Control and Optimisation of Mixing and
Combustion from a Precessing Jet Nozzle

Ph.D. Thesis

Jordan James Parham

December 2000
Abstract

The present study seeks to examine the effects of co-flow, confinement and a shaping jet on the mixing and combustion characteristics of a precessing jet flow. In particular, scientific analysis is used to investigate the physical mechanisms by which the control and optimisation of heat transfer and pollutant emissions from natural gas burners for rotary kilns can be achieved. To achieve these aims, a range of experimental techniques in reacting, non-reacting, confined and unconfined conditions have been employed. The precessing jet, in conjunction with a shaping jet, is shown to provide continuous control of mixing characteristics and corresponding combustion characteristics. Hence the optimum mixing characteristics for the maximum heat transfer and minimum emissions and the conditions under which the precessing jet nozzle produces such mixing characteristics are determined. A scaling procedure is also proposed for the precessing jet nozzle that, for the first time, provides a method to relate the results of small-scale isothermal mixing experiments to operating rotary kilns.

Flow visualisation using a two colour planar laser-induced fluorescence technique in an unconfined, isothermal environment is used to demonstrate that a central axial jet is the most effective form of shaping jet for controlling the mixing from a precessing jet nozzle. The characteristics of the combined jet flow are shown, by a semi-quantitative image processing technique, to be controlled by the ratio of the central axial jet momentum to the combined jet momentum, denoted by $\Gamma_{CAJ} \equiv \frac{G_{CAJ}}{G_{PR}+G_{CAJ}}$. The flow visualisation results also demonstrate that, when the momentum ratio is in the range $0 \leq \Gamma_{CAJ} \leq 0.2$, corresponding to low proportions of flow through the central axial jet, the combined flow field visually appears to be "precessing jet dominated". For momentum ratios in the range $0.23 \leq \Gamma_{CAJ} \leq 1$, the flow appears visually to be dominated by the features of the central axial jet.

The effect of a central axial jet on the characteristics of a precessing jet flame is assessed in an unconfined environment by recording the visible flame luminescence photographically. The results demonstrate that a significant change in the flame volume, length and width is achieved by varying the proportion of central axial jet to total flow rate and hence the momentum ratio, $\Gamma_{CAJ}$. These parameters were correlated with changes in the global residence time, radiant fraction and NO$_x$ emissions based on scaling criteria from the literature. These correlations suggest that, consistent with the flow visualisation results, the momentum ratio, $\Gamma_{CAJ}$, controls the combustion characteristics, which in turn change significantly in the precessing jet and central axial jet dominated flow regimes.

Confined combustion experiments are undertaken in a pilot-scale cement kiln simulator to quantify the heat flux and NO$_x$ emission characteristics as a function of the combined precessing jet and central axial jet flows and to compare them with that of a conventional burner in a well controlled, confined facility. These experiments demonstrate that the central axial jet provides good control over the heat flux profile, consistent with the experience in industrial installations. Furthermore, the heat transfer from a precessing jet burner is shown to be enhanced relative to a conventional burner and the NO$_x$ emissions reduced if the relationship between heat transfer, emissions and process interaction is taken into account.
To quantify the mixing characteristics of each of the above flows and so to provide insight into the characteristics of relatively “good” and “bad” mixing for the optimisation of combustion in rotary kilns, concentration measurements are performed in a confined, isothermal environment. The effect of co-flow, confinement and the central axial jet on the mixing from a precessing jet nozzle are also assessed. The experiments are performed in a water-tunnel using a quantitative planar laser-induced fluorescence technique to provide measurement of a conserved scalar. The effect of the central axial jet is quantified with respect to its influence upon concentration decay, concentration fluctuations, jet width and probability distribution functions. The effect of co-flow and confinement are also quantified by measurement of the concentration decay, concentration fluctuations, jet width and probability distribution functions. The data is used to develop equations relating the flow conditions and geometry to the mean concentration on the jet axis and jet spread. These equations can be used to describe the entire mean concentration distribution in the far field of the precessing jet flow. Based on the modelling equations, a scaling procedure is proposed that provides a method to scale the precessing jet flow, i.e. to relate isothermal laboratory scale investigations to full scale plant. The scaling procedure is based on a first order assessment of the separate effects of confinement, velocity ratio and mass flow ratio on the scalar mixing. The final scaling parameter represents an additional correction to a modified form of the well known Thring-Newby scaling criterion which distorts the mixture fraction ratio, i.e. the air-fuel ratio, in the model from that in the industrial scale. This correction enables similarity of the jet mixing characteristics to be preserved while correcting for the geometric distortion of the confinement ratio. The new scaling procedure is used to show that the isothermal concentration measurements are representative of the mixing conditions within the pilot-scale combustion facility and hence that the scaling procedure is appropriate for the precessing jet nozzle.

The optimum combustion characteristics of the precessing jet nozzle, defined as the maximum heat transfer and minimum NOx emissions, are shown to occur at the maximum momentum ratio that still generates a flow characterised as precessing jet dominated. The mixing characteristics associated with high radiation and low NOx emissions are shown, by the quantitative mixing experiments, to be associated with the maximum mean concentration and the widest range of instantaneous concentrations measured on the jet axis of any flows produced by the combined precessing jet and central axial jet flows. This suggest that such mixing characteristics are desired from any natural gas burner for the maximum heat transfer and minimum emissions in a rotary kiln. The optimal mixing characteristics for the maximum efficiency and lowest emissions from a gas-fired rotary kiln are hence shown to be generated by the precessing jet-central axial jet nozzle at a momentum ratio of $0.17 \leq \Gamma_{CAJ} \leq 0.23$. 

iii
# Table of Contents

Abstract ........................................................................................................... ii
Table of Contents ............................................................................................... iv
List of Tables ....................................................................................................... ix
List of Figures ...................................................................................................... xi
Notation ............................................................................................................... xxii
Statement of Originality ...................................................................................... xxvii
Permission to Copy ............................................................................................... xxvii
Acknowledgment ................................................................................................. xxviii

1. Introduction .................................................................................................... 1
   1.1. Background and Motivation ....................................................................... 1
       1.1.1. Combustion of Fossil Fuels and the Environment ......................... 1
       1.1.2. NOx Emissions ............................................................................. 1
       1.1.3. Rotary Kilns .................................................................................. 2
       1.1.4. Low Emission Burners for Rotary Kilns ....................................... 3
   1.2. The Optimisation of Combustion in a Rotary Kiln ................................... 6
       1.2.1. Mixing and Combustion ............................................................... 6
       1.2.2. Control of Combustion ................................................................. 6
       1.2.3. Optimisation of Mixing for Combustion ....................................... 7
   1.3. The Precessing Jet Nozzle ........................................................................ 9
       1.3.1. The Effect of Jet Precession on Mixing ....................................... 9
       1.3.2. The Effect of Jet Precession on Combustion ................................. 10
       1.3.3. Precessing Jet Burners for Rotary Kilns ...................................... 11
       1.3.4. Modelling of the Precessing Jet Burner ....................................... 11
   1.4. Thesis Outline ........................................................................................... 15
       1.4.1. Research Objectives ..................................................................... 15
       1.4.2. Thesis Structure .......................................................................... 16

2. Experimental Apparatus ............................................................................... 17
   2.1. Experimental Jet Nozzles .................................................................... 17
       2.1.1. Precessing Jet Nozzles ............................................................... 17
           2.1.1.1. PJ Nozzle for Unconfined Flow Visualisation ......................... 18
           2.1.1.2. PJ Nozzles for Confined Quantitative Concentration Experiments ... 18
           2.1.1.3. PJ Nozzle For Unconfined Flame Visualisation .................. 18
           2.1.1.4. PJ Nozzle for Pilot-Scale Combustion Experiments .............. 19
5.3.1.1. Error Analysis .................................................. 84
5.3.2. In-Flame Measurements ......................................... 88
  5.3.2.1. CO Emissions .................................................. 88
  5.3.2.2. NOx Emissions ............................................... 89
5.3.3. Flue Gas Emission Measurements .............................. 94
5.4. Flame and Process Interaction .................................... 96
5.5. Conclusions .......................................................... 100

   6.1. Quantitative Measurement of Concentration .................. 102
     6.1.1. Introduction .................................................. 102
     6.1.2. Quantitative PLIF ........................................... 103
     6.1.3. Quantitative PLIF Image Processing Fundamentals ....... 104
   6.2. Quantitative PLIF Technique ................................... 105
     6.2.1. Experimental Apparatus ..................................... 105
     6.2.2. Image Processing Corrections ............................... 105
       6.2.2.1. Correction for Background Noise, \( B_{ij} \) .......... 105
       6.2.2.2. Correction for Camera Gain Effects, \( G_{ij} \) ......... 105
       6.2.2.3. Correction for Geometric Distortion ................... 106
       6.2.2.4. Correction for Laser Spatial Intensity Distribution, \( I_{ij} \) .......... 106
       6.2.2.5. Correction for Absorption ............................... 107
     6.2.3. Image Processing Procedure ................................. 111
   6.3. Sources of Experimental Error .................................. 114
     6.3.1. Spatial Resolution ......................................... 114
     6.3.2. Temporal Resolution and Statistical Independence ...... 115
     6.3.3. Limited Number of Measurements ........................... 116
     6.3.4. Laser Sheet Intensity Distribution ....................... 116
     6.3.5. Signal to Noise Ratio ....................................... 117
     6.3.6. Summary ..................................................... 117
   6.4. Experimental Validation ......................................... 120
     6.4.1. Introduction .................................................. 120
       6.4.1.1. Properties of Axisymmetric Simple Jets ............. 120
       6.4.1.2. The Effect of Schmidt Number on Mixing .......... 121
       6.4.1.3. Previous Studies of the Scalar Mixing from a Turbulent Simple Jet .. 122
     6.4.2. Validation Experiments ...................................... 124
     6.4.3. Results of the Validation Experiments ..................... 125
       6.4.3.1. Planar Data ............................................... 125
       6.4.3.2. Statistical Analysis ..................................... 125
     6.4.4. Discussion .................................................... 126
     6.4.5. Conclusion .................................................... 128
6.5. Precessing Jet Experiments ......................................................... 135
  6.5.1. Experimental Design .......................................................... 135
    6.5.1.1. Precessing Jet Conditions ........................................... 135
    6.5.1.2. Scaling of Precessing Jet Nozzles for the Present Experiments 135
  6.5.2. Comparison with Previous Data ............................................ 139
    6.5.2.1. Planar Data ............................................................ 139
    6.5.2.2. Jet Axis Statistics .................................................... 139
  6.5.3. The Effect of Co-Flow Velocity on the Mixing from a PJ Nozzle ... 146
    6.5.3.1. Qualitative Trends from Planar Data ............................... 146
    6.5.3.2. Jet Axis Statistics .................................................... 146
  6.5.4. The Effect of Confinement on the Mixing from a PJ nozzle ......... 153
    6.5.4.1. Qualitative Trends from Planar Data ............................... 153
    6.5.4.2. Jet Axis Statistics .................................................... 153
  6.5.5. The Effect of the Central Axial Jet on the mixing from a PJ nozzle 159
    6.5.5.1. Qualitative Trends from Planar Data ............................... 159
    6.5.5.2. Jet Axis Statistics .................................................... 159
  6.5.6. The Probability Distribution of Jet Concentration .................. 165
    6.5.6.1. The Effect of Jet Type ............................................. 165
    6.5.6.2. The Effect of Co-Flow Velocity ................................... 166
    6.5.6.3. The Effect of Confinement ......................................... 166
    6.5.6.4. The Effect of Central Axial Jet Proportion ....................... 167
    6.6.1. Description of the Scaling Model .................................... 174
    6.6.2. Development of the Scaling Parameters .............................. 174
    6.6.3. Modelling the Effect of the Central Axial Jet ...................... 176
    6.6.4. Application of the Proposed Model to the Scaling of Operating Rotary Kilns 183
    6.6.5. Application of the Proposed Model to the Prediction of Impingement 187
  6.7. Comparison with Combustion Results ...................................... 191
  6.8. Conclusions ........................................................................... 194

