The University of Adelaide

School of Chemical Engineering

Cooperative Research Centre for Clean Power from Lignite

Physical Modelling of Mixing Between Rectangular Jets Present in Tangentially Fired Brown Coal Boilers

Ph.D. Thesis

Alessio Angelo Scarsella

………. A tutti coloro che hanno lasciato la loro terra per permettere una vita migliore per i propri figli.......

‘*I am an old man now, and when I die and go to heaven there are two matters on which I hope enlightenment. One is quantum electrodynamics and the other is turbulence in fluids. About the former I am rather optimistic’.*

Sir Horace Lamb, 1932.

Acknowledgement

The completion of this research project has only been possible thanks to the help of many people. Firstly the invaluable academic leadership of Associate Professors Peter Mullinger and Gus Nathan and Drs Peter Ashman and Barrie Jenkins. The technical support, feedback and guidance supplied by Dr Neil Smith was second to none; his assistance and participation was fundamental in the completion of this project. I thank Associate Professor Richard Kelso who allowed me to access the Coherent Innova 90 argon ion continuous wave laser and the Phantom v 4.1 camera. I also wish to thank the school of Chemical Engineering's workshop staff, in particular Mr Peter Kay, Mr Brian Mulchay and Mr Jason Peak. Their assistance in the assembly of the dark room, and experimental facility is much appreciated. Motivation behind the project and financial assistance would not have been possible without the Cooperative Research Centre from Clean Power from Lignite.

Thanks are also extended to the administrative staff of the School of Chemical Engineering, namely Ms Terri Withworth, Ms Mary Barrow and Ms Elaine Minerds. To my office mates thank you for ideas, assistance and conversation during the three and a half year period.

I am very grateful for the love and support of my family: My sisters Helen and Angela, brothers in law Manuel and Tony and nieces and nephews, Nadia, Georgia, Anthony and Nicholas. To Carla thank you for your support, motivation, and never ending happiness, may that be the case for many years to come.

A Mamma e Papa';
Tutto cio' la dedico a voi, gli sacfrici che avete fatto, lasciando la vostra terra per permettermi di asprirare ad una vita migliore, sacrifici che soltano il genitore emigrato possa capire.

Statement of originality

The Material in this thesis is original and has not been submitted or accepted for the award of 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.

Alessio Scarsella

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.

Alessio Scarsella

Executive Summary

Large scale power generation commences with the combustion of coal or other fuel, which in turn converts high pressure water into steam which then drives a turbine thus generating electricity. Burning high moisture coal, such as lignite, for power generation implies that a significant amount of energy is wasted in vaporising the moisture, which could otherwise be used in the steam raising process. This implies that more moist coal would be required to drive the same process than if the coal was drier, thus increasing the amount of combustion products such as greenhouses gases. Introducing a dried coal in an existing boiler will significantly change the heat flux profiles, which could result in boiler damage or excessive fouling. Flame temperature is influenced by the supply of reactants; in most cases the limiting reactant will be oxygen. The supply of oxygen (through air) to a pneumatically transported coal stream and subsequent reaction is controlled by the localised fluid mechanics or *'mixing'*. This research aims to provide an understanding of the mixing process between the pneumatically transported coal and air in brown coal fired boilers by modelling the individual jets. The effects of the change in velocity ratio for the air (secondary) jets and fuel (primary) jets of rectangular burners typical of those found in brown coal fired boilers has been studied experimentally and is reported in this thesis. In particular, scientific analysis was used to investigate the physical mechanisms which control fuel-air mixing, and to quantify the concentration of primary and secondary fluid. The concentration data was used in a regression model in conjunction with a reactive combustion model, developed from a 1:30 scale cold model of the Yallourn W' stage 2 boiler, in order that overall boiler performance can be assessed. This overall study is fundamental as a result of the questions raised concerning the future of brown coal in modern society.

A qualitative flow visualisation study of the unconfined 1:30 scaled primary, and two adjacent rectangular jets, was conducted using single colour planar laser induced fluorescence. The characteristics of the jet flow were examined by imaging individually seeded primary and secondary jets and were visualised through four different planes longitudinally, on the axes of each jet. In addition, a transverse qualitative and quantitative study on the rectangular jets was also conducted for the individually seeded jets, and was visualised through planes of flow perpendicular to the direction flow, specifically at axial stations of x/D =0.1, 0.2, 0.5, 1, 2, 4, 6 and 8. The flow characteristics were also examined under different co-flow conditions, particularly secondary to primary jet velocity ratios (λ) of 0, 0.55, 1.4, 2.8, 3.6 and ∞. This quantitative data yields the basis for a 3D regression model to predict fuel-air mixing in actual boilers. A semi-quantitative investigation into some geometrical modifications on the rectangular jets was also conducted at velocity ratios of λ=0, 0.55 and 1.4. The rectangular nozzles were fitted with base plates orientated at 90 degrees and 60 degrees to the direction of flow.

The longitudinal flow visualisation study highlighted the effect of velocity ratio on the flow field of the primary and secondary jets. In particular it showed that the main structures of the primary and secondary jets are sensitive to the co-flowing conditions. The primary jet also experienced the formation of coherent structures close to the bluff body re-circulation region for λ>2.8.

The quantitative transverse analysis of the rectangular jets showed that the primary jet and secondary jets close to the nozzle exit plane distorted with a change in co-flowing conditions. The primary jet experienced distortion for λ>1.4, and the secondary jets experienced distortion for λ <1.4. A plausible mechanism for this "distortion" can be explained by different co-flowing conditions altering the velocity gradients of the jet, thus changing the denomination of the counter rotating vortices present in the corners of rectangular jets, allowing them to alter jet shape.

The transverse quantitative analysis of the rectangular jets allowed for graphical representation of the normalised concentration of the primary and secondary jets in the radial direction and the centreline mixture fraction decay. The analysis of the latter showed that the primary jet, under all co-flow conditions, reached self-similarity at approximately x/D =4, whereas the secondary jets did so at x/D =2. The primary jets observed greater rates of centreline dilution at high velocity ratios, whereas the secondary jets did so at λ=0.55. The quantification of the centreline concentration decay obeyed the inverse rate law for all co-flowing conditions. The first order decay constant K_1, was found to be heavily dependant on velocity ratio.

The planar transverse quantitative data of the primary and secondary jets was used with the method of weighted squares to develop a regression model that would three-dimensionally reproduce the scalar mixing field as a function of velocity ratio. The regression model reproduces scalar quantities for λ=0 and λ=0.55 to 3.6 for the primary jet and λ=0.55 to 3.6 and ∞ for the secondary jet, and is capable of predicting primary and secondary bulk fluid concentrations within 30 to 40 % of the measured values. A sensitivity analysis on the regression model revealed that it is highly responsive to the momentum-controlling region between the jets with a change in velocity ratio.

Table of Contents

Acknowledgement .... **iii**

Statement of originality .... **iv**

Permission to Copy .... **iv**

Executive Summary .... **v**

Table of Contents .... **vii**

List of Tables .... **xiii**

List of Figures .... **xxi**

Nomenclature .... **xlviii**

1. Introduction **1**
  1.1. Background and Motivation 1
  1.2. Utilisation of De-watered Lignite in Existing Technologies 2
  1.3. Tangentially Fired Boilers 6
  1.4. Rectangular Slot Burners 10

2 Literature Review **14**
  2.1 Scales of Turbulence 14
  2.2 Equations of Motion 16
  2.3 Velocity and Concentration under Turbulent Conditions 17
  2.4 Turbulent Jets 19
    2.4.1 Circular Jets 21
    2.4.2 Concentric (co-annular) jets 29
    2.4.3 Rectangular jets 30
    2.4.4 Multiple jets 41
    2.4.5 Rectangular Jets Studies on Multiple Jets Rectangular Jets Commonly found on Brown Coal Fired Boilers 45
  2.5 Scaling Analysis of the Aerodynamic Trajectories of Coal Particles in Brown Coal Fired Boilers 50
  2.6 Conclusion 54

3 Experimental **56**
  3.1 Isothermal Jet Modelling 56
  3.2 Quantification of Mixing 57
  3.3 Range of Experimental Variables 60
    3.3.1 Downstream Distance 60

3.3.2 Range of Velocity Ratios in the Yallourn W1 Furnace 62
3.4 Experimental Jet Nozzles 64
3.4.1 Rectangular Jet Nozzles for Qualitative and Quantitative Investigation 64
3.4.1.1 Free Rectangular Jet Nozzles for Longitudinal and Transverse Investigation 64
3.4.1.2 Rectangular Jet Nozzles for Investigation of Wall Effects 65
3.4.1.3 Rectangular Jet Nozzles for Investigation of Wall Inclination 65
3.4.2 Conventional Jet Nozzles 72
3.5 Isothermal Experiments 72
3.5.1 Selection of Diagnostic Techniques 72
3.5.1.1 Invasive Techniques 72
3.5.1.2 Non-Invasive Techniques 72
3.5.1.3 Laser Induced Fluorescence Fundamentals 75
3.5.2 Experimental Apparatus 76
3.5.2.1 Water Tank 76
3.5.2.2 Laser Source and Optics 77
3.5.3 Experimental Procedure 79
3.5.3.1 Qualitative Measurements 79
3.5.3.2 Quantitative Measurements 79
4 Qualitative Longitudinal Flow Visualisation 81
4.1 Introduction 81
4.2 Experimental Conditions 82
4.3 Flow Visualisation Results 85
4.3.1 Primary Jet 85
4.3.1.1 Plane A 85
4.3.1.2 Plane C 101
4.3.2 Secondary Jet 108
4.3.2.1 Plane A 108
4.3.2.2 Plane B 116
4.3.3 Discussion 120
4.4 Time Averaged Analysis 123
4.4.1 Introduction 123
4.4.2 Image Processing Technique 123
4.4.3 Time Averaged Results 124
4.4.4 Statistical Analysis 133
4.5 Conclusions 137

5 Quantitative Methodology 139
5.1 Introduction 139
5.2 Quantitative PLIF 139
5.3 Quantitative PLIF Image Processing Fundamentals 140
5.4 Quantitative PLIF Technique 141
5.4.1 Experimental 141
5.4.2 Image Processing Technique 141
5.4.2.1 Correction for Background 142
5.4.2.2 Correction for Laser Spatial Intensity 142
5.4.2.3 Image Processing Procedure 143
5.4.3 Experimental Procedure 146
5.4.4 Sources of Error 147
5.4.4.1 Spatial Resolution 147
5.4.4.2 Temporal Resolution 150
5.4.4.3 Measurement Length 151
5.4.4.4 Laser Sheet Distribution and Power 151
5.4.4.5 Photobleaching 151
5.4.4.6 Absorbance 152
5.4.4.7 Mie Scattering 152
5.4.4.8 Signal to Noise Ratio 153
5.4.4.9 Water Quality 153
5.5 Experiment Validation 154
5.5.1 Introduction 154
5.5.2 Schmidt number Effects on Turbulent Mixing 154
5.5.3 Validation Experiments 158
5.5.4 Results of Validation Experiments 158
5.5.4.1 Planar Data 158
5.5.4.2 Statistical Analysis and Validation 159
5.6 Conclusion 163
6 Transverse Imaging of Multiple Rectangular Jets 164
6.1 Introduction 164
6.2 Experimental Design and Conditions 166
6.3 Quantitative Analysis 167
6.3.1 Primary Jet 167

6.3.1.1 Planar Data 167
6.3.1.2 Primary Fluid Mixture Fraction on the Jet Axis 176
6.3.1.3 Primary Jet Cross Stream Mixture Fraction 178
6.3.1.4 Discussion 190
6.3.2 Secondary Jet 191
6.3.2.1 Planar Data 191
6.3.2.2 Secondary Fluid Mixture Fraction on the Jet Axis 201
6.3.2.3 Secondary Jet Cross Stream Mixture Fraction 203
6.3.2.4 Discussion 213
6.3.3 Axis Switching 213
6.3.4 Bulk Entrainment 218
6.4 Conclusion 221
7 Mathematical Modelling of the Mean Scalar Mixing Field of Rectangular Jets 223
7.1 Introduction 223
7.2 Model Development 225
7.2.1 Model Selection 225
7.2.2 Regression Procedure 226
7.3 Model Results 229
7.3.1 Assessment of Mean Axial Data 229
7.3.2 Assessment of Cross Stream Concentration Profiles 230
7.3.3 Analysis of Variance 242
7.4 Applicability of the Mixing Model to an Overall Combustion Model for Coal Fired Boilers 254
7.5 Sensitivity Analysis 255
7.6 Conclusion 257
8 Conclusions and Further Work 259
8.1 Overview 259
8.1.1 Mixing Characteristics of Rectangular Jets under different Co-flowing Conditions 259
8.1.1.1 Qualitative Description of mixing Characteristics 259
8.1.1.2 Quantitative Description of the Control of Mixing Characteristics 260
8.1.2 Three Dimensional Modelling of Rectangular Jets under Different Co-flowing Conditions 261
8.2 Recommendations for Further Work 262
8.2.1 Variation of the Momentum Ratio Independently of Velocity Ratio 262

