Modelling the Solids
Transport Phenomena Within
Flighted Rotary Dryers

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Declaration

I declare that this thesis is my own work and has not been submitted in any form for another degree or diploma at any university or other institution of tertiary education. Information derived from the published or unpublished work of others has been acknowledged in the text and a list of references is given.

-- 30th July 2008

Andrew Lee

Table of Contents

1. INTRODUCTION......2

2. LITERATURE REVIEW......5

- 2.1. INTRODUCTION......5
- 2.2. PROPERTIES OF BULK SOLIDS......5
- 2.3. CHARACTERISATION OF SOLIDS TRANSPORT......8
  - *2.3.1. Experimental Methods......10*
    - 2.3.1.1. Industrial Scale versus Pilot Scale......10
    - 2.3.1.2. Measuring Dryer Holdup......11
    - 2.3.1.3. Measuring the Residence Time Distribution......12
    - 2.3.1.4. Dynamic Response Experiments......13
- 2.4. MODELLING APPROACHES......13
  - *2.4.1. Empirical Models......14*
  - *2.4.2. Mechanistic Models......17*
  - *2.4.3. Compartment Modelling......21*
    - 2.4.3.1. Theory of Compartment Modelling......21
    - 2.4.3.2. Compartment Models of Rotary Dryers......23
  - *2.4.4. Summary of Modelling Methods......26*
  - *2.4.5. Multi-Scale Modelling......27*
- 2.5. MODELLING OF FLIGHT HOLDUP......28
- 2.6. MODELLING OF KILNING BEDS......29
- 2.7. DRAG EFFECTS ON FALLING PARTICLES......30
  - *2.7.1. Integration of Drag Effects on Solids Transport......31*
- 2.8. SUMMARY OF LITERATURE REVIEW......33

3. DRYER MODEL DEVELOPMENT AND SIMULATION......35

- 3.1. A NUMERICAL APPROACH TO MODELLING A ROTARY DRYER......35
  - *3.1.1. Defining Dimensions......35*
  - *3.1.2. Model Development......36*
  - *3.1.3. Modes of Solids Transport......37*
  - *3.1.4. Describing the Behaviour of the Phases......39*
- 3.2. QUANTIFYING THE MODES OF SOLIDS TRANSPORT......40
  - *3.2.1. Form of the Solids Transport Equations......41*
  - *3.2.2. Effect of Dryer Loading on Flight Unloading......41*
  - *3.2.3. Passive Cycle Time......42*
  - *3.2.4. Active Cycle Time......44*
  - *3.2.5. Effects of Gas-Solids Interactions......46*
  - *3.2.6. Solids Transport via Kilning......48*
- 3.3. PROCESS SIMULATION USING GPROMS®......49
  - *3.3.1. Model Entities......50*

3.3.2. *Parameters and Variables* *51*
3.3.3. *Process Entities* *52*
3.3.4. *Estimation and Experiment Entities* *53*
3.3.5. *Other Entity Types* *53*
3.3.6. *Numerical Solvers in gPROMS®* *54*
3.3.7. *Drawbacks to gPROMS®* *54*
3.3.7.1. Interfacing with Excel® 55
3.4. MODEL IMPLEMENTATION USING GPROMS® 55
3.4.1. *Model Structure* *55*

4. GEOMETRIC ANALYSIS OF AN UNLOADING FLIGHT 57

4.1. THE SOLIDS DYNAMIC ANGLE OF REPOSE 58
4.2. CALCULATION OF FLIGHT HOLDUP AND UNLOADING 58
4.2.1. *Non-Perpendicular Flights* *59*
4.2.2. *Additional Geometric Definitions* *60*
4.2.3. *Calculation of Maximum Flight Holdup* *62*
4.2.3.1. Transition Points 65
4.2.3.2. Maximum Flight Holdup 72
First Unloading Phase, $\psi_1 \rightarrow \psi_2$ 72
Second Unloading Phase, $\psi_2 \rightarrow \psi_3$ 73
Third Unloading Phase, $\psi_3 \rightarrow \psi_4$ 75
Fourth Unloading Phase, $\psi_4 \rightarrow \psi_5$ 77
Effects of Serrated Flights 78
4.2.4. *Theoretical Unloading Profile* *79*
4.2.5. *Comparison of Unloading Profile to Previous Literature* *81*
4.2.6. *Limitations and Assumptions of the Geometry Model* *82*
4.3. APPLYING THE GEOMETRIC MODEL TO SOLIDS TRANSPORT 82
4.4. EFFECTS OF DRYER LOADING ON SOLIDS TRANSPORT 83
4.4.1. *The Design Load* *85*
4.4.2. *The Loading Factor* *87*
4.5. IMPLEMENTING GEOMETRIC MODEL IN SOLIDS TRANSPORT MODEL 89

5. EXPERIMENTAL VALIDATION OF THE GEOMETRIC UNLOADING MODEL 92

5.1. FLIGHT UNLOADING APPARATUS 92
5.2. COMMISSIONING AND TESTING 95
5.2.1. *Levelling the Collection Tray* *96*
5.2.2. *Influence of External Sources* *96*
5.2.3. *Dynamic Effects* *99*
5.2.4. *Centrifugal Effects* *100*
5.2.5. *Surface Friction Effects* *101*

