

Contents

1. Concepts and Definitions	1
1.1 Fluids and the Continuum	1
1.2 Properties at a Point	2
1.3 Point-to-Point Variation of Properties in a Fluid	5
1.4 Units	8
2. Fluid Statics	12
2.1 Pressure Variation in a Static Fluid	12
2.2 Uniform Rectilinear Acceleration	15
2.3 Forces on Submerged Surfaces	16
2.4 Buoyancy	19
2.5 Closure	21
3. Description of a Fluid in Motion	27
3.1 Fundamental Physical Laws	27
3.2 Fluid Flow Fields: Lagrangian and Eulerian Representations	27
3.3 Steady and Unsteady Flows	28
3.4 Streamlines	29
3.5 Systems and Control Volumes	30
4. Conservation of Mass: Control-Volume Approach	32
4.1 Integral Relation	32
4.2 Specific Forms of the Integral Expression	33
4.3 Closure	37
5. Newton's Second Law of Motion: Control-Volume Approach	44
5.1 Integral Relation for Linear Momentum	44
5.2 Applications of the Integral Expression for Linear Momentum	47
5.3 Integral Relation for Moment of Momentum	53
5.4 Applications to Pumps and Turbines	55
5.5 Closure	59
6. Conservation of Energy: Control-Volume Approach	68
6.1 Integral Relation for the Conservation of Energy	68
6.2 Applications of the Integral Expression	74
6.3 The Bernoulli Equation	77
6.4 Closure	81

7. Shear Stress in Laminar Flow 89

-
- | | | |
|-----|---|----|
| 7.1 | Newton's Viscosity Relation | 89 |
| 7.2 | Non-Newtonian Fluids | 90 |
| 7.3 | Viscosity | 91 |
| 7.4 | Shear Stress in Multidimensional Laminar Flows of a Newtonian Fluid | 96 |
| 7.5 | Closure | 98 |

8. Analysis of a Differential Fluid Element in Laminar Flow 101

-
- | | | |
|-----|--|-----|
| 8.1 | Fully Developed Laminar Flow in a Circular Conduit of Constant Cross Section | 101 |
| 8.2 | Laminar Flow of a Newtonian Fluid Down an Inclined-Plane Surface | 104 |
| 8.3 | Closure | 106 |

9. Differential Equations of Fluid Flow 109

-
- | | | |
|-----|--------------------------------------|-----|
| 9.1 | The Differential Continuity Equation | 109 |
| 9.2 | Navier-Stokes Equations | 112 |
| 9.3 | Bernoulli's Equation | 120 |
| 9.4 | Closure | 121 |

10. Inviscid Fluid Flow 124

-
- | | | |
|------|--|-----|
| 10.1 | Fluid Rotation at a Point | 124 |
| 10.2 | The Stream Function | 125 |
| 10.3 | Inviscid, Irrotational Flow about an Infinite Cylinder | 127 |
| 10.4 | Irrotational Flow, the Velocity Potential | 128 |
| 10.5 | Total Heat in Irrotational Flow | 129 |
| 10.6 | Utilization of Potential Flow | 130 |
| 10.7 | Potential Flow Analysis—Simple Plane Flow Cases | 131 |
| 10.8 | Potential Flow Analysis—Superposition | 132 |
| 10.9 | Closure | 134 |

11. Dimensional Analysis 137

-
- | | | |
|------|--|-----|
| 11.1 | Dimensions | 137 |
| 11.2 | Geometric and Kinematic Similarity | 138 |
| 11.3 | Dimensional Analysis of the Navier-Stokes Equation | 138 |
| 11.4 | The Buckingham Method | 140 |
| 11.5 | Model Theory | 142 |
| 11.6 | Closure | 144 |

12. Viscous Flow 149

-
- | | | |
|------|--|-----|
| 12.1 | Reynolds' Experiment | 149 |
| 12.2 | Drag | 150 |
| 12.3 | The Boundary-Layer Concept | 153 |
| 12.4 | The Boundary-Layer Equations | 155 |
| 12.5 | Blasius' Solution for the Laminar Boundary Layer on a Flat Plate | 156 |
| 12.6 | Flow with a Pressure Gradient | 160 |