7. Conclusions and Further Work ..................................................... 200
  7.1. Conclusions ........................................................................... 200
    7.1.1. Control of Mixing and Combustion by Combined Precessing and Shaping Jet Flows 200
      7.1.1.1. Qualitative Description of the Control of Mixing Characteristics 200
      7.1.1.2. Statistical Quantification of the Control of Mixing by a Central Axial Jet 201
      7.1.1.3. Control of the Combustion Characteristics ....................... 204
    7.1.2. Scaling of a Confined Precessing Jet Flow in a Co-Flow ........... 206
    7.1.3. Optimisation of the Combined PJ-CAJ Flows for Rotary Kiln Flames 209
    7.1.4. The Effect of Schmidt Number on Jet Mixing .......................... 211
  7.2. Recommendations for Further Work ......................................... 212
List of Tables

<table>
<thead>
<tr>
<th>Figure</th>
<th>Page number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chapter 2</td>
<td></td>
</tr>
<tr>
<td>Table 2-1. Summary of the inlet conditions and ratios of the critical diameters for the experimental precessing jet nozzles used in the present investigations. The complete geometric ratios are compared with the optimal geometric ratios derived by Hill et al. (1992) in Appendix B. The notation for the dimensions are shown in Figure 2-1, except for $d_{CAJ}$, the internal diameter of the central axial jet nozzle.</td>
<td>20</td>
</tr>
<tr>
<td>Chapter 3</td>
<td></td>
</tr>
<tr>
<td>Table 3-1. Experimental configurations and conditions for the PLIF flow visualisation experiments for different shaping jets and different shaping jet proportions, $\psi_{shaping} = \frac{m_{shaping}}{(m_{PJ} + m_{shaping})}$. The momentum of the PJ nozzle, $G_{PJ}$, is calculated at the chamber inlet; the momentum of the shaping jets, $G_{CAJ}$, is calculated at the jet exit. $S_t^{ex}$ is the Strouhal number of the “excitation” of the central axial jet based on the characteristic frequency of the precessing jet motion.</td>
<td>42</td>
</tr>
<tr>
<td>Chapter 4</td>
<td></td>
</tr>
<tr>
<td>Table 4-1. Experimental conditions for the unconfined flame experiments at different proportions of flow through the central axial jet, $\psi_{CAJ}$. The fuel is LPG (propane).</td>
<td>67</td>
</tr>
<tr>
<td>Chapter 5</td>
<td></td>
</tr>
<tr>
<td>Table 5-1. Fuel and primary air flow rates for the two multi-channel burner configurations and the precessing jet burner with different central axial jet proportions ($\psi_{CAJ}$). The notation for the precessing jet flames also includes the secondary air pre-heat temperature. Symbols indicate: * - the burner tip was retracted flush with the inlet baffle plates, while in all other cases the nozzle tip protrudes 475mm beyond the baffle; † - axial channel; ‡ - swirled channel.</td>
<td>82</td>
</tr>
<tr>
<td>Table 5-2. Summary of the peak heat flux and total heat release produced by all PJ burner and MCB flames at 640°C and 840°C pre-heat. The total radiant heat from the flame is calculated from a heat balance of the main heat transfer paths in each kiln segment. A correction has been made for the effective increase in kiln length and hence total heat flux when the burner is mounted flush with the inlet baffle plate, as indicated by the symbol *.</td>
<td>85</td>
</tr>
<tr>
<td>Table 5-3. Flue gas temperatures and emission levels (corrected to 3% $O_2$) for all MCB and PJ burner flames at different $\psi_{CAJ}$ and secondary air pre-heat temperatures. The symbol *, indicates the burner was mounted flush with the inlet baffle plate.</td>
<td>95</td>
</tr>
<tr>
<td>Chapter 6</td>
<td></td>
</tr>
<tr>
<td>Table 6-1. Comparison of the theoretical and measured change in fluorescence intensity in the spatial intensity distribution measurements due to the effects of absorption.</td>
<td>108</td>
</tr>
<tr>
<td>Table 6-2. The image processing procedure to determine the systematic correction images for background noise, absorption, camera gain response and laser sheet intensity distribution.</td>
<td>111</td>
</tr>
<tr>
<td>Table 6-3. Image processing procedure for the calculation of the average jet concentration of an experiment. The procedure is similar for the calculation of the Root Mean Square (RMS) of the concentration fluctuations.</td>
<td>112</td>
</tr>
</tbody>
</table>
Table 6-4. Estimated ratios of laser pulse-fluorescence duration ($\tau_{\text{pulse}}$) to experimental time scales for the principal jet types investigated. Values less than 1 indicate complete independence. ..................115

Table 6-5. Estimated ratios of laser pulse repetition rate and camera frame rate ($f_{\text{frame}}$) to different jet time scales. Values greater than 1 indicate complete independence. $\tau_{\text{pixel}}$ and $\tau_{\text{image}}$ are the time required for a fluid particle, based conservatively on the lowest co-flow velocity, to traverse the length of a pixel or image length respectively. $\tau_{\text{conv}}$ is the time required for the slowest moving structure at the end of the imaged region to traverse a fixed point. ..................116

Table 6-6. A comparison of the mixing statistics measured in previous investigations into the scalar concentration field from simple axisymmetric nozzles with the present results. The results are separated according to the type of jet nozzle and if the experiments were conducted in water or gas. Experimental boundary conditions and jet conditions are also shown. * - Indicates the concentration half-width spreading rate was estimated from 1/e-concentration contour values. .................................................................129

Table 6-7. The duct size and co-flow velocities of the PJ nozzle experimental conditions. Also shown are the values of the scaling parameters: geometric ratio, velocity ratio and modified Thring-Newby parameter calculated for the inlet jet to the PJ nozzle and the chamber diameter or estimated exit velocity conditions. The highlighted rows indicate the baseline conditions with approximately constant mass flux ratio of co-flowing fluid to jet fluid. The number of images are for precessing jet flow only ($\psi_{\text{CAH}}=0\%$). .................................................................138

Table 6-8. Geometry and conditions of the PJ nozzle experiments conducted in the pilot-scale rotary kiln simulator. Also shown are the values of the scaling parameters: geometric ratio, velocity ratio and modified Thring-Newby parameter calculated for the inlet jet to the PJ nozzle and the chamber diameter or estimated exit velocity conditions. Refer to Appendix B for the geometry and conditions of industrial installations of the PJ nozzle. ..................138

Table 6-9. The results of applying the present scaling procedure to the pilot-scale cement kiln simulator. The duct diameter for the model is calculated for a $d_{pJ}=38$mm PJ nozzle as used in the present experiments. Refer to Appendix B for details on the application of the scaling procedure to industrial installations of the PJ nozzle. .................................................................186

Appendix B

Table B-1. Complete geometric ratios and inlet conditions for the experimental precessing jet nozzles used in the present investigations compared with the optimal geometric ratios derived by Hill et al. (1992). The notation for the dimensions are shown in Figure 2-1, except for $d_{\text{CAH}}$, the internal diameter of the central axial jet nozzle and $l_{\text{CAH}}$, the distance the central axial jet nozzle protrudes from the external face of the centre-body. .................................................................219

Table B-2. Geometry and conditions of five installations of the PJ nozzle in operating rotary kiln facilities. Also shown are the values of the scaling parameters: geometric ratio, velocity ratio and modified Thring-Newby parameter calculated for the inlet jet to the PJ nozzle and the chamber diameter or estimated exit velocity conditions. .................................................................220

Table B-3. The results of applying the proposed PJ nozzle scaling procedure to five installations of the PJ nozzle in operating rotary kiln facilities. The duct diameter for the model is calculated for a $d_{pJ}=38$mm PJ nozzle as used in the present experiments. Refer to Table B-1 for more details on the combustion facilities. .................................................................220
# List of Figures

<table>
<thead>
<tr>
<th>Figure</th>
<th>Page number</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Chapter 1</strong></td>
<td></td>
</tr>
<tr>
<td>Figure 1-1. Schematic diagrams of the main elements of a rotary kiln. Top: major plant components in the production of cement clinker (Nobes, 1996). Bottom: the reaction zones inside a wet process cement kiln (Nathan and Rapson, 1995).</td>
<td>5</td>
</tr>
<tr>
<td>Figure 1-2. A schematic diagram of the fluid motions within an axisymmetric fluidic precessing jet nozzle.</td>
<td>14</td>
</tr>
<tr>
<td><strong>Chapter 2</strong></td>
<td></td>
</tr>
<tr>
<td>Figure 2-1. Schematic diagram of the precessing jet nozzle with centre-body showing the dimensional notation used here. Note that a range of different configurations of the inlet orifice are used in the present investigation.</td>
<td>20</td>
</tr>
<tr>
<td>Figure 2-2. Schematic diagram of the precessing jet nozzle with an annular shaping jet for flame shaping.</td>
<td>21</td>
</tr>
<tr>
<td>Figure 2-3. Schematic diagram of the precessing jet nozzle with a central axial jet for flame shaping. In the configuration shown, fluid to the central axial jet is supplied via an annular channel and two symmetrical feed pipes.</td>
<td>21</td>
</tr>
<tr>
<td>Figure 2-4. Schematic diagram of the multi-channel burner used for the pilot-scale cement kiln simulator experiments. The fuel and air channels are numbered outwards from the nozzle axis. Air is supplied through channels 1 (swirled by 45° vanes), 4 and 5 (unlabelled).</td>
<td>23</td>
</tr>
<tr>
<td>Figure 2-5. Schematic diagram of the experimental arrangement for flow visualisation of the interaction between a shaping jet and precessing jet by one and two colour planar laser-induced fluorescence on the nozzle centreline.</td>
<td>28</td>
</tr>
<tr>
<td>Figure 2-6. Schematic diagram of the water-tunnel facility and mounting arrangement of the precessing jet nozzle for the confined quantitative PLIF experiments.</td>
<td>33</td>
</tr>
<tr>
<td>Figure 2-7. Schematic diagram of the pilot-scale cement kiln simulator facility showing the main kiln section, pre-combustor and supply lines for the IFRF multi-channel burner.</td>
<td>37</td>
</tr>
<tr>
<td><strong>Chapter 3</strong></td>
<td></td>
</tr>
<tr>
<td>Figure 3-1. Video images of precessing jet flow only, ( \psi_{\text{CAJ}}=0% ), ( \Gamma_{\text{CAJ}}=0 ), from the ( d_{\text{PJ}}=44\text{mm} ) PJ nozzle (dye: rhodamine 6G, optical filter used). Refer to Table 3-1 for jet conditions. Every second frame shown, ( t=1/1000\text{s} ) exposure time.</td>
<td>45</td>
</tr>
<tr>
<td>Figure 3-2. High quality flow visualisation photographs of the interaction of the 5mm diameter, intermediate length insert, central axial jet and precessing jet fluid. Pure PJ fluid is red, pure CAJ fluid is yellow, ( t=1/1000\text{s} ) exposure time. Refer to Table 3-1 for detailed conditions: (a) ( \psi_{\text{CAJ}}=15% ), ( \Gamma_{\text{CAJ}}=0.07 ); (b) ( \psi_{\text{CAJ}}=30% ), ( \Gamma_{\text{CAJ}}=0.4 ).</td>
<td>46</td>
</tr>
<tr>
<td>Figure 3-3. Video images of the 5mm diameter central axial jet, intermediate length insert, with the precessing jet. Pure PJ fluid is red, pure CAJ fluid is yellow. Mass flow proportion is ( \psi_{\text{CAJ}}=15% ), momentum ratio is ( \Gamma_{\text{CAJ}}=0.07 ), conditions as per Table 3-1. Every second frame shown, ( t=1/1000\text{s} ) exposure time.</td>
<td>47</td>
</tr>
<tr>
<td>Figure 3-4. Video images of the 5mm diameter central axial jet, intermediate length insert, with the precessing jet. Pure PJ fluid is red, pure CAJ fluid is yellow. Mass flow proportion is ( \psi_{\text{CAJ}}=30% ), momentum ratio is ( \Gamma_{\text{CAJ}}=0.29 ), conditions as per Table 3-1. Every second frame shown, ( t=1/1000\text{s} ) exposure time.</td>
<td>48</td>
</tr>
</tbody>
</table>
Figure 3-5. Video images of the 5mm diameter central axial jet, intermediate length insert, with the precessing jet. Pure PJ fluid is red, pure CAJ fluid is yellow. Mass flow proportion is \( \psi_{CAJ}=40\% \), momentum ratio is \( \Gamma_{CAJ}=0.49 \), conditions as per Table 3-1. Every second frame shown, \( t=1/1000s \) exposure time. ............................................. 49