5.2.6. Camera Location 102

5.3. EXPERIMENTAL METHODS 102

5.3.1. Experimental Materials 102

5.3.2. Experimental Design 106

5.3.3. Experimental Procedures 107

5.4. DATA ANALYSIS 109

5.4.1. Image Analysis 109

5.4.2. Load Cell Data Analysis 112

5.4.3. Normalizing Time Values 112

5.4.3.1. Solids Bulk Density 117

5.4.4. Repeatability 118

5.4.5. Effects of Abrasive Surface 122

5.5. VALIDATION OF GEOMETRIC UNLOADING MODEL 125

5.5.1. Model Inputs 125

5.5.2. Measurement of the Dynamic Angle of Repose 126

5.5.3. Validation at Different Rotation Velocities 129

5.5.4. Validation with Different Flight Geometries 137

5.5.5. Validation with Different Solid Materials 142

5.5.6. Summary of Model Validation 147

5.6. ANALYSIS OF PHOTOGRAPHIC DATA 148

5.6.1. Curtain Thickness 148

5.6.2. Particle Velocity 152

5.6.3. Bulk Density of Moving Layer of Solids 157

5.6.4. Further Observations 159

6. MODELLING GAS-SOLID INTERACTIONS IN ROTARY DRYERS 161

6.1. THE AXIAL PARTITIONING COEFFICIENTS 161

6.2. EXPERIMENTAL MEASUREMENT OF SINGLE PARTICLE DRAG COEFFICIENTS 161

6.2.1. Theory 163

6.2.2. Experimental Method 164

6.2.3. Results 166

6.2.4. Discussion 167

6.2.5. Summary 169

6.3. METHODS FOR MODELLING THE GAS-SOLIDS INTERACTIONS FOR THE FALLING CURTAIN 169

6.4. COMPUTATIONAL FLUID DYNAMICS (CFD) MODELLING 169

6.5. CFD MODELLING OF TURBULENT FLOWS 171

6.5.1. RANS Equations 172

6.5.2. Eddy Viscosity Turbulence Models 173

6.5.3. Interphase Momentum Transfer 175

6.6. VERIFICATION AND VALIDATION OF CFD TECHNIQUES 175

6.6.1. Comparing CFD Simulations to Wind Tunnel Experiments 176

6.6.1.1. Model Structure and Conditions 176
6.6.1.2. Comparison of Results 177
Experiments with Air Flow 177
Experiments with No Air flow 184
6.6.1.3. Conclusions 185
6.7. CFD SIMULATION OF THE FALLING CURTAIN OF SOLIDS 186
6.7.1. Single Curtain Studies 186
6.7.1.1. Mesh Dependency 188
6.7.1.2. Simulation Results 188
6.7.1.3. Summary of Single Curtain Simulations 195
6.7.2. Multiple Curtain Studies 196
6.8. CONCLUSIONS 203

7. DRYER MODEL VERIFICATION AND VALIDATION 204

7.1. PARAMETER ESTIMATION 204
7.1.1. Dryer Geometry and Material Properties 206
7.1.1.1. Flight Serrations 206
7.1.1.2. Solids Density 207
7.1.1.3. Solids Dynamic Angle of Repose 208
7.1.1.4. Solids Moisture Content 208
7.1.2. Estimated Parameter Values 209
7.2. PHYSICAL REALISM OF RESULTS 211
7.2.1. Average Kilning Phase Velocity 211
7.2.2. Trends in Estimated Parameter Values 212
7.2.3. Discussion of Model Fit 215
7.3. ALTERNATIVE MODEL STRUCTURES 217
7.4. RESPONSE TO OPERATING CONDITIONS 219
7.4.1. Response to Dynamic Angle of Repose 220
7.4.2. Response to Dryer Feed Rate 223
7.5. EFFECT OF DESIGN LOAD 225
7.6. DISCUSSION 226

8. CONCLUSIONS AND RECOMMENDATIONS 228

8.1. CONCLUSIONS 228
8.2. RECOMMENDATIONS 230

9. REFERENCES 233

10. APPENDIX I – GPROMS® CODE 239

10.1. PROCESS ENTITY 239
10.2. MODEL ENTITIES 242
10.2.1. Active Phase 242
10.2.2. Passive Phase 243

10.2.3. Geometry Model 244
10.2.4. Cell Model 248
10.2.5. Outflow Model 248
10.2.6. Dryer Model 249
10.3. PARAMETER ESTIMATION ENTITY 250
10.4. EXPERIMENT ENTITY 251

11. APPENDIX II - MATLAB® CODE 253

11.1. FILTERING FLIGHT RIG DATA 253
11.2. FITTING MODEL TO FLIGHT RIG DATA 254

List of Figures

Figure 1.1. Schematic of a typical counter-current rotary dryer. 2

Figure 1.2. Cross section of an operating flighted rotary dryer. 3

Figure 1.3. Load conditions within a flighted rotary dryer; a) underloaded, b) design loaded and c) overloaded operations. 4

Figure 2.1. Experimental methods for determining the angle of repose (Woodcock and Mason, 1987[1]). 7

Figure 2.2. Residence time distribution for Invicta Sugar Mill dryer number 2 (Monro[10]). 10

Figure 2.3. Modified Cholette-Cloutier Model[33]. 24

Figure 2.4. Model proposed by Schneider *et al.*[35] 25

Figure 2.5. Model proposed by Sheehan *et al.*[38] 26

Figure 2.6. Diagram showing forces acting on a falling particle in a moving air stream. .. 30

