**Particle Image Velocimetry in the near field of a Particle-Laden Precessing Jet Flow**

C.H. Birzer\(^1,2\), P.A.M. Kalt\(^1\), N.L. Smith\(^2\) and G.J. Nathan\(^1\)

\(^1\)School of Mechanical Engineering, The University of Adelaide, S.A. 5005, AUSTRALIA
cristian.birzer@mecheng.adelaide.edu.au

\(^2\)School of Chemical Engineering, The University of Adelaide, S.A. 5005, AUSTRALIA

**ABSTRACT**

Particle Image Velocimetry (PIV) has been conducted in the near field of a solid fuel precessing jet (SFPJ) flow. Experiments were designed to simulate coal-fired rotary cement kiln burners. The influence of precessing jet (PJ) momentum on particle velocities has been assessed.

1. INTRODUCTION

The Precessing Jet (PJ) nozzle, commercially known as Gyrotor\(^\text{TM}\), is a nozzle design that has been developed by the University of Adelaide in partnership with FCT-Combustion. The PJ nozzle consists of a sudden axisymmetric expansion, into a cylindrical chamber with an exit centre-body and lip. This configuration generates a natural fluid mechanical instability in which an asymmetric jet flow precesses about the axis of the nozzle (Figure 1). The emerging flow also precesses and when there is no co-flow, is deflected at an angle of typically 45\(^\circ\) across the face of the nozzle. Within the chamber, approximately 1/3 of the annular gap between the centre body and the chamber diameter is occupied by the local particle laden flows. Downstream from the “neck” and the divergence from the “neck” region, particles diverge. The distance across the nozzle axis [1].

The instantaneous images of particle distribution [13] suggest that the central PJ flow interacts with the entire co-annular flow of particles at once, increasing the scale of coherent large-scale structures. The higher the momentum ratio of PJ to annular flow, the greater the scale of the motions and the particles and the fluid is not well understood, which limits the optimisation of the flows and flames.

Birzer et al. [13] presented quantitative measurements of the mean particle distribution in the near field of a SFPJ. They showed that, on average, the particles “converge” towards the centreline of the nozzle several diameters downstream from the nozzle exit. The convergence point, or “neck” region, was defined as the location of the peak mean concentration of particles and the narrowest location of the jet. Downstream from the “neck” region, particles diverge. The distance downstream from the nozzle of the “neck” and the divergence of particles downstream from the “neck” are functions of PJ to annular flow momentum flux ratio. However, it is important to note that this “convergence” is not instantaneously axisymmetric, but rather appears to be the mean result of an oscillating asymmetric behaviour. This is somewhat analogous to the time-averaged “convergence” of the single phase PJ flow resulting from the jet being instantaneously directed across the nozzle axis [1].

The combustion of coal is significantly different to gas or liquid combustion and needs to be treated as such. Coal combustion is a multi-staged process [4] which is a function of particle size [5], particle mass loading [6], as well as volatile matter content and combustion air temperature [7].

The fluid mechanics of particle laden flows are more complex than for single-phase flows. Fleckhaus et al. [8] showed that velocity decay rates of particles are lower than those of the transporting fluid. They also showed that the velocity decay rates of the fluid phase in a two-phase flow is lower than the corresponding single phase flow alone. Shuen et al. [9] reported that mass flow rate of particles reduces velocity decay rates of both phases. Other studies have shown that particles of Stokes number, St ~ 1, are preferentially concentrated in regions of high strain between large scale fluid structures [10].

A configuration of the PJ nozzle that is suitable for use in particle laden flows has been developed, called the Solid Fuel Precessing Jet (SFPJ) nozzle. Rather than attempting to introduce particles through the nozzle, they are introduced through a co-annular channel, to avoid erosion of the PJ nozzle (Figure 1). This configuration can beneficially influence a pulsed fuel flame.

By using jet precession to manipulate the local environment of volatile combustion, Smith et al. [11] showed ignition distance can be reduced by a factor of 3-5, NO\(_x\) emissions by about 30\%, and burnout improved in pilot-scale facilities. Nathan and Hill [12] showed that it provided a 3-5\% reduction in NO\(_x\) and a 5\% increase in fuel efficiency in a short-tern trial at Ashgrove cement. However, the complex interaction between the particles and the fluid is not well understood, which limits the optimisation of the flows and flames.