Figure 3-6. Cross-section PLIF experiments: video images of the 5mm diameter central axial jet, intermediate length insert, with the precessing jet, one chamber diameter \( (d_{PJ}=44mm) \) downstream of the nozzle tip. Pure PJ fluid is red, pure CAJ fluid is yellow. Mass flow proportion is \( \psi_{CAJ}=15\% \), momentum ratio is \( \Gamma_{CAJ}=0.07 \), conditions as per Table 3-1. Every second frame shown, \( t=1/1000s \) exposure time. ............................................. 50

Figure 3-7. Cross-section PLIF experiments: video images of the 5mm diameter central axial jet, intermediate length insert, with the Precessing Jet, one chamber diameter \( (d_{PJ}=44mm) \) downstream of the nozzle tip. Pure PJ fluid is red, pure CAJ fluid is yellow. Mass flow proportion is \( \psi_{CAJ}=30\% \), momentum ratio is \( \Gamma_{CAJ}=0.29 \), conditions as per Table 3-1. Every second frame shown, \( t=1/1000s \) exposure time. ............................................. 51

Figure 3-8. Video images of the 5mm diameter adjacent axial jet with the precessing jet. Pure PJ fluid is red, pure AJ fluid is yellow. Mass flow proportion is \( \psi_{AJ}=15\% \), momentum ratio is \( \Gamma_{AJ}=0.07 \), conditions as per Table 3-1. Every second frame shown, \( t=1/1000s \) exposure time. ............................................. 53

Figure 3-9. Video images of the annular shaping jet with precessing jet. Pure PJ fluid is red, pure AJ fluid appears yellow-green in this sequence. Mass flow proportion is \( \psi_{AJ}=40\% \), momentum ratio is \( \Gamma_{AJ}=0.04 \), conditions as per Table 3-1. Every second frame shown, \( t=1/1000s \) exposure time. ............................................. 55

Figure 3-10. The concentration half-widths of combined precessing jet and central axial jet flows, determined from local normalisation of every pixel to the maximum value in each row. Images shown are for the 5mm, intermediate length CAJ insert. Refer to Table 3-1 for the jet conditions. ............................................. 58

Figure 3-11. Variation in jet spread-angle for the combined precessing jet and central axial jet flows with CAJ proportion, \( \psi_{CAJ} = \frac{n_{CAJ}}{\theta_{PJ} + n_{CAJ}} \), for different CAJ exit diameters and Reynolds number conditions. Also shown is the variation in spread-angle for the annular shaping jet. ............................................. 59

Figure 3-12. Variation in jet spread-angle for the combined precessing jet and central axial jet flows with momentum ratio, \( \Gamma_{CAJ} = G_{CAJ} / (G_{PJ} + G_{CAJ}) \), for different CAJ exit diameters and Reynolds number conditions. Also shown is the variation in spread-angle for the annular shaping jet. The trend line is based on a line of best fit through all data, excluding the data for \( \psi_{CAJ}=100\% \) and data points greater than 10 degrees from the mean trend. ............................................. 59

Chapter 4

Figure 4-1. Instantaneous images of the visible flame structure from an unconfined PJ nozzle at different proportions of central axial jet to total flow rate. The fuel is propane at a constant input of 20kW, \( t=1/250s \) camera exposure time, \( f/8 \) aperture setting. Flow conditions: (a) \( \psi_{CAJ}=0\% \), \( \Gamma_{CAJ}=0 \); (b) \( \psi_{CAJ}=30\% \), \( \Gamma_{CAJ}=0.36 \); (c) \( \psi_{CAJ}=50\% \), \( \Gamma_{CAJ}=0.57 \) and (d) \( \psi_{CAJ}=100\% \), \( \Gamma_{CAJ}=1 \). ............................................. 69

Figure 4-2. Time-averaged images of the visible flame from an unconfined PJ nozzle at different proportions of central axial jet to total flow rate. The fuel is propane at a constant input of 20kW, \( t=8s \) exposure time, \( f/22 \) aperture setting. Flow conditions: (a) \( \psi_{CAJ}=0\% \), \( \Gamma_{CAJ}=0 \); (b) \( \psi_{CAJ}=15\% \), \( \Gamma_{CAJ}=0.19 \); (c) \( \psi_{CAJ}=30\% \), \( \Gamma_{CAJ}=0.36 \); (d) \( \psi_{CAJ}=50\% \), \( \Gamma_{CAJ}=0.57 \); (e) \( \psi_{CAJ}=75\% \), \( \Gamma_{CAJ}=0.80 \) and (f) \( \psi_{CAJ}=100\% \), \( \Gamma_{CAJ}=1 \) (aperture of \( f/19 \)). ............................................. 71

Figure 4-3. Time-averaged image of the base of the flame from an unconfined PJ nozzle at \( \psi_{CAJ}=0\% \). The fuel is propane at a constant input of 20kW, \( t=8s \) camera exposure time, \( f/27 \) aperture setting. ............................................. 72

Figure 4-4. Comparison of the constant value signal intensity contours defining the edge of the flame from the time-averaged images of the base of the PJ nozzle flame at different \( \psi_{CAJ} \). Momentum ratios are shown in Table 4-1. ............................................. 72
Figure 4.5. The variation in flame volume, normalised to the value at $\Gamma_{CAJ}=0$, with momentum ratio at constant total fuel flow rate. The "exact" method is based upon the area within the contour defining the time-average flame edge and the "conical approximation" is based upon the simplified equation derived by Turns and Myhr (1991). See Table 4-1 for jet conditions. The dashed line indicates the transition from PJ to CAJ dominated flow regime. ........... 75

Figure 4.6. The variation in signal intensity of the visible flame radiation, normalised to the value at $\Gamma_{CAJ}=0$, with momentum ratio at constant total fuel flow rate. The integrated signal is based on the sum of the measured pixel intensities within the flame volume. See Table 4-1 for jet conditions. The dashed line indicates the transition from PJ to CAJ dominated flow regime. ........... 75

Figure 4.7. The variation in flame length, normalised to the value at $\Gamma_{CAJ}=0$, with momentum ratio at constant total fuel flow rate. See Table 4-1 for jet conditions. The dashed line indicates the transition from PJ to CAJ dominated flow regime. ........... 76

Figure 4.8. The variation in maximum flame width, normalised to the value at $\Gamma_{CAJ}=0$, and the ratio of flame width to length with momentum ratio at constant total fuel flow rate. See Table 4-1 for jet conditions. The dashed line indicates the transition from PJ to CAJ dominated flow regime. ........... 76

Chapter 5

Figure 5.1. Profiles of the radiative heat flux, $Q_{rad}$, from precessing jet flames with various proportions of central axial jet to total flow rate, $\psi_{CAJ}$. The arrow indicates the axial distance which the peak in the heat flux profile is shifted by variation of axial jet proportion. Conditions: 2MW fuel input, 840°C pre-heat, see Table 5-1 for momentum ratios, $\Gamma_{CAJ}$ ........... 86

Figure 5.2. Profiles of the radiative heat flux, $Q_{rad}$, from precessing jet flames with various proportions of central axial jet to total flow rate, $\psi_{CAJ}$, compared to a low recirculation flame (MCB-CC0.6) and a typically good recirculation flame (MCB-CC2.7) from a multi-channel burner. Conditions: 2MW fuel input, 640°C pre-heat, see Table 5-1 for momentum ratios, $\Gamma_{CAJ}$ ........... 86

Figure 5.3. Profiles of the temperature at the inner surface of the kiln wall, $T_w$, for precessing jet flames with various proportions of central axial jet to total flow rate, $\psi_{CAJ}$. Conditions: 2MW fuel input, 840°C pre-heat, see Table 5-1 for momentum ratios, $\Gamma_{CAJ}$ ........... 87

Figure 5.4. Profiles of the temperature at the inner surface of the kiln wall, $T_w$, for precessing jet flames at various proportions, $\psi_{CAJ}$, compared to a low recirculation flame (MCB-CC0.6) and a typically good recirculation flame (MCB-CC2.7) from a multi-channel burner. Conditions: 2MW fuel input, 640°C pre-heat, see Table 5-1 for momentum ratios, $\Gamma_{CAJ}$ ........... 87

Figure 5.5. Concentration contours of carbon monoxide measured in the kiln simulator for the precessing jet burner with $\psi_{CAJ}=25\%$ (PJ-25-640 flame). Contours are in steps of 0.5%. See Table 5-1 for the jet conditions. ........... 90

Figure 5.6. Concentration contours of NOx measured in the kiln simulator for the precessing jet burner with $\psi_{CAJ}=25\%$ (PJ-25-640 flame). Contours are in steps of 25ppm. See Table 5-1 for the jet conditions. ........... 90

Figure 5.7. Concentration contours of carbon monoxide measured in the kiln simulator for the multi-channel burner with typically good recirculation (MCB-CC2.7 flame). Contours are in steps of 0.5%. See Table 5-1 for the jet conditions. ........... 91

Figure 5.8. Concentration contours of NOx measured in the kiln simulator for the multi-channel burner with typically good recirculation (MCB-CC2.7 flame). Contours are in steps of 25ppm. See Table 5-1 for the jet conditions. ........... 91

Figure 5.9. Concentration contours of carbon monoxide measured in the kiln simulator for the multi-channel burner with low recirculation (MCB-CC0.6 flame). Contours are in steps of 0.5%. See Table 5-1 for the jet conditions. ........... 92

Figure 5.10. Concentration contours of NOx measured in the kiln simulator for the multi-channel burner with low recirculation (MCB-CC0.6 flame). Contours are in steps of 25ppm. See Table 5-1 for the jet conditions. ........... 92
Chapter 6

Figure 5-11. LDA measurements of the axial component of velocity 1m from the inlet baffle plates with only secondary air flowing and a coal flame from the Multi-Channel Burner (CEMFLAME3 condition B50-NG). In the no-flame condition a small amount of primary air was passed through the MCB. The MCB was tested with the burner in two angular positions, to check the contribution of the burner to any asymmetry. The burner housing was flush with the inlet baffle plate.

