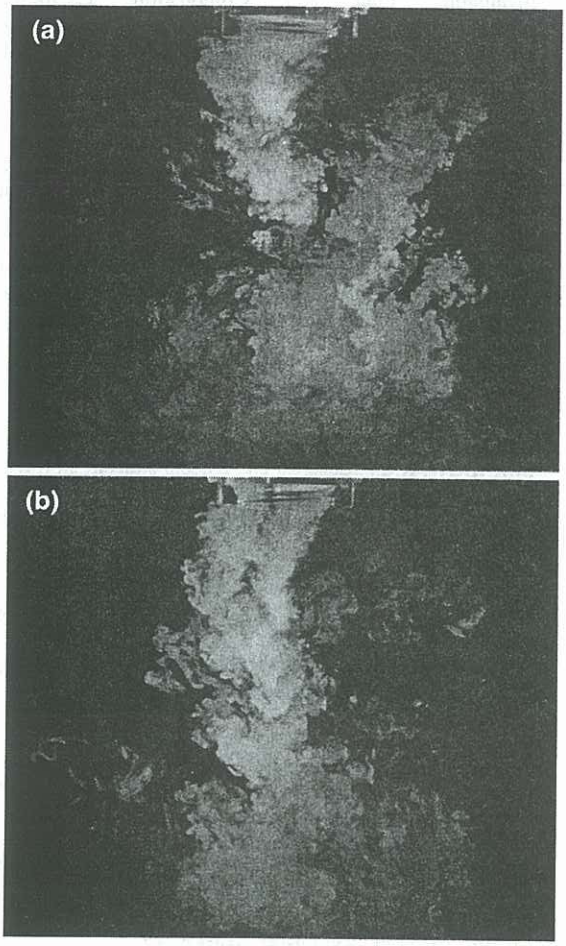


**Figure 3** : Flow visualisation image of: (a) 85% Precessing Jet (PJ) flow with 15% Central Axial Jet (CAJ) by mass flowrate; momentum ratio $G_{CAJ}$:$G_{PJ}$ = 0.07. (b) 70% PJ flow with 30% CAJ by mass flowrate; momentum ratio $G_{CAJ}$:$G_{PJ}$ = 0.4.

## Semi-Quantitative Measurement of Spreading Rate

The qualitative description of the mixing field from the flow visualisation images can be extended by semi-quantitative measurement of spreading rates, also used by Newbold (1997a). The video footage of the flow visualisation experiments was converted to digitised still images using a colour frame grabber. The colours in each raw digitised image are enhanced to balance the intensity from the different dyes and then converted into an 8-bit greyscale format. The resolution of the digital images is 640×480 pixels. Image processing was conducted to calculate an average of approximately 50 frames for each flow condition. Every pixel of this average is then locally normalised to the maximum centreline intensity at each local axial position. This technique does not require any corrections for light sheet variations such as for absolute reference of "pure" jet fluid. The images shown in Figure 5 (presented only for the 5mm CAJ insert) are scaled relative to the local maximum value instead of the centreline value. This normalisation allows for any image attenuation and for the fact that the maximum concentration is not always located on the nozzle axis. Only the left side of each image is presented in Figure 5 since the laser sheet was incident from the left, resulting in stronger signal strengths there. The half-spread angle of the jets is then measured using the "half maximum" or "half-width" (50%) contour.

The reduction in spreading angle with increased massflow proportion through the CAJ is clearly seen based upon the image processing results, as in Figure 5. However, this trend is even more apparent when plotted against the momentum ratio $G_{CAJ}$:$G_{PJ}$. The variation in spread angle with $G_{CAJ}$:$G_{PJ}$ for the three different CAJ diameter sizes collapses closely onto one profile. At low momentum ratios there is a marked change of half-spread angle with increasing momentum ratio, but as the momentum ratio increases above approximately 0.6, the influence of the PJ flow weakens as the flow approaches that of a simple jet. Using the same image processing technique as described above, the spread angle of the 5.0mm CAJ was measured to be 8°. This is larger than the spread angle of 6° determined by Becker *et al.* (1967) for an axisymmetric jet issuing from a smooth contraction, but the present jet may spread more rapidly since its initial conditions will produce greater turbulence intensity (see Figure 1).

