

Contents

Preface	vii
1. Introduction	1
1.1 Historical background.....	1
1.1.1 Forces exerted by a fluid and the equation of motion	2
1.1.2 Heat transfer.....	7
1.2 Terminology and nomenclature	9
1.2.1 Common terms and definitions	10
1.2.2 Nomenclature.....	11
1.2.2.1 Latin symbols.....	11
1.2.2.2 Greek symbols.....	12
1.2.2.3 Subscripts.....	13
1.2.2.4 Superscripts.....	13
1.2.3 Common abbreviations	14
1.2.4 Dimensionless numbers ($L_{ch}=2\alpha$).....	14
1.3 Examples of applications in science and technology	15
1.3.1 Oil and gas pipelines	16
1.3.2 Geothermal wells	17
1.3.3 Steam generation in boilers and burners	18
1.3.4 Sediment flow	18
1.3.5 Steam condensation.....	19
1.3.6 Petroleum refining.....	20
1.3.7 Spray drying.....	20
1.3.8 Pneumatic conveying	21
1.3.9 Fluidized beds	22
2. Fundamental equations and characteristics of particles, bubbles and drops	23
2.1 Fundamental equations of a continuum	23
2.1.1 The concept of a material continuum - basic assumptions	24
2.1.2 Fundamental equations in integral form.....	27

2.1.3	Fundamental equations in differential form	33
2.1.4	Generalized form of the fundamental equations.....	36
2.1.5	Conservation equations at the interfaces - jump conditions	37
2.2	Conservation equations for a single particle, bubble or drop	41
2.3	Characteristics of particles, bubbles and drops	43
2.3.1	Shapes of solid particles.....	44
2.3.1.1	Symmetric particles.....	44
2.3.1.2	Asymmetric or irregular particles.....	45
2.3.2	Shapes of bubbles and drops in motion - shape maps	48
2.4	Discrete and continuous size distributions.....	53
2.4.1	Useful parameters in discrete size distributions	54
2.4.2	Continuous size distributions	57
2.4.3	Drop distribution functions	59
3.	Low Reynolds number flows.....	63
3.1	Conservation equations.....	63
3.1.1	Heat-mass transfer analogy	65
3.1.2	Mass, momentum and heat transfer - Transport coefficients.....	66
3.2	Steady motion and heat/mass transfer at creeping flow	69
3.3	Transient, creeping flow motion	74
3.3.1	Notes on the history term	76
3.3.2	Hydrodynamic force on a viscous sphere.....	80
3.3.3	Equation of motion with interfacial slip.....	81
3.3.4	Transient motion of an expanding or collapsing bubble.....	84
3.4	Transient heat/mass transfer at creeping flow.....	85
3.5	Hydrodynamic force and heat transfer for a spheroid at creeping flow	89
3.6	Steady motion and heat/mass transfer at small Re and Pe	93
3.7	Transient hydrodynamic force at small Re	96
3.8	Transient heat/mass transfer at small Pe	102
4.	High Reynolds number flows	107
4.1	Flow fields around rigid and fluid spheres.....	107
4.1.1	Flow around rigid spheres.....	107
4.1.2	Flow inside and around viscous spheres	114
4.2	Steady hydrodynamic force and heat transfer	118
4.2.1	Drag on rigid spheres	118
4.2.2	Heat transfer from rigid spheres.....	121
4.2.3	Radiation effects	122
4.2.4	Drag on viscous spheres.....	124
4.2.5	Heat transfer from viscous spheres	128
4.2.6	Drag on viscous spheres with mass transfer - Blowing effects	133