Figure 5-12. LDA measurements of the tangential component of velocity 1m from the inlet baffle plates with only secondary air flowing and a coal flame from the multi-channel burner. Conditions as for Figure 5-11.

Figure 5-13. Variation in NOx emissions with total heat flux through the kiln walls for the precessing jet (PJ) and multi-channel burner (MCB) configurations. To account for the effective increase in kiln length and hence increased residence time of the combustion products in the kiln, a correction has been made to the measured NOx emissions from the flames where the PJ burner is mounted flush with the inlet baffle plate, indicated by the symbol +.

Figure 5-14. Variation in NOx emissions (normalised to the production rate) with heat input from a 300 ton/day gas-fired rotary cement kiln. The original burner produces a high velocity jet of fuel and is compared to a precessing jet using the adjacent axial jet burner at various flow rate proportions, $\psi_{\text{AAJ}}$, to provide flame shaping.

Figure 5-15. Variation in NOx emissions with production rate in a 750 ton/day gas-fired rotary cement kiln. The turbulent jet diffusion type burner incorporates multiple gas jets and is compared to a precessing jet burner with central axial jet for flame shaping. Averaged data points are taken from approximately three months continuous operation of each burner. Secondary air temperature is approximately 1000°C. Data courtesy of Lafarge (Canada).

Figure 5-16. Variation in NOx emissions with input fuel energy at constant specific fuel consumption in a 750 ton/day gas-fired rotary cement kiln. The constant specific fuel consumption selected for each burner corresponds to the most common operating condition of each burner. Operating range for the turbulent diffusion jet burner = 5,350-5,500 MJ/ton, PJ burner = 5,400-5,550 MJ/ton.

Chapter 6

Figure 6-1. Correction Images used in the image processing of raw PLIF images from the PJ3902 experiments: (a) Absorption correction image, $A_{ij}$; (b) Intensity distribution, corrected for absorption, $I_p^dG_p/A_{ij}$. The colourmap used to represent each image is normalised to the minimum and maximum values to show the relative distribution of actual values.

Figure 6-2. The typical location of the regions used in the image processing procedure to calculate the laser power (LP ref, $P_{\text{ref}}$), background concentration (BK ref, $B_{\text{ref}}$) and 100% jet fluid for the pipe jet (Jet Ref, $C_{\text{ref}}$). The images are false-colour representations of raw PLIF images.

Figure 6-3. Variation in the Batchelor scale, $\lambda_{\text{B}}$, and Kolmogorov scale, $\lambda_{\text{K}}$, to the spatial resolution of the camera, L, with axial distance for the principal jet types used in the present PLIF experiments. For the “worst case” calculation of the PJ nozzle, the jet is assumed to expand at the same rate as a simple jet issuing from the inlet orifice of the nozzle chamber. For the “realistic” calculation a constant spread half-angle of 40° is assumed from the PJ nozzle exit.

Figure 6-4. False colour images of the spatial distribution of the instantaneous, mean and RMS of the jet concentration, $\xi$, from the present pipe jet measurements. Conditions: Reynolds number=28,200, co-flow velocity $U_\text{c}=0.06m/s$, jet diameter $d=9.45mm$, water-tunnel cross-section=500x500mm.

Figure 6-5. Inverse of the mean concentration on the jet centreline, $\xi_{\text{inf}}$, for the present pipe jet measurements compared with the results of other liquid (Sc≈1000) and gaseous (Sc≈1) phase pipe jet investigations. Refer to Figure 6-4 and Table 6-6 for the jet conditions.

Figure 6-6. The scaled mean centreline concentration, $\chi\xi_{\text{inf}}$, for the present pipe jet measurements compared with the results of other liquid (Sc≈1000) and gaseous (Sc≈1) phase pipe jet investigations. Refer to Figure 6-4 and Table 6-6 for the jet conditions.
Figure 6-7. The concentration half-width, \( r_{1/2}/d \), for the present pipe jet measurements compared with the results of other liquid (Sc=1000) and gaseous (Sc=1) phase pipe jet investigations. Refer to Figure 6-4 and Table 6-6 for the jet conditions.

Figure 6-8. The intensity of jet concentration fluctuations along the nozzle centreline, \( \xi_{rms}/\xi_c \), for the present pipe jet measurements compared with the results of other liquid (Sc=1000) and gaseous (Sc=1) phase pipe jet investigations. Refer to Figure 6-4 and Table 6-6 for the jet conditions.

Figure 6-9. Radial profiles of the mean jet concentration normalised to the value on the centreline, \( \xi_c \), at different axial locations downstream of the jet exit for the present pipe jet measurements. Refer to Figure 6-4 for the jet conditions.

Figure 6-10. Radial profile at \( x=40d \) of the mean jet concentration normalised to the centreline value, \( \xi_c \), for the present pipe jet measurements compared with results in the far field of other liquid (Sc=1000) and gaseous (Sc=1) phase pipe jet investigations. Refer to Figure 6-4 and Table 6-6 for the jet conditions.

Figure 6-11. Radial profiles of the RMS of jet concentration fluctuations normalised to the value on the centreline, \( \xi_{rms}/\xi_{rms,c} \), at different axial locations downstream of the jet exit for the present pipe jet measurements. Refer to Figure 6-4 for the jet conditions.

Figure 6-12. Radial profile at \( x=50d \) of the RMS of jet concentration fluctuations normalised to the centreline value, \( \xi_{rms}/\xi_{rms,c} \), for the present pipe jet measurements compared with results in the far field of other liquid (Sc=1000) and gaseous (Sc=1) phase pipe jet investigations. Refer to Figure 6-4 and Table 6-6 for the jet conditions.

Figure 6-13. Instantaneous images of the scalar concentration field of a precessing jet nozzle: (a) Newbold (1997), Reynolds number=20,500, free jet in air; (b) Present experiments, \( d_P=38\text{mm} \) PJ nozzle, Reynolds number=66,100, \( U_a=0.6\text{m/s} \) co-flow, \( D_d/d_P=12.9 \) confinement in water. Axial and radial distances are normalised to the diameter of the PJ nozzle inlet orifice in both images.

Figure 6-14. Comparison of the inverse mean jet concentration on the jet axis, \( \xi_{inv} \), of a PJ nozzle for the present technique and the Mie-scattering technique of Newbold (1997) and different simple flow conditions. See Figure 6-13 and Table 6-6 for the jet conditions. Axial distance is normalised to the diameter of the PJ nozzle inlet orifice, \( d_{in} \), for the PJ nozzle jet flows.

Figure 6-15. Comparison of the jet concentration half-width, \( r_{1/2}/d_{in} \), of a PJ nozzle for the present technique and the Mie-scattering technique of Newbold (1997) and different simple jet conditions. See Figure 6-13 and Table 6-6 for the jet conditions. Axial distance is normalised to the diameter of the PJ nozzle inlet orifice, \( d_{in} \), for the PJ nozzle.

Figure 6-16. Comparison of the far field radial profiles of mean jet concentration normalised to the value on the jet axis, \( \xi_{rms}/\xi_{rms,jet} \), of a PJ nozzle for the present technique and that of Newbold (1997). See Figure 6-13 for the jet conditions.

Figure 6-17. Comparison of the far field radial profiles of RMS jet concentration fluctuation normalised to the value on the jet axis, \( \xi_{rms}/\xi_{rms,jet} \), of a PJ nozzle for the present technique and that of Newbold (1997). See Figure 6-13 for the jet conditions.

Figure 6-18. Comparison of the concentration fluctuation intensity on the jet axis, \( \xi_{rms,jet}/\xi_{jet} \), of a PJ nozzle for the present technique and that of Newbold (1997) and different simple jet conditions. See Figure 6-13 and Table 6-6 for the jet conditions. Axial distance is normalised to the diameter of the PJ nozzle inlet orifice, \( d_{in} \), for the PJ nozzle jet flows.

Figure 6-19. False colour images of the spatial distribution of instantaneous, mean and RMS jet concentration, \( \xi \), from the \( d_P=38\text{mm} \) PJ nozzle. Conditions: PJ flow only \( (\gamma_{CA}=0\%) \), Reynolds number=66,100, \( D_{d}/d_P=10.3 \), (a) \( U_d/U_{e,p}=0.035 \), and (b) \( U_d/U_{e,p}=0.055 \). The band at the bottom of the images is the tape joining the two halves of the duct together.

Figure 6-20. False colour images of the spatial distribution of instantaneous, mean and RMS jet concentration, \( \xi \), from the \( d_P=38\text{mm} \) PJ nozzle. Conditions: PJ flow only \( (\gamma_{CA}=0\%) \), Reynolds number=66,100, \( D_{d}/d_P=10.3 \), (a) \( U_d/U_{e,p}=0.098 \), and (b) \( U_d/U_{e,p}=0.196 \). The band at the bottom of the images is the tape joining the two halves of the duct together.
Figure 6-21. Illustration of the effect of the ratio of co-flow velocity to jet velocity on the structure of flow from a precessing jet nozzle: (a) at low velocity ratios, \( U_j/U_e-p_j \leq 0.055 \), the helix of flow structures formed by the motion of the exiting jet collapses on top of each other close to the nozzle exit and the large-scale structures detected by the PLIF technique are observed to merge; (b) at high velocity ratios, \( U_j/U_e-p_j > 0.098 \), the helix of flow structures is stretched out and hence does not collapse, the relative distance between large-scale structures is increased and merging is reduced.

Figure 6-22. The effect of co-flow velocity ratio on the mean jet concentration on the jet axis, \( \xi_{\psi_{\text{jet}}} \), of the \( d_p = 38 \text{mm} \) nozzle. Conditions: PJ flow only \( (\psi_{\text{CAJ}} = 0\%) \), Reynolds number \( = 66,100, D_{\text{d}uc} / d_p = 10.3 \).

Figure 6-23. The radial distribution of mean jet concentration, normalised to the mean concentration on the jet axis, \( \xi_{\psi_{\text{jet}}} \), at different axial distances downstream of the \( d_p = 38 \text{mm} \) nozzle exit. Conditions: PJ flow only \( (\psi_{\text{CAJ}} = 0\%) \), Reynolds number \( = 66,100, D_{\text{d}uc} / d_p = 10.3, U_j/U_e-p_j = 0.055 \).

Figure 6-24. The effect of co-flow velocity ratio on the concentration fluctuation intensity, \( \xi_{\text{rms,\psi_{\text{jet}}}^2} \), on the jet axis of the \( d_p = 38 \text{mm} \) nozzle. Conditions: PJ flow only \( (\psi_{\text{CAJ}} = 0\%) \), Reynolds number \( = 66,100, D_{\text{d}uc} / d_p = 10.3 \).

Figure 6-25. The effect of co-flow velocity ratio on the concentration half-width, \( r_{1/2} / d_p \), of the \( d_p = 38 \text{mm} \) nozzle. Conditions: PJ flow only \( (\psi_{\text{CAJ}} = 0\%) \), Reynolds number \( = 66,100, D_{\text{d}uc} / d_p = 10.3 \).

