# **C** o n t e n t s

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

**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

#### CONTENTS

### 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

#### **3–4** Property Diagrams for Phase-Change Processes 118

The *T-v* Diagram 118
 The *P-v* Diagram 120
 Extending the Diagrams to Include the Solid Phase 120
 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 Rates216Conservation of Mass Principle218Mass Balance for Steady-Flow Processes219Special Case: Incompressible Flow220

**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

CONTENTS

## 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<sub>out</sub>? 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,  $\Delta S_{\text{system}}$  375 Mechanisms of Entropy Transfer,  $S_{\text{in}}$  and  $S_{\text{out}}$  376 1 Heat Transfer 376 2 Mass Flow 377 Entropy Generation,  $S_{\text{gen}}$  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