

Contents

Preface	IX
1 Introduction	1
2 Single-Phase Gas Flow	5
2.1 Euler equations for one-dimensional flow	5
2.2 Quasi-one-dimensional flow in ducts of variable cross section	9
2.3 Characteristic analysis of flow equations	11
2.4 Shock waves	18
2.5 Flow through convergent–divergent nozzles	21
2.6 Shock tube	26
2.7 Multidimensional flow conditions	28
References	34
3 Two-Fluid Model of Two-Phase Flow	35
3.1 Balance equations of two fluid model of two-phase flow	35
3.2 Single pressure two-fluid model	37
3.3 Remarks on interfacial transfer terms	40
References	42
4 Simplified Two-Phase Flow Models	45
4.1 Homogeneous equilibrium model	45
4.1.1 Two-component two-phase flow	48
4.1.2 One-component two-phase flow	52
4.2 Homogeneous nonequilibrium two-phase flow	59
4.3 Wallis model	65
References	72
5 A Hyperbolic Model for Two-Phase Flow	73
5.1 One-dimensional flow	73
5.1.1 Interfacial momentum coupling terms	74
5.1.2 Final form of conservation equations	79
5.1.3 Characteristic analysis – eigenvalues	80
5.1.4 Characteristic analysis – eigenvectors and splitting of coefficient matrix	85
5.1.5 Homogeneous flow conditions as a limiting case	89

5.1.6	Use of conservative variables	90
5.1.7	Quasi-one-dimensional flow through channels of variable cross section	93
5.2	Two-dimensional two-phase flow conditions	99
5.2.1	Basic flow equations for two-dimensional flow	99
5.2.2	Eigenvalues and split matrices	101
5.2.3	Conservative form of flow equations	103
5.3	Final remarks to the hyperbolic two-phase flow model	104
	References	105
6	Dispersion of Sound Waves	107
6.1	Acoustic approximation of flow equations	107
6.2	Dispersion analysis of gas–particle flows	108
	References	114
7	Numerical Methods for Hyperbolic Two-Phase Flow System Equations	115
7.1	Mathematical nature of two-phase flow equations	115
7.2	Overview on hyperbolic numerical methods	116
7.3	The Split Coefficient Matrix method	117
7.4	Godunov methods and Approximate Riemann solver	120
7.4.1	General Godunov approach	120
7.4.2	The linearized Riemann solver	122
7.4.3	The Roe solver	124
7.5	Flux Vector Splitting method	126
	References	128
8	Remarks on the Advanced Two-Phase Flow Module	131
8.1	Basic modeling approach	131
8.1.1	Balance equations of two-fluid model	131
8.1.2	Flow topology and interfacial area	133
8.1.3	Algebraic source terms	135
8.1.4	State properties	136
8.2	Numerical method	136
8.2.1	Conservative form of flow equations	136
8.2.2	Finite volume discretization	138
8.2.3	Second-order accuracy	139
8.2.4	Implicit time integration	140
	References	141
9	Numerical Results and Applications	143
9.1	Phase separation and void waves	143
9.1.1	Analytical model	143
9.1.2	Numerical results	145
9.2	U-tube oscillations	147
9.2.1	Analytical solution	148
9.2.2	Numerical results	148

9.3	Pressure wave propagation phenomena	149
9.3.1	Single-phase gas flow	150
9.3.2	Two-phase flow	151
9.4	Shock tube	157
9.4.1	Single-phase gas	157
9.4.2	Two-phase flow	160
9.5	Multidimensional wave propagation and explosion phenomena	163
9.5.1	Single-phase gas flow	163
9.5.2	Two-phase flow	168
9.6	Flow through convergent–divergent nozzles	177
9.6.1	The ASTAR nozzle	177
9.6.2	Deich nozzle tests	188
9.6.3	Moby–Dick nozzle tests	191
9.7	Blowdown phenomena	195
9.7.1	Edwards’ pipe blowdown	195
9.7.2	Canon experiment	199
9.7.3	Two-vessel test case	202
	References	208

10	Summary and Concluding Remarks	209
-----------	---------------------------------------	------------

Appendices

A	Basic Flow Equations for Two-Fluid Model of Two-Phase Flow	213
A.1	Flow topology	213
A.1.1	Phase distribution function	213
A.1.2	Interfacial properties	214
A.1.3	Transport equation for interfacial area	216
A.2	Single-phase flow equations	218
A.3	Two-phase balance equations	218
A.3.1	Balance equation for mass	218
A.3.2	Balance equation for momentum	220
A.3.3	Balance equation for energy	223
A.3.4	Summary of two-phase balance equations	229
B	Characteristic Analysis of Flow Equations: Vectors and Matrices	233
B.1	Single-phase gas flow, one-dimensional conditions	233
B.2	Single-phase gas flow, two-dimensional conditions	236
B.3	Homogeneous nonequilibrium two-phase flow	239
B.4	Wallis model	243
B.5	Hyperbolic two-phase flow model – one-dimensional conditions	245
B.6	Hyperbolic two-phase flow model – two-dimensional conditions	266

Index	271
--------------	------------