CONTENTS

Preface xvii

CHAPTER ONE
INTRODUCTION AND BASIC CONCEPTS 1

1–1 Thermodynamics and Energy 2
Application Areas of Thermodynamics 3
1–2 Importance of Dimensions and Units 3
Some SI and English Units 6
Dimensional Homogeneity 8
Unity Conversion Ratios 9
1–3 Systems and Control Volumes 10
1–4 Properties of a System 12
Continuum 13
1–5 Density and Specific Gravity 13
1–6 State and Equilibrium 14
The State Postulate 15
1–7 Processes and Cycles 15
The Steady-Flow Process 16
1–8 Temperature and the Zeroth Law of Thermodynamics 17
Temperature Scales 18
The International Temperature Scale of 1990 (ITS-90) 20
1–9 Pressure 21
Variation of Pressure with Depth 23
1–10 The Manometer 26
Other Pressure Measurement Devices 28
1–11 The Barometer and Atmospheric Pressure 29
1–12 Problem-Solving Technique 33
Step 1: Problem Statement 33
Step 2: Schematic 33
Step 3: Assumptions and Approximations 33
Step 4: Physical Laws 34
Step 5: Properties 34
Step 6: Calculations 34
Step 7: Reasoning, Verification, and Discussion 34
Engineering Software Packages 35
Engineering Equation Solver (EES) 36
A Remark on Significant Digits 37
Summary 38
References and Suggested Readings 39
Problems 39

CHAPTER TWO
ENERGY, ENERGY TRANSFER, AND GENERAL ENERGY ANALYSIS 51

2–1 Introduction 52
2–2 Forms of Energy 53
Some Physical Insight to Internal Energy 55
More on Nuclear Energy 56
Mechanical Energy 58
2–3 Energy Transfer by Heat 60
Historical Background on Heat 61
2–4 Energy Transfer by Work 62
Electrical Work 65
2–5 Mechanical Forms of Work 66
Shaft Work 66
Spring Work 67
Work Done on Elastic Solid Bars 67
Work Associated with the Stretching of a Liquid Film 68
Work Done to Raise or to Accelerate a Body 68
Nonmechanical Forms of Work 69
2–6 The First Law of Thermodynamics 70
Energy Balance 71
Energy Change of a System, ΔE_{system} 72
Mechanisms of Energy Transfer, E_{in} and E_{out} 73
2–7 Energy Conversion Efficiencies 78
Efficiencies of Mechanical and Electrical Devices 82
2–8 Energy and Environment 86
Ozone and Smog 87
Acid Rain 88
The Greenhouse Effect: Global Warming and Climate Change 89
Topic of Special Interest: Mechanisms of Heat Transfer 92
Summary 96
References and Suggested Readings 97
Problems 98

CHAPTER THREE
PROPERTIES OF PURE SUBSTANCES 111

3–1 Pure Substance 112

3–2 Phases of a Pure Substance 112

3–3 Phase-Change Processes of Pure Substances 113

Compressed Liquid and Saturated Liquid 114
Saturated Vapor and Superheated Vapor 114
Saturation Temperature and Saturation Pressure 115
Some Consequences of T_{sat} and P_{sat} Dependence 116

3–4 Property Diagrams for Phase-Change Processes 118

1 The *T-v* Diagram 118
2 The *P-v* Diagram 120
Extending the Diagrams to Include the Solid Phase 120
3 The *P-T* Diag 122
The *P-v-T* Surface 123

3–5 Property Tables 124

Enthalpy—A Combination Property 124
1a Saturated Liquid and Saturated Vapor States 125
1b Saturated Liquid–Vapor Mixture 127
2 Superheated Vapor 130
3 Compressed Liquid 131
Reference State and Reference Values 132

3–6 The Ideal-Gas Equation of State 134

Is Water Vapor an Ideal Gas? 137

3–7 Compressibility Factor—A Measure of Deviation from Ideal-Gas Behavior 137

3–8 Other Equations of State 141

Van der Waals Equation of State 141
Beattie-Bridgeman Equation of State 142
Benedict-Webb-Rubin Equation of State 143
Virial Equation of State 143