Figure 6-26. False colour images of the spatial distribution of instantaneous, mean and RMS jet concentration, \( \xi \), from the \( d_p = 38 \text{mm} \) nozzle. Conditions: PJ flow only \( (\psi_{\text{CAJ}} = 0\%) \), Reynolds number \( = 66,100, U_j/U_e-p_j = 0.055 (U_a = 0.06 \text{m/s}) \). (a) \( D_{\text{d}uc} / d_p = 7.6 \) and (b) \( D_{\text{d}uc} / d_p = 12.9 \).

Figure 6-27. The effect of confinement on the inverse mean jet concentration on the jet axis, \( \xi_{\psi_{\text{jet}}} \), of the \( d_p = 38 \text{mm} \) nozzle. Conditions: PJ flow only \( (\psi_{\text{CAJ}} = 0\%) \), Reynolds number \( = 66,100, U_j/U_e-p_j = 0.055 (U_a = 0.06 \text{m/s}) \). Axial distance from the nozzle exit is normalised to the PJ nozzle chamber diameter, \( d_p \).

Figure 6-28. The effect of confinement on the inverse mean jet concentration on the jet axis, \( \xi_{\psi_{\text{jet}}} \), of the \( d_p = 38 \text{mm} \) nozzle. Conditions: PJ flow only \( (\psi_{\text{CAJ}} = 0\%) \), Reynolds number \( = 66,100, U_j/U_e-p_j = 0.055 (U_a = 0.06 \text{m/s}) \). Axial distance from the nozzle exit is normalised to the duct diameter, \( D_{\text{d}uc} \).

Figure 6-29. The effect of confinement on the concentration fluctuation intensity on the jet axis, \( \xi_{\text{rms,}\psi_{\text{jet}}} \), of the \( d_p = 38 \text{mm} \) nozzle. Conditions: PJ flow only \( (\psi_{\text{CAJ}} = 0\%) \), Reynolds number \( = 66,100, U_j/U_e-p_j = 0.055 (U_a = 0.06 \text{m/s}) \). Axial distance is normalised to the PJ nozzle chamber diameter, \( d_p \).

Figure 6-30. The effect of confinement on the concentration half-width, \( r_{1/2} / d_p \), of the \( d_p = 38 \text{mm} \) nozzle. Conditions: PJ flow only \( (\psi_{\text{CAJ}} = 0\%) \), Reynolds number \( = 66,100, U_j/U_e-p_j = 0.055 (U_a = 0.06 \text{m/s}) \). Axial distance is normalised to the PJ nozzle chamber diameter, \( d_p \).

Figure 6-31. The effect of confinement on the concentration half-width, \( r_{1/2} / d_p \), of the \( d_p = 38 \text{mm} \) nozzle. Conditions: PJ flow only \( (\psi_{\text{CAJ}} = 0\%) \), Reynolds number \( = 66,100, U_j/U_e-p_j = 0.196 (U_a = 0.216 \text{m/s}) \). Axial distance is normalised to the PJ nozzle chamber diameter, \( d_p \).

Figure 6-32. False colour images of the spatial distribution of instantaneous, mean and RMS jet concentration, \( \xi \), from the \( d_p = 38 \text{mm} \) nozzle. Conditions: \( U_a = 0.06 \text{m/s}, D_{\text{d}uc} / d_p = 10.3, m_j/m_{t} = 18.4 \). (a) \( \psi_{\text{CAJ}} = 15\%, \Gamma_{\text{CAJ}} = 0.05 \) and (b) \( \psi_{\text{CAJ}} = 25\%, \Gamma_{\text{CAJ}} = 0.17 \). The band at the bottom of the images is the tape joining the two halves of the duct together.

Figure 6-33. False colour images of the spatial distribution of instantaneous, mean and RMS jet concentration, \( \xi \), from the \( d_p = 38 \text{mm} \) nozzle. Conditions: \( U_a = 0.06 \text{m/s}, D_{\text{d}uc} / d_p = 10.3, \) (a) \( \psi_{\text{CAJ}} = 40\%, \Gamma_{\text{CAJ}} = 0.45, m_j/m_{t} = 18.4 \) and (b) \( \psi_{\text{CAJ}} = 100\%, \Gamma_{\text{CAJ}} = 1.0, m_j/m_{t} = 122 \). The band at the bottom of the images is the tape joining the two halves of the duct together.

Figure 6-34. The effect of CAJ proportion, \( \psi_{\text{CAJ}} \), on the mean jet concentration on the jet axis, \( \xi_{\psi_{\text{jet}}} \), of the \( d_p = 38 \text{mm} \) nozzle. Conditions: \( U_a = 0.06 \text{m/s}, D_{\text{d}uc} / d_p = 10.3, m_j/m_{t} = 18.4 \) except for \( \psi_{\text{CAJ}} = 100\% \) (CAJ only, \( m_j/m_{t} = 122 \)).
The effect of CAJ proportion, $\psi_{CAJ}$, on the concentration fluctuation intensity, $\xi_{rms,\psi_{CAJ}}$, on the jet axis of the $d_{p,J}=38\text{mm}$ PJ nozzle. Conditions: $U_{c}=0.06\text{m/s}$, $D_{diss}/d_{p,J}=10.3$, $m_{i}/m_{p}=18.4$ except for $\psi_{CAJ}=100\%$ (CAJ only, $m_{i}/m_{p}=122$)........163

The effect of CAJ proportion, $\psi_{CAJ}$, on the concentration half-width, $r_{1/2}/d_{p,J}$, of the $d_{p,J}=38\text{mm}$ PJ nozzle. Conditions: $U_{c}=0.06\text{m/s}$, $D_{diss}/d_{p,J}=10.3$, $m_{i}/m_{p}=18.4$ except for $\psi_{CAJ}=100\%$ (CAJ only, $m_{i}/m_{p}=122$)........164

The effect of jet type and CAJ proportion, $\psi_{CAJ}$, on the probability distribution functions of jet concentration on the jet axis, $pdk(\xi)$, Conditions: (a) Pipe jet, Reynolds number=28,200, co-flow velocity $U_{c}=0.06\text{m/s}$, no confinement; (b) $d_{p,J}=38\text{mm}$ PJ nozzle, co-flow velocity $U_{c}=0.06\text{m/s}$, $D_{diss}/d_{p,J}=10.3$, $m_{i}/m_{p}=18.4$ except for $\psi_{CAJ}=100\%$ (CAJ only, $m_{i}/m_{p}=122$)........168

The effect of co-flow velocity and confinement on the probability distribution functions of the jet concentration on the jet axis, $pdk(\xi)$, of the $d_{p,J}=38\text{mm}$ PJ nozzle. Conditions: (a)-(b) PJ only flow, Reynolds number=66,100, $D_{diss}/d_{p,J}=10.3$; (c)-(d) PJ flow only, Reynolds number=66,100, $U_{c}/U_{p,J}=0.055$ ($U_{c}=0.06\text{m/s}$)........169

Comparison of the probability distribution function of concentration on the jet axis, $pdk(\xi)$, of the pipe jet and $d_{p,J}=38\text{mm}$ PJ nozzle ($x/d_{p,J}=50$, $x/d_{p,J}=12$). Conditions: $Re_{pipe}=28,200$, $Re_{PJ}=66,100$, $U_{c}=0.06\text{m/s}$, $D_{diss}/d_{p,J}=12.9$........170

Comparison of the probability distribution function of local jet concentration on the jet axis in the far field of the pipe jet and PJ nozzle. Conditions as for Figure 6-39........170

The effect of co-flow velocity on the probability distribution function of concentration on the jet axis normalised to the local mean jet concentration in the far field of the pipe jet and $d_{p,J}=38\text{mm}$ PJ nozzle ($x/d_{p,J}=12$). Conditions: $Re_{pipe}=28,200$, $Re_{PJ}=66,100$, $U_{c}=0.06\text{m/s}$, $D_{diss}/d_{p,J}=10.3$........171

The effect of co-flow velocity on the probability distribution function of the local jet concentration on the jet axis in the far field of the PJ nozzle. Conditions as for Figure 6-41........171

The effect of confinement on the probability distribution function of concentration on the jet axis normalised to the local mean jet concentration in the far field of the $d_{p,J}=38\text{mm}$ PJ nozzle ($x/d_{p,J}=12$). Conditions: PJ flow only, Reynolds number=66,100, $U_{c}/U_{p,J}=0.055$........172

The effect of confinement on the probability distribution function of local jet concentration on the jet axis in the far field of the PJ nozzle. Conditions as for Figure 6-43........172

The effect of CAJ proportion, $\psi_{CAJ}$, on the probability distribution function of concentration on the jet axis normalised to the local mean jet concentration in the far field of the $d_{p,J}=38\text{mm}$ PJ nozzle ($x/d_{p,J}=12$). Conditions: $D_{diss}/d_{p,J}=10.3$, $U_{c}=0.06\text{m/s}$, $m_{i}/m_{p}=18.4$ except for $\psi_{CAJ}=100\%$ (CAJ only, $m_{i}/m_{p}=122$)........173

The effect of CAJ proportion, $\psi_{CAJ}$, on the probability distribution function of jet concentration on the jet axis in the far field of the PJ nozzle. Conditions as for Figure 6-45........173

Principal regions and mixing conditions for the flow from a precessing jet nozzle in a confined, co-flowing environment........178

Variation in the far field concentration decay constant, $K_d$, with confinement for different ratios of co-flow velocity to jet exit velocity and constant precessing jet nozzle conditions: PJ flow only ($\psi_{CAJ}=0\%$), Reynolds number=66,100........179

Variation in the far field concentration virtual origin, $x_{0,v}/D_{diss}$, with the ratio of co-flow velocity to jet exit velocity for different confinement and constant precessing jet nozzle conditions: PJ flow only ($\psi_{CAJ}=0\%$), Reynolds number=66,100........179

Variation in the reciprocal of the far field jet spreading rate, $K_2$, with the mass flux ratio of co-flowing fluid to jet fluid for different confinements and constant PJ nozzle conditions: precessing jet flow only ($\psi_{CAJ}=0\%$), Reynolds number=66,100........180

Variation in the far field jet spreading rate virtual origin, $x_{0,v}/d_{p,J}$, with the mass flux ratio of co-flowing fluid to jet fluid for different confinements and constant PJ nozzle conditions: precessing jet flow only ($\psi_{CAJ}=0\%$), Reynolds number=66,100........180
Figure 6-52. Variation in the far field concentration decay constant, $K_f$, normalised to the value at $\Gamma_{CAJ}=0$, with the momentum ratio $\Gamma_{CAJ}$ for different confinements and constant mass flux ratio. The data for $D_{dusc}/d_p=7.6$ and $D_{dusc}/d_p=12.9$ are corrected for the effects of confinement, relative to $D_{dusc}/d_p=10.3$, using Equation 6-26. The bold line indicates the line of best fit to the data (excluding $D_{dusc}/d_p=7.6$), the dashed line indicates the transition from PJ to CAJ dominated flow regime.

Figure 6-53. Variation in the far field concentration decay virtual origin, $x_0/D_{dusc}$, with the momentum ratio $\Gamma_{CAJ}$ for different confinements and constant mass flux ratio. The data for $D_{dusc}/d_p=7.6$ and $D_{dusc}/d_p=12.9$ are corrected for the effects of confinement, relative to $D_{dusc}/d_p=10.3$ using Equation 6-27. For $\Gamma_{CAJ}<0.2$ the data is normalised to the value at $\Gamma_{CAJ}=0$. The bold line indicates the line of best fit in the respective flow regime, the dashed line indicates the transition from PJ to CAJ dominated flow regime.

