

Contents

1	Introduction	1
2	Preliminary comments on microbial biofilms	3
2.1	Biofilm basics	3
2.1.1	Constituents	4
2.1.2	Biofilm structure and heterogeneity	5
2.1.3	Biofilm development	6
2.2	Biofilms in nature, technosphere and medicine	7
2.2.1	The role of biofilms in natural ecosystems	7
2.2.2	Biofilms in industrial applications	8
2.2.3	Medical biofilms	10
2.3	Historical Aspects	12
2.4	Perceptions of biofilm systems	13
3	Methodology and modeling	15
3.1	Methodology	15
3.1.1	Systems, Emergence and Complexity	15
3.1.2	Iterative Method	16
3.2	Biofilm processes	19
3.2.1	Intrinsic processes	19
3.2.2	Exchange with the environment	25
3.2.3	Biofilm detachment	28
3.3	Biofilm models	31
3.3.1	Microscopic mass balance for solute compounds	31
3.3.2	Representation of particulate components	32
3.3.3	Finite Element Modeling	33
3.4	Model development and simulation	34
3.4.1	Aspects of model development	34
3.4.2	Data Analysis	34

4	Reactor development and operation	37
4.1	Flow in tube reactors	38
4.2	The Biofilm Tube Reactor (BTR)	41
4.2.1	Development of CLSM-segments	41
4.2.2	Operation of BTR in long-term biofilm cultivations	42
4.3	The Flow-through Biofilm Tube Reactor (FTBTR)	46
4.4	Evaluation of reactor setups in biofilm research	47
4.5	Concept of substrate solution composition	48
4.6	Characterization of inoculum	51
5	Biofilm development in model and experiment	53
5.1	Applicability of biofilm reactors for experimental validation	53
5.2	Model construction	55
5.2.1	Biofilm mesoscale structure	55
5.2.2	Processes and Parameters	57
5.3	Biofilm growth and activity	59
5.4	Biofilm detachment	61
5.5	EPS-Production	66
5.6	Structural development	69
6	Mechanics of biofilm detachment	73
6.1	Mechanical properties of biofilms	73
6.1.1	Shear strength of biofilms	74
6.1.2	Elastic Modulus of biofilm matrix	75
6.1.3	The role of multivalent ions in biofilm systems	77
6.2	An analytical model of fluid-structure interactions in biofilm systems	78
6.3	Finite Element Method (FEM) simulations	82
6.3.1	Comparison of analytical model and FEM simulation	82
6.3.2	Fluid-structure interactions in real biofilm structures	83
6.3.3	Stress induced detachment of biofilm structures	85
6.4	Mechanics as explanation for biofilm detachment?	88
7	Concluding remarks	91

Appendix	92
A Numerical solutions of biofilm growth models	93
A.1 One dimensional biofilm model	93
A.2 Multidimensional biofilm model	93
B Experimental methods	95
B.1 Confocal Laser Scanning Microscopy	95
B.2 Laser diffraction spectroscopy	95
B.3 Nanoindentation	96
C The Rotating Disc Reactor (RDR)	97
C.1 Flow field above rotating discs	97
C.2 Characterization and test of RDR system	98
D Analytical model of fluid-structure interactions in biofilm systems	101
List of Symbols	106
Bibliography	109
Zusammenfassung	131