Topic of Special Interest: Vapor Pressure and Phase Equilibrium 146

Summary 150
References and Suggested Readings 151
Problems 151

CHAPTER FOUR
ENERGY ANALYSIS OF CLOSED SYSTEMS 163

4–1 Moving Boundary Work 164

Polytropic Process 168

4–2 Energy Balance for Closed Systems 169

4–3 Specific Heats 174

4–4 Internal Energy, Enthalpy, and Specific Heats of Ideal Gases 176

Specific Heat Relations of Ideal Gases 178

4–5 Internal Energy, Enthalpy, and Specific Heats of Solids and Liquids 183

Internal Energy Changes 184
Enthalpy Changes 184

Topic of Special Interest: Thermodynamic Aspects of Biological Systems 187

Summary 195
References and Suggested Readings 195
Problems 196

CHAPTER FIVE
MASS AND ENERGY ANALYSIS OF CONTROL VOLUMES 215

5–1 Conservation of Mass 216

Mass and Volume Flow Rates 216
Conservation of Mass Principle 218
Mass Balance for Steady-Flow Processes 219
Special Case: Incompressible Flow 220

5–2 Flow Work and the Energy of a Flowing Fluid 223

Total Energy of a Flowing Fluid 223
Energy Transport by Mass 224

5–3 Energy Analysis of Steady-Flow Systems 226

5–4 Some Steady-Flow Engineering Devices 229

1 Nozzles and Diffusers 230
2 Turbines and Compressors 233
3 Throttling Valves 235
4a Mixing Chambers 237
4b Heat Exchangers 238
5 Pipe and Duct Flow 241

5–5 Energy Analysis of Unsteady-Flow Processes 242

Topic of Special Interest: General Energy Equation 247

Summary 251
References and Suggested Readings 252
Problems 252

CHAPTER SIX
THE SECOND LAW OF THERMODYNAMICS 277

6–1 Introduction to the Second Law 278

6–2 Thermal Energy Reservoirs 279

6–3 Heat Engines 280

Thermal Efficiency 281
Can We Save Q_{out}? 283
The Second Law of Thermodynamics: Kelvin–Planck Statement 285

6–4 Refrigerators and Heat Pumps 285

Coefficient of Performance 286
Heat Pumps 287
Performance of Refrigerators, Air-Conditioners, and Heat Pumps 288
The Second Law of Thermodynamics: Clausius Statement 290
Equivalence of the Two Statements 291

6–5 Perpetual-Motion Machines 292

6–6 Reversible and Irreversible Processes 294

Irreversibilities 295
Internally and Externally Reversible Processes 297

6–7 The Carnot Cycle 297

The Reversed Carnot Cycle 299

6–8 The Carnot Principles 299

6–9 The Thermodynamic Temperature Scale 301

6–10 The Carnot Heat Engine 303

The Quality of Energy 305
Quantity versus Quality in Daily Life 305

6–11 The Carnot Refrigerator and Heat Pump 306

Topic of Special Interest: Household Refrigerators 309

Summary 313
References and Suggested Readings 314
Problems 314

CHAPTER SEVEN
ENTROPY 331

7–1 Entropy 332

A Special Case: Internally Reversible Isothermal Heat Transfer Processes 334

7–2 The Increase of Entropy Principle 335

Some Remarks about Entropy 338

7–3 Entropy Change of Pure Substances 339

7–4 Isentropic Processes 342

7–5 Property Diagrams Involving Entropy 344

7–6 What Is Entropy? 345

Entropy and Entropy Generation in Daily Life 347

7–7 The *T ds* Relations 349

7–8 Entropy Change of Liquids and Solids 350

7–9 The Entropy Change of Ideal Gases 354

Constant Specific Heats (Approximate Analysis) 354
Variable Specific Heats (Exact Analysis) 355
Isentropic Processes of Ideal Gases 357
Constant Specific Heats (Approximate Analysis) 357
Variable Specific Heats (Exact Analysis) 358
Relative Pressure and Relative Specific Volume 358

7–10 Reversible Steady-Flow Work 361

Proof that Steady-Flow Devices Deliver the Most and Consume the Least Work When the Process Is Reversible 364

7–11 Minimizing the Compressor Work 364

Multistage Compression with Intercooling 366

7–12 Isentropic Efficiencies of Steady-Flow Devices 368

Isentropic Efficiency of Turbines 369
Isentropic Efficiencies of Compressors and Pumps 371
Isentropic Efficiency of Nozzles 373

7–13 Entropy Balance 375

Entropy Change of a System, ΔS_{system} 375
Mechanisms of Entropy Transfer, S_{in} and S_{out} 376
1 Heat Transfer 376
2 Mass Flow 377
Entropy Generation, S_{gen} 377
Closed Systems 378
Control Volumes 379
Entropy Generation Associated with a Heat Transfer Process 386