Figure 3.1. Dimensions used in developing the model. 36

Figure 3.2. A slice of a dryer. 37

Figure 3.3. Example of the average particle fall path. 38

Figure 3.4. Maximum axial advance compared to cell length. 38

Figure 3.5. One-dimensional numerical model. 39

Figure 3.6. Average active and passive cycle times. 42

Figure 3.7. Average fall point and passive cycle arc. 43

Figure 3.8. Axial transport partition coefficients. 47

Figure 3.9. Diagram of Model Structure. 56

Figure 4.1. A generic straight 2-section flight. 59

Figure 4.2. Geometric variables for non-perpendicular flights. 59

Figure 4.3. Definition of some geometric variables. 61

Figure 4.4. Calculation of ψ_{ft} and R_F 62

Figure 4.5. Definition of a full flight. 63

Figure 4.6. Overview of transition points. 65

Figure 4.7. Transition point 1 ψ_1 66

Figure 4.8. Detail of lengths and angles at the second transition point. 66

Figure 4.9. Transition point 3, ψ_3. 68

Figure 4.10. Transition point 4, ψ_4. 69

Figure 4.11. Transition point 5, ψ_5. 70

Figure 4.12. Cross-sectional area of flighted material between ψ_1 and ψ_2. 73

Figure 4.13. Cross-sectional area of flighted material between ψ_2 and ψ_3. 74

Figure 4.14. Cross-sectional area of flighted material between ψ_3 and ψ_4. 76

Figure 4.15. Cross-sectional area of flighted material between ψ_3 and ψ_4 at higher ψ . 77
Figure 4.16. Cross-sectional area of flighted material between ψ_4 and ψ_5 . 78
Figure 4.17. Maximum flight holdup profile for Invicta Mill Dryer Number 2. 80
Figure 4.18. Flight discharge rate profile for Invicta Mill Dryer Number 2. 80
Figure 4.19. Relationship between dryer and flight loading factors for Invicta Dryer Number 2. 88
Figure 4.20. gPROMS® model structure. 91
Figure 5.1. Photograph of experimental apparatus. 93
Figure 5.2. Schematic of collection tray and flight cross-section (Alternative design). 94
Figure 5.3. Force diagram on collection tray. 96
Figure 5.4. Example of raw experimental data (2 rpm). 97
Figure 5.5. Derivative of example raw experimental data (2 rpm). 97
Figure 5.6. Example of experimental data after filtering (2 rpm). 98
Figure 5.7. Derivative of example raw experimental data after filtering (2 rpm). 99
Figure 5.8. Example of the effects of impact forces on accumulated mass measurement (Flight design 3, filter sand, 8 rpm). 100
Figure 5.9. Photograph of trommel apparatus in operation. 104
Figure 5.10. Material particle size distribution. 105
Figure 5.11. Initial location of flight. 110
Figure 5.12. Measuring angle of rotation from photographs. 110
Figure 5.13. Measuring material angle of repose. 110
Figure 5.14. Schematic of flight showing calculation of angle of repose from measurements. 111
Figure 5.15. Measuring the curtain thickness. 111
Figure 5.16. High-speed camera images showing a tracked particle (circled in black). 112
Figure 5.17. Measured mass flow rate profile (1/2 scale flight, 2 rpm, filter sand). 113
Figure 5.18. Example of alignment method for experimental data (Alternative Flight, Filter Sand, 2 rpm). 114
Figure 5.19. Comparison of accumulated mass data (Alternative Flight, Filter Sand, 2 rpm). 115
Figure 5.20. Comparison of accumulated mass data with 95% confidence interval (Alternative Flight, Filter Sand, 2 rpm). 116
Figure 5.21. Comparison of mass flow rate data with 95% confidence interval (Alternative Flight, Filter Sand, 2 rpm). 116
Figure 5.22. Comparison of results using consolidated and unconsolidated bulk densities (Alternative Flight, River Sand, 8 rpm). 117
Figure 5.23. Repeatability of accumulated mass data (Alternative Flight, Filter Sand, 2 rpm). 118
Figure 5.24. Repeatability of mass flow rate data (Alternative Flight, Filter Sand, 2 rpm). 119

Figure 5.25. Repeatability of accumulated mass data (Alternative Flight, Filter Sand, 8rpm). 119
Figure 5.26. Repeatability of mass flow rate data (Alternative Flight, Filter Sand, 8 rpm). 120
Figure 5.27. Repeatability of accumulated mass data (1/2 Scale Flight, Filter Sand, 2 rpm). 121
Figure 5.28. Repeatability of accumulated mass data (1/2 Scale Flight, Filter Sand, 8 rpm). 121
Figure 5.29. Repeatability of accumulated mass data (Full Scale Flight, Filter Sand, 2 rpm). 122
Figure 5.30. Comparison of experiments with and without abrasive surface at 1 rpm. 123
Figure 5.31. Comparison of experiments with and without abrasive surface at 2 rpm. 123
Figure 5.32. Comparison of experiments with and without abrasive surface at 4 rpm. 124
Figure 5.33. Comparison of experiments with and without abrasive surface at 8 rpm. 124
Figure 5.34. Example of angle of repose measurements from Experiments 5-8. 127
Figure 5.35. Dynamic angle of repose as a function of rotational velocity from Experiments 5-8. 127
Figure 5.36. Accumulated mass data (Alternative Flight, Filter Sand, 1 rpm). 131
Figure 5.37. Mass flow rate data (Alternative Flight, Filter Sand, 1 rpm). 131
Figure 5.38. Accumulated mass data (Alternative Flight, Filter Sand, 2 rpm). 132
Figure 5.39. Mass flow rate data (Alternative Flight, Filter Sand, 2 rpm). 132
Figure 5.40. Accumulated mass data (Alternative Flight, Filter Sand, 4 rpm). 133
Figure 5.41. Mass flow rate data (Alternative Flight, Filter Sand, 4 rpm). 133
Figure 5.42. Accumulated mass data (Alternative Flight, Filter Sand, 8 rpm). 134
Figure 5.43. Mass flow rate data (Alternative Flight, Filter Sand, 8 rpm). 134
Figure 5.44. Normalised accumulated mass profiles at different rotational speeds (Alternate Flight, Filter Sand). 135
Figure 5.45. Normalised mass flow rate profiles at different rotational speeds (Alternate Flight, Filter Sand). 136
Figure 5.46. Accumulated mass data (1/2 Scale Flight, Filter Sand, 2 rpm). 138
Figure 5.47. Mass flow rate data (1/2 Scale Flight, Filter Sand, 2 rpm). 138
Figure 5.48. Accumulated mass data (1/2 Scale Flight, Filter Sand, 8 rpm). 139
Figure 5.49. Mass flow rate data (1/2 Scale Flight, Filter Sand, 8 rpm). 139
Figure 5.50. Accumulated mass data (Full scale Flight, Filter Sand, 2 rpm). 140
Figure 5.51. Mass flow rate data (Full Scale Flight, Filter Sand, 2 rpm). 140
Figure 5.52. Accumulated mass data (Full Scale Flight, Filter Sand, 8 rpm). 141
Figure 5.53. Mass flow rate data (Full Scale Flight, Filter Sand, 8 rpm). 141
Figure 5.54. Accumulated mass data (Alternative Flight, Zeolite, 2 rpm). 143
Figure 5.55. Mass flow rate data (Alternative Flight, Zeolite, 2 rpm). 143
Figure 5.56. Accumulated mass data (Alternative Flight, River Sand, 2 rpm). 144