8.2.2 Velocity Measurements 262
8.2.3 Quantification of Fluctuating Scalar Statistics 263
8.2.4 Variations in Geometry 263
9 Publications Arising From This Thesis 265
10 References 266

Appendices

A Calculation Methodology and Example of Determination of Experimental Flow Rates 279
A.1 Proposed Experimental Flow Rates 279
A.1.1 Determination of Secondary to Primary Velocity Ratio in one of the Yallourn 'W' Boilers 279
A.1.2 Determination of Experimental Flow Rates. 282
B Cross Stream Concentration of the Primary and Secondary Jet 284
B.1 Primary Jet Cross Stream Normalised Concentration 284
B.2 Secondary Jet Cross Stream Normalised Concentration 296
C Transverse Flow Visualization 310
C.1 Transverse Flow Visualization of the Primary Jet 310
C.2 Transverse Flow Visualisation of the Secondary Jet 324
D Evaluation of the Effects of Changes in Boundary Conditions on the Scalar Mixing Field of Three Adjacent Rectangular Jets 338
D.1 Introduction 338
D.2 Experimental Conditions 340
D.2.1. Errors and Image Processing Technique 340
D.3 Scalar Mixing Field of Rectangular Jets with a Base Plate Perpendicular to the Flow. 341
D.3.1. Statistical Analysis of the Effects of Base Plate at 90 Degrees to the Burners ... 343
D.3.2. Conclusion 344
D.4 Scalar Mixing Field of the Rectangular Jets with a Base Plate Inclined at 60 Degrees 349
D.4.1. Statistical Analysis 351
D.4.2. Conclusion 353
E. Modelling Parameters for Prediction of Time-Averaged Scalar Mixing 358
E.1 Primary Jet Regression Parameters 358

E.1.1 Parameters for the Determination of the *b*-Regression Coefficient 359
E.1.2 Parameters for the Determination of the *c*-Regression Coefficient.....................361
E.1.3 Parameters for the Determination of the *d*-Regression Coefficient 363
E.1.4 Parameters for the Determination of the *e*-Regression Coefficient.....................365
E.1.5 Centreline Mixture Fraction Regression Parameters..367
E.2 Secondary Jet Regression Parameters 368
E.2.1 Parameters for the Determination of the *b*-Regression Coefficient 369
E.2.2 Parameters for the Determination of the *c*-Regression Coefficient.....................370
E.2.3 Parameters for the Determination of the *d*-Regression Coefficient 372
E.2.4 Parameters for the Determination of the *e*-Regression Coefficient.....................374
E.2.5 Centreline Mixture Fraction Regression parameters...376
E.2.6 Parameters for the Determination of the y_o Regression Coefficient....................377
E.2.7 Parameters for the Determination of the z_o Regression Coefficient....................380
F. Analysis of Variance Data………………………………………………………….385

List of Tables

Table 1.1: Moisture Content of Brown Coal Fields in Victoria, (Durie, 1991)………………6

Table 2.1: A comparison of the scalar mixing statistics measured by previous experimentalists from simple axissymmetric smooth contraction jets with low Schmidt number...27

Table 2.2: A comparison of the scalar mixing statistics measured by previous experimentalists from simple axissymmetric smooth contraction jets with high Schmidt number...27

Table 2.3: A comparison of the scalar mixing statistics measured by previous experimentalists from simple axissymmetric pipe jets with low Schmidt number.. 28

Table 2.4: A comparison of the scalar mixing statistics measured by previous experimentalists from simple axissymmetric pipe jets with high Schmidt number.. 28

Table 2.5: Empirical values of n, derived from experimental data for concentration profiles for a rectangular turbulent jet (Grandmaison and Pollard, 1991).........................37

Table 2.6: Model data for centerline mixture fraction and jet spread as a function of secondary to primary velocity ratio for a three plane jet system, AR= 40, *s/D* =0.56 (Grandmaison and Zettler, 1989). 43

Table 2.7: Average particle size distribution of coal particles feed to Yallourn W power station boilers, Salter and Nguyen, (2001). 52

Table 3.1: Operating Flow rates of coal feed system to Yallourn ‘W’ Boilers (Simpson and McIntosh, 1998 and Yallourn Energy Pty. Ltd., 2004)......................................63

Table 3.2: Operating air flow rates for the main secondary burners in the Yallourn W furnace with calculated secondary to primary velocity ratio (λ) using the calculated primary burner fow rate of 1368 tph ([i]Simpson and McIntosh, 1998, [ii]Yallourn Energy Pty. Ltd., 2004). 63

Table 3.3: Experimental secondary jet velocities, flow rates and Reynolds numbers, calculated using a constant primary Reynolds number of 10,000 (0.45 L/min) and experimental nozzle geometry (Section 3.4)...63

Table 3.4: Values of characteristic lengths for Figures 3.5, 3.8 and 3.9 66

Table 3.5: Experimental Procedure for the Qualitative Investigation 80

Table 4.1: Laser orientation and marked stream, the shaded green indicates the marking of either the primary or secondary jet, the horizontal or vertical line highlights the laser orientation. 84

Table 4.2: The calculated Momentum flux and momentum ratios for each experimental velocity ratio. 84

Table 4.3: Secondary to primary, velocity ratio, momentum flux ratio, momentum ratio, velocity and momentum gradients for the Yallourn W1 using velocity ratio similarity. 123

Table 4.4: Secondary to primary, velocity ratio, momentum flux ratio, momentum ratio, velocity and momentum gradients for the experimental conditions 123

Table 5.1: Values of K_1 for different nozzle exit conditions for a pipe flow issuing into a stagnant fluid. 157

Table 5.2: Values of K_1 for different nozzle exit conditions for a fluid issuing from a smooth contraction into a stagnant fluid. 157

Table 6.1: Secondary to primary jet momentum flux and momentum ratios with corresponding velocity ratio to be investigated with the transverse imaging 166

Table 6.2: Measured values of the Centreline decay constant K_1 and the primary virtual origin of the primary jet as a function of velocity ratio obtained between $4<x/D<8$. 178

Table 6.3: Calculated values of the Centreline decay constant K_1 and the primary virtual origin of the secondary jet as a function of velocity ratio. 203

Table 7.1: Average estimated error between measured and predicted centreline mixture fraction for the primary and secondary jets. 230

Table 7.2: Analysis of variance results for the measured and predicted centreline mixture fraction of the primary jet. 248

Table 7.3: Analysis of variance results for the measured and predicted centreline mixture fraction of the secondary jet. 249

Table 7.4: Calculated values of F_o for the primary jet $x/D=0.1$, $\lambda=0$ and $\lambda=3.6$, with $F_{crit\,(a=0.05)}=2.61$, $F_{crit\,(\alpha=0.1)}=2$. 253

Table 7.5: Calculated values of F_o for the primary jet, $x/D=2$, $\lambda=0$ and $\lambda=3.6$, with $F_{crit\,(\alpha=0.05)}=2.45$, $F_{crit\,(\alpha=0.1)}=2.0$ 253

Table 7.6: Calculated values of F_o for the primary jet $x/D=8$, $\lambda=0$ and $\lambda=3.6$, with $F_{crit\,(\alpha=0.05)}=2.45$, $F_{crit\,(\alpha=0.1)}=2.0$ 253

Table 7.7: Calculated values of F_o for the secondary jet, for x/D =0.1, λ=0 and λ=3.6, with $F_{crit\ (\alpha=0.05)}$ =2.37, $F_{crit\ (\alpha=0.1)}$=1.85. 253

Table 7.8: Calculated values of F_o for the secondary jet, for x/D =2, λ=0 and λ=3.6, with $F_{crit\ (\alpha=0.05)}$ =2.37, $F_{crit\ (\alpha=0.1)}$=1.85 253

Table 7.9: Calculated values of F_o for the secondary jet, for x/D =8, λ=0.55 and λ=3.6, with $F_{crit\ (\alpha=0.05)}$ =2.37, $F_{crit\ (\alpha=0.1)}$=1.85. 253

Table A. 1: Operating Flow rates of coal feed system to Yallourn ‘W’ Boilers 280

Table A. 2: Flue gas composition 280

Table A. 3: Composition of Morwell raw coal (Durie, (Durie 1991)) 281

Table A. 4: Operating secondary flow-rates, velocities and velocity ratios 282

Table A.5: Experimental secondary jet flow rates 283

Table D. 1: Laser orientation and marked stream (green indicates the marked flow) for the rectangular nozzles fitted with a base plate at 90 and 60 degrees to the direction of flow. 340

Table E. 1: Parameters and intervals for the determination of b regression coefficient at λ=0... 359

Table E. 2: Parameters and intervals for the determination of *a’* regression coefficient for $0.55<\lambda<1.4$ 359

Table E. 3: Parameters and intervals for the determination of *b’* regression coefficient for $0.55<\lambda<1.4$ 359

Table E. 4: Parameters and intervals for the determination of *a’* regression coefficient for $1.4<\lambda<2.8$ 360

Table E. 5: Parameters and intervals for the determination of *b’* regression coefficient for $1.4<\lambda<2.8$ 360

Table E. 6: Parameters and intervals for the determination of *a’* regression coefficient for $2.8<\lambda<3.6$ 360

Table E. 7: Parameters and intervals for the determination of *b’* regression coefficient for $2.8<\lambda<3.6$ 360

Table E. 8: Parameters and intervals for the determination of c regression coefficient at λ=0... 361

Table E. 9: Parameters and intervals for the determination of *a’* regression coefficient for $0.55<\lambda<1.4$ 361

Table E. 10: Parameters and intervals for the determination of *b’* regression coefficient for $0.55<\lambda<1.4$ 362

Table E. 11: Parameters and intervals for the determination of *a'* regression coefficient for $1.4<\lambda<2.8$ 362

Table E. 12: Parameters and intervals for the determination of *b'* regression coefficient for $1.4<\lambda<2.8$ 362

Table E. 13: Parameters and intervals for the determination of *a'* regression coefficient for $2.8<\lambda<3.6$ 362

Table E. 14: Parameters and intervals for the determination of *b'* regression coefficient for $2.8<\lambda<3.6$ 363

Table E. 15: Parameters and intervals for the determination of *a'* regression coefficient for $\lambda=0$. 363

Table E. 16: Parameters and intervals for the determination of *a'* regression coefficient for $0.55<\lambda<1.4$ 364

Table E. 17: Parameters and intervals for the determination of *b'* regression coefficient for $0.55<\lambda<1.4$ 364

Table E. 18: Parameters and intervals for the determination of *a'* regression coefficient for $1.4<\lambda<2.8$ 364

Table E. 19: Parameters and intervals for the determination of *b'* regression coefficient $1.4<\lambda<2.8$ 364

Table E. 20: Parameters and intervals for the determination of *a'* regression coefficient for $2.8<\lambda<3.6$ 365

Table E. 21: Parameters and intervals for the determination of *b'* regression coefficient for $2.8<\lambda<3.6$ 365

Table E. 22: Parameters and intervals for the determination of *a'* regression coefficient for $\lambda=0$. 365

Table E. 23: Parameters and intervals for the determination of *a'* regression coefficient for $0.55<\lambda<1.4$ 366

Table E. 24: Parameters and intervals for the determination of *b'* regression coefficient for $0.55<\lambda<1.4$ 366

Table E. 25: Parameters and intervals for the determination of *a'* regression coefficient for $1.4<\lambda<2.8$ 366

Table E. 26: Parameters and intervals for the determination of *b'* regression coefficient for $1.4<\lambda<2.8$ 366

Table E. 27: Parameters and intervals for the determination of *a'* regression coefficient for $2.8<\lambda<3.6$ 367

Table E. 28: Parameters and intervals for the determination of *b'* regression coefficient for $2.8<\lambda<3.6$ 367

Table E. 29: Parameters and intervals for the determination of α, for centreline mixture fraction determination 368

Table E. 30: Parameters and intervals for the determination of β, for centreline mixture fraction determination. 368

Table E. 31: Parameters and intervals for the determination of γ, for centreline mixture fraction determination 368

Table E. 32: Parameters and intervals for the determination of *a'* regression coefficient for $0.55<\lambda<1.4$ 369

Table E. 33: Parameters and intervals for the determination of *b'* regression coefficient for $0.55<\lambda<1.4$ 369

Table E. 34: Parameters and intervals for the determination of *a'* regression coefficient for $1.4<\lambda<2.8$ 369

Table E. 35: Parameters and intervals for the determination of *b'* regression coefficient for $1.4<\lambda<2.8$ 369

Table E. 36: Parameters and intervals for the determination of *a'* regression coefficient for $2.8<\lambda<3.6$ 370

Table E. 37: Parameters and intervals for the determination of *b'* regression coefficient for $2.8<\lambda<3.6$ 370

Table E. 38: Parameters and intervals for the determination of *a'* regression coefficient for $0.55<\lambda<1.4$ 370

Table E. 39: Parameters and intervals for the determination of *b'* regression coefficient for $0.55<\lambda<1.4$ 371

Table E.40: Parameters and intervals for the determination of *a'* regression coefficient for $1.4<\lambda<2.8$ 371

Table E.41: Parameters and intervals for the determination of *b'* regression coefficient for $1.4<\lambda<2.8$ 371

