

Contents

PREFACE	ix
1. Introduction	1
2. Regimes of flow	
2.1 Introduction	4
2.2 Flow regimes in vertical flow	5
2.3 Flow regimes in horizontal and inclined flow	6
2.4 Flow regime maps	7
2.5 Flow pattern transitions in vertical flow	11
2.5.1 The bubbly flow–slug flow transition	11
2.5.2 Flooding and flow reversal	13
2.5.3 The slug flow–churn flow transition	14
2.5.4 The churn flow–annular flow transition	16
2.5.5 Transition to wispy-annularflow	18
2.6 Regimes of flow in a boiling channel	18
3. Simple momentum and energy balances and their applications	
3.1 Introduction	21
3.2 Single-phase flow	21
3.2.1 Force (momentum) balance for single-phase flow	21
3.2.2 Single-phase energy balance	22
3.3 Two-phase flow	23
3.3.1 General momentum and energy balances for two-phase flow systems	23
3.3.2 Separated flow models	24
3.3.3 Separated annular flow with liquid entrainment	26
3.3.4 Experimental determination of individual components of pressure gradient	28
3.4 The homogeneous model	29
3.5 The Lockhart–Martinelli model	31
3.6 Pressure losses in expansions, contractions, orifices, bends and valves	36
3.6.1 Pressure change at a sharp expansion	36
3.6.2 Pressure change at a sudden contraction	39
3.6.3 Two-phase flow through orifices	40
3.6.4 Flow in bends, T's , valves, etc.	43
3.7 Critical two-phase flow	44
3.7.1 Overall models	45
3.7.2 Detailed examination of interface heat and mass transfer processes	48
4. Simple analytical models of annular two-phase flow and their applications	
4.1 Introduction	50
4.2 Single-phase flow	50
4.3 Application of single-phase flow concepts to the prediction of annular two-phase flow	55
4.3.1 Evaluation of interfacial shear stress	55
4.3.2 Shear stress distribution in the liquid film	57
4.3.3 Velocity profile and mass flowrate in laminar film flow in a vertical tube	59
4.3.4 Velocity profile and mass flowrate in turbulent film flow	60
4.4 Applications of the smooth film theories	63

4.4.1	Direct tests of the triangular interrelationship between liquid film flowrate, liquid film thickness and pressure gradient	63
4.4.2	Minimum pressure drop and zero wall shear stress	65
4.4.3	Flooding	68
4.4.4	Empirical correlation of flooding for liquids of low viscosity	72
4.4.5	Results and correlations for viscous liquids	72
4.5	Horizontal annular flow (liquid film distribution)	74
5.	Empirical relationships for annular flow	
5.1	Introduction	76
5.2	Empirical correlations inherently based on the triangular relationship	78
5.2.1	Simplified form of the triangular relationship in terms of friction factor	78
5.2.2	Empirical correlations relating pressure drop and void fraction	80
5.2.3	Comparison of empirical correlations with experimental data	81
5.3	Gas phase distribution and interfacial interaction	84
5.3.1	Gas flow distribution	84
5.3.2	Correlation between interfacial roughness and film thickness	88
6.	Interfacial waves	
6.1	Introduction	98
6.2	The Kelvin–Helmholtz instability	100
6.3	The critical layer	102
6.4	The effect of viscosity	107
6.5	An example of an interfacial stability calculation	110
6.6	Wave velocity	118
6.7	Experimental observations of the interface in annular or stratified flow	120
6.7.1	Vertical upward co-current annular flow	120
6.7.2	Vertical annular flow (co-current downwards)	123
6.7.3	Horizontal parallel flow	125
6.7.4	Horizontal annular flow	126
7.	Stability against de-wetting	
7.1	Introduction	127
7.2	The effects of flow on re-wetting	127
7.2.1	Wetting in annular flow	127
7.2.2	The stability of rivulet flow	130
7.3	Film breakdown under conditions of heat and mass transfer	132
7.4	The role of nucleate boiling and "sputtering" in the wetting of hot surfaces	133
7.5	Conclusion	135
8.	The creation and behaviour of entrained droplets in annular flow	
8.1	Introduction	136
8.2	Mechanisms of droplet entrainment	136
8.2.1	Wave entrainment	136
8.2.2	Entrainment by release of bubbles	139
8.3	Onset of droplet entrainment	141
8.3.1	Definition of the point of onset of entrainment	141
8.3.2	Experimental observations of the onset of droplet entrainment	142
8.3.3	Dimensional analysis of the onset of liquid entrainment	146
8.4	Observations and correlations of entrained fraction	148
8.4.1	Effect of liquid and gas flowrates on liquid entrainment	149
8.4.2	Correlation of entrained fraction	151
8.5	Distribution of entrained droplet flow	156
8.6	Droplet size and breakup	159
8.7	Droplet mass transfer	162
8.7.1	Introduction	162
8.7.2	Particle deposition: general	163
8.7.3	Measurements of droplet interchange rate in annular two-phase flow	165
8.7.4	Droplet mass transfer in the absence of reentrainment	169

9. Introduction to two-phase heat transfer	
9.1 Vapour–liquid equilibrium	173
9.2 Vapour generation and boiling	176
9.2.1 Bubble nucleation	176
9.2.2 Bubble growth and departure	179
9.2.3 Terminology used in the description of boiling	181
9.2.4 A general qualitative description of pool boiling	181
9.2.5 Forced convective boiling	183
9.3 Condensation	184
9.3.1 Droplet nucleation	184
9.3.2 Modes of condensation	184
10. Heat transfer in annular flow	
10.1 Introduction	186
10.2 Heat transfer through the liquid film	187
10.2.1 Heat transfer in the absence of nucleation	188
10.2.1.1 Laminar heat transfer: local coefficients	188
10.2.1.2 Turbulent heat transfer: local coefficients	192
10.2.1.3 Pressure gradient and interfacial shear stress in heat transfer systems	197
10.2.1.4 Empirical correlations	201
10.2.1.5 Integral heat transfer coefficients	202
10.2.1.6 Enhancement of heat transfer coefficients	205
10.2.2 Onset and suppression of nucleate boiling	206
10.2.3 Heat transfer in the presence of nucleation	208
10.3 Temperature difference across the interface in evaporation or condensation	210
10.4 Heat and mass transfer in the gas core	213
11. Burnout	
11.1 Introduction	219
11.2 Comparison of burnout in pool boiling and channel flow	221
11.3 Studies of mechanisms of burnout in annular flow	223
11.3.1 Visual studies	223
11.3.2 Liquid film flowrate measurement	225
11.3.3 The entrainment curve and its applications	227
11.3.4 Droplet deposition control	233
11.4 Parametric effects	238
11.5 Burnout correlations for water	244
11.5.1 Burnout correlations for water flow in vertical round tubes	244
11.5.2 Rectangular channels	248
11.5.3 Annuli and rod bundles	250
12. Experimental techniques for annular flow	
12.1 Introduction	253
12.2 The determination of flow pattern	253
12.2.1 Photographic methods	253
12.2.2 Pressure drop methods	256
12.2.3 Probe methods	258
12.3 Measurements of liquid film thickness	259
12.3.1 Film average methods	259
12.3.2 Localized methods	261
12.3.3 Point methods	264
12.4 Measurements of entrainment and droplet size	269
12.4.1 Measurement of total entrainment flow	269
12.4.2 Sampling and isokinetic probe studies	271
12.4.3 Droplet size measurement	272
12.5 Pressure drop measurement	274
NOMENCLATURE	277
REFERENCES	287
APPENDIX: S.I. unit conversion table for chemical engineering	301
INDEX	307