FIGURE 5.57. MASS FLOW RATE DATA (ALTERNATIVE FLIGHT, RIVER SAND, 2 RPM). 144
FIGURE 5.58. ACCUMULATED MASS DATA (ALTERNATIVE FLIGHT, ZEOLITE, 8 RPM). 145
FIGURE 5.59. MASS FLOW RATE DATA (ALTERNATIVE FLIGHT, ZEOLITE, 8 RPM). 145
FIGURE 5.60. ACCUMULATED MASS DATA (ALTERNATIVE FLIGHT, RIVER SAND, 8 RPM). 146
FIGURE 5.61. MASS FLOW RATE DATA (ALTERNATIVE FLIGHT, RIVER SAND, 8 RPM). 146
FIGURE 5.62. COMPARISON OF THE THICKNESS OF THE MOVING LAYER OF SOLIDS COMPARED TO THE UNLOADING PROFILE OF THE FLIGHT (ALTERNATE FLIGHT, FILTER SAND, 1 RPM). 149
FIGURE 5.63. COMPARISON OF THE THICKNESS OF THE MOVING LAYER OF SOLIDS COMPARED TO THE UNLOADING PROFILE OF THE FLIGHT (ALTERNATIVE FLIGHT, FILTER SAND, 4 RPM). 150
FIGURE 5.64. COMPARISON OF THE THICKNESS OF THE MOVING LAYER OF SOLIDS COMPARED TO THE UNLOADING PROFILE OF THE FLIGHT (ALTERNATIVE FLIGHT, FILTER SAND, 8 RPM). 150
FIGURE 5.65. THICKNESS PROFILE AT INCREASING ROTATIONAL SPEEDS (ALTERNATIVE FLIGHT, FILTER SAND). 151
FIGURE 5.66. AVERAGE CURTAIN THICKNESS AT INCREASING ROTATIONAL SPEEDS (ALTERNATIVE FLIGHT, FILTER SAND). 152
FIGURE 5.67. COMPARISON OF THE VELOCITY OF THE MOVING LAYER OF SOLIDS COMPARED TO THE UNLOADING PROFILE OF THE FLIGHT (ALTERNATIVE FLIGHT, FILTER SAND, 1 RPM). 153
FIGURE 5.68. COMPARISON OF THE VELOCITY OF THE MOVING LAYER OF SOLIDS COMPARED TO THE UNLOADING PROFILE OF THE FLIGHT (ALTERNATIVE FLIGHT, FILTER SAND, 4 RPM). 153
FIGURE 5.69. COMPARISON OF THE VELOCITY OF THE MOVING LAYER OF SOLIDS COMPARED TO THE UNLOADING PROFILE OF THE FLIGHT (ALTERNATIVE FLIGHT, FILTER SAND, 8 RPM). 154
FIGURE 5.70. PARTICLE VELOCITY PROFILE AT INCREASING ROTATIONAL SPEEDS (ALTERNATIVE FLIGHT, FILTER SAND). 155
FIGURE 5.71. BULK DENSITY OF THE MOVING LAYER OF SOLIDS AT DIFFERENT ROTATIONAL VELOCITIES (ALTERNATIVE FLIGHT, FILTER SAND). 158
FIGURE 5.72. HIGH-SPEED CAMERA IMAGES OF A FLIGHT DURING UNLOADING AT INTERVALS OF 0.016 SECONDS (ALTERNATIVE FLIGHT, RIVER SAND, 8 RPM). 160
FIGURE 6.1. ELECTRON MICROSCOPE IMAGE OF RAW SUGAR CRYSTALS. 162
FIGURE 6.2. IMAGE OF A FALLING SUGAR CRYSTAL. 165
FIGURE 6.3. DRAG COEFFICIENT OF A FALLING SUGAR CRYSTAL. 167
FIGURE 6.4. WIND TUNNEL APPARATUS USED BY WARDJIMAN *ET AL.* [68] 176
FIGURE 6.5. PARTICLE CURTAIN TRAJECTORIES FOR PARTICLE CURTAIN WITH INLET THICKNESS OF 2 CM, SOLID MASS FLOW RATE OF 0.040 KG/S, AND MEAN GAS VELOCITY OF 0.9 M/S (○ RUN 1, □ RUN 2, Δ RUN 3, ● CFD MODEL)[68] 178
FIGURE 6.6. PARTICLE CURTAIN TRAJECTORIES FOR PARTICLE CURTAIN WITH INLET THICKNESS OF 10 CM, SOLID MASS FLOW RATE OF 0.040 KG/S, AND MEAN GAS VELOCITY OF 0.9 M/S (○ RUN 1, □ RUN 2, Δ RUN 3, ● CFD MODEL)[68] 178
FIGURE 6.7. PARTICLE CURTAIN TRAJECTORIES FOR PARTICLE CURTAIN WITH INLET THICKNESS OF 2 CM, SOLID MASS FLOW RATE OF 0.040 KG/S, AND MEAN GAS VELOCITY OF 1.2 M/S (○ RUN 1, □ RUN 2, Δ RUN 3, ● CFD MODEL)[68] 179

FIGURE 6.8. PARTICLE CURTAIN TRAJECTORIES FOR PARTICLE CURTAIN WITH INLET THICKNESS OF 10 CM, SOLID MASS FLOW RATE OF 0.040 KG/S, AND MEAN GAS VELOCITY OF 1.2 M/S (○ RUN 1, □ RUN 2, Δ RUN 3, ● CFD MODEL)[68] 179

FIGURE 6.9. PARTICLE CURTAIN TRAJECTORIES FOR PARTICLE CURTAIN WITH INLET THICKNESS OF 5 CM, SOLID MASS FLOW RATE OF 0.047 KG/S, AND MEAN GAS VELOCITY OF 0.9 M/S (○ RUN 1, □ RUN 2, Δ RUN 3, ● CFD MODEL)[68] 180

FIGURE 6.10. GAS VELOCITY PROFILE AT THE TRAILING EDGE FOR PARTICLE CURTAIN WITH INLET THICKNESS OF 2 CM, SOLID MASS FLOW RATE OF 0.040 KG/S, AND MEAN GAS VELOCITY OF 0.9 M/S (○ MEASURED, — CFD MODEL)[68]. 181

FIGURE 6.11. GAS VELOCITY PROFILE AT THE TRAILING EDGE FOR PARTICLE CURTAIN WITH INLET THICKNESS OF 10 CM, SOLID MASS FLOW RATE OF 0.040 KG/S, AND MEAN GAS VELOCITY OF 0.9 M/S (○ MEASURED, — CFD MODEL)[68]. 181

