

# Contents

Preface xvii

## Chapter 1

### 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 12
- 1-5 Density and Specific Gravity 13
- 1-6 State and Equilibrium 14
  - The State Postulate 14
- 1-7 Processes and Cycles 15
  - The Steady-Flow Process 16
- 1-8 Temperature and the Zeroth Law of Thermodynamics 17
  - Temperature Scales 17
  - 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 29
- 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 34
  - 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 38

Summary 39  
References and Suggested Readings 39  
Problems 40

## Chapter 2

### 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,  $\Delta E_{\text{system}}$  72
    - Mechanisms of Energy Transfer,  $E_{\text{in}}$  and  $E_{\text{out}}$  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 3

### 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  $T_{\text{sat}}$  and  $P_{\text{sat}}$  Dependence 117
- 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 121
  - 3 The  $P$ - $T$  Diagram 124
  - The  $P$ - $v$ - $T$  Surface 125
- 3-5 Property Tables 126
  - Enthalpy—A Combination Property 126
  - 1a Saturated Liquid and Saturated Vapor States 127
  - 1b Saturated Liquid–Vapor Mixture 129
  - 2 Superheated Vapor 132
  - 3 Compressed Liquid 133
  - Reference State and Reference Values 135
- 3-6 The Ideal-Gas Equation of State 137
  - Is Water Vapor an Ideal Gas? 139
- 3-7 Compressibility Factor—A Measure of Deviation from Ideal-Gas Behavior 139
- 3-8 Other Equations of State 144
  - Van der Waals Equation of State 144
  - Beattie-Bridgeman Equation of State 145
  - Benedict-Webb-Rubin Equation of State 145
  - Virial Equation of State 145
- Topic of Special Interest: Vapor Pressure and Phase Equilibrium 149**
  - Summary 153
  - References and Suggested Readings 154
  - Problems 154

## Chapter 4

### ENERGY ANALYSIS OF CLOSED SYSTEMS | 165

- 4-1 Moving Boundary Work 166
  - Polytropic Process 171
- 4-2 Energy Balance for Closed Systems 173
- 4-3 Specific Heats 178

- 4-4 Internal Energy, Enthalpy, and Specific Heats of Ideal Gases 180
  - Specific Heat Relations of Ideal Gases 182
- 4-5 Internal Energy, Enthalpy, and Specific Heats of Solids and Liquids 189
  - Internal Energy Changes 189
  - Enthalpy Changes 189
- Topic of Special Interest: Thermodynamic Aspects of Biological Systems 193**
  - Summary 200
  - References and Suggested Readings 201
  - Problems 201

## Chapter 5

### MASS AND ENERGY ANALYSIS OF CONTROL VOLUMES | 221

- 5-1 Conservation of Mass 222
  - Mass and Volume Flow Rates 222
  - Conservation of Mass Principle 224
  - Mass Balance for Steady-Flow Processes 225
  - Special Case: Incompressible Flow 226
- 5-2 Flow Work and the Energy of a Flowing Fluid 228
  - Total Energy of a Flowing Fluid 229
  - Energy Transport by Mass 230
- 5-3 Energy Analysis of Steady-Flow Systems 232
- 5-4 Some Steady-Flow Engineering Devices 235
  - 1 Nozzles and Diffusers 235
  - 2 Turbines and Compressors 238
  - 3 Throttling Valves 241
  - 4a Mixing Chambers 242
  - 4b Heat Exchangers 244
  - 5 Pipe and Duct Flow 246
- 5-5 Energy Analysis of Unsteady-Flow Processes 248
  - Topic of Special Interest: General Energy Equation 254**
    - Summary 257
    - References and Suggested Readings 258
    - Problems 258

## Chapter 6

### THE SECOND LAW OF THERMODYNAMICS | 283

- 6-1 Introduction to the Second Law 284
- 6-2 Thermal Energy Reservoirs 285

6-3	Heat Engines	286
	Thermal Efficiency	287
	Can We Save $Q_{\text{out}}$ ?	289
	The Second Law of Thermodynamics:	
	Kelvin–Planck Statement	291
6-4	Refrigerators and Heat Pumps	291
	Coefficient of Performance	292
	Heat Pumps	293
	The Second Law of Thermodynamics:	
	Clausius Statement	296
	Equivalence of the Two Statements	296
6-5	Perpetual-Motion Machines	297
6-6	Reversible and Irreversible Processes	300
	Irreversibilities	301
	Internally and Externally Reversible Processes	2302
6-7	The Carnot Cycle	303
	The Reversed Carnot Cycle	305
6-8	The Carnot Principles	305
6-9	The Thermodynamic Temperature Scale	307
6-10	The Carnot Heat Engine	308
	The Quality of Energy	311
	Quantity versus Quality in Daily Life	312
6-11	The Carnot Refrigerator and Heat Pump	313
	<b>Topic of Special Interest: Household Refrigerators</b>	315
	Summary	319
	References and Suggested Readings	320
	Problems	320