12.7	von Kármán Momentum Integral Analysis	162
12.8	Closure	166
13.	The Effect of Turbulence on Momentum Transfer	170
13.1	Description of Turbulence	170
13.2	Turbulent Shearing Stresses	171
13.3	The Mixing-Length Hypothesis	173
13.4	Velocity Distribution from the Mixing-Length Theory	174
13.5	The Universal Velocity Distribution	176
13.6	Further Empirical Relations for Turbulent Flow	177
13.7	The Turbulent Boundary Layer on a Flat Plate	178
13.8	Factors Affecting the Transition from Laminar to Turbulent Flow	180
13.9	Closure	180
14.	Flow in Closed Conduits	183
14.1	Dimensional Analysis of Conduit Flow	183
14.2	Friction Factors for Fully Developed Laminar, Turbulent, and Transition Flow in Circular Conduits	185
14.3	Friction Factor and Head-Loss Determination for Pipe Flow	188
14.4	Pipe-Flow Analysis	191
14.5	Friction Factors for Flow in the Entrance to a Circular Conduit	195
14.6	Closure	198
15.	Fundamentals of Heat Transfer	201
15.1	Conduction	201
15.2	Thermal Conductivity	202
15.3	Convection	208
15.4	Radiation	209
15.5	Combined Mechanisms of Heat Transfer	209
15.6	Closure	214
16.	Differential Equations of Heat Transfer	219
16.1	The General Differential Equation for Energy Transfer	219
16.2	Special Forms of the Differential Energy Equation	222
16.3	Commonly Encountered Boundary Conditions	223
16.4	Closure	224
17.	Steady-State Conduction	226
17.1	One-Dimensional Conduction	226
17.2	One-Dimensional Conduction with Internal Generation of Energy	233
17.3	Heat Transfer from Extended Surfaces	236
17.4	Two- and Three-Dimensional Systems	243
17.5	Closure	255
18.	Unsteady-State Conduction	263
18.1	Analytical Solutions	263
18.2	Temperature-Time Charts for Simple Geometric Shapes	272
18.3	Numerical Methods for Transient Conduction Analysis	275

18.4	An Integral Method for One-Dimensional Unsteady Conduction	278
18.5	Closure	283
19.	Convective Heat Transfer	288
19.1	Fundamental Considerations in Convective Heat Transfer	288
19.2	Significant Parameters in Convective Heat Transfer	289
19.3	Dimensional Analysis of Convective Energy Transfer	290
19.4	Exact Analysis of the Laminar Boundary Layer	293
19.5	Approximate Integral Analysis of the Thermal Boundary Layer	297
19.6	Energy- and Momentum-Transfer Analogies	299
19.7	Turbulent Flow Considerations	301
19.8	Closure	307
20.	Convective Heat-Transfer Correlations	312
20.1	Natural Convection	312
20.2	Forced Convection for Internal Flow	320
20.3	Forced Convection for External Flow	326
20.4	Closure	333
21.	Boiling and Condensation	340
21.1	Boiling	340
21.2	Condensation	345
21.3	Closure	351
22.	Heat-Transfer Equipment	354
22.1	Types of Heat Exchangers	354
22.2	Single-Pass Heat-Exchanger Analysis: The Log-Mean Temperature Difference	357
22.3	Crossflow and Shell-and-Tube Heat-Exchanger Analysis	361
22.4	The Number-of-Transfer-Units (NTU) Method of Heat-Exchanger Analysis and Design	365
22.5	Additional Considerations in Heat-Exchanger Design	373
22.6	Closure	375
23.	Radiation Heat Transfer	379
23.1	Nature of Radiation	379
23.2	Thermal Radiation	380
23.3	The Intensity of Radiation	382
23.4	Planck's Law of Radiation	383
23.5	Stefan-Boltzmann Law	388
23.6	Emissivity and Absorptivity of Solid Surfaces	388
23.7	Radiant Heat Transfer Between Black Bodies	394
23.8	Radiant Exchange in Black Enclosures	400
23.9	Radiant Exchange in Reradiating Surfaces Present	401
23.10	Radiant Heat Transfer Between Gray Surfaces	402
23.11	Radiation from Gases	410
23.12	The Radiation Heat-Transfer Coefficient	414
23.13	Closure	414

