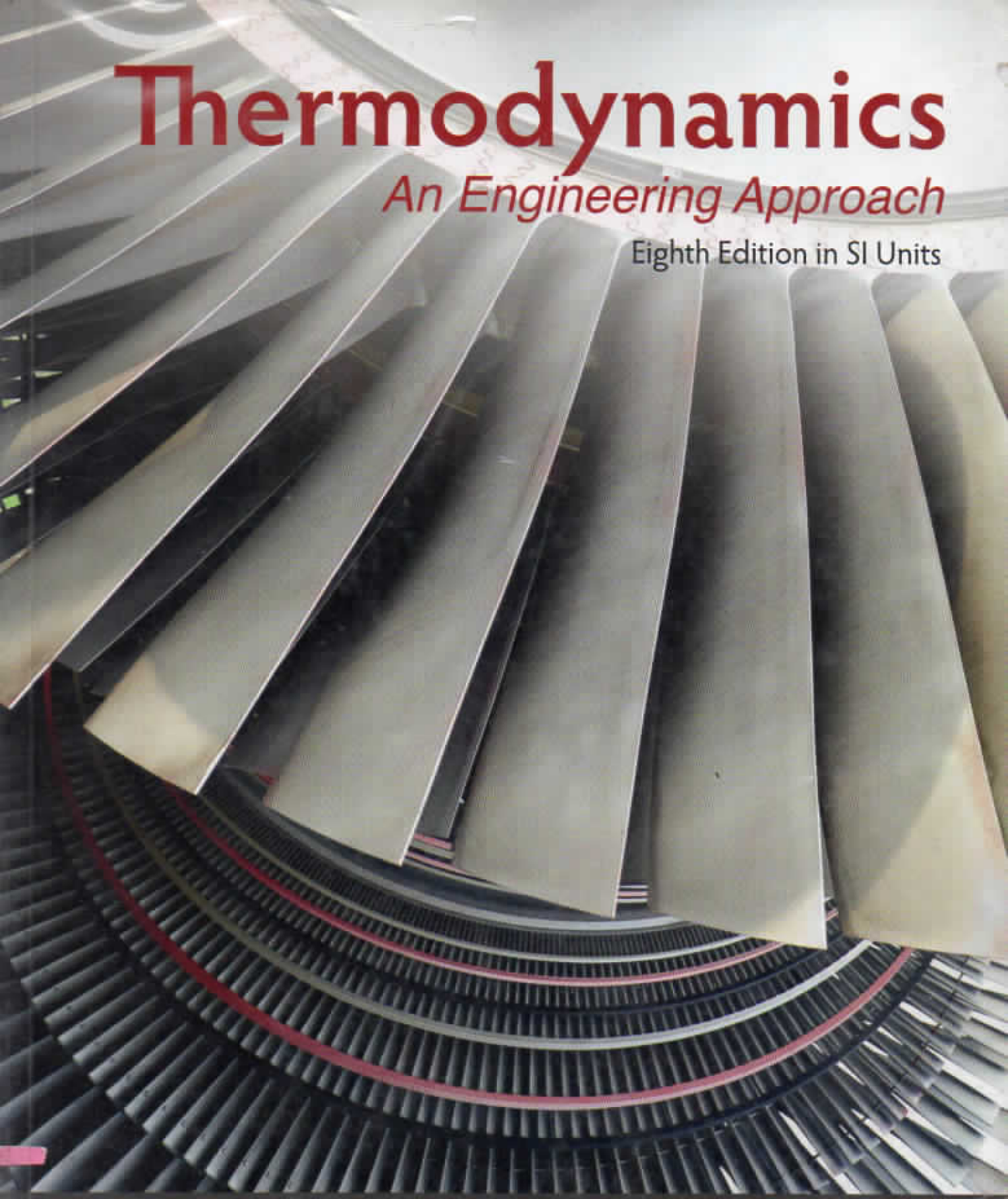
Thermodynamics

An Engineering Approach

Eighth Edition in SI Units



Yunus A. Çengel, Michael A. Boles

Ref
536.7
C549
2019
c

THERMODYNAMICS

-1875-m

AN ENGINEERING APPROACH

EIGHTH EDITION IN SI UNITS

CONTENTS

Preface xxii

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 12

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 22
Variation of Pressure with Depth 24

1–10 Pressure Measurement Devices 27
The Barometer 27
The Manometer 30
Other Pressure Measurement Devices 33