Topic of Special Interest: Reducing the Cost of Compressed Air 387

Summary 396
References and Suggested Readings 397
Problems 398

CHAPTER EIGHT

EXERGY: A MEASURE OF WORK POTENTIAL 423

8–1 Exergy: Work Potential of Energy 424

Exergy (Work Potential) Associated with Kinetic and Potential Energy 425

8–2 Reversible Work and Irreversibility 427

8–3 Second-Law Efficiency, η_{II} 432

8–4 Exergy Change of a System 435

Exergy of a Fixed Mass: Nonflow (or Closed System) Exergy 435
Exergy of a Flow Stream: Flow (or Stream) Exergy 438

8–5 Exergy Transfer by Heat, Work, and Mass 440

Exergy by Heat Transfer, *Q* 441
Exergy Transfer by Work, *W* 442
Exergy Transfer by Mass, *m* 442

8–6 The Decrease of Exergy Principle and Exergy Destruction 443

Exergy Destruction 444

8–7 Exergy Balance: Closed Systems 445

8–8 Exergy Balance: Control Volumes 456

Exergy Balance for Steady-Flow Systems 457
Reversible Work, W_{rev} 458
Second-Law Efficiency of Steady-Flow Devices, η_{II} 458

Topic of Special Interest: Second-Law Aspects of Daily Life 465

Summary 469
References and Suggested Readings 470
Problems 470

CHAPTER NINE

GAS POWER CYCLES 487

9–1 Basic Considerations in the Analysis of Power Cycles 488

9–2 The Carnot Cycle and Its Value in Engineering 490

9–3 Air-Standard Assumptions 492

9–4 An Overview of Reciprocating Engines 492

9–5 Otto Cycle: The Ideal Cycle for Spark-Ignition Engines 494

9–6 Diesel Cycle: The Ideal Cycle for Compression-Ignition Engines 500

9–7 Stirling and Ericsson Cycles 503

9–8 Brayton Cycle: The Ideal Cycle for Gas-Turbine Engines 507

Development of Gas Turbines 510
Deviation of Actual Gas-Turbine Cycles from Idealized Ones 513

9–9 The Brayton Cycle with Regeneration 514

9–10 The Brayton Cycle with Intercooling, Reheating, and Regeneration 517

9–11 Ideal Jet-Propulsion Cycles 521

Modifications to Turbojet Engines 525

9–12 Second-Law Analysis of Gas Power Cycles 527

Topic of Special Interest: Saving Fuel and Money by Driving Sensibly 531

Summary 537
References and Suggested Readings 539
Problems 539

CHAPTER TEN

VAPOR AND COMBINED POWER CYCLES 555

10–1 The Carnot Vapor Cycle 556

10–2 Rankine Cycle: The Ideal Cycle for Vapor Power Cycles 557

Energy Analysis of the Ideal Rankine Cycle 557

10–3 Deviation of Actual Vapor Power Cycles from Idealized Ones 560

10–4 How Can We Increase the Efficiency of the Rankine Cycle? 563

Lowering the Condenser Pressure (*Lowers* $T_{low,avg}$) 563
Superheating the Steam to High Temperatures (*Increases* $T_{high,avg}$) 564
Increasing the Boiler Pressure (*Increases* $T_{high,avg}$) 564

10–5 The Ideal Reheat Rankine Cycle 567

10–6 The Ideal Regenerative Rankine Cycle 571
Open Feedwater Heaters 571
Closed Feedwater Heaters 573
10–7 Second-Law Analysis of Vapor Power Cycles 579
10–8 Cogeneration 581
10–9 Combined Gas–Vapor Power Cycles 586
Topic of Special Interest: Binary Vapor Cycles 589
Summary 592
References and Suggested Readings 592
Problems 593

CHAPTER ELEVEN
REFRIGERATION CYCLES 611
11–1 Refrigerators and Heat Pumps 612
11–2 The Reversed Carnot Cycle 613
11–3 The Ideal Vapor-Compression Refrigeration Cycle 614
11–4 Actual Vapor-Compression Refrigeration Cycle 617
11–5 Second-Law Analysis of Vapor-Compression Refrigeration Cycle 619
11–6 Selecting The Right Refrigerant 624
11–7 Heat Pump Systems 626
11–8 Innovative Vapor-Compression Refrigeration Systems 627
Cascade Refrigeration Systems 628
Multistage Compression Refrigeration Systems 630
Multipurpose Refrigeration Systems with a Single Compressor 632
Liquefaction of Gases 633
11–9 Gas Refrigeration Cycles 634
11–10 Absorption Refrigeration Systems 637
Topic of Special Interest: Thermoelectric Power Generation and Refrigeration Systems 640
Summary 642
References and Suggested Readings 643
Problems 643