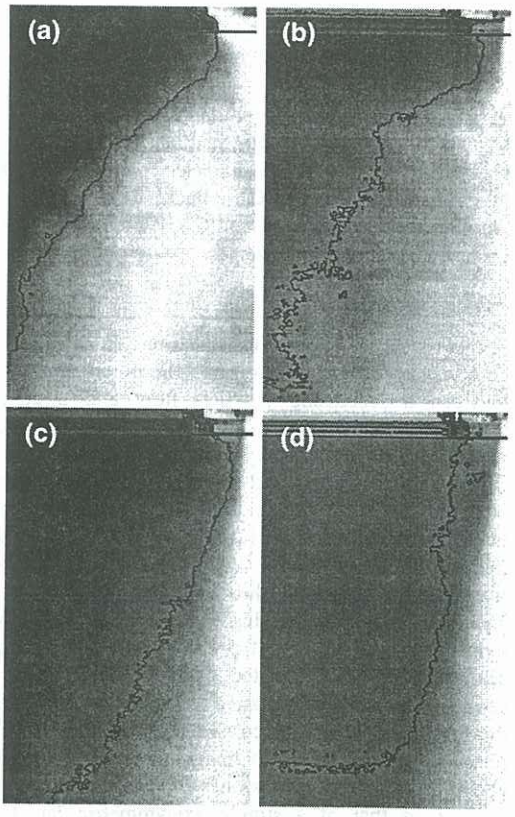


**Figure 5** : The concentration half-widths of Precessing Jet (PJ) with Central Axial Jet (CAJ) flows, determined from local normalisation under the following conditions:
(a) 100% PJ, $G_{CAJ}$:$G_{PJ}$=0, spread angle=40°;
(b) 85%PJ, 15% CAJ, $G_{CAJ}$:$G_{PJ}$=0.07, spread angle=34°;
(c) 70%PJ, 30% CAJ, $G_{CAJ}$:$G_{PJ}$=0.4, spread angle=25°;
(d) 60%PJ, 40% CAJ, $G_{CAJ}$:$G_{PJ}$=0.64, spread angle=14°, high background noise levels are present in this image.

The flow visualisation demonstrates that coherent large scale motions occur across the entire width of the jet. This implies that the size of the largest scale structures in the flow also vary with momentum ratio. Hence variation of the ratio of the CAJ to PJ momentum provides a means of controlling the scale of the largest turbulent flow motions. A decrease in spreading angle can also be expected to correlate with increased jet velocity. For a burner nozzle, this would result in the flame being pushed further away from the nozzle tip. This is consistent with changes in heat-flux profile from a similar PJ burner, measured in semi-industrial scale combustion experiments (Parham *et al.*, 1998b).

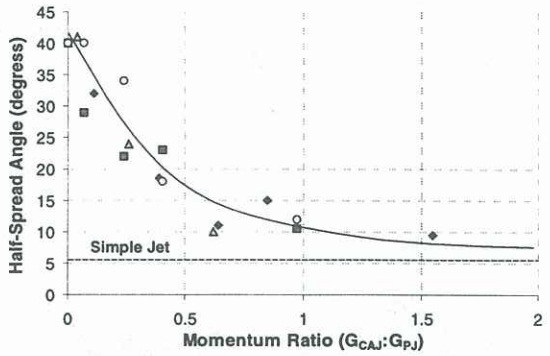


**Figure 6** : Variation in combined Precessing Jet (PJ) and Central Axial Jet (CAJ) with momentum ratio ($G_{CAJ}$:$G_{PJ}$) from different CAJ exit diameters, $d_{CAJ}$=(◆, 4.0mm; ■, 5.0mm; ▲, 6.2mm; O, 5.0mm, different Reynolds Number conditions for PJ and CAJ). Trend line is based on manual fitting of a curve.

## CONCLUSION

A two-colour flow visualisation technique has demonstrated that controlling the momentum ratio between a precessing jet (PJ) flow and a centrally mounted axial jet (CAJ) can control the initial growth rate of the largest turbulent motions in a jet. The two flows interact strongly and merge, so that the half-width of scalar concentration is a representative measure of the largest scales of motion. For the present configuration, momentum ratios below 0.3 (corresponding to a low massflow proportion through the CAJ) can be characterised as precessing jet dominated, while at momentum ratios above 0.3 the flow visually appears central axial jet dominated. This compares with the results of the semi-quantitative technique for determining the spread angle of the combined flows, based on the image processing of video images, which indicated that above momentum ratios of 0.6 the spread angle approaches that of a simple axisymmetric jet. Below momentum ratios of approximately 0.6 the spread angle, and hence the scale of the largest turbulent structures varies directly with the momentum ratio. Hence control of the properties of a combined precessing jet and central axial jet flow can be achieved by variation of the momentum ratio between the two jets.

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