FIGURE 6.12. GAS VELOCITY PROFILE AT THE TRAILING EDGE FOR PARTICLE CURTAIN WITH INLET THICKNESS OF 2 CM, SOLID MASS FLOW RATE OF 0.040 KG/S, AND MEAN GAS VELOCITY OF 1.2 M/S (○ MEASURED, — CFD MODEL)[68]. 182

FIGURE 6.13. GAS VELOCITY PROFILE AT THE TRAILING EDGE FOR PARTICLE CURTAIN WITH INLET THICKNESS OF 10 CM, SOLID MASS FLOW RATE OF 0.040 KG/S, AND MEAN GAS VELOCITY OF 1.2 M/S (○ MEASURED, — CFD MODEL)[68]. 182

FIGURE 6.14. GAS VELOCITY PROFILE AT THE TRAILING EDGE FOR PARTICLE CURTAIN WITH INLET THICKNESS OF 5 CM, SOLID MASS FLOW RATE OF 0.031 KG/S, AND MEAN GAS VELOCITY OF 0.9 M/S (○ MEASURED, — CFD MODEL)[68]. 183

FIGURE 6.15. GAS VELOCITY PROFILE AT THE TRAILING EDGE FOR PARTICLE CURTAIN WITH INLET THICKNESS OF 5 CM, SOLID MASS FLOW RATE OF 0.047 KG/S, AND MEAN GAS VELOCITY OF 0.9 M/S (○ MEASURED, — CFD MODEL)[68]. 183

FIGURE 6.16. SIMULATED GAS VELOCITY PROFILE ALONG THE CENTRELINE OF THE TUNNEL (SOLIDS INLET 10CM, 0.070 KG/S AND INLET GAS VELOCITY 1.2 M/S) WITH CURTAIN BOUNDARIES SHOWN. 184

FIGURE 6.17. CURTAIN STRUCTURE WITH INLET THICKNESS OF 2CM AND MASS FLOWRATES OF 0.040 KG/S (···· CFD, ○ RUN 1, □ RUN 2, Δ RUN 3) [70]. 185

FIGURE 6.18. CURTAIN STRUCTURE WITH INLET THICKNESS OF 8CM AND MASS FLOWRATES OF 0.040 KG/S (···· CFD, ○ RUN 1, □ RUN 2, Δ RUN 3)[70]. 185

FIGURE 6.19. SOLID CURTAIN PROFILES USING DIFFERENT MESHES 188

FIGURE 6.20. SOLIDS CURTAIN PROFILE AT DIFFERENT GAS VELOCITIES. 189

FIGURE 6.21. HORIZONTAL GAS VELOCITY COLOUR MAP AT 1 M ABOVE TUNNEL FLOOR (1 M/S INITIAL GAS VELOCITY, 0.5 M INLET, 5.18 KG/M.S SOLIDS FLOW RATE). UNITS ARE M/S. 190

FIGURE 6.22. HORIZONTAL GAS VELOCITY COLOUR MAP AT 1 M ABOVE TUNNEL FLOOR (2 M/S INITIAL GAS VELOCITY, 0.5 M INLET, 5.18 KG/M.S SOLIDS FLOW RATE). UNITS ARE M/S. 190

FIGURE 6.23. SOLIDS CURTAIN PROFILE AT DIFFERENT CURTAIN LENGTHS. 192

FIGURE 6.24. HORIZONTAL GAS VELOCITY COLOUR MAP AT 0.5 M ABOVE TUNNEL FLOOR (1 M/S INITIAL GAS VELOCITY, 0.1 M INLET, 5.18 KG/M.S SOLIDS FLOW RATE). UNITS ARE M/S. 192

FIGURE 6.25. SOLIDS CURTAIN PROFILE AT DIFFERENT MASS FLOW RATES. 193
FIGURE 6.26. SIMULATED CURTAIN DISPLACEMENT OVER 2 METRES AT DIFFERENT GAS VELOCITIES. ..194
FIGURE 6.27. SIMULATED CURTAIN DISPLACEMENT OVER 2 METRES AT DIFFERENT MASS FLOW RATES. 194
FIGURE 6.28. SOLIDS VOLUME FRACTION COLOUR MAP AT 0.25 M ABOVE TUNNEL FLOOR WITH 50 MM CURTAIN SPACING. 198
FIGURE 6.29. SOLIDS VOLUME FRACTION COLOUR MAP AT 0.25 M ABOVE TUNNEL FLOOR WITH 60 MM CURTAIN SPACING. 198
FIGURE 6.30. SOLIDS VOLUME FRACTION COLOUR MAP AT 0.25 M ABOVE TUNNEL FLOOR WITH 70 MM CURTAIN SPACING. 199
FIGURE 6.31. SOLIDS VOLUME FRACTION COLOUR MAP AT 0.25 M ABOVE TUNNEL FLOOR WITH 80 MM CURTAIN SPACING. 199
FIGURE 6.32. HORIZONTAL GAS VELOCITY COLOUR MAP AT 0.25 M ABOVE TUNNEL FLOOR WITH 50 MM CURTAIN SPACING. UNITS ARE M/S. 200
FIGURE 6.33. HORIZONTAL GAS VELOCITY COLOUR MAP AT 0.25 M ABOVE TUNNEL FLOOR WITH 60 MM CURTAIN SPACING. UNITS ARE M/S. 200
FIGURE 6.34. HORIZONTAL GAS VELOCITY COLOUR MAP AT 0.25 M ABOVE TUNNEL FLOOR WITH 70 MM CURTAIN SPACING. UNITS ARE M/S. 201
FIGURE 6.35. HORIZONTAL GAS VELOCITY COLOUR MAP AT 0.25 M ABOVE TUNNEL FLOOR WITH 80 MM CURTAIN SPACING. UNITS ARE M/S. 201
FIGURE 6.36. PLOT OF CURTAIN PROFILES FOR DIFFERENT CURTAIN SPACINGS. 202
FIGURE 7.1. EXPERIMENTAL TRACER DATA FROM INVICTA MILL DRYER NUMBER 2 (MONRO[10]) 204
FIGURE 7.2. PREDICTED RTD CURVES AT DIFFERENT VALUES OF N 210
FIGURE 7.3. ESTIMATED VALUES OF t_{kiln} AT DIFFERENT VALUES OF N 213
FIGURE 7.4. ESTIMATED VALUES OF C_B AT DIFFERENT VALUES OF N 214
FIGURE 7.5. ESTIMATED VALUES OF C_F^G AT DIFFERENT VALUES OF N 214
FIGURE 7.6. COMPARISON OF DIFFERENT MODEL STRUCTURES. 219
FIGURE 7.7. INTERNAL SOLIDS FLOWRATES VERSUS DYNAMIC ANGLE OF REPOSE 221
FIGURE 7.8. TOTAL PASSIVE HOLDUP VERSUS DRYER FEED RATE. 224