CHAPTER TWELVE
THERMODYNAMIC PROPERTY RELATIONS 661
12–1 A Little Math—Partial Derivatives and Associated Relations 662
Partial Differentials 663
Partial Differential Relations 665
12–2 The Maxwell Relations 667
12–3 The Clapeyron Equation 668
12–4 General Relations for du, dh, ds, c_v and c_p 671
Internal Energy Changes 672
Enthalpy Changes 672
Entropy Changes 673
Specific Heats c_v and c_p 674
12–5 The Joule-Thomson Coefficient 678
12–6 The Δh, Δu, and Δs of Real Gases 680
Enthalpy Changes of Real Gases 680
Internal Energy Changes of Real Gases 681
Entropy Changes of Real Gases 682
Summary 685
References and Suggested Readings 686
Problems 686

CHAPTER THIRTEEN
GAS MIXTURES 693
13–1 Composition of a Gas Mixture: Mass and Mole Fractions 694
13–2 P-v-T Behavior of Gas Mixtures: Ideal and Real Gases 696
Ideal-Gas Mixtures 697
Real-Gas Mixtures 697
13–3 Properties of Gas Mixtures: Ideal and Real Gases 701
Ideal-Gas Mixtures 702
Real-Gas Mixtures 705
Topic of Special Interest: Chemical Potential and the Separation Work of Mixtures 709
Summary 720
References and Suggested Readings 721
Problems 721

CHAPTER FOURTEEN
GAS–VAPOR MIXTURES AND AIR-CONDITIONING 731

14–1 Dry and Atmospheric Air 732

14–2 Specific and Relative Humidity of Air 733

14–3 Dew-Point Temperature 735

14–4 Adiabatic Saturation and Wet-Bulb Temperatures 737

14–5 The Psychrometric Chart 740

14–6 Human Comfort and Air-Conditioning 741

14–7 Air-Conditioning Processes 743

Simple Heating and Cooling (ω = constant) 744
Heating with Humidification 745
Cooling with Dehumidification 746
Evaporative Cooling 748
Adiabatic Mixing of Airstreams 749
Wet Cooling Towers 751

Summary 753
References and Suggested Readings 755
Problems 755

CHAPTER FIFTEEN
CHEMICAL REACTIONS 767

15–1 Fuels and Combustion 768

15–2 Theoretical and Actual Combustion Processes 772

15–3 Enthalpy of Formation and Enthalpy of Combustion 779

15–4 First-Law Analysis of Reacting Systems 782

Steady-Flow Systems 783
Closed Systems 784

15–5 Adiabatic Flame Temperature 788

15–6 Entropy Change of Reacting Systems 790

15–7 Second-Law Analysis of Reacting Systems 792

Topic of Special Interest: Fuel Cells 798

Summary 800
References and Suggested Readings 801
Problems 801

CHAPTER SIXTEEN
CHEMICAL AND PHASE EQUILIBRIUM 813

16–1 Criterion for Chemical Equilibrium 814

16–2 The Equilibrium Constant for Ideal-Gas Mixtures 816

16–3 Some Remarks about the K_p of Ideal-Gas Mixtures 820

16–4 Chemical Equilibrium for Simultaneous Reactions 824

16–5 Variation of K_p with Temperature 826

16–6 Phase Equilibrium 828

Phase Equilibrium for a Single-Component System 828
The Phase Rule 830
Phase Equilibrium for a Multicomponent System 830

Summary 836
References and Suggested Readings 837
Problems 837

CHAPTER SEVENTEEN
COMPRESSIBLE FLOW 847

17–1 Stagnation Properties 848

17–2 Speed of Sound and Mach Number 851

17–3 One-Dimensional Isentropic Flow 853

Variation of Fluid Velocity with Flow Area 856
Property Relations for Isentropic Flow of Ideal Gases 858

