The McGraw Hill Companies



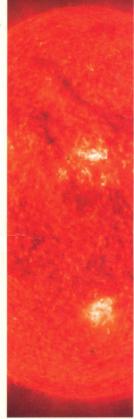


Thermodynamics An Engineering Approach SI Units









Yunus A Çengel | Michael A Boles

For Sale in India, Pakistan, Nepal, Bangladesh, Sri Lanka and Bhutan only

Contents

Preface xvii

Chapter 1

INTRODUCTION AND BASIC CONCEPTS | 1

- 1–1 Thermodynamics and Energy 2 Application Areas of Thermodynamics 3
- 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, 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

ix

x Contents

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_{sat} and P_{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

- 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

Contents | xi

- 6-3 Heat Engines 286 Thermal Efficiency 287 Can We Save Q_{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

Topic of Special Interest: Household Refrigerators 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, ΔS_{system} 384
 Mechanisms of Entropy Transfer, S_{in} and S_{out} 384
 Heat Transfer 384
 Mass Flow 385
 Entropy Generation, S_{gen} 386
 Closed Systems 387
 Control Volumes 387
 Entropy Generation Associated with a Heat Transfer Process 395

of Compressed Air 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, $\eta_{\rm H}$ 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

xii Contents

- 8-7 Exergy Balance: Closed Systems 454
- 8–8 Exergy Balance: Control Volumes 467 Exergy Balance for Steady-Flow Systems 468 Reversible Work, W_{rev} 469 Second-Law Efficiency of Steady-Flow Devices, η_{11} 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_{low,avg}*) 574
 Superheating the Steam to High Temperatures (*Increases T_{high,avg}*) 575
 Increasing the Boiler Pressure (*Increases T_{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

Contents | xiii

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 1 669

- 12–1 A Little Math—Partial Derivatives and Associated Relations 670 Partial Differentials 671 Partial Differential Relations 673
- 012-2 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 Δh, Δu, and Δs 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

- UND MINTORED 1 701
- 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
- 14-7Air-Conditioning Processes749Simple Heating and Cooling ($\omega = \text{constant}$)750Heating with Humidification751Cooling with Dehumidification752Evaporative Cooling754Adiabatic Mixing of Airstreams755Wet Cooling Towers757

Summary 759 References and Suggested Readings 761 Problems 761

Chapter 15

CHEMICAL REACTIONS | 773

- 15-1 Fuels and Combustion 774 B and lot
- 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

5168]

xiv Contents 1

Topic of Special Interest: Fuel Cells 802 Summary 804 References and Suggested Readings 805 Problems 805

Chapter 1

COMPRESSIBLE FLOW 817

- Stagnation Properties 818 16-1
- 16-2 Speed of Sound and Mach Number 821
- 16-3 One-Dimensional Isentropic Flow 823 Variation of Fluid Velocity with Flow Area 826 Property Relations for Isentropic Flow of Ideal Gases 828
- 16-4 Isentropic Flow through Nozzles 830 Converging Nozzles 830 Converging-Diverging Nozzles 835
- 16-5 Shock Waves and Expansion Waves 839 Normal Shocks 839 Oblique Shocks 846 Prandtl-Meyer Expansion Waves 850
- 16-6 Duct Flow with Heat Transfer and Negligible Friction (Rayleigh Flow) 854 Property Relations for Rayleigh Flow 860 Choked Rayleigh Flow 861
- 16-7 Steam Nozzles 863 Summary 866 References and Suggested Readings 867 Problems 868

Appendix

PROPERTY TABLES AND CHARTS 877

- Table A-1 Molar mass, gas constant, and critical point properties 878
- Table A-2 Ideal-gas specific heats of various common gases 879
- Table A-3 Properties of common liquids, solids, and foods 882

Table A-4	Saturated water—Temperature table 884
Table A–5	Saturated water—Pressure table 886
Table A-6	Superheated water 888
Table A-7	Compressed liquid water 892
Table A–8	Saturated ice-water vapor 893
Figure A–9	T-s diagram for water 894
Figure A–10	Mollier diagram for water 895
Table A–11	Saturated refrigerant-134a— Temperature table 896
Table A–12	Saturated refrigerant-134a— Pressure table 898
Table A-13	Superheated refrigerant-134a 899
Figure A–14	<i>P-h</i> diagram for refrigerant- 134a 901
Figure A–15	Nelson–Obert generalized compressibility chart 902
Table A–16	Properties of the atmosphere at high altitude 903
Table A-17	Ideal-gas properties of air 904
Table A–18	Ideal-gas properties of nitrogen, $N_2 = 906$
Table A–19	Ideal-gas properties of oxygen, $O_2 = 908$
Table A-20	Ideal-gas properties of carbon dioxide, CO_2 910
Table A–21	Ideal-gas properties of carbon monoxide, CO 912
Table A–22	Ideal-gas properties of hydrogen, H_2 914
Table A-23	Ideal-gas properties of water vapor, H_2O 915
Table A–24	Ideal-gas properties of monatomic oxygen, O 917
Table A_25	Ideal-gas properties of hydroxyl

Iadie w Ideal-gas properties of hydroxyl, OH 917

Contents | xv

Table A-26Enthalpy of formation, Gibbs
function of formation, and absolute
entropy at 25°C, 1 atm

- Table A-27
 Properties of some common fuels and hydrocarbons
 919
- Table A-28Natural logarithms of the
equilibrium constant K_p 920
- Figure A-29 Generalized enthalpy departure chart 921
- Figure A-30 Generalized entropy departure chart 922

Figure A-31 Psychrometric chart at 1 atm total pressure 923

- Table A-32One-dimensional isentropic
compressible-flow functions for an
ideal gas with k = 1.4924
- Table A-33One-dimensional normal-shock
functions for an ideal gas with
k = 1.4 925

Table A-34Rayleigh flow functions for an ideal
gas with k = 1.4 926

Index 927

The McGraw Hill Companies



Thermodynamics An Engineering Approach SI Units

This new edition of the bestseller, *Thermodynamics: An Engineering Approach* brings further refinement to an approach that emphasizes a physical understanding of the fundamental concepts of thermodynamics in a simple yet precise manner. A genuine attempt has been made to offer a text that caters directly to tomorrow's engineers.

Salient features

- \Rightarrow In SI units
- ⇒ Stress on the physical aspects of the subject matter in addition to mathematical representations and manipulations
- ⇒ Early introduction of First law of thermodynamics helps in setting the framework for understanding various forms of energy, mechanism of energy transfer, and balance of energy
- \Rightarrow More than 700 new comprehensive problems
- ⇒ Hundreds of industry-related problems for better understanding of concepts
- ⇒ Excellent pedagogy includes
 - 2462 Real-world end-of-chapter problems
 - 200 Solution procedure

URL: http://www.mhhe.com/cengel/thermodynamics6esi



Tata McGraw-Hill

Visit us at : www.tatamcgrawhill.com