Figure 6-54. Variation in the far field jet spreading rate, $K_2$, with the momentum ratio $\Gamma_{CAJ}$ for different confinements at constant mass flux ratio. The data for $D_{dusc}/d_p=7.6$ and $D_{dusc}/d_p=12.9$ are corrected for the effects of confinement, relative to $D_{dusc}/d_p=10.3$ using Equation 6-28. For $\Gamma_{CAJ}<0.2$ the data is normalised to the value at $\Gamma_{CAJ}=0$. The bold line indicates the line of best fit in the respective flow regime, the dashed line indicates the transition from PJ to CAJ dominated flow regime.

Figure 6-55. Variation in the far field jet spreading rate virtual origin, $x_0/D_{dusc}$, with the momentum ratio $\Gamma_{CAJ}$ for different confinement ratios at constant mass flux ratio. The data for $D_{dusc}/d_p=7.6$ and $D_{dusc}/d_p=12.9$ are corrected for the effects of confinement, relative to $D_{dusc}/d_p=10.3$ using Equation 6-29. For $\Gamma_{CAJ}<0.2$ the data is normalised to the value at $\Gamma_{CAJ}=0$. The bold line indicates the line of best fit in the respective flow regime, the dashed line indicates the transition from PJ to CAJ dominated flow regime.

Figure 6-56. The effect of co-flow velocity ratio on the mean 2% jet concentration contour of the $d_p=38$mm PJ nozzle. Conditions: PJ flow only ($\Psi_{CAJ}=0$), Reynolds number=66,100, $D_{dusc}/d_p=10.3$. The approximate location of the break points for the two jet conditions that touch the duct wall are also illustrated.

Figure 6-57. The radial location of the "break" point of the 2% jet concentration contour normalised to the duct half-width, $r_{break}/(D_{dusc}/2)$ with the mass flow ratio of jet fluid to co-flowing fluid. Break points are shown for both the near laser side (right hand side of the images) and far laser side (left hand side of the images).

Figure 6-58. The correlation between the predicted axial location of the 2% jet concentration "break" point and the measured location of the break point from experimental data. Perfect correlation is indicated by the dashed line, $y=x$.

Figure 6-59. Comparison of isothermal jet concentration measurements and CO concentration in combustion experiments for PJ flow only ($\Psi_{CAJ}=0$). Isothermal conditions: $Re_p=66,100$, 390m duct: $U_d/U_{in,p}=0.055$ and $D_{dusc}/d_p=10.3$, 490mm duct: $U_d/U_{in,p}=0.035$ and $D_{dusc}/d_p=12.9$. Combustion conditions: 2MW fuel input, $D_{dusc}/d_p=13.5$, 640°C pre-heat: $U_d/U_{in,p}=0.050$, 840°C pre-heat: $U_d/U_{in,p}=0.063$. The corrected isothermal concentration profile is based on a value of $\kappa=0.88$ for the reference concentration ratio, see Table 6-9.

Figure 6-60. Comparison of isothermal jet concentration measurements and CO concentration in combustion experiments for the PJ nozzle with $\Psi_{CAJ}=25\%$. Isothermal duct and combustion conditions as for Figure 6-59, but incorporating CAJ proportion and with $U_d/U_{in,p}=0.039$ at 420°C pre-heat (for $\Psi_{CAJ}=0$).

Appendix A

Figure A-1. Concentration contours of carbon monoxide measured in the pilot-scale kiln for the precessing jet burner with flow only through the PJ nozzle ($\Psi_{CAJ}=0$) at a secondary air pre-heat temperature of 640°C (PJ-90-640 flame). Contours are in steps of 0.5% and the colour map is identical to that used for all the in-flame CO results. The dashed line indicates the boundary of the in-flame measurement region.
Figure A-2. Concentration contours of NO\textsubscript{x} measured in the pilot-scale kiln for the precessing jet burner with flow only through the PJ nozzle (Ψ\textsubscript{CA}=0\%) at a secondary air pre-heat temperature of 640°C (PJ-Ψ0-640 flame). Contours are in steps of 25 ppm and the colour map is identical to that used for all the in-flame NO\textsubscript{x} results at 640°C pre-heat. The dashed line indicates the boundary of the in-flame measurement region.

Figure A-3. Concentration contours of carbon monoxide measured in the pilot-scale kiln for the precessing jet burner with flow only through the PJ nozzle (Ψ\textsubscript{CA}=0\%) at a secondary air pre-heat temperature of 840°C (PJ-Ψ0-840 flame). Contours are in steps of 0.5% and the colour map is identical to that used for all the in-flame CO results. The dashed line indicates the boundary of the in-flame measurement region.

Figure A-4. Concentration contours of NO\textsubscript{x} measured in the pilot-scale kiln for the precessing jet burner with flow only through the PJ nozzle (Ψ\textsubscript{CA}=0\%) at a secondary air pre-heat temperature of 840°C (PJ-Ψ0-640 flame). Contours are in steps of 25 ppm, but the colour map is changed due to the higher NO\textsubscript{x} concentrations at 840°C pre-heat. The dashed line indicates the boundary of the in-flame measurement region.

Figure A-5. Concentration contours of carbon monoxide measured in the pilot-scale kiln for the precessing jet burner with central axial jet (Ψ\textsubscript{CA}=25\%, Γ\textsubscript{CA}=0.25) at a secondary air pre-heat temperature of 420°C (PJ-Ψ25-420 flame). Contours are in steps of 0.5% and the colour map is identical to that used for all the in-flame CO results. The dashed line indicates the boundary of the in-flame measurement region.

Figure A-6. Concentration contours of NO\textsubscript{x} measured in the pilot-scale kiln for the precessing jet burner with central axial jet (Ψ\textsubscript{CA}=25\%, Γ\textsubscript{CA}=0.25) at a secondary air pre-heat temperature of 420°C (PJ-Ψ25-420 flame). Contours are in steps of 25ppm and the colour map is identical to that used for all the in-flame NO\textsubscript{x} results at 640°C pre-heat. The dashed line indicates the boundary of the in-flame measurement region.

Figure A-7. Concentration contours of carbon monoxide measured in the pilot-scale kiln for the precessing jet burner with central axial jet (Ψ\textsubscript{CA}=25\%, Γ\textsubscript{CA}=0.25) at a secondary air pre-heat temperature of 840°C (PJ-Ψ25-840 flame). Contours are in steps of 0.5% and the colour map is identical to that used for all the in-flame CO results. The dashed line indicates the boundary of the in-flame measurement region.

Figure A-8. Concentration contours of NO\textsubscript{x} measured in the pilot-scale kiln for the precessing jet burner with central axial jet (Ψ\textsubscript{CA}=25\%, Γ\textsubscript{CA}=0.25) at a secondary air pre-heat temperature of 840°C (PJ-Ψ25-840 flame). Contours are in steps of 25ppm, but the colour map is changed due to the higher NO\textsubscript{x} concentrations at 840°C pre-heat. The dashed line indicates the boundary of the in-flame measurement region.

Appendix C

Figure C-1. The effect of co-flow velocity ratio on the inverse mean jet concentration on the jet axis, \(\overline{E}_{v,j}^{\text{inverse}}\), of the \(d_{p,j}=38\) mm PJ nozzle. Conditions: PJ flow only (Ψ\textsubscript{CA}=0\%), Reynolds number=66,100, \(D_{j,\text{out}}/d_{p,j}=7.6\).

Figure C-2. The effect of co-flow velocity ratio on the concentration fluctuation intensity, \(\overline{E}_{\text{rms},j}^{\text{rms}}\), on the jet axis of the \(d_{p,j}=38\) mm PJ nozzle. Conditions: PJ flow only (Ψ\textsubscript{CA}=0\%), Reynolds number=66,100, \(D_{j,\text{out}}/d_{p,j}=7.6\).

Figure C-3. The effect of co-flow velocity ratio on the concentration half-width, \(r_{1/2}/d_{p,j}\), of the \(d_{p,j}=38\) mm PJ nozzle. Conditions: PJ flow only (Ψ\textsubscript{CA}=0\%), Reynolds number=66,100, \(D_{j,\text{out}}/d_{p,j}=7.6\).

Figure C-4. The effect of co-flow velocity ratio on the inverse mean jet concentration on the jet axis, \(\overline{E}_{v,j}^{\text{inverse}}\), of the \(d_{p,j}=38\) mm PJ nozzle. Conditions: PJ flow only (Ψ\textsubscript{CA}=0\%), Reynolds number=66,100, \(D_{j,\text{out}}/d_{p,j}=12.9\).

Figure C-5. The effect of co-flow velocity ratio on the concentration fluctuation intensity, \(\overline{E}_{\text{rms},j}^{\text{rms}}\), on the jet axis of the 38 mm PJ nozzle. Conditions: PJ flow only (Ψ\textsubscript{CA}=0\%), Reynolds number=66,100, \(D_{j,\text{out}}/d_{p,j}=12.9\).
The effect of \( r_{l/d_p} \) on the concentration half-width, of the \( d_p = 38 \text{mm} \) nozzle. Conditions: PJ flow only (\( \psi_{CA} = 0\% \)), Reynolds number = 66,400, \( D_{duct}/d_p = 12.9 \).  

Figure C-7. The effect of \( r_{l/d_p} \) on the inverse mean jet concentration on the jet axis, \( \xi_{jet} \), of the 28mm PJ nozzle. Conditions: PJ flow only (\( \psi_{CA} = 0\% \)), Reynolds number = 62,400, \( D_{duct}/d_p = 10.4 \).  

Figure C-8. The effect of co-flow velocity ratio on the concentration fluctuation intensity, \( \xi_{rms-jet} \), on the jet axis of the 28mm PJ nozzle. Conditions: PJ flow only (\( \psi_{CA} = 0\% \)), Reynolds number = 62,400, \( D_{duct}/d_p = 10.4 \).  

Figure C-9. The effect of co-flow velocity ratio on the concentration half-width, \( r_{l/d_p} \), of the 28mm PJ nozzle. Conditions: PJ flow only (\( \psi_{CA} = 0\% \)), Reynolds number = 62,400, \( D_{duct}/d_p = 10.4 \).  

Figure C-10. The effect of co-flow velocity ratio on the inverse mean jet concentration on the jet axis, \( \xi_{jet} \), of the 28mm PJ nozzle. Conditions: PJ flow only (\( \psi_{CA} = 0\% \)), Reynolds number = 62,400, \( D_{duct}/d_p = 13.9 \).  

Figure C-11. The effect of co-flow velocity ratio on the concentration fluctuation intensity, \( \xi_{rms-jet} \), on the jet axis of the 28mm PJ nozzle. Conditions: PJ flow only (\( \psi_{CA} = 0\% \)), Reynolds number = 62,400, \( D_{duct}/d_p = 13.9 \).  

Figure C-12. The effect of co-flow velocity ratio on the concentration half-width, \( r_{l/d_p} \), of the 28mm PJ nozzle. Conditions: PJ flow only (\( \psi_{CA} = 0\% \)), Reynolds number = 62,400, \( D_{duct}/d_p = 13.9 \).  

Figure C-13. The effect of confinement on the inverse mean jet concentration on the jet axis, \( \xi_{jet} \), of the \( d_p = 38 \text{mm} \) nozzle. Conditions: PJ flow only (\( \psi_{CA} = 0\% \)), Reynolds number = 66,100, \( U_d/U_e,p_f = 0.035 \) \( (U_d = 0.038 \text{m/s}) \). Axial distance from the nozzle exit is normalised to the duct diameter, \( D_{duct} \).  