List of Tables

TABLE 2.1. RELATIONSHIP BETWEEN ANGLE OF REPOSE AND FLOW PROPERTIES (WOODCOCK AND MASON, 1987[1]). 7

TABLE 4.1. GEOMETRY OF THE INVICTA SUGAR MILL DRYER NUMBER 2. 71

TABLE 4.2. SUMMARY OF TRANSITION POINTS FOR INVICTA SUGAR MILL DRYER NUMBER 2. 71

TABLE 5.1. DIMENSIONS OF EXPERIMENTAL FLIGHTS. 94

TABLE 5.2. MEASURED SOLIDS PROPERTIES. 104

TABLE 5.3. MATERIAL PARTICLE SIZE DISTRIBUTION. 105

TABLE 5.4. LIST OF EXPERIMENTS AND CONDITIONS. 107

TABLE 5.5. MEASURED MATERIAL ANGLES OF REPOSE (EXPERIMENT NUMBERS CORRESPOND WITH TABLE 5.4). 128

TABLE 5.6. MEASURED PARTICLE VELOCITIES (EXPERIMENT NUMBERS CORRESPOND WITH TABLE 5.4). 156

TABLE 6.1. SINGLE CURTAIN SIMULATION CONDITIONS. 187

TABLE 6.2. MULTIPLE CURTAIN SIMULATION CONDITIONS. 197

TABLE 7.1. BULK DENSITIES OF RAW SUGAR. 207

TABLE 7.2. ESTIMATED PARAMETER VALUES. 209

TABLE 7.3. COMPARISON OF MOMENTS OF THE RTD. 211

TABLE 7.4. CALCULATED AVERAGE KILNING PHASE VELOCITY. 212

TABLE 7.5. DEPENDENCE OF PREDICTED SOLIDS FLOWRATES VALUES ON N. 215

TABLE 7.6. AFFECT OF SOLIDS DYNAMIC ANGLE OF REPOSE ON SOLIDS TRANSPORT MODEL. 220

TABLE 7.7. DRYER HOLDUP AT DIFFERENT DYNAMIC ANGLES OF REPOSE. 222

TABLE 7.8. RATIO OF ACTIVE TO PASSIVE MASSES FOR DIFFERENT DYNAMIC ANGLES OF REPOSE. 222

TABLE 7.9. PASSIVE HOLDUP AND KILNING FLOWRATE AT DIFFERENT DRYER FEED RATES. 223

TABLE 7.10. EFFECT OF INCREASING THE MODEL DESIGN LOAD ON HOLDUPS. 225

List of Equations

EQUATION 2.1. RELATIONSHIP FOR THE KINETIC ANGLE OF REPOSE[4] 8
EQUATION 2.2. CALCULATION OF THE MEAN RESIDENCE TIME. 8
EQUATION 2.3. CALCULATION OF THE MEAN RESIDENCE TIME FROM NORMALISED TRACER CONCENTRATIONS 9
EQUATION 2.4. MILLER, SMITH AND SCHUETTE EQUATION[18]. 14
EQUATION 2.5. FRIEDMAN AND MARSHALL EQUATION[11]. 15
EQUATION 2.6. ALTERNATE FORM OF THE FRIEDMAN AND MARSHALL EQUATION. 15
EQUATION 2.7. MODIFIED FRIEDMAN AND MARSHALL EQUATION[19]. 16
EQUATION 2.8. ALVAREZ AND SHENE EQUATION[20] 16
EQUATION 2.9. SCHOFIELD AND GLIKIN EQUATION[4] 17
EQUATION 2.10. MATCHETT AND BAKER MODEL[23]. 18
EQUATION 2.11. EXTENDED TANKS-IN-SERIES MODEL[28]. 22
EQUATION 2.12. FLIGHT DISCHARGE RATE BASED ON CROSS-SECTIONAL AREA OF SOLIDS[15]. 29
EQUATION 2.13. SCHILLER-NAUMANN EQUATION[44]. 32
EQUATION 2.14. VELOCITY CORRECTION FACTOR[27]. 32
EQUATION 3.1. GENERAL EQUATION FOR THE RATE OF SOLIDS TRANSPORT. 41
EQUATION 3.2. DEFINITION OF SOLIDS TRANSPORT INTO ACTIVE PHASE. 42
EQUATION 3.3. CALCULATION OF MASS AVERAGED FALL POINT. 44
EQUATION 3.4. AVERAGE RESIDENCE TIME OF FLIGHTED SOLIDS. 44
EQUATION 3.5. CALCULATION OF MASS AVERAGED FALL HEIGHT 45
EQUATION 3.6. CALCULATING MASS AVERAGED FALL TIME. 45
EQUATION 3.7. FORWARD AXIAL PARTITIONING COEFFICIENT WITH ZERO AIRFLOW. 45
EQUATION 3.8. DEFINITION OF FORWARD PARTITIONING COEFFICIENT 47
EQUATION 3.9. DEFINITION OF KILNING MASS 48
EQUATION 4.1. PERPENDICULAR FLIGHT BASE ANGLE. 60
EQUATION 4.2. PERPENDICULAR FLIGHT TIP ANGLE. 60
EQUATION 4.3. PERPENDICULAR FLIGHT BASE LENGTH 60
EQUATION 4.4. PERPENDICULAR FLIGHT TIP LENGTH. 60
EQUATION 4.5. CALCULATION OF THE ANGLE OF ROTATION BETWEEN TWO FLIGHTS. 62
EQUATION 4.6. CALCULATION OF THE FLIGHT TIP RADIUS. 62
EQUATION 4.7. CALCULATION OF FLIGHT TIP ANGLE. 62
EQUATION 4.8. MAXIMUM HOLDUP IN A FULL FLIGHT 64
EQUATION 4.9. CALCULATION OF THE FIRST TRANSITION POINT, ψ_1 65
EQUATION 4.10. CALCULATION OF THE SECOND TRANSITION POINT, ψ_2. 67
EQUATION 4.11. CALCULATION OF THE THIRD TRANSITION POINT, ψ_3. 68
EQUATION 4.12. CALCULATION OF THE FOURTH TRANSITION POINT, ψ_4. 69