Table E.42: Parameters and intervals for the determination of *a'* regression coefficient for $2.8<\lambda<3.6$ 371

Table E.43: Parameters and intervals for the determination of *b'* regression coefficient for $2.8<\lambda<3.6$ 371

Table E. 44: Parameters and intervals for the determination of *a'* regression coefficient for $0.55<\lambda<1.4$ 372

Table E.45: Parameters and intervals for the determination of *b'* regression coefficient for $0.55<\lambda<1.4$ 372
Table E.46: Parameters and intervals for the determination of *a'* regression coefficient for $1.4<\lambda<2.8$ 372
Table E.47: Parameters and intervals for the determination of *b'* regression coefficient for $1.4<\lambda<2.8$ 373
Table E.48: Parameters and intervals for the determination of *a'* regression coefficient for $2.8<\lambda<3.6$ 373
Table E.49: Parameters and intervals for the determination of *b'* regression coefficient for $2.8<\lambda<3.6$ 373
Table E.50: Parameters and intervals for the determination of d regression coefficient for $\lambda=\infty$. 373
Table E.51: Parameters and intervals for the determination of *a'* regression coefficient for $0.55<\lambda<1.4$ 374
Table E.52: Parameters and intervals for the determination of *b'* regression coefficient for $0.55<\lambda<1.4$ 374
Table E.53: Parameters and intervals for the determination of *a'* regression coefficient for $1.4<\lambda<2.8$ 374
Table E.54: Parameters and intervals for the determination of *b'* regression coefficient for $1.4<\lambda<2.8$ 375
Table E.55: Parameters and intervals for the determination of *a'* regression coefficient for $2.8<\lambda<3.6$ 375
Table E.56: Parameters and intervals for the determination of *b'* regression coefficient for $2.8<\lambda<3.6$ 375
Table E.57: Parameters and intervals for the determination of *e* regression coefficient for $\lambda=\infty$. 375
Table E.58: Values of *a'* and *b'* for calculation of α at different intervals of λ. 376
Table E.59: Values of *a'* and *b'* for calculation of β at different intervals of λ. 376
Table E.60: Values of *a'* and *b'* for calculation of γ at different intervals of λ. 376
Table E.61: Parameters and intervals for the determination of *a'* regression coefficient for $0.55<\lambda<1.4$, for $z/D < 0$. 377
Table E.62: Parameters and intervals for the determination of *b'* regression coefficient for $0.55<\lambda<1.4$, for $z/D < 0$. 377

Table E.63: Parameters and intervals for the determination of *a’* regression coefficient for $0.55<\lambda<1.4$, for $z/D > 0$. 377

Table E.64: Parameters and intervals for the determination of *b’* regression coefficient for $0.55<\lambda<1.4$, for $z/D > 0$. 378

Table E.65: Parameters and intervals for the determination of *b’* regression coefficient for $1.4<\lambda<2.8$, for $z/D < 0$. 378

Table E.66: Parameters and intervals for the determination of *b’* regression coefficient for $1.4<\lambda<2.8$, for $z/D < 0$. 378

Table E.67: Parameters and intervals for the determination of *a’* regression coefficient for $1.4<\lambda<2.8$, for $z/D > 0$. 378

Table E.68: Parameters and intervals for the determination of *b’* regression coefficient for $1.4<\lambda<2.8$, for $z/D > 0$. 379

Table E.69: Parameters and intervals for the determination of *a’* regression coefficient for $2.8<\lambda<3.6$, for $z/D < 0$. 379

Table E.70: Parameters and intervals for the determination of *b’* regression coefficient for $2.8<\lambda<3.6$, for $z/D < 0$. 379

Table E.71: Parameters and intervals for the determination of *a’* regression coefficient for $2.8<\lambda<3.6$, for $z/D > 0$. 379

Table E.72: Parameters and intervals for the determination of *b’* regression coefficient for $2.8<\lambda<3.6$, for $z/D > 0$. 380

Table E.73: Parameters and intervals for the determination of *a’* regression coefficient for $0.55<\lambda<1.4$, for $z/D < 0$. 380

Table E.74: Parameters and intervals for the determination of *b’* regression coefficient for $0.55<\lambda<1.4$, for $z/D < 0$. 381

Table E.75: Parameters and intervals for the determination of *a’* regression coefficient for $0.55<\lambda<1.4$, for $z/D > 0$. 381

Table E.76: Parameters and intervals for the determination of *b’* regression coefficient for $0.55<\lambda<1.4$, for $z/D > 0$. 381

Table E.77: Parameters and intervals for the determination of *a’* regression coefficient for $1.4<\lambda<2.8$, for $z/D < 0$. 381

Table E.78: Parameters and intervals for the determination of *b’* regression coefficient for $1.4<\lambda<2.8$, for $z/D < 0$. 382

Table E.79: Parameters and intervals for the determination of *a’* regression coefficient for $1.4<\lambda<2.8$, for $z/D > 0$. 382

Table E.80: Parameters and intervals for the determination of *b'* regression coefficient for $1.4<\lambda<2.8$, for $z/D > 0$. 382

Table E.81: Parameters and intervals for the determination of *a'* regression coefficient for $2.8<\lambda<3.6$, for $z/D < 0$. 382

Table E.82: Parameters and intervals for the determination of *b'* regression coefficient for $2.8<\lambda<3.6$, for $z/D < 0$. 383

Table E.83: Parameters and intervals for the determination of *a'* regression coefficient for $2.8<\lambda<3.6$, for $z/D > 0$. 383

Table E.84: Parameters and intervals for the determination of *b'* regression coefficient for $2.8<\lambda<3.6$, for $z/D > 0$. 383

Table E.85: Parameters and intervals for the determination of *a'* regression coefficient for $\lambda=\infty$, for $z/D < 0$. 384

Table E.86: Parameters and intervals for the determination of *b'* regression coefficient for $\lambda=\infty$, for $z/D > 0$. 384

Table F.1: Analysis of variance data of the primary jet, x/D =0.1, λ=0 385

Table F.2: Analysis of variance data of the primary jet, x/D =0.1, λ=3.6 385

Table F.3: Analysis of variance data of the primary jet, x/D =2, λ=0 386

Table F.4: Analysis of variance data of the primary jet, x/D =2, λ=3.6 386

Table F.5: Analysis of variance data of the primary jet, x/D =8, λ=0 386

Table F.6: Analysis of variance data of the primary jet, x/D =8, λ=3.6 387

Table F.7: Analysis of variance data of the secondary jet, x/D =0.1, λ=0 387

Table F.8: Analysis of variance data of the secondary jet, x/D =0.1, λ=3.6 387

Table F.9: Analysis of variance data of the secondary jet, x/D =2, λ=0 387

Table F.10: Analysis of variance data of the secondary jet, x/D =2, λ=3.6 388

Table F.11: Analysis of variance data of the secondary jet, x/D =8, λ=0.55 388

Table F.12: Analysis of variance data of the secondary jet, x/D =8, λ=3.6 388

List of Figures

Figure 1.1: Variation of net specific energy with bed moisture content for Latrobe Valley brown coals (Durie, 1991). 4
Figure 1.2: Effect of different fuels on heat flux patterns in a combustion system (Jenkins and Moles, 1981). 5
Figure 1.3: Effect of using pre-dried coal, on mean boiler operation. Illustrated are the 0-D model outputs of the adiabatic flame temperature and flue gas temperature versus coal moisture content (Smith *et al.*, 2001). 5
Figure 1.4: Effect of using pre-dried coal, on mean boiler operation. Illustrated are the 0-D model outputs of the radiative and sensible heat transfers versus coal moisture content (Smith *et al.*, 2001). 6
Figure 1.5: Power generation cycle from brown coal for The Loy Yang Power Station. 8
Figure 1.6: Schematic diagram of a typical tangentially fired boiler with cross sectional view of the main central vortex, source: (Hart, 2001) 9
Figure 1.7: Schematic diagram of typical coal drying and milling system used in Victorian coal fired power stations a) together with a fireside view of the burners b) (Mullinger *et al.*, 2002). 9
Figure 1.8: Basic used burner geometries. P – primary Jet, S – secondary jet a)Type I burner, b) Type II burner and c)Type III burner. 11
Figure 1.9: Schematic diagram of the front view of a Loy Yang burner bank a) and a magnified view of a single burner illustrating primary and secondary jets b). 12
Figure 1.10: Orientation of refractory cooling Air Jets a) and photograph refractory jet position with respect to the main burners b). 12
Figure 1.11: Schematic diagram of a circular co-axial jet configuration typically used in many other combustion systems, illustrating primary and secondary streams. 13
Figure 2.1: Eulerian description of the variation of the single point velocity component u in turbulent flow. 18
Figure 2.2: Diagram of a confined jet with external recirculation zone highlighted 20
Figure 2.3: Schematic diagram of the developing regions of a round turbulent jet issuing from a smooth contraction. 21

Figure 2.4: Developing regions of a rectangular turbulent jet Trentacoste and Sforza (1967). However, it has been noted by Deo, (2005) and Mi *et al.*, (2005) that the potential core only arises when a top-hat velocity profile is encountoured similar to that of a smooth contraction..38

Figure 2.5: Dimensionless scalar profiles of a rectangular orifice jet in the radial direction with emphasis on the “saddle back” profile effect on the scalar in the near field where T_c is the centreline temperature T_y is the temperature at a radial position, y is the coordinate on the major axis (spanwise plane) and $r_{1/2}$ is the temperature half width (Tschuyia *et al.*, 1986)..38

Figure 2.6: Predicted dimensionless entrainment ratios versus axial distance for rectangular free jets of different aspect ratios of AR =1, 2, 3 and 4 (Elrod, 1954, Trentacoste and Sforza 1967, Miller *et al.*, 1995, Grinstein, 2001)......................................39

Figure 2.7: Experimental spanwise (major axis) and transverse (minor axis) half widths for a series of turbulent rectangular jets of aspect ratios of AR = 2, 10 and 30 (Sfier 1976, Grandmaison *et al.*, 1991, Sforza *et al.*, 1979 and Tsuchyia *et al.*, 1986). 39

Figure 2.8: Comparison of Experimental dimensionless scalars versus dimensionless radial distance in the transverse (minor axis) direction at axial stations of x/D = 5.6, 8.4 and 11.2 for a rectangular turbulent jet with AR = 10 (Grandmaison and Pollard 1991, Sfier 1976)..40

Figure 2.9: Comparison of Experimental dimensionless scalars versus dimensionless radial distance in the spanwise (major axis) direction at axial stations of x/D = 5.6, 8.4 and 11.2 for a rectangular turbulent jet with AR = 10 (Grandmaison and Pollard 1991, Sfier 1976)..40

Figure 2.10: Schematic Diagram of the three flow regions for a multiple plane jet system, highlighting the converging, merging and combined regions (Lin *et al.*, 1991)....... 44

Figure 2.11: Models of flow patterns of three parallel plane jets described by Tanaka et al., (1975), for operating at different velocity ratios: a) for $\lambda < 1$ both secondary jets are entrained into the primary, b) for $\lambda \sim 1$ the primary jet is equal entrained into the secondaries which merge further downstream and c) $\lambda > 1$, where the primary merges first into one secondary and the resultant into the other. 44

Figure 2.12: Schematic diagram of the triple jet configuration present in the Yallourn W boilers 47

Figure 2.13: Diagram of different geometries used in the study conducted by Perry and Pleasance (1983b), Geometry A; perpendicular to wall, Geometry B; at 60 degrees to the wall, Geometry C with the removed separation plates at 60 degrees to wall, Geometry D, with removal of separation plates as well as an expanded recess. 48

Figure 2.14: Schematic of Refractory cooling Air Jets........ 48

Figure 2.15: Photograph of Rectangular Jets Present in a Brown Coal Fired Boiler, illustrating the primary and secondary jet pairings and refractory cooling air jets (Loy Yang Power Station, Courtesy of Loy Yang Power). 49

Figure 2.16: Dimensionless centreline jet velocity versus dimensionless axial distance for Geometries A, B, C and D, at $\lambda = 1$ (Perry et al., 1982), $\overline{u_o}$ is the source velocity and $\overline{u_c}$ is the centreline velocity. 49

Figure 2.17: Dimensionless centreline jet velocity versus dimensionless axial distance for Geometries C and D, at $\lambda = 1$, $\lambda = 1.4$ and $\lambda = 3$ (Perry et al., 1986)........ 50

Figure 2.18: Dependence of Particle Reynolds number on particle size for coal particles fed to the Yallourn W1 boilers. 53

Figure 2.19: The effect of particle diameter on the Stokes number of the particle calculated for four characteristic length scales........ 53

Figure 3.1: Top view of a tangentially coal fired boiler, with reference to the projected distance of the rectangular jets. 61

Figure 3.2: Top view of a tangentially fired boiler indicating jet directions of 8 burner banks a). Front on view of a single burner bank b). Front view of a single burner indicating primary and secondary jets and position of the Cartesian coordinates y and z. Source of diagram: Goodhand et al., (2001). 61

Figure 3.3: Block diagram of coal conveying process in the Yallourn Power station.(Simpson and McIntosh, 1998)........ 64

Figure 3.4: Schematic of cross sectional view of the rectangular jet system........ 65

