

CONTENTS

Preface	v
Chapter I: Bioreactors	1
1.1 Scope	3
1.2 Process Considerations	4
1.3 Present State and Future Trends	8
1.4 The Objectives	10
Chapter II: Some Fundamentals	12
2.1 Gas-Liquid Mass Transfer	12
2.1.1 The mass transfer models	15
2.2 Gas-Liquid Hydrodynamics	21
2.2.1 Gas holdup	21
2.2.2 Liquid circulation	24
2.2.3 Dispersion in phases	27
2.3 Flow Properties of Fluids	29
Chapter III: Airlift Reactors: Current Technology	33
3.1 General Concepts	33
3.1.1 Classification	37
3.1.2 Bubble columns vs. the airlifts	40
3.2 Reactor Performance	42
3.2.1 Liquid circulation and mixing in airlift reactors	42
3.2.1.1 Gas velocity effects	45
3.2.1.2 Effects of reactor geometry and fluid properties	47
3.2.1.3 The mechanics of liquid circulation	53
3.2.1.4 Summary	57
3.2.2 Gas holdup and gas-liquid mass transfer	58
3.2.2.1 Sparger influences	63
3.2.2.2 Effects of reactor geometry and fluid properties	65
3.2.3 Gas-liquid interfacial area	80
3.2.4 Liquid phase axial dispersion coefficient	80
3.2.5 Heat transfer considerations	83
3.3 Summary	86
Chapter IV: Experimental Techniques of Investigation into Bioreactors	87
4.1 The Reactors: Scale and Configuration	87
4.1.1 The rectangular bubble column (BC1)	88
4.1.2 The rectangular airlift column (RAL)	92
4.1.3 The circular bubble column (BC2)	92

4.1.4 The split-cylinder airlift reactors	94
4.1.5 The external-loop airlift reactors (EL1, EL2)	97
4.1.6 The concentric draught-tube internal-loop airlift (CCT) device	99
4.2 The Flow Arrangement	101
4.3 Power Input into Pneumatic Devices	102
4.4 Simulation of Biofluids	103
4.5 The Rheological Methods	111
4.5.1 Coaxial cylinder viscometer	111
4.5.2 Impeller viscometry	112
4.6 Hydrodynamic Measurements	113
4.6.1 Flow visualizations	114
4.6.2 Gas holdup	114
4.6.3 Liquid circulation velocity	116
4.6.4 Dispersion coefficients	117
4.7 Gas-Liquid Mass Transfer Measurements	118
4.7.1 The steady state DO profiles	119
4.7.2 The overall volumetric mass transfer coefficient	119
4.7.2.1 The gas-phase composition	124
4.7.2.2 The mixing in the liquid	124
4.7.2.3 The influence of DO electrode dynamics	127
4.7.2.4 Other techniques for the measurement of overall volumetric mass transfer coefficient	128
Chapter V: Airlift Reactors: Advances in Hydrodynamics	132
5.1 Flow Visualization Studies	132
5.1.1 Gas sparger location in airlift reactors	133
5.1.2 Bulk fluid movement	137
5.1.2.1 The rectangular airlift (RAL)	137
5.1.2.2 The split-cylinder airlifts	144
5.1.3 Summary	149
5.2 Fractional Gas Holdup	149
5.2.1 The hydrodynamic basis of the gas holdup equations	151
5.2.1.1 Newtonian fluids	151
5.2.1.2 Non-Newtonian fluids	154
5.2.2 Gas holdup in pneumatic reactors	161
5.2.2.1 Bubble columns	161
5.2.2.2 Airlift reactors	181
5.2.3 Summary	202
5.3 Liquid Circulation in Airlift Reactors	203
5.3.1 Liquid circulation model	203
5.3.2 Liquid circulation velocity	206
5.3.3 Liquid circulation time	220
5.3.4 Summary	221
5.3.5 Liquid circulation in non-Newtonian media	221
5.3.5.1 Laminar flow	223
5.3.5.2 Turbulent flow	223
5.3.5.3 Prediction of liquid circulation velocity	225
5.3.5.4 Summary	229
Chapter VI: Airlift Reactors: Advances in Gas-Liquid Mass Transfer	230
6.1 Gas-Liquid Mass Transfer	230
6.1.1 Mass transfer and fluid mixing	231
6.1.2 Effects of the flow area shape	240
6.1.3 The mass transfer coefficient in slurries in split-cylinder reactors	247
6.1.3.1 Effect of the supplementary baffle gap	249

6.1.4 Effect of solids on gas-liquid mass transfer	251
6.1.4.1 Relationship between mass transfer coefficient and the bubble size	251
6.1.5 Summary	264
Chapter VII: Overall Design	266
7.1 Some Examples	266
7.2 Solving Difficult Design Problems	269
7.2.1 Gas holdup and liquid circulation	269
7.2.2 Gas-liquid mass transfer	271
Chapter VIII: Conclusions	273
8.1 Flow Visualizations	273
8.2 Liquid Circulation in Airlift Reactors	274
8.3 Gas Holdup	275
8.4 Gas-Liquid Mass Transport	277
8.5 Some Gray Areas	278
Appendix A: The Liquid Film Resistance at Cell-Liquid Interface	281
Appendix B: The Relationship Between Various Gas Holdups in Airlift Reactors	284
Appendix C: Interfacial Area and Gas Holdup	285
Appendix D: Contributions to the Power Input into Pneumatic Reactors	287
D.1 Isothermal Gas Expansion	287
D.2 The Kinetic Energy Term	290
Appendix E: The Tyler Standard Screen Scale	293
Appendix F: Manometric Determination of the Fractional Gas Holdup	294
F.1 The U-Tube Manometer	294
F.2 The Inverted U-Tube Manometer	296
Appendix G: The Mean Residence Time of the Gas in Dispersion	298
Appendix H: Energy Dissipation in the Circulation Loop	300
Appendix I: The Time Taken for 95% of the Possible Oxygen Mass Transfer to Take Place	302
Nomenclature	303
Roman Symbols	303
Greek Symbols	315

References	318
Author Index	335
Subject Index	339