## Chapter 7

### ENTROPY | 337

7-1	Entropy	338
	A Special Case: Internally Reversible Isothermal Heat Transfer Processes	340
7-2	The Increase of Entropy Principle	341
	Some Remarks about Entropy	343
7-3	Entropy Change of Pure Substances	345
7-4	Isentropic Processes	349
7-5	Property Diagrams Involving Entropy	350
7-6	What Is Entropy?	352
	Entropy and Entropy Generation in Daily Life	354
7-7	The $T ds$ Relations	356
7-8	Entropy Change of Liquids and Solids	357
7-9	The Entropy Change of Ideal Gases	360
	Constant Specific Heats (Approximate Analysis)	361
	Variable Specific Heats (Exact Analysis)	362

	Isentropic Processes of Ideal Gases	364
	Constant Specific Heats (Approximate Analysis)	364
	Variable Specific Heats (Exact Analysis)	365
	Relative Pressure and Relative Specific Volume	365
7-10	Reversible Steady-Flow Work	368
	Proof that Steady-Flow Devices Deliver the Most and Consume the Least Work when the Process Is Reversible	371
7-11	Minimizing the Compressor Work	372
	Multistage Compression with Intercooling	373
7-12	Isentropic Efficiencies of Steady-Flow Devices	376
	Isentropic Efficiency of Turbines	377
	Isentropic Efficiencies of Compressors and Pumps	379
	Isentropic Efficiency of Nozzles	381
7-13	Entropy Balance	383
	Entropy Change of a System, $\Delta S_{\text{system}}$	384
	Mechanisms of Entropy Transfer, $S_{\text{in}}$ and $S_{\text{out}}$	384
	1 Heat Transfer	384
	2 Mass Flow	385
	Entropy Generation, $S_{\text{gen}}$	386
	Closed Systems	387
	Control Volumes	387
	Entropy Generation Associated with a Heat Transfer Process	395
	<b>Topic of Special Interest: Reducing the Cost of Compressed Air</b>	397
	Summary	406
	References and Suggested Readings	407
	Problems	408

## Chapter 8

### EXERGY: A MEASURE OF WORK POTENTIAL | 433

8-1	Exergy: Work Potential of Energy	434
	Exergy (Work Potential) Associated with Kinetic and Potential Energy	435
8-2	Reversible Work and Irreversibility	437
8-3	Second-Law Efficiency, $\eta_{\text{II}}$	442
8-4	Exergy Change of a System	444
	Exergy of a Fixed Mass: Nonflow (or Closed System) Exergy	445
	Exergy of a Flow Stream: Flow (or Stream) Exergy	447
8-5	Exergy Transfer by Heat, Work, and Mass	450
	Exergy by Heat Transfer, $Q$	450
	Exergy Transfer by Work, $W$	452
	Exergy Transfer by Mass, $m$	452
8-6	The Decrease of Exergy Principle and Exergy Destruction	453
	Exergy Destruction	454



- 8–7 Exergy Balance: Closed Systems 454
- 8–8 Exergy Balance: Control Volumes 467
  - Exergy Balance for Steady-Flow Systems 468
  - Reversible Work,  $W_{\text{rev}}$  469
  - Second-Law Efficiency of Steady-Flow Devices,  $\eta_{\text{II}}$  469
- Topic of Special Interest: Second-Law Aspects of Daily Life 475**
- Summary 479
- References and Suggested Readings 480
- Problems 480

## Chapter 9

### GAS POWER CYCLES | 497

- 9–1 Basic Considerations in the Analysis of Power Cycles 498
- 9–2 The Carnot Cycle and Its Value in Engineering 500
- 9–3 Air-Standard Assumptions 502
- 9–4 An Overview of Reciprocating Engines 503
- 9–5 Otto Cycle: The Ideal Cycle for Spark-Ignition Engines 504
- 9–6 Diesel Cycle: The Ideal Cycle for Compression-Ignition Engines 5100
- 9–7 Stirling and Ericsson Cycles 513
- 9–8 Brayton Cycle: The Ideal Cycle for Gas-Turbine Engines 517
  - Development of Gas Turbines 520
  - Deviation of Actual Gas-Turbine Cycles from Idealized Ones 523
- 9–9 The Brayton Cycle with Regeneration 525
- 9–10 The Brayton Cycle with Intercooling, Reheating, and Regeneration 527
- 9–11 Ideal Jet-Propulsion Cycles 531
  - Modifications to Turbojet Engines 535
- 9–12 Second-Law Analysis of Gas Power Cycles 537
- Topic of Special Interest: Saving Fuel and Money by Driving Sensibly 540**
- Summary 547
- References and Suggested Readings 548
- Problems 549