EQUATION 4.13. CALCULATION OF THE FIFTH TRANSITION POINT, ψ_5 69
EQUATION 4.14. CALCULATION OF THE MAXIMUM FLIGHT HOLDUP BETWEEN ψ_1 AND ψ_2 73
EQUATION 4.15. CALCULATION OF THE MAXIMUM FLIGHT HOLDUP BETWEEN ψ_2 AND ψ_3 75
EQUATION 4.16. CALCULATION OF THE MAXIMUM FLIGHT HOLDUP BETWEEN ψ_3 AND ψ_4 76
EQUATION 4.17. CALCULATION OF THE MAXIMUM FLIGHT HOLDUP BETWEEN ψ_4 AND ψ_5 78
EQUATION 4.18. CALCULATION OF AVERAGE FLIGHT-TIP LENGTH. 79
EQUATION 4.19. PORTER'S ASSUMPTION[54]. 85
EQUATION 4.20. DETERMINING THE DESIGN LOAD OF A DRYER. 86
EQUATION 4.21. DESIGN LOAD OF A ROTARY DRYER. 86
EQUATION 4.22. CALCULATING FLIGHT LOADING FACTOR. 87
EQUATION 4.23. RELATIONSHIP BETWEEN FLIGHT AND DRYER LOADING FACTORS 88
EQUATION 4.24. CORRELATION FOR THE MASS-AVERAGED FALL HEIGHT $\left(R^2 = 0.997\right)$. 89
EQUATION 4.25. CORRELATION FOR THE MASS-AVERAGED FALL TIME $\left(R^2 = 0.996\right)$. 90
EQUATION 4.26. CORRELATION FOR THE MASS-AVERAGED FALL ANGLE. 90
EQUATION 4.27. CORRELATION FOR THE DRYER DESIGN LOAD $\left(R^2 = 0.999\right)$. 90
EQUATION 4.28. CORRELATION FOR THE FLIGHT LOADING FACTOR $\left(R^2 = 0.991\right)$ 90
EQUATION 5.1. LOCATING THE CENTRE OF MASS. 95
EQUATION 5.2. RELATIONSHIP FOR THE DYNAMIC ANGLE OF REPOSE (SCHOFIELD AND GLIKIN[4]) 101
EQUATION 5.3. CALCULATION OF PARTICLE DENSITY. 103
EQUATION 5.4. RELATING MASS FLOW RATE TO MOVING LAYER DIMENSIONS. 157
EQUATION 6.1. HAIDER AND LEVENSPIEL CORRELATION[56]. 162
EQUATION 6.2. FORCE BALANCE ON A FALLING PARTICLE. 163
EQUATION 6.3. CALCULATION OF DRAG FORCES BASED ON A DRAG COEFFICIENT. 163
EQUATION 6.4. EQUATION FOR DETERMINING THE DRAG COEFFICIENT. 164
EQUATION 6.5. GENERAL FORM OF DRAG COEFFICIENT CORRELATION. 164
EQUATION 6.6. MODIFIED SCHILLER-NAUMANN EQUATION. 167
EQUATION 6.7. RANS CONTINUITY EQUATION. 172
EQUATION 6.8. RANS MOMENTUM EQUATION. 172
EQUATION 6.9. EDDY VISCOSITY MODEL FOR REYNOLDS STRESSES. 173
EQUATION 6.10. MODIFIED RANS MOMENTUM EQUATION. 174
EQUATION 6.11. $k-\varepsilon$ MODEL FOR TURBULENCE VISCOSITY. 174
EQUATION 6.12. TURBULENCE KINETIC ENERGY EQUATION 174
EQUATION 6.13. TURBULENCE DISSIPATION RATE EQUATION. 174
EQUATION 6.14. TURBULENCE PRODUCTION DUE TO VISCOUS AND BUOYANT FORCES. 175
EQUATION 6.15. INTERPHASE MOMENTUM TRANSFER COEFFICIENT[67]. 175
EQUATION 7.1. CALCULATION OF EFFECTIVE FLIGHT TIP LENGTH. 207

EQUATION 7.2. RELATIONSHIP BETWEEN DYNAMIC ANGLE OF REPOSE AND SOLIDS MOISTURE CONTENT[72]. 208

EQUATION 7.3. ASSUMED MOISTURE CONTENT FUNCTION. 208

Nomenclature

A - Area (m^2)

C - Concentration (mol/L)

C_B - Backmixing Partitioning Coefficient

C_D - Drag Coefficient

C_F^G - Reduction in Forward Partitioning Coefficient due to Drag

C_F^0 - Forward Partitioning Coefficient with no Drag

C_R - Undisplaced Partitioning Coefficient

c - Curtain Thickness (m)

D - Diameter (m)

d_{load} - Dryer Loading Factor

d_p - Particle Diameter (m)

$\bar{d}^0$ - Average Forward Step of Material with no Gas Flow (m)

E - Normalised Concentration

F - Solids Flow Rate (kg/s)

F_D - Drag Force (N)

f_{load} - Flight Loading Factor

G - Gas Flow Rate (kg/s)

g - Acceleration due to Gravity (m/s^2)

H - Flight Holdup (kg)

h - Height (m)

k - Turbulence Kinetic Energy per unit Mass (m^2/s^2)

L - Length of Dryer (m)

M - Total Mass (kg)

m - Mass (kg)

N - Cell Number

N_F - Number of Flight in Dryer

R - Radius of Dryer (m)

R_F - Radius of a Flight Tip (m)

r - Solids Volume Fraction

Re - Reynolds Number

s - Slope of dryer (mm/m)

s_1 - Base Length of a Flight (m)

s_2 - Tip Length of a Flight (m)

t - Time (s)

$\overline{t}$ - Average Time (s)

U - Velocity (m/s)