4.2.7	Heat transfer from viscous spheres with mass transfer – Blowing effects.....	136
4.2.8	Effects of compressibility and rarefaction.....	141
4.3	Transient hydrodynamic force	144
4.4	Transient heat transfer	151
4.4.1	Transient temperature measurements.....	155
5.	Non-spherical particles, bubbles and drops	157
5.1	Transport coefficients of rigid particles at low Re.....	157
5.1.1	Hydrodynamic force and drag coefficients	158
5.1.2	Heat and mass transfer coefficients.....	161
5.2	Hydrodynamic force for rigid particles at high Re	165
5.2.1	Drag coefficients for disks and spheroids	165
5.2.2	Drag coefficients and flow patterns around cylinders	168
5.2.3	Drag coefficients of irregular particles.....	172
5.3	Heat transfer for rigid particles at high Re.....	175
5.3.1	Heat transfer coefficients for disks and spheroids.....	175
5.3.2	Heat transfer coefficients for cylinders	177
5.3.3	Heat transfer coefficients for irregular particles.....	179
5.4	Non-spherical bubbles and drops.....	181
5.4.1	Drag coefficients	181
5.4.2	Heat transfer coefficients	190
6.	Effects of rotation, shear and boundaries.....	191
6.1	Effects of relative rotation	192
6.2	Effects of flow shear.....	195
6.3	Effects of boundaries	202
6.3.1	Main flow perpendicular to the boundary	203
6.3.2	Main flow parallel to the boundary	205
6.3.3	Equilibrium positions of spheres above horizontal boundaries.....	211
6.4	Constrained motion in an enclosure.....	213
6.4.1	Rigid spheres.....	213
6.4.2	Viscous spheres.....	217
6.4.3	Immersed objects at off-center positions.....	218
6.4.4	Taylor bubbles	219
6.4.5	Effects of enclosures on the heat and mass transfer	221
6.5	Effects of boundaries on bubble and drop deformation	222
6.6	A note on the lift force in transient flows	225
7.	Effects of turbulence	227
7.1	Effects of free stream turbulence	227
7.2	Turbulence modulation.....	232

7.3	Drag reduction	238
7.4	Turbulence models for immersed objects	242
7.4.1	The trajectory model	242
7.4.2	The Monte-Carlo method	243
7.4.3	The two-fluid model	251
7.5	Heat transfer in pipelines with particulates	254
7.6	Turbophoresis and wall deposition	256
7.7	Turbulence and coalescence of viscous spheres	260
8.	Electro-kinetic, thermo-kinetic and porosity effects	261
8.1	Electrophoresis	261
8.1.1	Electrophoretic motion	262
8.1.2	Electro-osmosis	264
8.1.3	Effects of the double layer on the electrophoretic motion	265
8.1.4	Electrophoresis in capillaries-microelectrophoresis	268
8.2	Brownian motion	270
8.3	Thermophoresis	272
8.3.1	Particle interactions and wall effects in thermophoresis	278
8.3.2	Thermophoresis in turbulent flows	280
8.4	Porous particles	282
8.4.1	Surface boundary conditions	283
8.4.2	Drag force on a porous sphere at low Re	284
8.4.3	Heat transfer from porous particles	285
8.4.4	Mass transfer from an object inside a porous medium	286
9.	Effects of higher concentration and collisions	289
9.1	Interactions between dispersed objects	289
9.1.1	Hydrodynamic interactions	290
9.1.2	Thermal interactions and phase change	296
9.2	Effects of concentration	297
9.2.1	Effects on the hydrodynamic force	298
9.2.2	Effects on the heat transfer	306
9.2.3	Bubble columns	307
9.3	Collisions of spheres	307
9.3.1	Hard sphere model	308
9.3.2	Soft-sphere model	311
9.3.3	Drop collisions and coalescence	312
9.4	Collisions with a wall – Mechanical effects	316
9.5	Heat transfer during wall collisions	318
9.5.1	Spray deposition	319
9.5.2	Cooling enhancement by drop impingement	322
9.5.3	Critical heat flux with drops	323

10. Molecular and statistical modeling	325
10.1 Molecular dynamics.....	325
10.1.1 MD applications with particles, bubbles and drops.....	331
10.2 Stokesian dynamics	333
10.3 Statistical methods	337
10.3.1 The probability distribution function (PDF).....	338
11. Numerical methods-CFD	343
11.1 Forms of Navier-Stokes equations used in CFD.....	345
11.1.1 Primitive variables	345
11.1.2 Streamfunction-vorticity	346
11.1.3 False transients.....	347
11.2 Finite difference method.....	348
11.3 Spectral and finite-element methods.....	350
11.3.1 The spectral method.....	350
11.3.2 The finite element and finite volume methods	351
11.4 The Lattice-Boltzmann method	354
11.5 The force coupling method	359
11.6 Turbulent flow models.....	360
11.6.1 Direct numerical simulations (DNS).....	360
11.6.2 Reynolds decomposition and averaged equations	364
11.6.3 The k- ϵ model	365
11.6.4 Large Eddy simulations (LES).....	367
11.7 Potential flow-boundary integral method	370
References	373
Subject Index	407