For gas-fired cement kilns, relative to a simple jet, the PJ nozzle has been shown to result in NO\(_x\) reductions by 40 to 70\%, improve fuel consumption by 3-4\% and improve product quality [3]. However, approximately 90\% of rotary cement kilns world wide utilise solid fuels. Hence the application of PJ flows to pulverised fuels is being pursued.

The combustion of coal is significantly different to gas or liquid combustion and needs to be treated as such. Coal combustion is a multi-staged process [4] which is a function of particle size [5], particle mass loading [6], as well as volatile matter content and combustion air temperature [7].

The fluid mechanics of particle laden flows are more complex than for single-phase flows. Fleckhaus et al. [8] showed that velocity decay rates of particles are lower than those of the transporting fluid. They also showed that the velocity decay rates of the fluid phase in a two-phase flow is lower than the corresponding single phase flow alone. Shuen et al. [9] reported that mass flow rate of particles reduces velocity decay rates of both phases. Other studies have shown that particles of Stokes number, St ~ 1, are preferentially concentrated in regions of high strain between large scale fluid structures [10].

A configuration of the PJ nozzle that is suitable for use in particle laden flows has been developed, called the Solid Fuel Precessing Jet (SFPJ) nozzle. Rather than attempting to introduce particles through the nozzle, they are introduced through a co-annular channel, to avoid erosion of the PJ nozzle (Figure 1). This configuration can beneficially influence a pulsed fuel flame.

By using jet precession to manipulate the local environment of volatile combustion, Smith et al. [11] showed ignition distance can be reduced by a factor of 3-5, NO\(_x\) emissions by about 30\%, and burnout improved in pilot-scale facilities. Nathan and Hill [12] showed that it provided a 3-5\% reduction in NO\(_x\) and a 5\% increase in fuel efficiency in a short-tern trial at Ashgrove cement. However, the complex interaction between the particles and the fluid is not well understood, which limits the optimisation of the flows and flames.

Birzer et al. [13] presented quantitative measurements of the mean particle distribution in the near field of a SFPJ. They showed that, on average, the particles “converge” towards the centreline of the nozzle several diameters downstream from the nozzle exit. The convergence point, or “neck” region, was defined as the location of the peak mean concentration of particles and the narrowest location of the jet. Downstream from the “neck” region, particles diverge. The distance downstream from the nozzle of the “neck” and the divergence of particles downstream from the “neck” are functions of PJ to annular flow momentum flux ratio. However, it is important to note that this “convergence” is not instantaneously axisymmetric, but rather appears to be the mean result of an oscillating asymmetric behaviour. This is somewhat analogous to the time-averaged “convergence” of the single phase PJ flow resulting from the jet being instantaneously directed across the nozzle axis [1].

The instantaneous images of particle distribution [13] suggest that the central PJ flow interacts with the entire co-annular flow of particles at once, increasing the scale of coherent large-scale structures. The higher the momentum ratio of PJ to annular flow, the greater the scale of the motions and the
influence of the PJ flow, but the qualitative features of the particle distribution appear to be quite similar.

The images of particle concentration [13] provide no insight into particle direction. Hence it is difficult to interpret the near-field behaviour from that information alone. To address this lack of information, new measurements of particle velocity in the near field of the emerging flow using particle image velocimetry (PIV) have been performed.

2. EQUIPMENT

2.1 Kiln Scaling

Experiments were conducted at the Turbulence, Energy and Combustion (TEC) laboratories, at the University of Adelaide in a purpose built two-phase wind tunnel, scaled to simulate the pre-ignition region of a typical rotary cement kiln (Figure 2). Geometric ratios between nozzle and tunnel were chosen to avoid interaction with the wall in the near-nozzle region. Constant momentum ratio and Stokes number scaling methods have been applied to the flow rates and particle types respectively. Low temperature gradients expected in the pre-ignition region of a pulverised fuel (PF) flame enable useful modelling of particle behaviour using isothermal experiments.

![Figure 2: Schematic diagram of the experimental rig.](image)

The two-phase tunnel is a vertically orientated, open loop wind tunnel with 650mm x 650mm square cross section. A bell-mouth inlet and flow conditioning screens provide a coflow velocity of approximately 8m/s.

