

# Contents

Nomenclature . . . . .	xiii
<b>Part I Momentum Transfer In Single-Phase Flows</b>	
<b>1 Basic Properties of Fluid Flow . . . . .</b>	<b>3</b>
1.1 Introduction . . . . .	3
1.2 Fluid Definition and Some Properties . . . . .	4
1.2.1 Definition of a Fluid . . . . .	4
1.2.2 Density . . . . .	5
1.2.3 Pressure . . . . .	5
1.2.4 Temperature . . . . .	11
1.3 Compressibility . . . . .	11
1.3.1 Bulk Modulus of Elasticity, $K$ . . . . .	11
1.3.2 Speed of Sound . . . . .	12
1.3.3 Mach Number . . . . .	12
1.4 Newton's Law of Viscosity . . . . .	12
1.4.1 Dynamic Viscosity . . . . .	12
1.4.2 Newtonian and Non-Newtonian Fluid . . . . .	13
1.5 Surface Energy . . . . .	15
1.5.1 Surface Tension and Contact Angle . . . . .	15
1.5.2 Capillary Force . . . . .	15
References . . . . .	16
<b>2 Momentum Transfer . . . . .</b>	<b>17</b>
2.1 Conservation Laws . . . . .	17
2.1.1 Equation of Continuity . . . . .	17
2.1.2 Navier–Stoke's Equation . . . . .	22
2.2 Inviscid Flow and Bernoulli Equation . . . . .	25

2.3	Flow Regime . . . . .	28
2.3.1	Laminar–Turbulent Transition . . . . .	28
2.3.2	Reverse Transition . . . . .	30
2.3.3	Instantaneous Velocity . . . . .	30
2.4	Flow in a Pipe . . . . .	30
2.4.1	Flow Development . . . . .	30
2.4.2	Velocity Distribution . . . . .	32
2.4.3	Pressure Drop . . . . .	34
2.4.4	Friction Coefficient, $\lambda$ . . . . .	35
2.4.5	Hydraulic Diameter, $D_h$ . . . . .	39
2.4.6	Pipe Elements and Loss Coefficient, $\zeta$ . . . . .	42
2.5	Boundary Layer Flow on a Flat Plate . . . . .	49
2.5.1	Laminar Flow . . . . .	49
2.5.2	Turbulent Flow . . . . .	51
2.5.3	Transition Flow . . . . .	51
2.6	Flow Around a Solid Body . . . . .	53
2.6.1	Flow Around a Sphere . . . . .	53
2.6.2	Flow Around a Circular Cylinder . . . . .	54
2.6.3	Pressure Drag and Drag Coefficient . . . . .	54
2.6.4	Karman’s Vortex Street . . . . .	58
2.7	Dimensional Analysis . . . . .	59
2.7.1	Lord Rayleigh Method . . . . .	59
2.7.2	Buckingham II Theorem . . . . .	62
2.7.3	Physical Meaning of Dimensionless Numbers . . . . .	66
	References . . . . .	69
<b>3</b>	<b>Special Topics in Fluid Mechanics</b> . . . . .	<b>71</b>
3.1	Rheology . . . . .	71
3.1.1	Definition of Rheology . . . . .	71
3.1.2	Classification of Non-Newtonian Fluids . . . . .	72
3.1.3	Apparent Dynamic Viscosity, $\mu_{app}$ . . . . .	73
3.2	Flow in Porous Media . . . . .	75
3.2.1	Packed Bed or Packed Column . . . . .	75
3.2.2	Pressure Drop in a Packed Bed with Spherical Particles . . . . .	76
3.2.3	Ergun Equation . . . . .	77
3.2.4	Pressure Drop in Packed Bed with Nonspherical Particles . . . . .	77
3.3	Microscale and Nanoscale Fluid Mechanics . . . . .	78
3.3.1	Flow in Micro Reactor . . . . .	79
3.3.2	Fluid Flow Characteristics in Micro Reactor . . . . .	79
3.4	Surface Forces . . . . .	80
3.4.1	Role of Surface Tension Force . . . . .	80
3.4.2	Flow Control in Micro Reactors . . . . .	81
3.4.3	Applications . . . . .	84
	References . . . . .	85