24. Fundamentals of Mass Transfer	421
24.1 Molecular Mass Transfer	421
24.2 The Diffusion Coefficient	431
24.3 Convective Mass Transfer	450
24.4 Closure	451
25. Differential Equations of Mass Transfer	457
25.1 The Differential Equation for Mass Transfer	457
25.2 Special Forms of the Differential Mass-Transfer Equation	460
25.3 Commonly Encountered Boundary Conditions	462
25.4 Steps for Modeling Processes Involving Molecular Diffusion	465
25.5 Closure	472
26. Steady-State Molecular Diffusion	479
26.1 One-Dimensional Mass Transfer Independent of Chemical Reaction	479
26.2 One-Dimensional Systems Associated with Chemical Reaction	491
26.3 Two- and Three-Dimensional Systems	503
26.4 Simultaneous Momentum, Heat, and Mass Transfer	506
26.5 Closure	516
27. Unsteady-State Molecular Diffusion	527
27.1 Unsteady-State Diffusion and Fick's Second Law	527
27.2 Transient Diffusion in a Semi-Infinite Medium	529
27.3 Transient Diffusion in a Finite-Dimensional Medium Under Conditions of Negligible Surface Resistance	531
27.4 Concentration-Time Charts for Simple Geometric Shapes	541
27.5 Closure	544
28. Convective Mass Transfer	550
28.1 Fundamental Considerations in Convective Mass Transfer	550
28.2 Significant Parameters in Convective Mass Transfer	552
28.3 Dimensional Analysis of Convective Mass Transfer	554
28.4 Exact Analysis of the Laminar Concentration Boundary Layer	557
28.5 Approximate Analysis of the Concentration Boundary Layer	564
28.6 Mass, Energy, and Momentum-Transfer Analogies	567
28.7 Models for Convective Mass-Transfer Coefficients	576
28.8 Closure	579
29. Convective Mass Transfer Between Phases	586
29.1 Equilibrium	586
29.2 Two-Resistance Theory	589
29.3 Closure	599
30. Convective Mass-Transfer Correlations	605
30.1 Mass Transfer to Plates, Spheres, and Cylinders	605
30.2 Mass Transfer Involving Flow Through Pipes	616
30.3 Mass Transfer in Wetted-Wall Columns	617

30.4	Mass Transfer in Packed and Fluidized Beds	621
30.5	Gas-Liquid Mass Transfer in Stirred Tanks	622
30.6	Capacity Coefficients for Packed Towers	624
30.7	Steps for Modeling Mass-Transfer Processes Involving Convection	625
30.8	Closure	633

31. Mass-Transfer Equipment 645

31.1	Types of Mass-Transfer Equipment	645
31.2	Gas-Liquid Mass-Transfer Operations in Well-Mixed Tanks	648
31.3	Mass Balances for Continuous Contact Towers: Operating-Line Equations	653
31.4	Enthalpy Balances for Continuous-Contact Towers	663
31.5	Mass-Transfer Capacity Coefficients	664
31.6	Continuous-Contact Equipment Analysis	665
31.7	Closure	680

Nomenclature	687
--------------	-----

APPENDIXES

A.	Transformations of the Operators ∇ and ∇^2 to Cylindrical Coordinates	695
B.	Summary of Differential Vector Operations in Various Coordinate Systems	698
C.	Symmetry of the Stress Tensor	701
D.	The Viscous Contribution to the Normal Stress	702
E.	The Navier-Stokes Equations for Constant ρ and μ in Cartesian, Cylindrical, and Spherical Coordinates	704
F.	Charts for Solution of Unsteady Transport Problems	706
G.	Properties of the Standard Atmosphere	719
H.	Physical Properties of Solids	722
I.	Physical Properties of Gases and Liquids	725
J.	Mass-Transfer Diffusion Coefficients in Binary Systems	738
K.	Lennard-Jones Constants	741
L.	The Error Function	744
M.	Standard Pipe Sizes	745
N.	Standard Tubing Gages	747

Author Index	751
--------------	-----

Subject Index	753
---------------	-----