Q-Cel™ hollow glass spheres with particle diameters in the range of 25-45 µm and a density of approximately 700kg/m³ were used to simulate coal. The glass particles have equivalent Stokes number to 75 µm coal particles in a 35MW, 3 metre diameter cement kiln. Particles were introduced into the annular stream at a constant mass loading ratio of 0.125 kg particles / kg annular air. Although this provides volume ratios that are an order of magnitude lower than is typical of full-scale operation, it was considered to be a reasonable compromise to avoid too large an attenuation of the laser beam.

2.2 Experimental Nozzle

A smooth contraction from a 1500 mm long × 50 mm diameter pipe to a 10 mm diameter opening is used to provide the inlet flow to the PJ chamber. The PJ chamber itself has a 50 mm internal diameter and length of 150 mm. A small lip at the exit with a 45° bevel results in a 40 mm PJ exit diameter. The annular jet has inner and outer diameters of 60 mm and 70 mm respectively. The total annular nozzle length exceeds 1700 mm, corresponding to 340 annular gap widths. Care was taken to maintain a uniform gap of 5 mm at the exit plane.

Regulated compressed air was used for both central and annular jets. The annular jet conveying particles had a constant bulk exit velocity of 18m/s, producing a bulk axial momentum at annulus exit of \( G_{\text{ANN}} = 0.39 \text{kgm/s} \). The PJ nozzle had a velocity range at the throat from 0 - 287m/s. Therefore the approximate bulk axial PJ momentum at the PJ exit ranges from \( G_{\text{PJ}} = 0.0 \) to 2.42 kgm/s.

It should be noted that the particle distribution at the nozzle exit plane is biased, with a higher particle concentration on the right hand side (Figure 3). This biases the axial momentum in proportion to the bias in particle mass so that the influence of jet precession is lower on the right hand side. Though not ideal, these types of eccentricities are difficult to eliminate in large-scale particle laden flows.

2.3 Laser Diagnostics

A dual cavity frequency doubled Nd:YAG laser, pulsed at 10Hz was used. A telescope arrangement, consisting of a pair of vertically orientated ±100 mm cylindrical lenses and a horizontally orientated +25mm cylindrical lens produced a light sheet approximately 2 - 2.5mm thick through the central plane of the jet. This sheet thickness was selected in consideration of the large out-of-plane motion experienced in the highly unsteady 3D flow produced by the PJ nozzle. The pulse delay between lasers was set to 30µs and controlled using a Quantel DPS01 timing box. Images were recorded on a Kodak Megaplus Class 1 CCD camera with a Nikon ED 70-300mm AF Nikkor 1:4-56.0 lens set with f# 4. The CCD array is 1008 × 1018 pixels with 10 bit resolution, and was synchronised to the master laser flash-lamp.

![Figure 3: Mean particle distribution for varying momentum flux ratios. The PIV ROI is shown by the square draw on each image. Peak centreline concentration is indicated by the white arrow. [13]](image)
centreline and 0.5 chamber diameters to the right of the nozzle centreline. The location of the ROI corresponds approximately to the peak centreline concentration of the zero PJ momentum case presented in Birzer et al. [13], as shown in Figure 3. No flow-tracer particles were seeded into the flow, so that the measurement is only of the simulated coal particles.

PIVView 2.1 was used to determine velocity vectors. Cross-correlation of image pairs used 3 point Gaussian peak detection with a multi-grid interrogation analysis starting with $128 \times 128$ pixel windows, down to $32 \times 32$ pixel windows. Outliers are determined by vectors with a displacement variation greater than 6 pixels (12m/s) to neighbouring vectors.

Figure 3 shows mean near-field particle distributions determined previously [13]. Concentrations are determined from the scattered light of particles. The scale indicates the maximum and minimum concentration of particles. These particle distributions are shown to highlight the nature of the flows investigated. The approximate location of the PIV ROI is indicated on each image with a white square, while that of the “neck” region is indicated by an arrow.

3. RESULTS AND DISCUSSION

The mean velocity profiles shown in Figure 4 support the mean flow description given by Birzer et al. [13]. However, the instantaneous contour plots shown in Figure 5 highlight the unsteady motion created by jet precession.

In Case 1, there is no PJ momentum flux and the instantaneous image does not differ significantly from the mean image. The particles show an instantaneous velocity profile consistent with actual divergence from the centreline.