Figure C-14. The effect of confinement on the concentration fluctuation intensity on the jet axis, \( \xi_{rms-jet} \), of the \( d_p = 38 \text{mm} \) nozzle. Conditions: PJ flow only (\( \psi_{CA} = 0\% \)), Reynolds number = 66,100, \( U_d/U_e,p_f = 0.035 \) \( (U_d = 0.038 \text{m/s}) \). Axial distance from the nozzle exit is normalised to the jet nozzle chamber diameter, \( d_{np} \).  

Figure C-15. The effect of confinement on the concentration half-width, \( r_{l/d_p} \), of the \( d_p = 38 \text{mm} \) nozzle. Conditions: PJ flow only (\( \psi_{CA} = 0\% \)), Reynolds number = 66,100, \( U_d/U_e,p_f = 0.035 \) \( (U_d = 0.038 \text{m/s}) \). Axial distance from the nozzle exit is normalised to the PJ nozzle chamber diameter, \( d_{np} \).  

Figure C-16. The effect of confinement on the inverse mean jet concentration on the jet axis, \( \xi_{jet} \), of the \( d_p = 38 \text{mm} \) nozzle. Conditions: PJ flow only (\( \psi_{CA} = 0\% \)), Reynolds number = 66,100, \( U_d/U_e,p_f = 0.098 \) \( (U_d = 0.108 \text{m/s}) \). Axial distance from the nozzle exit is normalised to the duct diameter, \( D_{duct} \).  

Figure C-17. The effect of confinement on the concentration fluctuation intensity on the jet axis, \( \xi_{rms-jet} \), of the \( d_p = 38 \text{mm} \) nozzle. Conditions: PJ flow only (\( \psi_{CA} = 0\% \)), Reynolds number = 66,100, \( U_d/U_e,p_f = 0.098 \) \( (U_d = 0.108 \text{m/s}) \). Axial distance from the nozzle exit is normalised to the jet nozzle chamber diameter, \( d_{np} \).  

Figure C-18. The effect of confinement on the concentration half-width, \( r_{l/d_p} \), of the \( d_p = 38 \text{mm} \) nozzle. Conditions: PJ flow only (\( \psi_{CA} = 0\% \)), Reynolds number = 66,100, \( U_d/U_e,p_f = 0.098 \) \( (U_d = 0.108 \text{m/s}) \). Axial distance from the nozzle exit is normalised to the PJ nozzle chamber diameter, \( d_{np} \).  

Figure C-19. The effect of confinement on the inverse mean jet concentration on the jet axis, \( \xi_{jet} \), of the \( d_p = 38 \text{mm} \) nozzle. Conditions: PJ flow only (\( \psi_{CA} = 0\% \)), Reynolds number = 66,100, \( U_d/U_e,p_f = 0.147 \) \( (U_d = 0.162 \text{m/s}) \). Axial distance from the nozzle exit is normalised to the duct diameter, \( D_{duct} \).  

Figure C-20. The effect of confinement on the concentration fluctuation intensity on the jet axis, \( \xi_{rms-jet} \), of the \( d_p = 38 \text{mm} \) nozzle. Conditions: PJ flow only (\( \psi_{CA} = 0\% \)), Reynolds number = 66,100, \( U_d/U_e,p_f = 0.147 \) \( (U_d = 0.162 \text{m/s}) \). Axial distance is normalised to the PJ nozzle chamber diameter, \( d_{np} \).  

Figure C-21. The effect of confinement on the concentration half-width, \( r_{l/d_p} \), of the \( d_p = 38 \text{mm} \) nozzle. Conditions: PJ flow only (\( \psi_{CA} = 0\% \)), Reynolds number = 66,100, \( U_d/U_e,p_f = 0.147 \) \( (U_d = 0.162 \text{m/s}) \). Axial distance is normalised to the PJ nozzle chamber diameter, \( d_{np} \).
Figure C-22. The effect of confinement on the inverse mean jet concentration on the jet axis, $\xi_{\text{jet}}$, of the $d_{PF}=38\text{mm}$ PJ nozzle. Conditions: PJ flow only ($\psi_{CAJ}=0\%$), Reynolds number $= 66,100$, $U_d/U_{e-PF}=0.196$ ($U_d=0.216\text{m/s}$). Axial distance from the nozzle exit is normalised to the duct diameter, $D_{\text{duct}}$.

Figure C-23. The effect of confinement on the concentration fluctuation intensity on the jet axis, $\xi_{\text{rms-jet}}$, of the $d_{PF}=38\text{mm}$ PJ nozzle. Conditions: PJ flow only ($\psi_{CAJ}=0\%$), Reynolds number $= 66,100$, $U_d/U_{e-PF}=0.196$ ($U_d=0.216\text{m/s}$). Axial distance is normalised to the PJ nozzle chamber diameter, $d_{PF}$.

Figure C-24. The effect of confinement on the concentration half-width, $r_{1/2}/d_{PF}$, of the $d_{PF}=38\text{mm}$ PJ nozzle. Conditions: PJ flow only ($\psi_{CAJ}=0\%$), Reynolds number $= 66,100$, $U_d/U_{e-PF}=0.196$ ($U_d=0.216\text{m/s}$). Axial distance is normalised to the PJ nozzle chamber diameter, $d_{PF}$.

Figure C-25. The effect of CAJ proportion, $\psi_{CAJ}$, on the mean jet concentration on the jet axis, $\xi_{\text{jet}}$, of the $38\text{mm}$ PJ nozzle. Conditions: co-flow velocity $U_a=0.108\text{m/s}$, confinement $D_{\text{duct}}/d_{PF}=7.6$, mass flux ratio $m_d/m_0=18.4$.

Figure C-26. The effect of CAJ proportion, $\psi_{CAJ}$, on the concentration fluctuation intensity, $\xi_{\text{rms-jet}}$, on the jet axis of the $d_{PF}=38\text{mm}$ PJ nozzle. Conditions: co-flow velocity $U_a=0.108\text{m/s}$, confinement $D_{\text{duct}}/d_{PF}=7.6$, mass flux ratio $m_d/m_0=18.4$.

Figure C-27. The effect of CAJ proportion, $\psi_{CAJ}$, on the concentration half-width, $r_{1/2}/d_{PF}$, of the $d_{PF}=38\text{mm}$ PJ nozzle. Conditions: co-flow velocity $U_a=0.108\text{m/s}$, confinement $D_{\text{duct}}/d_{PF}=7.6$, mass flux ratio $m_d/m_0=18.4$.

Figure C-28. The effect of CAJ proportion, $\psi_{CAJ}$, on the mean jet concentration on the jet axis, $\xi_{\text{jet}}$, of the $38\text{mm}$ PJ nozzle. Conditions: co-flow velocity $U_a=0.038\text{m/s}$, confinement $D_{\text{duct}}/d_{PF}=10.9$, mass flux ratio $m_d/m_0=18.4$.

Figure C-29. The effect of CAJ proportion, $\psi_{CAJ}$, on the concentration fluctuation intensity, $\xi_{\text{rms-jet}}$, of the jet axis of the $d_{PF}=38\text{mm}$ PJ nozzle. Conditions: co-flow velocity $U_a=0.038\text{m/s}$, confinement $D_{\text{duct}}/d_{PF}=10.9$, mass flux ratio $m_d/m_0=18.4$.

Figure C-30. The effect of CAJ proportion, $\psi_{CAJ}$, on the concentration half-width, $r_{1/2}/d_{PF}$, of the $d_{PF}=38\text{mm}$ PJ nozzle. Conditions: co-flow velocity $U_a=0.038\text{m/s}$, confinement $D_{\text{duct}}/d_{PF}=10.9$, mass flux ratio $m_d/m_0=18.4$. 

xxi
Notation

Abbreviations and Constants

AAJ  Adjacent Annular Jet  
ASJ  Annular Shaping Jet  
CAJ  Central Axial Jet  
CCD  Charge-Coupled Device  
EINO_x  Emission Index of Nitrogen Oxides  
FPJ/PJ  Fluidic Precessing Jet  
MCB  Multi-Channel Burner  
MPJ  Mechanical Precessing Jet  
Nd:YAG  Neodium Yttrium Aluminium Garnet laser  
PDF/pdf  Probability Distribution Function  
PLIF  Planar Laser-Induced Fluorescence  
RMS  Root Mean Square  
SNR  Signal to Noise Ratio  
σ  Stefan-Boltzmann constant = 5.67x10^{-8} W/m^2.K^4  