## Chapter 10

### VAPOR AND COMBINED POWER CYCLES | 565

- 10–1 The Carnot Vapor Cycle 566
- 10–2 Rankine Cycle: The Ideal Cycle for Vapor Power Cycles 567
  - Energy Analysis of the Ideal Rankine Cycle 568
- 10–3 Deviation of Actual Vapor Power Cycles from Idealized Ones 571
- 10–4 How Can We Increase the Efficiency of the Rankine Cycle? 574
  - Lowering the Condenser Pressure (*Lowers  $T_{\text{low,avg}}$* ) 574
  - Superheating the Steam to High Temperatures (*Increases  $T_{\text{high,avg}}$* ) 575
  - Increasing the Boiler Pressure (*Increases  $T_{\text{high,avg}}$* ) 575
- 10–5 The Ideal Reheat Rankine Cycle 578
- 10–6 The Ideal Regenerative Rankine Cycle 582
  - Open Feedwater Heaters 582
  - Closed Feedwater Heaters 584
- 10–7 Second-Law Analysis of Vapor Power Cycles 590
- 10–8 Cogeneration 592
- 10–9 Combined Gas–Vapor Power Cycles 597
- Topic of Special Interest: Binary Vapor Cycles 600**
- Summary 603
- References and Suggested Readings 603
- Problems 604

## Chapter 11

### REFRIGERATION CYCLES | 623

- 11–1 Refrigerators and Heat Pumps 624
- 11–2 The Reversed Carnot Cycle 625
- 11–3 The Ideal Vapor-Compression Refrigeration Cycle 626
- 11–4 Actual Vapor-Compression Refrigeration Cycle 630
- 11–5 Selecting the Right Refrigerant 632
- 11–6 Heat Pump Systems 634
- 11–7 Innovative Vapor-Compression Refrigeration Systems 636
  - Cascade Refrigeration Systems 636
  - Multistage Compression Refrigeration Systems 639

Multipurpose Refrigeration Systems  
with a Single Compressor 641  
Liquefaction of Gases 642

## 11-8 Gas Refrigeration Cycles 644

## 11-9 Absorption Refrigeration Systems 647

**Topic of Special Interest: Thermoelectric Power Generation  
and Refrigeration Systems 650**

Summary 652  
References and Suggested Readings 653  
Problems 653

## Chapter 12

### THERMODYNAMIC PROPERTY RELATIONS | 669

#### 12-1 A Little Math—Partial Derivatives and Associated Relations 670

Partial Differentials 671  
Partial Differential Relations 673

#### 12-2 The Maxwell Relations 674

#### 12-3 The Clapeyron Equation 676

#### 12-4 General Relations for $du$ , $dh$ , $ds$ , $c_v$ , and $c_p$ 679

Internal Energy Changes 679  
Enthalpy Changes 680  
Entropy Changes 681  
Specific Heats  $c_v$  and  $c_p$  682

#### 12-5 The Joule-Thomson Coefficient 686

#### 12-6 The $\Delta h$ , $\Delta u$ , and $\Delta s$ of Real Gases 687

Enthalpy Changes of Real Gases 688  
Internal Energy Changes of Real Gases 689  
Entropy Changes of Real Gases 689

Summary 692  
References and Suggested Readings 693  
Problems 693

## Chapter 13

### GAS MIXTURES | 701

#### 13-1 Composition of a Gas Mixture: Mass and Mole Fractions 702

#### 13-2 $P$ - $v$ - $T$ Behavior of Gas Mixtures: Ideal and Real Gases 704

Ideal-Gas Mixtures 705  
Real-Gas Mixtures 705

#### 13-3 Properties of Gas Mixtures: Ideal and Real Gases 709

Ideal-Gas Mixtures 710  
Real-Gas Mixtures 713

**Topic of Special Interest: Chemical Potential  
and the Separation Work of Mixtures 717**

Summary 728  
References and Suggested Readings 729  
Problems 729

## Chapter 14

### GAS-VAPOR MIXTURES AND AIR-CONDITIONING | 737

#### 14-1 Dry and Atmospheric Air 738

#### 14-2 Specific and Relative Humidity of Air 739

#### 14-3 Dew-Point Temperature 741

#### 14-4 Adiabatic Saturation and Wet-Bulb Temperatures 743

#### 14-5 The Psychrometric Chart 746

#### 14-6 Human Comfort and Air-Conditioning 747

#### 14-7 Air-Conditioning Processes 749

Simple Heating and Cooling ( $\omega = \text{constant}$ ) 750  
Heating with Humidification 751  
Cooling with Dehumidification 752  
Evaporative Cooling 754  
Adiabatic Mixing of Airstreams 755  
Wet Cooling Towers 757