Figure 3.5: Schematic of side view of the free rectangular jet system with base plate angled at 60 degrees, top view with associated characteristic lengths in Table 2.1. 66

Figure 3.6: Major axis a), minor axis b) and cross sectional c) views of the round to rectangular transition encountered in the primary experimental nozzles. 67

Figure 3.7: Major axis a), minor axis b) and cross sectional c) views of the round to rectangular transition encountered in the secondary experimental nozzles. 68

Figure 3.8: Schematic of side view of the rectangular system with associated characteristic lengths in Table 3.4 70

Figure 3.9: Schematic of side view of the rectangular jet system with base plate angled at 60 degrees, top view a), side view, b). 71

Figure 3.10: Illustration of the basic process involved in Stokes a) and anti-Stokes b) Raman scattering (Warnatz *et al*., 1999). 74

Figure 3.11: A comparison for different signal strength laser diagnostic Techniques (Eckbreth 1988). 75

Figure 3.12 Schematic diagram of experimental setup for longitudinal flow visualisation with rectangular nozzles vertically immersed into the water tunnel, optics orientated giving a vertical sheet with camera position at 90 degrees 78

Figure 3.13: Schematic diagram of experimental setup for transverse flow visualisation with rectangular nozzles vertically immersed into the water tunnel, optics orientated giving a horizontal sheet delivering a fluorescent signal to a mirror below the tank positioned at 45 degrees to a camera positioned also below the tank. 79

Figure 4.1 Generic Laser Orientation and Nomenclature of Plane of Visualised Flow. 83

Figure 4.2: Video images of the primary jet at 0.08 second intervals with the laser orientated through Plane A. Velocity ratio is λ =0, flow region is $0<x/D<6$. 89

Figure 4.3: Video images of the primary jet at 0.08 second intervals with the laser orientated through Plane A. Velocity ratio is λ =0, flow region is $6<x/D<12$. The white lines highlight the sinuous motion of the main coherent structure, A an estimate of the amplitude and l, an estimate of the wavelength. 89

Figure 4.4: Video images of the primary jet at 0.08 second intervals with the laser orientated through Plane A. Velocity ratio is λ=0.55, flow region is $0<x/D<6$. 90

Figure 4.5: Video images of the primary jet at 0.08 second intervals with the laser orientated through Plane A. Velocity ratio is λ =0.55, flow region is $6<x/D<12$. The white lines highlight the sinuous motion of the main coherent structure, A an estimate of the amplitude and l, an estimate of the wavelength. 90

Figure 4.6: Video images of the primary jet at 0.08 second intervals with the laser orientated through Plane A. Velocity ratio is λ =1.4, flow region is $0<x/D<6$. 91

Figure 4.7: Video images of the primary jet at 0.08 second intervals with the laser orientated through Plane A. Velocity ratio is λ =1.4, flow region is $6<x/D<12$. The white lines highlight the sinuous motion of the main coherent structure, A an estimate of the amplitude and l, an estimate of the wavelength. 91

Figure 4.8: Video images of the primary jet at 0.08 second intervals with the laser orientated through Plane A. Velocity ratio is λ =2.8, flow region is $0<x/D<6$. 92

Figure 4.9: Video images of the primary jet at 0.08 second intervals with the laser orientated through Plane A. Velocity ratio is λ =2.8, flow region is $6<x/D<12$. The white lines highlight the sinuous motion of the main coherent structure, A an estimate of the amplitude and l, an estimate of the wavelength. 92

Figure 4.10: Video images of the primary jet at 0.08 second intervals with the laser orientated through Plane A. Velocity ratio is λ =3.6, flow region is $0<x/D<6$. 93

Figure 4.11: Video images of the primary jet at 0.08 second intervals with the laser orientated through Plane A. Velocity ratio is λ =3.6, flow region is $6<x/D<12$. The white lines highlight the sinuous motion of the main coherent structure, A an estimate of the amplitude and l, an estimate of the wavelength. 93

Figure 4.12: High resolution image of the instantaneous flow field of the primary jet through plane A, for λ=0, and $0< x/D<6$. 94

Figure 4.13: High resolution image of the instantaneous flow field of the primary jet through plane A, for λ=0.55, and $0< x/D<6$. 94

Figure 4.14: High resolution image of the instantaneous flow field of the primary jet through plane A, and λ=1.4, and $0< x/D<6$. 95

Figure 4.15: High resolution image of the instantaneous flow field of the primary jet through plane A, for λ=2.8, and $0< x/D<6$. 95

Figure 4.16: High resolution image of the instantaneous flow field of the primary jet through plane A, for λ=3.6, and $0< x/D<6$. 96

Figure 4.17: Dependence on the velocity ratio of the dimensionless wavelength, l/D and amplitude, A/D of the sinuous motion of the main coherent structure of the primary jet through Plane A, as estimated visually and time averaged over ten sequential frames. 96

Figure 4.18: Wake region in the vicinity of the bluff body between the primary and secondary jets, a) λ=0, b) λ <1, c) λ>1 97

Figure 4.19: Schematic diagrams of the first order analysis of large-scale structures of the primary jet through Plane A, a), λ=0, b), λ=0.55, c), λ=1.4-3.6. 97

Figure 4.20: α/D versus λ for the primary jet through plane A. α/D was measured over ten frames of sequential footage and then time-averaged. 98

Figure 4.21: Schematic diagrams of the second order analysis of intermediate-scale structures of the Primary jet through Plane A, a), λ=0-0.55, b), λ=1.4, c), λ=2.8-3.6 98

Figure 4.22: Schematic Diagrams for the instantaneous and time-averaged entrainment mechanisms for the primary jet at λ=0-0.55 a), and λ=1.4-3.6 b). 100

Figure 4.23: A sequence of video images of the primary jet with the laser orientated through Plane C at 0.08 second intervals. Velocity ratio: λ =0, flow region: $0<x/D<6$. 102

Figure 4.24: A sequence of video images of the primary jet at 0.12 second intervals with the laser orientated through Plane C. Velocity ratio: λ =0, flow region: $6<x/D<12$. 102

Figure 4.25: A sequence of Video images of the primary jet with the laser orientated through Plane C at 0.08 second intervals. Velocity ratio: λ =0.55, flow region: $0<x/D<6$. 102

Figure 4.26: A sequence of Video images of the primary jet at 0.12 second intervals with the laser orientated through Plane C. Velocity ratio: λ =0.55, flow region: $6<x/D<12$. The white lines highlight the sinuous motion of the main coherent structure, *A* being the amplitude and *l*, being the wavelength. 103

Figure 4.27: A sequence of Video images of the primary jet at 0.08 second intervals with the laser orientated through Plane C. Velocity ratio: λ =1.4, flow region: $0<x/D<6$. The white lines highlight the sinuous motion of the main coherent structure, A being the amplitude and l, being the wavelength. 103

Figure 4.28: A sequence of Video images of the primary jet at 0.16 second intervals with the laser orientated through Plane C. Velocity ratio: λ =1.4, flow region: $6<x/D<12$. The white lines highlight the sinuous motion of the main coherent structure, *A* being the amplitude and *l*, being the wavelength. 103

Figure 4.29: A sequence of Video images of the primary jet with the laser orientated through Plane C at 0.08 second intervals. Velocity ratio: λ =2.8, flow region: $0<x/D<6$. The white lines highlight the sinuous motion of the main coherent structure, *A* being the amplitude and *l*, being the wavelength. 104

Figure 4.30: A sequence of Video images of the primary jet at 0.16 second intervals with the laser orientated through Plane C. Velocity ratio: λ =2.8, flow region: $6<x/D<12$. The white lines highlight the sinuous motion of the main coherent structure, *A* being the amplitude and *l*, being the wavelength. 104

Figure 4.31: A sequence of Video images of the primary jet at 0.08 second intervals with the laser orientated through Plane C. Velocity ratio: λ =3.6, flow region: 0<*x/D*<6. The white lines highlight the sinuous motion of the main coherent structure, *A* being the amplitude and *l*, being the wavelength. 104

Figure 4.32: A sequence of Video images of the primary jet at 0.16 second intervals with the laser orientated through Plane C. Velocity ratio: λ =3.6, flow region: 6<*x/D*<12. The white lines highlight the sinuous motion of the main coherent structure, *A* being the amplitude and *l*, being the wavelength. 105

Figure 4.33: High resolution image of the instantaneous flow field of the primary jet through plane C, for λ =0, and 0< *x/D*<6. 105

Figure 4.34: High resolution image of the instantaneous flow field of the primary jet through plane C, for λ =0.55, and 0< *x/D*<6. 106

Figure 4.35: High resolution image of the instantaneous flow field of the primary jet through plane C, for λ =1.4, and 0< *x/D*<6. 106

Figure 4.36: High resolution image of the instantaneous flow field of the primary jet through plane C, for λ =2.8, and 0< *x/D*<6. 107

Figure 4.37: High resolution image of the instantaneous flow field of the primary jet through plane C, and λ =3.6, between 0< *x/D*<6. 107

Figure 4.38: Dependency on the velocity ratio of the dimensionless wavelength, *l/D* and amplitude *A/D* of the sinuous motion of the main coherent structure of the primary jet through Plane C, as estimated visually and time averaged over ten sequential frames. 108

Figure 4.39: Video images of the secondary jet at 0.12 second intervals with the laser orientated through Plane A. Velocity ratio is =0.55, flow region is 0<*x/D*<6. The white lines highlight the sinuous motion of the main coherent structure, *A* being the amplitude and *l*, being the wavelength. 109

Figure 4.40: Video images of the secondary jet at 0.12 second intervals with the laser orientated through Plane A. Velocity ratio is λ =1.4, flow region is 0<*x/D*<6. The white lines highlight the sinuous motion of the main coherent structure, *A* being the amplitude and *l*, being the wavelength. 110

Figure 4.41: Video images of the secondary jet at 0.12 second intervals with the laser orientated through Plane A. Velocity ratio is λ =2.8, flow region is 0<*x/D*<6. The white lines highlight the sinuous motion of the main coherent structure, *A* being the amplitude and *l*, being the wavelength. 110

Figure 4.42: Video images of the secondary jet at 0.12 second intervals with the laser orientated through Plane A. Velocity ratio is λ =3.6, flow region is 0<*x/D*<6. The white lines highlight the sinuous motion of the main coherent structure, *A* being the amplitude and *l*, being the wavelength. 110

Figure 4.43: Video images of the secondary jet at 0.12 second intervals with the laser orientated through Plane A. Velocity ratio is λ =∞, flow region is 0<*x/D*<6. The white lines highlight the sinuous motion of the main coherent structure, A being the amplitude and l, being the wavelength. 111

Figure 4.44: High resolution image of the instantaneous flow field of the secondary jet through plane A, and λ=0.55, between 0< *x/D*<6 111

Figure 4.45: High resolution image of the instantaneous flow field of the secondary jet through plane A, and λ=1.4, between 0< *x/D*<6 112

Figure 4.46: High resolution image of the instantaneous flow field of the secondary jet through plane A, and λ=2.8, between 0< *x/D*<6 112

Figure 4.47: High resolution image of the instantaneous flow field of the secondary jet through plane A, and λ=3.6, between 0< *x/D*<6 113

Figure 4.48: High resolution image of the instantaneous flow field of the secondary jet through plane A, and λ=∞, between 0< *x/D*<6. 113

Figure 4.49: Dependency on the velocity ratio of the dimensionless wavelength, *l/D* and amplitude *A/D*, of the sinuous motion of the main coherent structure of the secondary jet through Plane A, as estimated visually and time averaged over ten sequential frames. 114

Figure 4.50: Schematic diagram of the nature of the shear layer between the primary and secondary jet for the cases when a) λ =0.55, b) 1.4≤ λ ≤3.6 and c) λ = ∞........ 114

Figure 4.51: Video images of the secondary jet at 0.08 second intervals with the laser orientated through Plane B. Velocity ratio is λ =0.55, flow region is 0<*x/D*<6. 116

Figure 4.52: Video images of the secondary jet at 0.16 second intervals with the laser orientated through Plane B. Velocity ratio is λ =0.55, flow region is 6<*x/D*<12. The white lines highlight the sinuous motion of the main coherent structure, *A* being the amplitude and *l*, being the wavelength. 116
Figure 4.53: Video images of the secondary jet at 0.08 second intervals with the laser orientated through Plane B. Velocity ratio is λ =1.4, flow region is 0<*x/D*<6. 117
Figure 4.54: Video images of the secondary jet at 0.16 second intervals with the laser orientated through Plane B. Velocity ratio is λ =1.4, flow region is 6<*x/D*<12. The white lines highlight the sinuous motion of the main coherent structure, *A* being the amplitude and *l*, being the wavelength. 117
Figure 4.55: Video images of the secondary jet at 0.08 second intervals with the laser orientated through Plane B. Velocity ratio is λ =2.8, flow region is 0<*x/D*<6. ..117
Figure 4.56: Video images of the secondary jet at 0.16 second intervals with the laser orientated through Plane B. Velocity ratio is λ =2.8, flow region is 6<*x/D*<12. The white lines highlight the sinuous motion of the main coherent structure, *A* being the amplitude and *l*, being the wavelength. 118
Figure 4.57: Video images of the secondary jet at 0.08 second intervals with the laser orientated through Plane B. Velocity ratio is λ =3.6, flow region is 0<*x/D*<6. 118
Figure 4.58: Video images of the secondary jet at 0.16 second intervals with the laser orientated through Plane B. Velocity ratio is λ =3.6, flow region is 6<*x/D*<12. The white lines highlight the sinuous motion of the main coherent structure, *A* being the amplitude and *l*, being the wavelength. 118
Figure 4.59: Video images of the secondary jet at 0.08 second intervals with the laser orientated through Plane B. Velocity ratio is λ =∞, flow region is 0<*x/D*<6..119
Figure 4.60: Video images of the secondary jet at 0.16-second intervals with the laser orientated through Plane B. Velocity ratio is λ =∞, flow region is 6<*x/D*<12. The white lines highlight the sinuous motion of the main coherent structure, *A* being the amplitude and *l*, being the wavelength. 119