**Part II Single-Phase Heat Transfer**

<b>4 Basic Principles of Heat Transfer</b> . . . . .	89
4.1 Introduction . . . . .	89
4.1.1 Conduction . . . . .	89
4.1.2 Convection . . . . .	90
4.1.3 Radiation . . . . .	90
4.2 Conduction . . . . .	90
4.3 Convection . . . . .	92
4.4 Radiation . . . . .	92
4.5 Hydrodynamic Boundary Layer and Thermal Boundary Layer . . . . .	92
4.6 Relevant Dimensionless Numbers . . . . .	93
References . . . . .	94
<b>5 One-Dimensional Heat Conduction</b> . . . . .	95
5.1 Fourier’s Law . . . . .	95
5.2 Heat-Transfer Coefficient . . . . .	96
5.3 Heat Transfer Through Multiple Plates . . . . .	98
5.3.1 Steady-State Conduction . . . . .	98
5.3.2 Combined Convection and Conduction . . . . .	99
5.4 Conduction Through a Long Hollow Cylinder . . . . .	99
5.4.1 Steady-State Conduction . . . . .	99
5.4.2 Combined Conduction and Convection . . . . .	102
5.5 Heat Transfer Through Composite Hollow Cylinder . . . . .	102
5.5.1 Steady-State Conduction . . . . .	102
5.5.2 Combined Convection and Conduction . . . . .	104
<b>6 Convection Heat Transfer</b> . . . . .	105
6.1 Convection from Sphere and Circular Cylinder . . . . .	105
6.1.1 Natural Convection . . . . .	105
6.1.2 Forced Convection . . . . .	110
6.2 Convection from Flat Plate . . . . .	113
6.2.1 Natural Convection from Vertical Flat Plate . . . . .	113
6.2.2 Forced Convection from Vertical Flat Plate . . . . .	114
6.2.3 Forced Convection from Horizontal Flat Plate . . . . .	114
6.3 Phase Transformation . . . . .	117
6.3.1 Solidification and Melting . . . . .	117
6.3.2 Boiling Heat Transfer . . . . .	117
References . . . . .	121
<b>7 Radiation Heat Transfer</b> . . . . .	123
7.1 Basic Definitions . . . . .	123
7.2 Stefan–Boltzmann Law . . . . .	123
7.3 Gray Body Radiation . . . . .	125
7.4 Radiation Between Two Black Bodies . . . . .	125

7.5	Radiation Between Two Surfaces . . . . .	126
7.5.1	Shape Factor . . . . .	126
7.5.2	Radiation Heat Transfer Between Two Gray Flat Plates with No Medium Between Them . . . . .	127
7.5.3	Radiation Heat Transfer Between Two Infinite Parallel Planes . . . . .	128
7.5.4	Radiation Heat Transfer Between Two Concentric Long Coaxial Cylinders . . . . .	130
7.5.5	Radiation Heat Transfer Between Two Concentric Spherical Surfaces . . . . .	131
7.6	Relevant Dimensionless Parameters in Heat Transfer . . . . .	131
7.6.1	Grashof Number . . . . .	131
7.6.2	Nusselt Number . . . . .	132
7.6.3	Peclet Number . . . . .	132
7.6.4	Prandtl Number . . . . .	132
7.6.5	Rayleigh Number . . . . .	132

### Part III Mass Transfer

<b>8</b>	<b>Diffusion and Mass Transfer . . . . .</b>	<b>135</b>
8.1	Introduction . . . . .	135
8.2	Formulating Diffusion in Homogeneous Media . . . . .	136
8.3	Diffusion in Porous Media . . . . .	137
8.4	Mass Transfer with Chemical Reaction . . . . .	139
8.4.1	Mass Diffusion . . . . .	140
8.4.2	Chemical Reaction Model . . . . .	141
8.5	Boundary Conditions for Mass Transfer . . . . .	142
	References . . . . .	147