Summary 759  
References and Suggested Readings 761  
Problems 761

## Chapter 15

### CHEMICAL REACTIONS | 773

#### 15-1 Fuels and Combustion 774

#### 15-2 Theoretical and Actual Combustion Processes 778

#### 15-3 Enthalpy of Formation and Enthalpy of Combustion 784

#### 15-4 First-Law Analysis of Reacting Systems 787

Steady-Flow Systems 787  
Closed Systems 789

#### 15-5 Adiabatic Flame Temperature 792

#### 15-6 Entropy Change of Reacting Systems 795

#### 15-7 Second-Law Analysis of Reacting Systems 797



**Topic of Special Interest: Fuel Cells 802**

Summary 804

References and Suggested Readings 805

Problems 805

## Chapter 16

**CHEMICAL AND PHASE EQUILIBRIUM | 817**

16-1 Criterion for Chemical Equilibrium 818

16-2 The Equilibrium Constant  
for Ideal-Gas Mixtures 82016-3 Some Remarks about the  $K_p$   
of Ideal-Gas Mixtures 82316-4 Chemical Equilibrium for Simultaneous  
Reactions 82816-5 Variation of  $K_p$  with Temperature 830

16-6 Phase Equilibrium 832

Phase Equilibrium for a Single-Component System 832

The Phase Rule 833

Phase Equilibrium for a Multicomponent System 834

Summary 839

References and Suggested Readings 840

Problems 841

## Chapter 17

**COMPRESSIBLE FLOW | 849**

17-1 Stagnation Properties 850

17-2 Speed of Sound and Mach Number 853

17-3 One-Dimensional Isentropic Flow 855  
Variation of Fluid Velocity with Flow Area 858  
Property Relations for Isentropic Flow of Ideal Gases 86017-4 Isentropic Flow through Nozzles 862  
Converging Nozzles 862  
Converging-Diverging Nozzles 86717-5 Shock Waves and Expansion Waves 871  
Normal Shocks 871  
Oblique Shocks 878  
Prandtl-Meyer Expansion Waves 88217-6 Duct Flow with Heat Transfer and Negligible  
Friction (Rayleigh Flow) 886  
Property Relations for Rayleigh Flow 892  
Choked Rayleigh Flow 893

17-7 Steam Nozzles 895

Summary 898

References and Suggested Readings 899

Problems 900

## Appendix

**PROPERTY TABLES AND CHARTS | 909**Table A-1 Molar mass, gas constant, and critical-  
point properties 910Table A-2 Ideal-gas specific heats of various  
common gases 911Table A-3 Properties of common liquids, solids,  
and foods 914Table A-4 Saturated water—Temperature  
table 916

Table A-5 Saturated water—Pressure table 918

Table A-6 Superheated water 920

Table A-7 Compressed liquid water 924

Table A-8 Saturated ice–water vapor 925

Figure A-9  $T$ - $s$  diagram for water 926

Figure A-10 Mollier diagram for water 927

Table A-11 Saturated refrigerant-134a—  
Temperature table 928Table A-12 Saturated refrigerant-134a—Pressure  
table 930

Table A-13 Superheated refrigerant-134a 931

Figure A-14  $P$ - $h$  diagram for refrigerant-134a 933Figure A-15 Nelson–Obert generalized  
compressibility chart 934Table A-16 Properties of the atmosphere at high  
altitude 935

Table A-17 Ideal-gas properties of air 936

Table A-18 Ideal-gas properties of nitrogen,  
 $N_2$  938Table A-19 Ideal-gas properties of oxygen,  $O_2$  940Table A-20 Ideal-gas properties of carbon dioxide,  
 $CO_2$  942Table A-21 Ideal-gas properties of carbon  
monoxide,  $CO$  944Table A-22 Ideal-gas properties of hydrogen,  
 $H_2$  946Table A-23 Ideal-gas properties of water vapor,  
 $H_2O$  947

<b>Table A-24</b>	Ideal-gas properties of monatomic oxygen, O 949	<b>Figure A-30</b>	Generalized entropy departure chart 954
<b>Table A-25</b>	Ideal-gas properties of hydroxyl, OH 949	<b>Figure A-31</b>	Psychrometric chart at 1 atm total pressure 955
<b>Table A-26</b>	Enthalpy of formation, Gibbs function of formation, and absolute entropy at 25°C, 1 atm 950	<b>Table A-32</b>	One-dimensional isentropic compressible-flow functions for an ideal gas with $k = 1.4$ 956
<b>Table A-27</b>	Properties of some common fuels and hydrocarbons 951	<b>Table A-33</b>	One-dimensional normal-shock functions for an ideal gas with $k = 1.4$ 957
<b>Table A-28</b>	Natural logarithms of the equilibrium constant $K_p$ 952	<b>Table A-34</b>	Rayleigh flow functions for an ideal gas with $k = 1.4$ 958
<b>Figure A-29</b>	Generalized enthalpy departure chart 953		