Figure 4.61: Dependency on the velocity ratio of the dimensionless wavelength, l/D and amplitude, A/D of the sinuous motion of the main coherent structure of the secondary jet through Plane B, as estimated visually and time averaged over ten sequential frames. 120

Figure 4.62: Normalised intensity for the primary jet with the laser orientated through Plane A in the region between $0<x/D<6$. Refer to Table 4.2 for jet conditions. 126

Figure 4.63: Normalised intensity for the primary jet with the laser orientated through Plane A in the region between $6<x/D<12$. Refer to Table 4.2 for jet conditions. 127

Figure 4.64: Normalised intensity for the primary jet with the laser orientated through Plane C in the region between $0<x/D<6$. Refer to Table 4.2 for jet conditions. 128

Figure 4.65: Normalised intensity for the primary jet with the laser orientated through Plane C in the region between $6<x/D<12$. Refer to Table 4.2 for jet conditions. 129

Figure 4.66: Normalised intensity for the secondary jet with the laser orientated through Plane A in the region between $0<x/D<6$. Refer to Table 4.2 for jet conditions. 130

Figure 4.67: Normalised intensity for the secondary jet with the laser orientated through Plane B in the region between $0<x/D<6$. Refer to Table 4.2 for jet conditions. 131

Figure 4.68: Normalised intensity for the secondary jet with the laser orientated through Plane B in the region between $6<x/D<12$. Refer to Table 4.2 for jet conditions. 132

Figure 4.69: Normalised half width versus axial distance for the primary jet on plane A. Refer to Table 4.2 for jet conditions. 134

Figure 4.70: Normalised half width versus axial distance for the primary jet on plane C. Refer to Table 4.2 for jet conditions. 135

Figure 4.71: Normalised half width versus axial distance for the secondary jet on plane A, with the origin positioned on the axis of the secondary jets. The side sharing an interface with the primary jet is $r_{1/2}/D < 0$. Refer to Table 4.2 for jet conditions. 135

Figure 4.72: Summary and comparison of the normalised half width versus axial distance of the secondary jet on plane B. Refer to Table 4.2 for jet conditions. 136

Figure 4.73: The half-width spread constant for the secondary jet, K_2, and spread virtual origin, $x_{o,2}/D$, for the primary jet on planes A and C. 136

Figure 4.74: The half-width spread constant, K_2 and spread virtual origin, $x_{o,2}/D$, of the secondary jet interfacing with the primary jet and stagnant fluid on plane A and plane B. 137

Figure 5.1: Time averaged background corrections with a) laser off, with b) laser on and c) fluorescent response for a 0.1mg/L Flourescein solution. 145

Figure 5.2: Laser sheet intensity profile, with respect to the direction of flow 146

Figure 5.3 Ratio between probe size and Kolomogrov and Batchelor scales versus axial distance, for a 15 mm round jet operated at Re = 10,000. 149

Figure 5.4: Instantaneous a) and time-averaged b) mixture fraction of the 15 mm round jet at, $x/D < 12.79$, Re = 10,000, $\tau_{shutter}$ = 1/50 secs. 158

Figure 5.5 Instantaneous a) and time-averaged b) mixture fraction of the 15 mm round jet at, $12.79 < x/D < 25.58$, Re = 10,000, $\tau_{shutter}$ = 1/50 secs. 159

Figure 5.6 Time-averaged centreline mixture fraction of the 15 mm jet at compared with the results of other liquid (Sc ~ 1000) and gaseous (Sc ~ 1) pipe jets. 161

Figure 5.7: Jet spread of the 15 mm jet at compared with the results of a other liquid (Sc ~ 1000) jet. 162

Figure 5.8 Radial profiles of the mean jet concentration normalised to the centreline value. Comparison between data for high Schmidt number jets. 162

Figure 6.1: Vortices formed in free rectangular pipe jet (Gutmark and Grinstein, 1999). 166

Figure 6.2: Time averaged normalised concentration of the primary jet at x/D =0.1, for a) λ=0, b) λ=0.55, c) λ=1.4, d) λ=2.8, e) λ=3.6. The white arrows highlight the coherent vortices on corners of the primary jet. 169

Figure 6.3: Time averaged normalised concentration of the primary jet at x/D =0.2, for a) λ=0, b) λ=0.55, c) λ=1.4, d) λ=2.8, e) λ=3.6. The white arrows highlight the change in jet structure at the corners of the primary jet. 169

Figure 6.4: Time averaged normalised concentration of the primary jet at x/D =0.5, for a) λ=0, b) λ=0.55, c) λ=1.4, d) λ=2.8, e) λ=3.6. The white arrows highlight the change in jet structure vortices at the corners of the primary jet. The red arrows outline the shortening of the primary jet in the y-direction. 170

Figure 6.5: Time averaged normalised concentration of the primary jet at x/D =1, for a) λ=0, b) λ=0.55, c) λ=1.4, d) λ=2.8, e) λ=3.6. The white arrows highlight the change in jet structure at the corners of the primary jet. The red arrows outline the contraction of the primary jet in the y-direction. 170

Figure 6.6: Time averaged normalised concentration of the primary jet at x/D =2, for a) λ=0, b) λ=0.55, c) λ=1.4, d) λ=2.8, e) λ=3.6. The red arrows outline the contraction of the primary jet in the y-direction. 171

Figure 6.7: Time averaged normalised concentration of the primary jet at *x/D* =4, for a) λ=0, b) λ=0.55, c) λ=1.4, d) λ=2.8, e) λ=3.6. The white arrows highlight the expansion with respect to *x/D* =2 (Figure 6.6) in the *y*-direction, the red arrows outline the contraction of the primary jet in the *z*-direction. 171

Figure 6.8: Time averaged normalised concentration of the primary jet at *x/D* =6, for a) λ=0, b) λ=0.55, c) λ=1.4, d) λ=2.8, e) λ=3.6. The red arrows outline the contraction of the primary jet in the *y*-direction. The white arrows highlight the progressive expansion of the primary jet in the *z*-direction with respect to *x/D* =4, λ=3.6 (Figure 6.7 e). 172

Figure 6.9: Time averaged normalised concentration of the primary jet at *x/D* =8, for a) λ=0, b) λ=0.55, c) λ=1.4, d) λ=2.8, e) λ=3.6. The white arrows highlight the progressive expansion of the primary jet in the *z*-direction with respect to *x/D* =4, λ=1.4, 2.8 and 3.6 (Figures 6.7 c, d and e). 172

Figure 6.10: *y* and *z*-direction velocity gradients of the primary jet alone 173

Figure 6.11: *y* and *z*-direction velocity gradients of the primary and secondary jets..............173

Figure 6.12: Sketch of the progressive formation of the coherent corner vortices on the primary jet for λ=0, 0.55, 1.4, 2.8 and 3.6, *x/D*=0.1. 174

Figure 6.13: Sketch of the progressive development of the coherent corner vortices on the primary jet for λ=0, 0.55, 1.4, 2.8 and 3.6, *x/D*=0.5. The terms $L_{\lambda=0.55}$, $L_{\lambda=1.4}$ $L_{\lambda=2.8}$ $L_{\lambda=3.6}$ are the length scales of the corner vortices. 174

Figure 6.14: Sketch of the progressive development with λ of the coherent corner vortices on the primary jet for λ=0, 0.55, 1.4, 2.8 and 3.6, *x/D*=1. The terms $L_{\lambda=0.55}$, $L_{\lambda=1.4}$ $L_{\lambda=2.8}$ $L_{\lambda=3.6}$ are the length scales of the corner vortices.. 175

Figure 6.15: Sketch of the progressive development of the primary jet for a progressive increase in velocity ratio from λ=0 to 3.6 at *x/D* =2. 175

Figure 6.16 Inverse centreline mixture fraction versus dimensionless axial distance for the primary jet at velocity ratios of λ=0, 0.55, 1.4, 2.8 and 3.6 compared with round pipe jet data (Current results, Section 5.5.4 and Parham, 2000). The straight line represents the linear fits in the self-similar region. 177

Figure 6.17 Correlation between K_1 of the primary and the secondary to primary velocity ratio...177

Figure 6.18: Normalised Concentration of the primary jet versus *y/D* through different *z/D* planes, at *x/D* =0.1, a) λ=0, b) λ=0.55, c) λ=1.4, d) λ=2.8, e) λ=3.6. The black arrows highlight the peaks corresponding to the distortion of the exit jet by the emergence of the corner vortex. 180

Figure 6.19: Normalised Concentration of the primary jet versus *y/D* through different *z/D* planes, at *x/D* =0.2, a) λ=0, b) λ=0.55, c) λ=1.4, d) λ=2.8, e) λ=3.6. The black arrows highlight the peaks corresponding to the distortion of the exit jet by the emergence of the corner vortex. 181

Figure 6.20: Normalised Concentration of the primary jet versus *y/D* through different *z/D* planes, at *x/D* =0.5, a) λ=0, b) λ=0.55, c) λ=1.4, d) λ=2.8, e) λ=3.6. The black arrows highlight the peaks corresponding, to the coherent corner vortices of fluid in close proximity to the corners of the primary jet. 182

Figure 6.21: Normalised Concentration of the primary jet versus *y/D* through different *z/D* planes, at *x/D* =1, a) λ=0, b) λ=0.55, c) λ=1.4, d) λ=2.8, e) λ=3.6. The black arrows outline a progressive increase in concentration gradient with an increase in co-flowing conditions (λ). 183

Figure 6.22: Normalised Concentration of the primary jet versus *y/D* through different *z/D* planes, at *x/D* =2, a) λ=0, b) λ=0.55, c) λ=1.4, d) λ=2.8, e) λ=3.6. The black arrows outline a progressive increase in concentration gradient with an increase in co-flowing conditions (λ). 184

Figure 6.23: Normalised Concentration of the primary jet versus *z/D* through different *y/D* planes, at *x/D* =4, a) λ=0, b) λ=0.55, c) λ=1.4, d) λ=2.8, e) λ=3.6. The black arrows outline a progressive increase in concentration gradient with an increase in co-flowing conditions of λ=0.55, 1.4 and 2.8. The white arrows highlight a decrease in concentration gradient at λ=3.6. 185

Figure 6.24: Absolute value of the dimensionless concentration gradient in the *y*-direction versus velocity ratio of the primary jet, for *z/D* =0. 186

Figure 6.25: Normalised Concentration of the primary jet versus *z/D* through different *y/D* planes, at *x/D* =1, a) λ=0, b) λ=0.55, c) λ=1.4, d) λ=2.8, e) λ=3.6. The black arrows outline a progressive decrease in concentration gradient with an increase in co-flowing conditions (λ). 187

Figure 6.26: Normalised Concentration of the primary jet versus *z/D* through different *y/D* planes, at *x/D* =2, a) λ=0, b) λ=0.55, c) λ=1.4, d) λ=2.8, e) λ=3.6. The black arrows outline a progressive increase in concentration gradient with an increase in co-flowing conditions from λ=0.55 to 1.4 and 2.8. The white arrows highlight a decrease in concentration gradient at λ=3.6. 188

Figure 6.27: Normalised Concentration of the primary jet versus *z/D* through different *y/D* planes, at *x/D* =4, a) λ=0, b) λ=0.55, c) λ=1.4, d) λ=2.8, e) λ=3.6. The black arrows outline a progressive increase in concentration gradient with an increase in co-flowing conditions of λ=0.55, 1.4 and 2.8. The white arrows highlight a decrease in concentration gradient at λ=3.6. 189

Figure 6.28: Absolute value of the dimensionless concentration gradient in the *z*-direction versus velocity ratio of the primary jet for *y/D* =0. 190

Figure 6.29: Time averaged normalised concentration of the primary jet at *x/D* =0.1, for a) λ=0.55, b) λ=1.4, c) λ=2.8, d) λ=3.6, e) $\lambda=\infty$. The white arrows highlight the mean field distortion by increased strength of corner vortices of the secondary jets......192

Figure 6.30: Time averaged normalised concentration of the primary jet at *x/D* =0.2, for a) λ=0.55, b) λ=1.4, c) λ=2.8, d) λ=3.6, e) $\lambda=\infty$. Mean field distortion by increased strength of corner vortices of the secondary jets. 193