Roman Symbols

\( A_{ij} \)  Correction for the spatial distribution of absorption of laser intensity  
\( b \)  Absolute path length (m)  
\( b_{ij}(r) \)  Position of pixel \((i,j)\) along the r-axis of a CCD camera image  
\( b_{ij}(x) \)  Position of pixel \((i,j)\) along the x-axis of a CCD camera image  
\( b_{ij}^{(r)} \)  Corrected position of pixel \((i,j)\) along the r-axis of a CCD camera image  
\( b_{ij}^{(x)} \)  Corrected position of pixel \((i,j)\) along the x-axis of a CCD camera image  
\( B_{ij} \)  Spatial distribution of the background noise of a CCD camera  
\( c, C \)  Fluid concentration  
\( C_{ij} \)  Fluid concentration measured at pixel location \((i,j)\)  
\( C_{ref} \)  Reference concentration representing 100% jet fluid  
\( d \)  Jet exit diameter (m)  
\( d_c \)  Centre-body diameter (m)  
\( d_{CAJ} \)  Central axial jet exit diameter (m)  
\( d_e \)  Momentum or effective diameter of a jet (m)  
\( d_{or} \)  PJ nozzle inlet orifice diameter (m)  
\( d_{PJ} \)  PJ nozzle chamber diameter (m)  
\( d_2 \)  PJ nozzle exit orifice diameter (m)  
\( D \)  Molecular diffusion coefficient (m^2/s)
$D_{duct}$ Diameter of a confining duct (m)
$D_{klin}$ Diameter of a kiln (m)
$f$ Frequency (Hz)
$f_p$ Frequency of precessional motion (Hz)
$F$ Fluorescence intensity
$G$ Jet source momentum (N or kg.m/s²)
$G_{CAJ}$ Momentum of the central axial jet at the jet exit (N or kg.m/s²)
$G_{ij}$ Spatial distribution of the gain response of a CCD camera and optics
$G_{PJ}$ Momentum of the precessing jet calculated at the upstream orifice inlet to the nozzle chamber (N or kg.m/s²)
$G_{shaping}$ Momentum of the shaping jet at the jet exit (N or kg.m/s²)
$G_0$ The excess momentum flux of a jet relative to the surrounding co-flow (N or kg.m/s²)
$I_{ij}$ Spatial distribution of laser intensity
$I_0$ Incident laser intensity
$K_1$ Concentration decay constant
$K_2$ Spreading rate (slope) of the jet concentration half-width
$l_{CAJ}$ Protrusion distance of the central axial jet exit from the face of the centre-body (m)
$l_c$ Local length scale in a flow (m)
$l_c$ Distance between the upstream face of the centre-body and the inlet orifice of the PJ nozzle chamber (m)
$L_{shelf}$ Flame length (m)
$m$ Craya-Curtet scaling parameter
$m_0$ Mass flow rate (kg/s)
$m_{in}$ Mass flow rate of co-flow/secondary fluid (kg/s)
$m_{out}$ Mass flow rate of jet fluid (kg/s)
$P_n$ Instantaneous laser power in image $n$
$P_{min}$ Minimum instantaneous laser power in a set of images
$P_{max}$ Maximum instantaneous laser power in a set of images
$P_{ref}$ Calculated reference laser power for the correction of laser power fluctuations
$Q$ Rate of energy transfer (W)
$Q_{rad}$ Total measured rate of radiant energy transfer (W)
$Q_{loss}$ Rate of total heat transfer through the kiln simulator walls (W)
$Q_{wall,abs}$ Rate of radiant energy absorbed by the kiln simulator walls (W)
$Q_{wall,emit}$ Rate of radiant energy transfer emitted by the kiln simulator walls (W)
$Q_{flame}$ Rate of radiant energy transfer directly emitted by the flame (W)
$Q_f$ Energy input in the fuel (W)
$r$ Span-wise (radial) location in cylindrical co-ordinates (m)
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( r_{CCD} )</td>
<td>Size of the CCD array in pixels along the r-axis</td>
</tr>
<tr>
<td>( r_{break} )</td>
<td>Radial distance from the PJ nozzle axis at which the jet edge “breaks” due to the effects of confinement (m)</td>
</tr>
<tr>
<td>( r_{\text{1/2}} )</td>
<td>Jet centreline concentration half-width (m)</td>
</tr>
<tr>
<td>( s_c )</td>
<td>Ocular distance of the optical system of a CCD camera</td>
</tr>
<tr>
<td>( S_p )</td>
<td>Average signal strength from the laser power reference cell</td>
</tr>
<tr>
<td>( S_{\text{ref}} )</td>
<td>Average signal strength from the jet reference concentration cell</td>
</tr>
<tr>
<td>( S_{ij} )</td>
<td>Spatial distribution of fluorescence intensity</td>
</tr>
<tr>
<td>( R )</td>
<td>Background dye concentration</td>
</tr>
<tr>
<td>( t )</td>
<td>Time (s)</td>
</tr>
<tr>
<td>( T_f )</td>
<td>Non-adiabatic flame temperature (°K)</td>
</tr>
<tr>
<td>( T_w )</td>
<td>Wall surface temperature (°K)</td>
</tr>
<tr>
<td>( T_h )</td>
<td>Becker scaling parameter</td>
</tr>
<tr>
<td>( u )</td>
<td>Fluid velocity (m/s)</td>
</tr>
<tr>
<td>( U )</td>
<td>Bulk mean fluid velocity (m/s)</td>
</tr>
<tr>
<td>( U_a )</td>
<td>Bulk mean velocity of co-flow/secondary air or water (m/s)</td>
</tr>
<tr>
<td>( U_{e-PJ} )</td>
<td>Estimated velocity of the precessing jet at the exit of the nozzle chamber (m/s)</td>
</tr>
<tr>
<td>( U_{or} )</td>
<td>Velocity of the precessing jet at the inlet orifice to the PJ nozzle chamber (m/s)</td>
</tr>
<tr>
<td>( V_{\text{flame}} )</td>
<td>Flame volume (m³)</td>
</tr>
<tr>
<td>( w_c )</td>
<td>Axial width of the centre-body (m)</td>
</tr>
<tr>
<td>( W_{\text{flame}} )</td>
<td>Maximum flame width (m)</td>
</tr>
<tr>
<td>( x )</td>
<td>Stream-wise (axial) location in cylindrical co-ordinates (m)</td>
</tr>
<tr>
<td>( x_{\text{break}} )</td>
<td>Axial distance from the PJ nozzle exit at which the jet edge “breaks” due to the effects of confinement (m)</td>
</tr>
<tr>
<td>( x_{\text{CCD}} )</td>
<td>Size of the CCD array in pixels along the x-axis</td>
</tr>
<tr>
<td>( x_{0,1} )</td>
<td>Virtual origin based on the inverse concentration (m)</td>
</tr>
<tr>
<td>( x_{0,2} )</td>
<td>Virtual origin based on the jet concentration half-width (m)</td>
</tr>
</tbody>
</table>

**Greek Symbols**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \alpha )</td>
<td>Constant of proportionality in the equation relating the Kolmogorov and Batchelor length scales</td>
</tr>
<tr>
<td>( \beta )</td>
<td>Ratio of the laser power signal strength to the jet reference concentration signal strength</td>
</tr>
<tr>
<td>( \chi )</td>
<td>Non-dimensional axial distance on the jet axis, ( = (z - z_{0,1}) / d_e )</td>
</tr>
<tr>
<td>( \chi_r )</td>
<td>Flame radiant fraction</td>
</tr>
<tr>
<td>( \Delta )</td>
<td>Difference</td>
</tr>
<tr>
<td>( \varepsilon )</td>
<td>Extinction coefficient of a fluorescent dye</td>
</tr>
<tr>
<td>( \varepsilon )</td>
<td>Emissivity</td>
</tr>
<tr>
<td>( \eta )</td>
<td>Non-dimensional radial distance from the jet axis, ( = r / (z - z_{0,2}) )</td>
</tr>
<tr>
<td>( \phi )</td>
<td>Quantum efficiency of a fluorescent dye</td>
</tr>
<tr>
<td>( \Gamma^* )</td>
<td>Momentum ratio based similarity parameter for swirl and bluff-body nozzles</td>
</tr>
</tbody>
</table>
\( \Gamma_{\text{shaping}} \) Ratio of shaping jet momentum to the sum of the momentum of the precessing jet, calculated at the upstream orifice inlet to the nozzle chamber, and shaping jet = \( G_{\text{shaping}}/(G_{PJ} + G_{\text{shaping}}) \)

\( \Gamma_{\text{CAJ}} \) Ratio of central axial jet momentum to the sum of the momentum of the precessing jet, calculated at the upstream orifice inlet to the nozzle chamber, and central axial jet = \( G_{\text{CAJ}}/(G_{PJ} + G_{\text{CAJ}}) \)

\( \kappa \) Reference concentration ratio scaling parameter

\( \lambda \) Resolution length scale (m)

\( \lambda_b \) Batchelor length scale (m)

\( \lambda_k \) Kolmogorov length scale (m)

\( \mu \) Experimental uncertainty

\( \theta \) Thring-Newby parameter

\( \rho \) Fluid density (kg/m³)

\( \sigma \) Standard deviation

\( \tau_G \) Global flame time scale (s)

\( \tau_b \) Batchelor time scale (s)

\( \tau_{\text{pulse}} \) Laser pulse-fluorescence time scale (s)

\( \tau_{\text{frame}} \) Laser pulse repetition rate and camera frame rate (s)

\( \xi \) Conserved scalar jet concentration

\( \xi_{ij} \) Conserved scalar jet concentration measured at pixel location \((i,j)\)

\( \bar{\xi} \) Mean jet concentration

\( \xi_{rms} \) Root mean square of jet concentration fluctuations

\( \Psi_{\text{shaping}} \) Mass proportion of the total jet flow rate through the shaping jet = \( m_{\text{shaping}}/(m_{PJ} + m_{\text{shaping}}) \)

\( \Psi_{\text{CAJ}} \) Mass proportion of the total jet flow rate through the central axial jet = \( m_{\text{CAJ}}/(m_{PJ} + m_{\text{CAJ}}) \)

Non-Dimensional Parameters

\( Re \) Reynolds number = \( \frac{ud}{v} \)

\( Sc \) Schmidt number = \( \frac{v}{D} \)

\( Fr \) Froude number = \( \frac{U}{\sqrt{gD}} \)

\( St_{ex} \) Strouhal number of jet excitation = \( \frac{fd}{u} \)

\( St_M \) Strouhal number of precession from the fluidic precessing jet nozzle, based on jet source momentum = \( \frac{f \sqrt{d_{PJ}^2}}{\sqrt{G}} \)

\( St_p \) Strouhal number of precession from the mechanical precessing jet = \( \frac{fd}{U} \)

Subscripts

\( a \) Denotes quantity in the co-flow/secondary flow

\( e-PJ \) Estimated quantity for the precessing jet

\( f \) Flame

\( ij \) Denotes quantity at a given pixel \((i,j)\) of a CCD array

XXV
\textit{min} \quad \text{Minimum value} \\
\textit{max} \quad \text{Maximum value} \\
\textit{n} \quad n^{th} \text{ measurement, e.g. image number} \\
\textit{r} \quad \text{radiation} \\
\textit{ref} \quad \text{Reference value} \\
\textit{rms} \quad \text{Root Mean Square of fluctuating component} \\
\textit{w} \quad \text{Wall} \\
\textit{0} \quad \text{Denotes quantity at the jet source} \\
\textit{\infty} \quad \text{Denotes quantity in the ambient environment/far-field} \\
\text{=} \quad \text{Time mean value}
Statement of Originality

The material in this thesis is original and has not been submitted or accepted for the award of a degree or diploma at any other university and to the best of my knowledge and belief, the thesis contains no material previously published or written by another person except where due reference is made in the text of the thesis.

Jordan Parham

Permission to Copy

The author consents to the thesis being made available for loan and photocopying provided that the thesis is accepted for the award of the degree.

Jordan Parham
Acknowledgment

The completion of this research project has only been possible thanks to the generosity of a wide range of people. In particular, the academic leadership of Emeritus Professor Sam Luxton and Dr. Gus Nathan has successfully guided the research to fruition and contributed significantly to a rewarding research and life experience. The patience, dedication, friendship and inspiration of Gus will always be remembered.

The experiments conducted in this research have benefited significantly from the contributions made by members of the Turbulence, Energy and Combustion (TEC) group. Thanks must go to the many postgraduate students in the TEC group, especially those who have spent time in room S217, for their ideas, assistance and conversation. Dr. David Nobes, Dr. Greg Newbold, Dr. Neil Smith, Mr. Philip Cutler and Mr. Bad Ghazali have especially helped to focus, strengthen and execute the aims of this research. The generosity of Dr. Richard Kelso in providing access to the water-tunnel, image recording and frame-grabbing equipment is most appreciated. The major quantitative mixing experiments would not have been possible without the assistance of Associate Professor Keith King of the Department of Chemical Engineering in securing the Infinity Nd:YAG laser. The contribution of equipment, advice and comments by Dr. David Nobes towards these experiments (which continued from the other side of the world!) was extremely generous. The laser wizardry of Dr. Zeyad Alwahabi ensured the laser based experiments were conducted safely and to the highest standards.

The efforts of the many and varied staff members of the Department of Mechanical Engineering contributed to the development (and repair) of much of the experimental equipment used throughout this research. In particular the contributions of Mr. Graham Kelly, Mr. Anthony Sherry, Mr. Ron Jager, Mr. Craig Price and Mr. Billy Constantine are greatly appreciated. The co-operation and technical input of the staff of the International Flame Research Foundation, especially Mr. Jochen Haas, in conducting the pilot-scale combustion experiments is much appreciated.

This project was made possible by the financial assistance of Fuel and Combustion Technology Ltd. and the Australian Research Council through the Collaborative Grants Scheme. However, the contribution of Fuel and Combustion Technology Ltd. to this research has extended well beyond their financial support. The provision of industrial data, advice, ideas and years of industrial experience from Mr. Steven Hill, Dr. Barrie Jenkins and Dr. Peter Mullinger has ensured a successful commercial and academic outcome from this research.

I am very grateful for the love and support of my partner, Cassie White, and my family who have both helped to share in the highs and lows of the last few years.

Many thanks to you all,

[Signature]

Jordan Parham, December 2000