### Part IV Multiphase Flow

<b>9</b>	<b>Gas-Liquid Two-Phase Flow . . . . .</b>	<b>151</b>
9.1	Introduction . . . . .	151
9.2	Fluid Mechanics . . . . .	152
9.2.1	Basic Parameters . . . . .	152
9.2.2	Speed of Sound in a Mixture of Gas and Liquid . . . . .	157
9.3	Dynamical Models . . . . .	157
9.3.1	Mixture Model . . . . .	158
9.3.2	Two-Fluid Model . . . . .	158
9.4	Characteristics of Flow in Bottom-Blown Bath . . . . .	158
9.4.1	Bubble Characteristics . . . . .	158
9.4.2	Liquid Flow Characteristics: Velocity Distribution in Bottom-Blown Bath . . . . .	177
9.4.3	Measurement of Flow Phenomena . . . . .	181

9.5	Heat and Mass Transfer . . . . .	187
9.5.1	Heat Transfer from Sphere Immersed in Bubbling Jet . . . . .	187
9.5.2	Mass Transfer from Solid Body Immersed in Bottom-Blown Bath . . . . .	188
9.6	Dimensionless Parameters . . . . .	191
9.7	Concluding Remarks . . . . .	194
	References . . . . .	194
<b>10</b>	<b>Flows Involving Solid Phase . . . . .</b>	<b>197</b>
10.1	Introduction . . . . .	197
10.2	Dynamics of Solid Particles in Two-Phase Systems . . . . .	198
10.2.1	Shape and Size of Particle . . . . .	198
10.2.2	Mixing Ratio and Concentration . . . . .	198
10.2.3	Flow Pattern of Solid–Gas Two-Phase Flows . . . . .	199
10.2.4	Solid–Liquid Two-Phase Flow . . . . .	203
10.2.5	Liquid–Liquid Two-Component One-Phase Flow . . . . .	203
10.2.6	Gas–Liquid–Liquid Two-Phase Flow . . . . .	203
10.2.7	Solid–Liquid Two-Phase Flow (Slurry) . . . . .	203
10.2.8	Gas–Liquid–Solid Three-Phase Flow . . . . .	204
10.3	Experimental Techniques . . . . .	204
10.3.1	Shape, Size, Number, and Moving Velocity of a Solid Particle . . . . .	204
10.3.2	Coulter Counter . . . . .	206
10.3.3	Sheath Flow Method . . . . .	207
10.3.4	Ultrasonic Sensor . . . . .	207
10.3.5	In Situ (Direct) Measurement Technique . . . . .	207
10.4	Concluding Remarks . . . . .	211
	References . . . . .	212
<b>11</b>	<b>Multiphase Flow in Microscale Systems . . . . .</b>	<b>215</b>
11.1	Introduction . . . . .	215
11.2	Basic Characteristics of Gas–Liquid Two-Phase Flow in Micro Channel . . . . .	216
11.2.1	Flow Pattern in Horizontal Circular Micro Channels . . . . .	216
11.2.2	Flow Pattern in Horizontal Rectangular Micro Channels . . . . .	216
11.2.3	Flow Pattern in Horizontal Channels with Arbitrary Cross Section . . . . .	216
11.2.4	Pressure Drop . . . . .	218
11.3	Effect of Pipe Wettability on Gas–Liquid Flow in Micro Channel . . . . .	218
11.3.1	Equilibrium Contact Angle, $\theta_c$ . . . . .	218
11.3.2	Dynamic Wettability: The Advancing and Receding Contact Angles . . . . .	220

11.4	Gas–Liquid Flow Through Abrupt Expansion in Micro Channel . . . . .	220
11.5	Gas–Liquid Flow Through Orifice in Micro Channel . . . . .	221
11.6	Examples of Microscale Devices . . . . .	222
11.6.1	Microfluidics . . . . .	222
11.6.2	Fuel Cells . . . . .	222
11.6.3	Lab-on-a-Chip . . . . .	223
11.6.4	Cooling System for Electronic Devices Such as Personal Computers . . . . .	223
11.6.5	Microelectromechanical Systems (MEMS) . . . . .	223
11.6.6	Generation of Micro- and Nanoparticles . . . . .	223
11.7	Concluding Remarks . . . . .	224
	References . . . . .	224
	<b>Problems and Answers . . . . .</b>	<b>227</b>
	<b>Index . . . . .</b>	<b>257</b>