Figure 6.31: Time averaged normalised concentration of the primary jet at *x/D* =0.5, for a) λ=0.55, b) λ=1.4, c) λ=2.8, d) λ=3.6, e) $\lambda=\infty$. Mean field distortion by increased strength of corner vortices of the secondary jets. The black arrows outline a deformation of the secondary jet from a rectangular structure to a rhombus like shape. 194

Figure 6.32: Time averaged normalised concentration of the primary jet at *x/D* =1, for a) λ=0.55, b) λ=1.4, c) λ=2.8, d) λ=3.6, e) $\lambda=\infty$. Mean field distortion by increased strength of corner vortices of the secondary jets. The black arrows outline a deformation of the secondary jet from a rectangular structure to a rhombus like shape. 195

Figure 6.33: Time averaged normalised concentration of the primary jet at *x/D* =2, for a) λ=0.55, b) λ=1.4, c) λ=2.8, d) λ=3.6, e) $\lambda=\infty$. 196

Figure 6.34: Time averaged normalised concentration of the primary jet at *x/D* =4, for a) λ=0.55, b) λ=1.4, c) λ=2.8, d) λ=3.6, e) λ=∞. The white arrows highlight the deviation of the secondary jets from their geometric axis when λ=0.55............197

Figure 6.35: Time averaged normalised concentration of the primary jet at *x/D* =6, for a) λ=0.55, b) λ=1.4, c) λ=2.8, d) λ=3.6, e) λ=∞. The white arrows highlight the deviation of the secondary jets from their geometric axis when λ=0.55............198

Figure 6.36: Time averaged normalised concentration of the primary jet at *x/D* =8, for a) λ=0.55, b) λ=1.4, c) λ=2.8, d) λ=3.6, e) λ=∞. The white arrows highlight the deviation of the secondary jets from their geometric axis when λ=0.55............199

Figure 6.37: Sketch of the progressive development with λ of the coherent corner vortices on the secondary jet for λ= 0.55, 1.4, 2.8, 3.6 and ∞, *x/D*=0.1. 200

Figure 6.38: Sketch of the progressive development with λ of the coherent corner vortices on the secondary jet and their effect on general jet distortion, for λ= 0.55, 1.4, 2.8, 3.6 and ∞, *x/D*=0.5. 200

Figure 6.39: Sketch of the progressive development with λ of the coherent corner vortices on the secondary jet their effect on general jet distortion, for λ= 0.55, 1.4, 2.8, 3.6 and ∞, *x/D*=1. 201

Figure 6.40 Inverse centreline mixture fraction versus dimensionless axial distance for the secondary jet at velocity ratios of λ=0.55, 1.4, 2.8, 3.6 and ∞. The straight lines represent the linear fits in the self-similar region...202

Figure 6.41: Correlation between K_1 of the secondary and the secondary to primary velocity ratio...202

Figure 6.42: Normalised Concentration of the secondary jet versus *y/D* through different *z/D* planes, at *x/D* =0.1, a) λ=0.55, b) λ=1.4, c) λ=2.8, d) λ=3.6, e) λ=∞. The black arrows highlight the peaks corresponding, to the coherent corner vortices in close proximity to the corners of the secondary jet. 204

Figure 6.43: Normalised Concentration of the secondary jet versus *y/D* through different *z/D* planes, at *x/D* =0.2, a) λ=0.55, b) λ=1.4, c) λ=2.8, d) λ=3.6, e) λ=∞. The black arrows highlight the peaks corresponding, to the coherent corner vortices of fluid in close proximity to the corners of the secondary jet.......................................205

Figure 6.44: Normalised Concentration of the secondary jet versus *z/D* through different *y/D* planes, at *x/D* =0.5, a) λ=0.55, b) λ=1.4, c) λ=2.8, d) λ=3.6, e) λ=∞. The black arrow highlights the peak corresponding, to the coherent corner vortex in close proximity to the corners of the secondary jet. 206

Figure 6.45: Normalised Concentration of the secondary jet versus *y/D* through different *z/D* planes, at *x/D* =2, a) λ=0.55, b) λ=1.4, c) λ=2.8, d) λ=3.6, e) λ=∞. The black arrows outline a progressive increase in concentration gradient with an increase in co-flowing conditions. 207

Figure 6.46: Normalised Concentration of the secondary jet versus *y/D* through different *z/D* planes, at *x/D* =4, a) λ=0.55, b) λ=1.4, c) λ=2.8, d) λ=3.6, e) λ=∞. The black arrows outline a progressive increase in concentration gradient with an increase in co-flowing conditions. 208

Figure 6.47: Absolute value of the dimensionless concentration gradient in the *y*-direction versus velocity ratio of the secondary jet, for *z/D* =0. 209

Figure 6.48: Normalised Concentration of the secondary jet versus *z/D* through different *y/D* planes, at *x/D* =4, a) λ=0.55, b) λ=1.4, c) λ=2.8, d) λ=3.6, e) λ=∞. The black arrows highlight a favoured merging between the two jets for λ=∞. 210

Figure 6.49: Normalised Concentration of the secondary jet versus *z/D* through different *y/D* planes, at *x/D* =6, a) λ=0.55, b) λ=1.4, c) λ=2.8, d) λ=3.6, e) λ=∞. The black arrows highlight the merging point between the two jets for λ=1.4, λ=2.8, λ=3.6, and λ=∞. 211

Figure 6.50: Normalised Concentration of the secondary jet versus *z/D* through different *y/D* planes, at *x/D* =8, a) λ=0.55, b) λ=1.4, c) λ=2.8, d) λ=3.6, e) λ=∞. The black arrows highlight the merged jets for λ=2.8, λ=3.6, and λ=∞. 212

Figure 6.51: Normalised lengths of the major and minor axis sides of the primary jet as a function of downstream distance, *x/D*, a) λ =0, b) λ =0.55, c) λ =1.4, d) λ =2.8, e), λ =3.6. The black arrows show positions of axis switching. 216

Figure 6.52: Normalised lengths of the major and minor axis sides of the secondary jet as a function of downstream distance, *x/D*, a) λ =0, b) λ =0.55, c) λ =1.4, d) λ =2.8, e), λ =3.6. 217

Figure 6.53: Point of cross-over between the major and minor axis lengths versus aspect ratio various rectangular jets, illustrating the strong linear correlation between the first point of axis switching and jet aspect ratio (Gutmark and Grinstein, 1999). 218

Figure 6.54: Relative entrainment ratio of the primary/secondary jet versus axial distance *x/D* system for λ=0, 0.55, 1.4, 2.8, 3.6, ∞ and round pipe jet (Ricou and Spalding, 1963). 220

Figure 6.55: Entrainment coefficient of the primary/secondary jet system versus velocity ratio. 220

Figure 7.1: Schematic diagram of a form of the modified Gaussian error curve (Equation 7.1) with upper and lower tangential intersections illustrating the effect of parameters *b*, *c*, *d* and e on the modified Gaussian error curve. 226

Figure 7.2: A time averaged primary flow image at x/D =0.1 for λ=0 a) the original image, b) cropped image and c) reduced image. 228

Figure 7.3: Comparison of measured and predicted values of centreline mean mixture fraction of the primary jet at velocity ratios of λ=0, 0.55, 1.4, 2.8 and 3.6. 229

Figure 7.4 : Comparison of measured and predicted values of centreline mean mixture fraction of the secondary jet at velocity ratios of λ=0.55, 1.4, 2.8, 3.6 and ∞..................230

Figure 7.5: Comparison of the measured and predicted normalised concentration of the primary jet varying z/D at λ=0, x/D=0.1. 233

Figure 7.6: Comparison of the measured and predicted normalised concentration of the primary jet varying z/D at λ=3.6, x/D=0.1. 234

Figure 7.7: Comparison of the measured and predicted normalised concentration of the primary jet varying of z/D at λ=0, x/D=1. 234

Figure 7.8: Comparison of the measured and predicted normalised concentration of the primary jet for different values of z/D, λ=3.6, x/D=1. 235

Figure 7.9: Comparison of the measured and predicted normalised concentration of the primary jet for different values of z/D, λ=0, x/D=2. 235

Figure 7.10: Comparison of the measured and predicted normalised concentration of the primary jet varying of z/D at λ=3.6, x/D=2. 236

Figure 7.11: Comparison of the measured and predicted normalised concentration of the primary jet for different values of z/D, λ=0, x/D=8. 236

Figure 7.12: Comparison of the measured and predicted normalised concentration of the primary jet varying z/D at λ=3.6, x/D=8. 237

Figure 7.13: Relative Error of model predictions of the primary jet at axial stations of x/D = 0.1, 1, 2 and 8, for λ=0 and 3.6. 237

Figure 7.14: Comparison of the measured and predicted normalised concentration of the secondary jet varying z/D at λ=0.55, x/D=0.1. 238

Figure 7.15: Comparison of the measured and predicted normalised concentration of the secondary jet for varying z/D, λ=3.6 at x/D=0.1. 238

Figure 7.16: Comparison of the measured and predicted normalised concentration of the secondary jet for different values of z/D, λ=0.55, x/D=1. 239

Figure 7.17: Comparison of the measured and predicted normalised concentration of the secondary jet for different values of z/D, λ=3.6, x/D=1. 239

Figure 7.18: Comparison of the measured and predicted normalised concentration of the secondary jet for different values of z/D, λ=0.55, x/D=2. 240

Figure 7.19: Comparison of the measured and predicted normalised concentration of the secondary jet for different values of z/D, λ=3.6, x/D=2. 240

Figure 7.20: Comparison of the measured and predicted normalised concentration of the secondary jet for different values of z/D, λ=0.55, x/D=8. 241

Figure 7.21: Comparison of the measured and predicted normalised concentration of the secondary jet for different values of z/D, λ=3.6, x/D=8. 241

Figure 7.22: Relative Error of model predictions of the primary jet at axial stations of x/D = 0.1, 1, 2 and 8, for λ=0 and 3.6. 242

Figure 7.23: Standardised residuals versus normalised axial distance for the primary jet. 247

Figure 7.24: Standardised residuals versus normalised axial distance for the secondary jet. 248

Figure 7.25: Localised R^2 versus y/D for the primary jet at x/D =0.1, 2 and 8 for velocity ratios of λ=0 and λ=3.6. 249

Figure 7.26: Localised R^2 versus y/D for the secondary jet at x/D =0.1, 2 and 8 for velocity ratios of λ=0 and λ=3.6. 250

Figure 7.27: Averaged mean square error versus x/D for the primary jet at velocity ratios of λ=0, 0.55, 1.4, 2.8 and 3.6. 250

Figure 7.28: Averaged mean square error versus x/D for the secondary jet at velocity ratios of λ=0.55, 1.4, 2.8, 3.6 and ∞. 251

Figure 7.29: Averaged R^2 values versus x/D for the primary jet at velocity ratios of λ=0, 0.55, 1.4, 2.8 and 3.6. 251

Figure 7.30: Averaged R^2 values versus x/D for the secondary jet at velocity ratios of λ=0.55, 1.4, 2.8, 3.6 and ∞. 252

Figure 7.31: Dimensionless sensitivity of the response of bulk mixture fraction change with a change in secondary to primary velocity ratio versus downstream distance x/D of the primary jet. 257

Figure A.1: Block diagram of coal conveying process in the Yallourn Power station. 280

Figure B. 1: Normalised Concentration of the primary jet versus y/D through different z/D planes, at x/D =0.1, a) λ =0, b) λ =0.55, c) λ =1.4, d) λ =2.8, e) λ =3.6. 284

Figure B. 2: Normalised Concentration of the primary jet versus z/D through different y/D planes, at x/D =0.1, a) λ =0, b) λ =0.55, c) λ =1.4, d) λ =2.8, e) λ =3.6. 285

Figure B. 3: Normalised Concentration of the primary jet versus *y/D* through different *z/D* planes, at *x/D* =0.2, a) λ=0, b) λ=0.55, c) λ=1.4, d) λ=2.8, e) λ=3.6............286

Figure B. 4: Normalised Concentration of the primary jet versus *z/D* through different *y/D* planes, at *x/D* =0.2, a) λ=0, b) λ=0.55, c) λ=1.4, d) λ=2.8, e) λ=3.6............287

Figure B. 5: Normalised Concentration of the primary jet versus *y/D* through different *z/D* planes, at *x/D* =0.5, a) λ=0, b) λ=0.55, c) λ=1.4, d) λ=2.8, e) λ=3.6............288

Figure B. 6: Normalised Concentration of the primary jet versus z/D through different *y/D* planes, at *x/D* =0.5, a) λ=0, b) λ=0.55, c) λ=1.4, d) λ=2.8, e) λ=3.6............289

Figure B. 7: Normalised Concentration of the primary jet versus *y/D* through different *z/D* planes, at *x/D* =1, a) λ=0, b) λ=0.55, c) λ=1.4, d) λ=2.8, e) λ=3.6...............290

Figure B. 8: Normalised Concentration of the primary jet versus *z/D* through different *y/D* planes, at *x/D* =1, a) λ=0, b) λ=0.55, c) λ=1.4, d) λ=2.8, e) λ=3.6...............291

Figure B. 9: Normalised Concentration of the primary jet versus *y/D* through different *z/D* planes, at *x/D* =2, a) λ=0, b) λ=0.55, c) λ=1.4, d) λ=2.8, e) λ=3.6...............292