$\forall$ - Volume (m^3)

v - Solids Velocity (m/s)

w - Solids Moisture content (kg/kg)

x - Length (m)

Greek Symbols

α_1 - Attachment Angle of a Flight to the Wall of the Dryer (degrees)

α_2 - Tip Angle of a Two-Section Flight (degrees)

β - Solids Partitioning Coefficient

ε - Turbulence Dissipation Rate (m^2/s^3)

θ - Inclination of Dryer (degrees)

μ - Kinetic Coefficient of Friction

ρ - Density (kg/m^3)

ρ_b - Bulk Density (kg/m^3)

ρ_p - Particle Density (kg/m^3)

τ - Mean Residence Time (s)

ϕ - Solids Angle of Repose (degrees)

ψ - Angle of Rotation (degrees)

ψ_{fl} - Angle of Rotation between Flights (degrees)

ψ_{ft} - Angle of Rotation Described by a Flight Tip (degrees)

ω - Angular Velocity (radians/sec)

Subscripts

a - Active Phase
des - Design Load Conditions
k - Kilning Phase
m - Mass Averaged
p - Passive Phase
s - Solids
t - Total

Abstract

This thesis presents the development and testing of a solids transport model for flighted rotary dryers based on the physical and geometric properties of the system. Particular emphasis was placed on understanding the internal flows and phenomena. An introduction to flighted rotary dryers is given in Chapter 1, where the context and relevance of this research is outlines. Chapter 2 gives a review of literature pertaining to the modelling and analysis of solids transport in flighted rotary dryers.

Chapter 3 discusses the development of the solids transport model based on the physical behaviour of a flighted rotary dryer. The solids transport model was developed based on numerical methods, dividing the dryer into a number of discrete slices, and each slice was further separated into two discrete phases. One phase selected to represent the material contain in the flights and in the bottom of the drum, whilst the other phase was selected to represent the solids falling through the moving gas stream. The flow of solids between phases was based on the physical movement of solids that occurs within an actual dryer. The magnitude of these flows was described using solid residence times and partitioning coefficients.

The solids transport phenomena occurring in the two phases were described using the geometry of the dryer and the physical properties of the solids. Chapter 4 presents a model for the unloading profile of a generic unserrated, straight, two-section flight, which was developed based on geometric analysis of the holdup within a flight. This unloading profile was then used to calculate the average fall path of a solid particle within a dryer, and thus the time spent within each phase of the dryer. Using measurements from CSR Invicta Mill's raw sugar dryer number 2, the average fall time of a particle was found to be in the order of 0.9 seconds, and the average time a particle spent in the flights to be in the order of 9 seconds. These residence times were then used to govern the flow of solids within the overall solids transport model, and the methodology describes a generic approach to modelling flighted rotary dryers.

A flight unloading apparatus was used to validate the geometric flight unloading model, the methods and results of which are presented in Chapter 5. The apparatus consisted of a 1m length of a full scale industrial dryer flight, which was rotated at a

controlled rate, and the rate at which material was discharged recorded. Tests were conducted using three different flight geometries and three different solid materials at rotational speeds between 1 and 8 rpm. It was found that the geometric unloading model accurately represents the experimental unloading profiles across the full range of conditions tested. High-speed photography was used to observe the solid material during unloading, and to measure factors such as the cascading curtain thickness, surface particle velocity and dynamic angle of repose. It was found that the dynamic angle of repose of the solids was dependent on the rotational velocity of the apparatus and showed significant variability. Surface velocities were found to be in the order of 1 m/s and surface thickness was found to be closely linked to the unloading rate of the flight. The data from these experiments was used in simulating interactions between gas and solids in the falling curtain in the following chapter.

Study of the high-speed photographs and unloading profiles revealed that the unloading of the flight was discontinuous, even though the materials used were generally regarded as free flowing. Observation of both the unloading profile and the high-speed images showed the flight unloading in pulses, with periods of high flow, and periods where less material was unloaded. This resulted in a varying material surface within the flight, which contributed to the high variability in measurements of surface properties. The effects of flight serrations and the methodology of modelling air drag in particulate curtains was also described.

Chapter 6 presents a study on using computational fluid dynamics (CFD) to simulate the gas-solids interactions within a falling curtain of solids. Experimental results from wind tunnel experiments conducted at Monash University, Melbourne, were used to verify and validate the CFD model. The simulated results showed good agreement with the experimental data for solids displacement and velocity. Data from the flight unloading experiments were then used to simulate the behaviour of the falling curtains of solids that occur within a rotary dryer. Simulations with a single curtain showed that gas-solids interactions were minimal for the conditions studied, with solids only being displaced in the first 10-20cm of the falling curtain. Simulation using multiple curtains in close proximity (50-80mm apart) showed that channelling of the gas flow between the curtains was significant (increases in gas velocity of up to 25% were observed), and resulted in greater displacement of the falling curtains. However, limits on computational requirements prevented further study of this phenomena.

Chapter 7 presents the validation of the solids transport model using experimental data from an industrial flighted rotary dryer. The geometric flight unloading model was integrated into the overall solids transport model for a rotary dryer, and experimental data from Invicta Sugar Mill's dryer number 2 was used to statistically determine the remaining model parameters to validate the model. For a model using 33 slices, the kilning phase residence time was estimated to be 7.7 seconds, with 54% of the falling solids undergoing backmixing. It was found that the solids transport model provided a good fit to the experimental data, however it was unable to match the extended tail of the experimental curve. It was found that the number of slices used in the model to represent the dryer had a minimal influence on the quality of the statistical fit to the experimental data. Due to the inability of the solids transport model to match the extended tail of the experimental RTD, alternative model structures were considered and studied. However, the alternative model structures considered showed similar or poorer fits to the experimental data, and techniques to enhance the fit are described.

Further study of the model predictions revealed an improbable amount of kilning material within the dryer, with less than 5% of the solids within the dryer present in the falling curtains of solids. This in turn resulted in large amount of solids undergoing kilning, resulting in kilning being the dominant mode of solids transport within the model. This is believed to be unrealistic, and emphasised the need to undertake further experimental research into kilning and holdup in flighted rotary dryers. Based on the observations made in this thesis, a number of recommendations are made for the further development of solids transport models for rotary dryers, and these are presented in Chapter 8.