Previous concentration measurements [13] indicated that, relative to the case with no PJ momentum, Case 2 and Case 3, with $G_{PJ}/G_{ANN} = 0.03$ and 0.18 respectively, have lower spread of particles. It was speculated that, under these conditions, the PJ flow has minimal influence on the particle laden annular jet; however, the addition of a central flow prevents bluff body recirculation.

The instantaneous velocity contour plot for Case 2 shows a strong similarity to the mean velocity contour plot. The unsteady motion of the PJ flow is not evident at the location which PIV data was recorded.

The mean spread of particles and velocity profiles for Case 3 are very similar to Case 2; however, the instantaneous velocity profile for the PIV ROI of Case 3 is significantly different from the mean of Case 3 and both mean and instantaneous of Case 2. Unlike Case 1 and Case 2, the effects of large scale mixing can be seen in the PIV ROI of Case 3. Hence, the unsteady motion of the PJ flow is influential at momentum ratios cases as low as $G_{PJ}/G_{ANN} = 0.18$. 

![Figure 4: Contour plots of mean velocity profiles](image)

![Figure 5: Contour plots of instantaneous velocity profiles](image)

Mean and representative instantaneous velocity contour plots that correspond to the flow and ROI indicated in Figure 3, are given in Figures 4 and 5 respectively. The colour of the contours corresponds to the magnitude of the local velocities of the coal simulating particles. Cases 1-5 have the same colour map, whereas Case 6, which has small velocity gradients, has a colour map scaled to highlight flow features.
The effects of large scale mixing and dissimilarities between instantaneous and mean velocities fields are also evident in the PIV ROI for cases 4 and 5. In these higher momentum ratio cases, the instantaneous radial momentum of the PJ flow is sufficient to significantly modify the instantaneous directions of the particles. Mean data does not show any of the unsteady motion created by the PJ nozzle, which is evident in the instantaneous velocity profiles.

Figure 6 shows the mean and instantaneous contour plots of Case 6 with streamlines generated in Tecplot™. The co-flow velocity of 8m/s has been removed from the particle axial velocity component of the flows used to generate streamlines.

Some asymmetry is present in the mean image, which is attributed to the bias of particles discussed in section 2.2, although this is to be confirmed. (Note that the reverse direction is an artefact of the subtraction of the 8m/s in obtaining the streamlines, but this highlights the transverse components). However, the degree of asymmetry is much greater in the instantaneous image, with the flow instantaneously being directed across the nozzle axis. This confirms that the increase spread is attributable to the unsteady, oscillatory nature of the precessing jet flow. That is, the unsteady motion of the PJ is still influential in the downstream from the mean “neck”.

4. CONCLUSIONS

PIV measurements of solid particles were conducted in the flow from a solid fuel precessing jet (SFPJ). Experiments were scaled to simulate typical pulverised fuel fired rotary cement kilns. The ROI was located 2.8 PJ chamber diameters downstream and incorporated 1.2 x 1.2 PJ chamber diameters in area.

Results indicate that mean and instantaneous data can be significantly different with sufficient momentum of PJ flow. A small amount of PJ momentum, \( G_{PJ}/G_{ANN} = 0.03 \), has little influence on particle velocities apart from reducing the bluff body recirculation. For \( G_{PJ}/G_{ANN} > 0.18 \), the mean velocity and concentration profiles are similar to \( G_{PJ}/G_{ANN} = 0.03 \). However, the instantaneous velocity profile shows large-scale mixing created by the PJ flow. This mixing is not evident in the mean velocity profile. Further increases in PJ momentum flux, as seen with when \( G_{PJ}/G_{ANN} > 0.18 \) show increasing differences in the mean and instantaneous flows. The data highlight the unsteady nature of the PJ flow and the significant differences between the mean and instantaneous flows.

The work highlights the advantages of planar techniques over single point measurements in investigating unsteady flows. More work is planned at a wider range of locations, including at the nozzle exit plane.

ACKNOWLEDGMENTS

The authors acknowledge the financial assistance provided to the project by the Australian Research Council through its large grant scheme.

The authors also thank Mr. Grant England and Mr. Billy Constantine of the School of Mechanical Engineering, The University of Adelaide, for their assistance and to industry partner, FCT-Combustion for their input.

REFERENCES