Figure B. 10: Normalised Concentration of the primary jet versus *z/D* through different *y/D* planes, at *x/D* =2, a) λ=0, b) λ=0.55, c) λ=1.4, d) λ=2.8, e) λ=3.6...............293

Figure B. 11: Normalised Concentration of the primary jet versus *y/D* through different *z/D* planes, at *x/D* =4, a) λ=0, b) λ=0.55, c) λ=1.4, d) λ=2.8, e) λ=3.6...............294

Figure B. 12: Normalised Concentration of the primary jet versus *z/D* through different *y/D* planes, at *x/D* =4, a) λ=0, b) λ=0.55, c) λ=1.4, d) λ=2.8, e) λ=3.6...............295

Figure B. 13: Normalised Concentration of the secondary jet versus *y/D* through different *z/D* planes, at *x/D* =0.1, a) λ=0.55, b) λ=1.4, c) λ=2.8, d) λ=3.6, e) $\lambda=\infty$...........296

Figure B. 14: Normalised Concentration of the secondary jet versus *z/D* through different *y/D* planes, at *x/D* =0.1, a) λ=0.55, b) λ=1.4, c) λ=2.8, d) λ=3.6, e) $\lambda=\infty$................297

Figure B. 15: Normalised Concentration of the secondary jet versus *y/D* through different *z/D* planes, at *x/D* =0.2, a) λ=0.55, b) λ=1.4, c) λ=2.8, d) λ=3.6, e) $\lambda=\infty$...........298

Figure B. 16: Normalised Concentration of the secondary jet versus *z/D* through different *y/D* planes, at *x/D* =0.2, a) λ=0.55, b) λ=1.4, c) λ=2.8, d) λ=3.6, e) $\lambda=\infty$...........299

Figure B. 17: Normalised Concentration of the secondary jet versus *z/D* through different *y/D* planes, at *x/D* =0.5, a) λ=0.55, b) λ=1.4, c) λ=2.8, d) λ=3.6, e) $\lambda=\infty$...........300

Figure B. 18: Normalised Concentration of the secondary jet versus *z/D* through different *y/D* planes, at *x/D* =0.5, a) λ=0.55, b) λ=1.4, c) λ=2.8, d) λ=3.6, e) $\lambda=\infty$............301

Figure B. 19: Normalised Concentration of the secondary jet versus *y/D* through different *z/D* planes, at *x/D* =1, a) λ=0.55, b) λ=1.4, c) λ=2.8, d) λ=3.6, e) $\lambda=\infty$..............302

Figure B. 20: Normalised Concentration of the secondary jet versus z/D through different y/D planes, at x/D =1, a) λ =0.55, b) λ =1.4, c) λ =2.8, d) λ =3.6, e) λ =∞..............303

Figure B. 21: Normalised Concentration of the secondary jet versus y/D through different z/D planes, at x/D =2, a) λ=0.55, b) λ=1.4, c) λ =2.8, d) λ =3.6, e) λ =∞................304

Figure B. 22: Normalised Concentration of the secondary jet versus z/D through different y/D planes, at x/D =2, a) λ =0.55, b) λ =1.4, c) λ =2.8, d) λ =3.6, e) λ =∞..............305

Figure B. 23: Normalised Concentration of the secondary jet versus y/D through different z/D planes, at x/D =4, a) λ =0.55, b) λ =1.4, c) λ =2.8, d) λ =3.6, e) λ =∞..............306

Figure B. 24: Normalised Concentration of the secondary jet versus z/D through different y/D planes, at x/D =4, a) λ =0.55, b) λ =1.4, c) λ =2.8, d) λ =3.6, e) λ =∞..............307

Figure B. 25: Normalised Concentration of the secondary jet versus z/D through different y/D planes, at x/D =6, a) λ =0.55, b) λ =1.4, c) λ =2.8, d) λ =3.6, e) λ =∞..............308

Figure B. 26: Normalised Concentration of the secondary jet versus z/D through different y/D planes, at x/D =8, a) λ =0.55, b) λ =1.4, c) λ =2.8, d) λ =3.6, e) λ =∞..............309

Figure C. 1: Instantaneous flow visualisation of the normalised concentration for the primary jet at x/D=0.1, at 0.05 second intervals and λ = 0, γ=0, κ =0..............................310

Figure C. 2: Instantaneous flow visualisation of the normalised concentration for the primary jet at x/D=0.1, at 0.05 second intervals and λ = 0.55, γ=0.3, κ =0.18.................310

Figure C. 3: Instantaneous flow visualisation of the normalised concentration for the primary jet at x/D=0.1, at 0.05 second intervals and λ = 1.4, γ=1.96, κ =1.18.................310

Figure C. 4: Instantaneous flow visualisation of the normalised concentration for the primary jet at x/D=0.1, at 0.05 second intervals and λ = 2.8, γ=7.84, κ =4.7. Red arrows illustrate the distortion of the primary jet fluid with a change in velocity gradient due to the higher velocity ratio...311

Figure C. 5: Instantaneous flow visualisation of the normalised concentration for the primary jet at x/D=0.1, at 0.05 second intervals and λ = 3.6, γ=12.96, κ =7.78. Red arrows illustrate the distortion of the primary jet fluid with a change in velocity gradient due to the higher velocity ratio...311

Figure C. 6: Instantaneous flow visualisation of the normalised concentration for the primary jet at x/D=1, at 0.05 second intervals and λ = 0, γ=0, κ =0. Red arrows indicate oscillation of the lobes of the primary structure...311

Figure C. 7: Instantaneous flow visualisation of the normalised concentration for the primary jet at x/D=1, at 0.05 second intervals and λ = 0.55, γ=0.3, κ =0.18. Red arrows indicate out of phase shortening of the primary structure in the y-direction.......312

Figure C. 8: Instantaneous flow visualisation of the normalised concentration for the primary jet at x/D=1, at 0.05 second intervals and λ = 1.4, γ=1.96, κ =1.18. Red arrows indicate out of phase shortening of the primary structure in the y-direction.......312

Figure C. 9: Instantaneous flow visualisation of the normalised concentration for the primary jet at x/D=1, at 0.05 second intervals and λ = 2.8, γ=7.84, κ =4.7. Red arrows indicate the out of phase shortening of the primary structure in the y-direction, and the white arrows illustrate primary jet distortion proximity to the corners due to the change in velocity gradient at higher velocity ratios...............................313

Figure C. 10: Instantaneous flow visualisation of the normalised concentration for the primary jet at x/D=1, at 0.05 second intervals and λ = 3.6 γ=12.96, κ =7.78. Red arrows indicate the out of phase shortening of the primary structure in the y-direction, and the white arrows illustrate primary jet distortion proximity to the corners due to the change in velocity gradient at higher velocity ratios...............................313

Figure C. 11: Instantaneous flow visualisation of the normalised concentration for the primary jet at x/D=2, at 0.05 second intervals and λ = 0, γ=0, κ =0................................314

Figure C. 12: Instantaneous flow visualisation of the normalised concentration for the primary jet at x/D=2, at 0.05 second intervals and λ = 0.55, γ=0.3, κ =0.18....................314

Figure C. 13: Instantaneous flow visualisation of the normalised concentration for the primary jet at x/D=2, at 0.05 second intervals and λ = 1.4, γ=1.96, κ =1.18. The red arrows highlight the out of phase distortion of the primary jet whilst the white arrows indicate the original rectangular shape...315

Figure C. 14: Instantaneous flow visualisation of the normalised concentration for the primary jet at x/D=2, at 0.05 second intervals and λ = 2.8, γ=7.84, κ =4.7. The red arrows highlight the out of phase shortening in the y-direction of the jet......................315

Figure C. 15: Instantaneous flow visualisation of the normalised concentration for the primary jet at x/D=2, at 0.05 second intervals and λ = 3.6 γ =12.96, κ =7.78. The red arrows highlight the out of phase shortening in the y-direction of the jet...........316

Figure C. 16: Instantaneous flow visualisation of the normalised concentration for the primary jet at x/D=4, at 0.05 second intervals and λ = 0, γ=0, κ =0................................316

Figure C. 17: Instantaneous flow visualisation of the normalised concentration for the primary jet at x/D=4, at 0.05 second intervals and λ = 0.55, γ=0.3, κ =0.18. The red arrows indicate the out of phase distortion of the primary jet.......................................317

Figure C. 18: Instantaneous flow visualisation of the normalised concentration for the primary jet at x/D=4, at 0.05 second intervals and λ = 1.4, γ=1.96, κ =1.18. The red arrows indicate the out of phase shortening of the jet in the y-direction. 317

Figure C. 19: Instantaneous flow visualisation of the normalised concentration for the primary jet at *x/D*=4, at 0.05 second intervals and $\lambda = 2.8$, γ=7.84, κ =4.7. The red arrows indicate the out of phase shortening of the jet in the y-direction. 318

Figure C. 20: Instantaneous flow visualisation of the normalised concentration for the primary jet at *x/D*=4, at 0.05 second intervals and $\lambda = 3.6$, γ=12.96, κ =7.78. The red arrows indicate the out of phase shortening of the jet in the z-direction. 318

Figure C. 21: Instantaneous flow visualisation of the normalised concentration for the primary jet at *x/D*=6, at 0.1 second intervals and $\lambda = 0$ γ=0, κ =0. 319

Figure C. 22: Instantaneous flow visualisation of the normalised concentration for the primary jet at *x/D*=6, at 0.1 second intervals and $\lambda = 0.55$, γ=0.3, κ =0.18. The red arrows highlight the out of phase shortening of the jet in the y-direction. 319

Figure C. 23: Instantaneous flow visualisation of the normalised concentration for the primary jet at *x/D*=6, at 0.1 second intervals and $\lambda = 1.4$, γ=1.96, κ =1.18. The red arrows highlight out of phase shortening of the jet in the z-direction. 320

Figure C. 24: Instantaneous flow visualisation of the normalised concentration for the primary jet at *x/D*=6, at 0.1 second intervals and $\lambda = 2.8$, γ=7.84, κ =4.7. The red arrows highlight out of phase shortening of the jet in the z-direction. 320

Figure C. 25: Instantaneous flow visualisation of the normalised concentration for the primary jet at *x/D*=6, at 0.1 second intervals and $\lambda = 3.6$, γ=12.96, κ =7.78. 321

Figure C. 26: Instantaneous flow visualisation of the normalised concentration for the primary jet at *x/D*=8, at 0.1 second intervals and $\lambda = 0$, γ=0, κ =0. 321

Figure C. 27: Instantaneous flow visualisation of the normalised concentration for the primary jet at *x/D*=8, at 0.1 second intervals and $\lambda = 0.55$, γ=0.3, κ =0.18. 322

Figure C. 28: Instantaneous flow visualisation of the normalised concentration for the primary jet at *x/D*=8, at 0.1 second intervals and $\lambda = 1.4$, γ=1.96, κ =1.18. 322

Figure C. 29: Instantaneous flow visualisation of the normalised concentration for the primary jet at *x/D*=8, at 0.1 second intervals and $\lambda = 2.8$ γ=7.84, κ =4.7. 323

Figure C. 30: Instantaneous flow visualisation of the normalised concentration for the primary jet at *x/D*=8, at 0.1 second intervals and $\lambda = 3.6$, γ=12.96, κ =7.78. 323

Figure C. 31: Instantaneous flow visualisation of the normalised concentration of the secondary jet at *x/D*=0.5, at 0.05 second intervals, $\lambda = 0.55$, γ=0.3, κ =0.18. The white arrows highlight the distortion of the secondary jets with an alteration in the local velocity gradients. 324

Figure C. 32: Instantaneous flow visualisation of the normalised concentration of the secondary jet at *x/D*=0.5, at 0.05 second intervals, $\lambda = 1.4$, γ=1.96, κ =1.18. 324

Figure C. 33: Instantaneous flow visualisation of the normalised concentration of the secondary jet at *x/D*=0.5, at 0.05 second intervals and λ = 2.8, γ=7.84, κ =4.7....................324

Figure C. 34: Instantaneous flow visualisation of the normalised concentration of the secondary jet at *x/D*=0.5, at 0.05 second intervals and λ = 3.6, γ=12.96, κ =7.78................325

Figure C. 35: Instantaneous flow visualisation of the normalised concentration of the secondary jet at *x/D*=0.5, at 0.05 second intervals, $\lambda = \infty$, *x/D*=0.5....................................325

Figure C. 36: Instantaneous flow visualisation of the normalised concentration of the secondary jet at *x/D*=1, at 0.05 second intervals and λ = 0.55, γ=0.3, κ =0.18. The white arrows highlight the distortion of the secondary jets with an alteration in the local velocity gradients...325

Figure C. 37: Instantaneous flow visualisation of the normalised concentration of the secondary jet at *x/D*=1, at 0.05 second intervals and λ = 1.4, γ=1.96, κ =4.7. The white arrows highlight the distortion of the secondary jets with an alteration in the local velocity gradients...326

Figure C. 38: Instantaneous flow visualisation of the normalised concentration of the secondary jet at *x/D*=1, at 0.05 second intervals and λ = 2.8, γ=7.84, κ =4.7. The white arrows highlight the distortion of the secondary jets with an alteration in the local velocity gradients...326