17–4 Isentropic Flow Through Nozzles 860

Converging Nozzles 860
Converging–Diverging Nozzles 865

17–5 Shock Waves and Expansion Waves 869

Normal Shocks 869
Oblique Shocks 876
Prandtl–Meyer Expansion Waves 880

17–6 Duct Flow with Heat Transfer and Negligible Friction (Rayleigh Flow) 884

Property Relations for Rayleigh Flow 890
Choked Rayleigh Flow 891

17–7 Steam Nozzles 893

Summary 896
References and Suggested Readings 897
Problems 898

APPENDIX 1

PROPERTY TABLES AND CHARTS (SI UNITS) 907

TABLE A–1 Molar mass, gas constant, and critical-point properties 908
TABLE A–2 Ideal-gas specific heats of various common gases 909
TABLE A–3 Properties of common liquids, solids, and foods 912
TABLE A–4 Saturated water—Temperature table 914
TABLE A–5 Saturated water—Pressure table 916
TABLE A–6 Superheated water 918
TABLE A–7 Compressed liquid water 922
TABLE A–8 Saturated ice–water vapor 923
FIGURE A–9 *T-s* diagram for water 924
FIGURE A–10 Mollier diagram for water 925
TABLE A–11 Saturated refrigerant-134a—Temperature table 926
TABLE A–12 Saturated refrigerant-134a—Pressure table 928
TABLE A–13 Superheated refrigerant-134a 929
FIGURE A–14 *P-h* diagram for refrigerant-134a 931
FIGURE A–15 Nelson–Obert generalized compressibility chart 932
TABLE A–16 Properties of the atmosphere at high altitude 933
TABLE A–17 Ideal-gas properties of air 934
TABLE A–18 Ideal-gas properties of nitrogen, N_2 936
TABLE A–19 Ideal-gas properties of oxygen, O_2 938
TABLE A–20 Ideal-gas properties of carbon dioxide, CO_2 940
TABLE A–21 Ideal-gas properties of carbon monoxide, CO 942
TABLE A–22 Ideal-gas properties of hydrogen, H_2 944
TABLE A–23 Ideal-gas properties of water vapor, H_2O 945
TABLE A–24 Ideal-gas properties of monatomic oxygen, O 947
TABLE A–25 Ideal-gas properties of hydroxyl, OH 947
TABLE A–26 Enthalpy of formation, Gibbs function of formation, and absolute entropy at 25°C, 1 atm 948
TABLE A–27 Properties of some common fuels and hydrocarbons 949
TABLE A–28 Natural logarithms of the equilibrium constant K_p 950
FIGURE A–29 Generalized enthalpy departure chart 951
FIGURE A–30 Generalized entropy departure chart 952
FIGURE A–31 Psychrometric chart at 1 atm total pressure 953
TABLE A–32 One-dimensional isentropic compressible-flow functions for an ideal gas with $k = 1.4$ 954
TABLE A–33 One-dimensional normal-shock functions for an ideal gas with $k = 1.4$ 955
TABLE A–34 Rayleigh flow functions for an ideal gas with $k = 1.4$ 956

APPENDIX 2

PROPERTY TABLES AND CHARTS (ENGLISH UNITS) 957

TABLE A–1E Molar mass, gas constant, and critical-point properties 958
TABLE A–2E Ideal-gas specific heats of various common gases 959
TABLE A–3E Properties of common liquids, solids, and foods 962
TABLE A–4E Saturated water—Temperature table 964
TABLE A–5E Saturated water—Pressure table 966
TABLE A–6E Superheated water 968
TABLE A–7E Compressed liquid water 972
TABLE A–8E Saturated ice—water vapor 973
FIGURE A–9E *T-s* diagram for water 974
FIGURE A–10E Mollier diagram for water 975
TABLE A–11E Saturated refrigerant-134a—Temperature table 976

TABLE A–12E Saturated refrigerant-134a—Pressure table 977
TABLE A–13E Superheated refrigerant-134a 978
FIGURE A–14E *P-h* diagram for refrigerant-134a 980
TABLE A–16E Properties of the atmosphere at high altitude 981
TABLE A–17E Ideal-gas properties of air 982
TABLE A–18E Ideal-gas properties of nitrogen, N_2 984
TABLE A–19E Ideal-gas properties of oxygen, O_2 986
TABLE A–20E Ideal-gas properties of carbon dioxide, CO_2 988
TABLE A–21E Ideal-gas properties of carbon monoxide, CO 990
TABLE A–22E Ideal-gas properties of hydrogen, H_2 992
TABLE A–23E Ideal-gas properties of water vapor, H_2O 993
TABLE A–26E Enthalpy of formation, Gibbs function of formation, and absolute entropy at 77°F, 1 atm 995
TABLE A–27E Properties of some common fuels and hydrocarbons 996
FIGURE A–31E Psycrometric chart at 1 atm total pressure 997

Index 999