

Contents

Preface	i
Abstract	iii
Contents	iii
Symbols	vii
1 Introduction	1
1.1 Spouted bed technology	1
1.1.1 General process description	1
1.1.2 Continuous operation	9
1.2 Numerical simulations	13
1.3 Objective and strategy	15
1.4 Outline of the thesis	16
2 Experimental methods	19
2.1 Introduction	19
2.2 Particle characterization	19
2.2.1 Particle size and size distribution	20
2.2.2 Apparent particle density	20
2.2.3 Envelope density	21
2.2.4 Restitution coefficient	22
2.2.5 Young's modulus	22
2.2.6 Friction coefficient	24
2.2.7 Minimum fluidization velocity	25
2.3 Spouted bed apparatuses	26
2.3.1 Laboratory spouted bed	27
2.3.2 Laboratory transparent replica	30
2.3.3 Pilot scale spouted bed	30
2.4 Residence time measurements	34
2.4.1 Tracer production	34
2.4.2 RTD experiments	35
2.4.3 Analysis of the RTD measurements	35
2.4.4 Residence time models	36
2.5 Analysis of coated particles	41

2.5.1	Optical coherence tomography (OCT)	41
2.5.2	Particle size analysis	43
2.5.3	Theoretical growth model	44
2.5.4	Light microscope	45
2.5.5	X-ray microtomography	45
3	Fundamentals of numerical simulations	47
3.1	Introduction	47
3.2	Particle properties	48
3.3	CFD-DEM coupling procedure	53
3.3.1	Coarse-graining approach	57
3.3.2	Simulation parameters	59
3.4	Liquid injection	60
3.5	Process quantification	62
3.5.1	Fourier transform	62
3.5.2	Circulation frequencies	63
3.6	Recurrence CFD (rCFD)	64
3.6.1	Recurrence analysis	64
3.6.2	Simulations with rCFD	65
4	Digital image analysis	67
4.1	Introduction	67
4.2	Particle tracking velocimetry (PTV)	67
4.2.1	Particle detection	68
4.2.2	Particle tracking	74
4.3	Quantification of coating quality	79
5	Characterization of laboratory spouted bed	85
5.1	Introduction	85
5.2	Experimental determination of spouting stability	85
5.2.1	Experiments with γ -Al ₂ O ₃ particles	86
5.2.2	Experiments with <i>Cellets</i> [®] 500 particles	91
5.3	Simulation conditions	96
5.3.1	Mesh independence	96
5.3.2	Turbulence model	100
5.3.3	Drag model	100
5.4	Validation	104
5.5	Insertion of draft plates	105
5.6	Binary system	110
6	Coating process	111
6.1	Introduction	111
6.2	Numerical investigations	111
6.2.1	Droplet injection	112
6.2.2	Circulation frequencies	114
6.2.3	Spray coating analysis with rCFD	117
6.3	Experimental analysis of coating quality	120
6.3.1	Digital image analysis	121

6.4	Experimental analysis of coating quantity	128
6.4.1	Optical coherence tomography	129
6.4.2	Theoretical growth model	131
6.4.3	Light microscope	132
6.4.4	X-ray microtomography	133
6.4.5	Particle size analysis	134
7	Continuous process in pilot scale spouted bed	137
7.1	Introduction	137
7.2	Tracer characterization	137
7.3	Residence time measurements	141
7.4	Back-mixing: qualitative description	148
7.5	Back-mixing: quantitative description	149
7.6	Conclusions	153
8	Conclusions	155
A	Specifications of used equipment	157
A.1	Components of laboratory <i>ProCell®</i> 5	157
A.2	Components of transparent replica	157
A.3	Components of pilot scale <i>ProCell®</i> 25	158
B	Behavior of the empty transparent replica	159
C	Liquid injection in CFD-DEM simulations	161
D	Algorithms used for PTV	163
	Bibliography	165
	Curriculum vitae	177