Figure C. 39: Instantaneous flow visualisation of the normalised concentration of the secondary jet at *x/D*=1, at 0.05 second intervals and λ = 3.6, γ=12.96, κ =7.78. The white arrows highlight the distortion of the secondary jets with an alteration in the local velocity gradients...327

Figure C. 40: Instantaneous flow visualisation of the normalised concentration of the secondary jet at *x/D*=1, at 0.05 second intervals and $\lambda = \infty$...327

Figure C. 41: Instantaneous flow visualisation of the normalised concentration of the secondary jet at 0.05 second intervals and λ =0.55, γ=0.3, κ =0.18, *x/D*=2.........................328

Figure C. 42: Instantaneous flow visualisation of the normalised concentration of the secondary jet at 0.05 second intervals and λ =1.4, γ=1.96, κ =1.18, *x/D*=2. The white arrows highlight the distortion of the secondary jets with an alteration in the local velocity gradients...328

Figure C. 43: Instantaneous flow visualisation of the normalised concentration of the secondary jet at 0.05 second intervals and λ =2.8, γ=7.84, κ =4.7, *x/D*=2. The white arrows highlight the distortion of the secondary jets with an alteration in the local velocity gradients...329

Figure C. 44: Instantaneous flow visualisation of the normalised concentration of the secondary jet at 0.05 second intervals and λ =3.6, γ=12.96, κ =7.78, x/D=2. The white arrows highlight the distortion of the secondary jets with an alteration in the local velocity gradients......329

Figure C. 45: Instantaneous flow visualisation of the normalised concentration of the secondary jet at 0.05 second intervals and λ =∞, x/D=2......330

Figure C. 46: Instantaneous flow visualisation of the normalised concentration of the secondary jet at 0.05 second intervals and λ =0.55, γ=0.3, κ =0.18 x/D=4......330

Figure C. 47: Instantaneous flow visualisation of the normalised concentration of the secondary jet at 0.05 second intervals and λ =1.4, γ=1.96, κ =1.18, x/D=4......331

Figure C. 48: Instantaneous flow visualisation of the normalised concentration of the secondary jet at 0.05 second intervals and λ =2.8, γ=7.84, κ =7.78, x/D=4......331

Figure C. 49: Instantaneous flow visualisation of the normalised concentration of the secondary jet at 0.05 second intervals and λ =3.6, γ=12.96, κ =7.78, x/D=4......332

Figure C. 50: Instantaneous flow visualisation of the normalised concentration of the secondary jet at 0.05 second intervals and λ =∞, x/D=4......332

Figure C. 51: Instantaneous flow visualisation of the normalised concentration of the secondary jet at 0.05 second intervals and λ =0.55, γ=0.3, κ =0.18, x/D=6......333

Figure C. 52: Instantaneous flow visualisation of the normalised concentration of the secondary jet at 0.05 second intervals and λ =1.4, γ=1.96, κ =1.18, x/D=6......333

Figure C. 53: Instantaneous flow visualisation of the normalised concentration of the secondary jet at 0.05 second intervals and λ =2.8, γ=7.84, κ =4.7, x/D=6......334

Figure C. 54: Instantaneous flow visualisation of the normalised concentration of the secondary jet at 0.05 second intervals and λ =3.6, γ=12.96, κ =7.78, x/D=6......334

Figure C. 55: Instantaneous flow visualisation of the normalised concentration of the secondary jet at 0.05 second intervals and λ =∞, x/D=6......335

Figure C. 56: Instantaneous flow visualisation of the normalised concentration of the secondary jet at 0.05 second intervals and λ =0.55, γ=0.3, κ =0.18, x/D=8......335

Figure C. 57: Instantaneous flow visualisation of the normalised concentration of the secondary jet at 0.05 second intervals and λ =1.4, γ=1.96, κ =1.18, x/D=8......336

Figure C. 58: Instantaneous flow visualisation of the normalised concentration of the secondary jet at 0.05 second intervals and λ =2.8, γ=7.84, κ =4.7, x/D=8......336

Figure C. 59: Instantaneous flow visualisation of the normalised concentration of the secondary jet at 0.05 second intervals and λ =3.6, γ=12.96, κ =7.78, x/D=8......337

Figure C. 60: Instantaneous flow visualisation of the normalised concentration of the secondary jet at 0.05 second intervals and $\lambda = \infty$, x/D=8. 337

Figure D. 1: Normalised intensity for the primary jet with the laser orientated through Plane A with $\lambda = 0$ a), $\lambda = 0.55$ b), $\lambda = 1.4$ c)... 341

Figure D. 2: Normalised intensity for the primary jet with the laser orientated through Plane C with $\lambda = 0$ a), $\lambda = 0.55$ b), $\lambda = 1.4$ c)... 342

Figure D. 3: Normalised intensity for the secondary jet with the laser orientated through Plane A with $\lambda = 0.55$ a), $\lambda = 1.4$ b). 342

Figure D. 4: Normalised intensity for the secondary jet with the laser orientated through Plane B with $\lambda = 0.55$ a), $\lambda = 1.4$ b). 343

Figure D. 5: Normalised half widths of the primary jet in Plane A, with (WP) and without the base plate at 90 degrees to the flow. 345

Figure D. 6: Normalised half widths of the primary jet in Plane C, with (WP) and without the base plate at 90 degrees to the flow. 345

Figure D. 7: Normalised half widths of the Secondary jet in Plane A, with (WP) and without the base plate at 90 degrees to the flow. 346

Figure D. 8: Summary and comparison of the normalised half width versus axial distance of the secondary jet on plane B under free conditions and with a base plate at 90 degrees to the flow (π). 346

Figure D. 9: Time-averaged entrainment pattern of the surrounding fluid into the primary jet through plane C. 347

Figure D. 10: Comparison of the secondary decay constant K_2 versus velocity ratio for the Primary jet under free conditions and with a base plate at 90 degrees to the flow (WP) through planes A and C.. 347

Figure D. 11: Comparison of the secondary virtual origin $x_{o,2}/D$ versus velocity ratio for the Primary jet under free conditions and with a base plate at 90 degrees to the flow (WP) through planes A and C.. 348

Figure D. 12: Comparison of the secondary decay constant K_2 versus the inverse velocity ratio for the secondary jet under free conditions and with a base plate at 90 degrees to the flow (WP) through planes A and B. 348

Figure D. 13: Comparison of the secondary virtual origin $x_{o,2}/D$ versus the inverse velocity ratio for the secondary jet under free conditions with a base plate at 90 degrees to the flow (WP) through planes A and B. 349

Figure D. 14: Normalised intensity for the primary jet with the laser orientated through Plane A with $\lambda = 0$ a), $\lambda = 0.55$ b), $\lambda = 1.4$ c)....................350

Figure D. 15: Normalised intensity for the primary jet with the laser orientated through Plane C with $\lambda = 0$ a), $\lambda = 0.55$ b)....................350

Figure D. 16: Normalised intensity for the secondary jet with the laser orientated through Plane A with $\lambda = 0.55$ a), $\lambda = 1.4$ b)....................351

Figure D. 17: Normalised intensity for the secondary jet with the laser orientated through Plane B with $\lambda = 0.55$ a), $\lambda = 1.4$ b)....................351

Figure D. 18: Summary and comparison of the normalised half width versus axial distance of the primary jet on plane A, under free conditions and with a base plate orientated at 60 degrees to the flow (π). 353

Figure D. 19: Summary and comparison of the normalised half width versus axial distance of the primary jet on plane C under free conditions and with a base plate orientated at 60 degrees to the flow (π). 354

Figure D. 20: Summary and comparison of the normalised half width versus axial distance of the secondary jet on plane A under free conditions and with a base plate orientated at 60 degrees to the flow (π). 354

Figure D. 21: Summary and comparison of the normalised half width versus axial distance of the secondary jet on plane B under free conditions and with a base plate orientated at 60 degrees to the flow (π). 355

Figure D. 22: Schematic diagram of the entrainment of free stream fluid into the primary jet through plane C. 355

Figure D. 23: Comparison of the secondary decay constant K_2 versus velocity ratio for the Primary jet under free conditions and with a base plate orientated at 60 degrees to the flow through planes A and C....................356

Figure D. 24: Comparison of the secondary virtual origin $x_{o,2}/D$ versus velocity ratio for the Primary jet under free conditions and with a base plate orientated at 60 degrees to the flow through planes A and C....................356

Figure D. 25: Comparison of the secondary decay constant K_2 versus the inverse velocity ratio for the secondary jet under free conditions and with a base plate orientated at 60 degrees to the flow (WP) through planes A and B....................357

Figure D. 26: Comparison of the secondary virtual origin $\frac{x_{o,2}}{D}$ versus the inverse velocity ratio for the secondary jet under free conditions with a base plate orientated at 60 degrees to the flow through planes A and B..357

Nomenclature

Abbreviations and Constants

AR	Aspect ratio
MSE	Mean square error
MSR	Mean square regression
SNR	Signal to noise ratio
SSE	Sum square error
SSR	Regression sum of squares
SST	Total sum of squares

Roman Symbols

a	Regression coefficient
b	Regression coefficient
c	Regression coefficient
d	Regression coefficient
e	Regression coefficient
A	Jet Area
A_{ij}	Laser fluorescent response minus background
B_{ij}	Background image matrix
b_v	Velocity half-width
C	Concentration
C_{ref}	Reference concentration
$C_1, C_2 \ldots C_n$	Proportionality constants
C_E	Entrainment Coefficient
D	Equivalent Diameter
D_e	Equivalent momentum diameter
D_f	Molecular diffusivity
d_i	Studentized residuals
d_p	Particle diameter
F_o	F-Test value
H	Nozzle Height
I_{ij}	Laser distribution matrix
J	Momentum Flux
k	Turbulent kinetic energy
K	Number of images
K_1	Centreline decay constant
K_2	Jet spread proportionality constant
L	Characteristic flow length
l_o	Integral scale
m	Mass flow rate
M_{ij}	Correction matrix

n	Empirical constants
P	Pressure
P_{ij}	Raw measured fluorescent signal
Q	Volumetric flow rate
r	Radial coordinate
R	Accumulated background signal
$r_{1/2}$	Concentration half width
R^2	Coefficient of determination
R_i	Model response
S	Spacing between Jets
S_i	Sensitivity of Model response
T	Temperature
t	Time
u	Velocity
u_s	Slip velocity between fluid and Particle
W	Nozzle Width
x	Jet axial direction
X	Averaged column of the laser fluorescent response minus background matrix
X_c	Axis switching cross over point
$x_{o,1}$	First order virtual origin
$x_{o,2}$	Second order virtual origin
y	Jet radial direction (major axis)
z	Jet radial direction (minor axis)
y_o	Regression coefficient
z_o	Regression coefficient

Greek Symbols

α	Regression Coefficient
β	Regression Coefficient
γ	Regression Coefficient
δ	Regression Coefficient
ε	Rate of turbulent dissipation
ϕ	Quantum yield
γ	Secondary to primary jet momentum flux ratio
φ	Secondary to primary jet mass flow ratio
κ	Secondary to primary jet momentum ratio
κ'	Modified secondary to primary jet momentum ratio
λ	Secondary to primary jet velocity ratio
λ'	Modified secondary to primary jet velocity ratio
λ_B	Batchelor Scale
λ_T	Taylor microscale
μ	Dynamic Viscosity
ν	Dimensionless radial coordinate
ρ_f	Fluid density
ρ_p	Particle density
ρ_s	Source density

σ	Standard Deviation
τ_B	Temporal Batchelor Scale
τ_f	Fluid response time
τ_p	Particle response time
ν	Kinematic Viscosity
Ω	Level of uncertainty
ξ	Mixture fraction

Non Dimensional Parameters

Pe	Peclet number = $\frac{\bar{u}D}{D_f}$
Re, Re_f	Fluid Reynolds number = $\frac{\bar{u}D}{\nu}$
$Re_{b\nu}$	Local velocity based half width Reynolds number = $\frac{\bar{u}D}{\nu}$
Re_p	Particle Reynolds Number = $\frac{\overline{u_s} d_p}{\nu}$
Sc	Schmidt number = $\frac{\nu}{D_f}$
St	Stokes number = $\frac{\bar{u}(d_p)^2}{18\nu L}$
Stl	Strouhal Number = $\frac{D}{t\bar{u}}$

Subscripts/Superscripts

1	Denotes quantity from primary jet
2	Denotes quantity from secondary jet
3	Denotes quantity from surrounding fluid
$'$	Denotes fluctuating quantity
$\bar{\ }$	Denotes time-averaged quantity
α	Denotes range of confidence for F-test
B	Bulk mixture quantity
c	Denotes centreline quantity
i	Matrix column
j	Matrix row
k	Matrix number in a 3-D matrix
m	Degrees of freedom
n	Degrees of freedom
o	Denotes quantity at jet source
off	Denotes measured quantity with laser off
on	Denotes measured quantity with laser on
PB	Primary bulk mixture quantity
rms	Random mean square quantity

SB	Secondary bulk mixture quantity
TB	Denotes total combined bulk mixture quantity