1–11 Problem-Solving Technique 34
Step 1: Problem Statement 34
Step 2: Schematic 35
Step 3: Assumptions and Approximations 35
Step 4: Physical Laws 35
Step 5: Properties 35
Step 6: Calculations 35
Step 7: Reasoning, Verification, and Discussion 35
Engineering Software Packages 36
Engineering Equation Solver (EES) 37
A Remark on Significant Digits 39
Summary 40
References and Suggested Readings 41
Problems 41

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 70

2–6 The First Law of Thermodynamics 70
Energy Balance 72
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 85
Ozone and Smog 86
Acid Rain 87
The Greenhouse Effect: Global Warming and Climate Change 88

Topic of Special Interest: Mechanisms of Heat Transfer 91
Summary 96
References and Suggested Readings 97
Problems 97

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* Diagram 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 138
3–8 Other Equations of State 141
van der Waals Equation of State 142
Beattie-Bridgeman Equation of State 142
Benedict-Webb-Rubin Equation of State 143
Virial Equation of State 144
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 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 213

5–1 Conservation of Mass 214
Mass and Volume Flow Rates 214
Conservation of Mass Principle 216
Mass Balance for Steady-Flow Processes 218
Special Case: Incompressible Flow 219
5–2 Flow Work and the Energy of a Flowing Fluid 221
Total Energy of a Flowing Fluid 222
Energy Transport by Mass 223
5–3 Energy Analysis of Steady-Flow Systems 225
5–4 Some Steady-Flow Engineering Devices 228
1 Nozzles and Diffusers 229
2 Turbines and Compressors 232
3 Throttling Valves 234
4a Mixing Chambers 236
4b Heat Exchangers 238
5 Pipe and Duct Flow 240
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 275

6–1 Introduction to the Second Law 276
6–2 Thermal Energy Reservoirs 277
6–3 Heat Engines 278
Thermal Efficiency 279
Can We Save Q_{out}? 281
The Second Law of Thermodynamics: Kelvin–Planck Statement 283
6–4 Refrigerators and Heat Pumps 283
Coefficient of Performance 284
Heat Pumps 285
Performance of Refrigerators, Air-Conditioners, and Heat Pumps 286
The Second Law of Thermodynamics: Clausius Statement 288
Equivalence of the Two Statements 289
6–5 Perpetual-Motion Machines 290
6–6 Reversible and Irreversible Processes 292
Irreversibilities 293
Internally and Externally Reversible Processes 294
6–7 The Carnot Cycle 295
The Reversed Carnot Cycle 297
6–8 The Carnot Principles 297
6–9 The Thermodynamic Temperature Scale 299
6–10 The Carnot Heat Engine 301
The Quality of Energy 302
Quantity versus Quality in Daily Life 303
6–11 The Carnot Refrigerator and Heat Pump 304
Topic of Special Interest: Household Refrigerators 307
Summary 311
References and Suggested Readings 312
Problems 312

CHAPTER SEVEN
ENTROPY 329

7–1 Entropy 330
A Special Case: Internally Reversible Isothermal Heat Transfer Processes 333
7–2 The Increase of Entropy Principle 334
Some Remarks about Entropy 336
7–3 Entropy Change of Pure Substances 337
7–4 Isentropic Processes 340
7–5 Property Diagrams Involving Entropy 342
7–6 What Is Entropy? 343
Entropy and Entropy Generation in Daily Life 346
7–7 The $T\,ds$ Relations 347
7–8 Entropy Change of Liquids and Solids 349
7–9 The Entropy Change of Ideal Gases 352
Constant Specific Heats (Approximate Analysis) 353
Variable Specific Heats (Exact Analysis) 353
Isentropic Processes of Ideal Gases 355
Constant Specific Heats (Approximate Analysis) 355
Variable Specific Heats (Exact Analysis) 356
Relative Pressure and Relative Specific Volume 356
7–10 Reversible Steady-Flow Work 359
Proof that Steady-Flow Devices Deliver the Most and Consume the Least Work When the Process is Reversible 362
7–11 Minimizing the Compressor Work 363
Multistage Compression with Intercooling 364
7–12 Isentropic Efficiencies of Steady-Flow Devices 367
Isentropic Efficiency of Turbines 367
Isentropic Efficiencies of Compressors and Pumps 369
Isentropic Efficiency of Nozzles 371
7–13 Entropy Balance 373
Entropy Change of a System, ΔS_{system} 374
Mechanisms of Entropy Transfer, S_{in} and S_{out} 374
1 Heat Transfer 374
2 Mass Flow 375
Entropy Generation, S_{gen} 376
Closed Systems 377
Control Volumes 378
Entropy Generation Associated with a Heat Transfer Process 385
Topic of Special Interest: Reducing the Cost of Compressed Air 386
Summary 395
References and Suggested Readings 396
Problems 397

CHAPTER EIGHT
EXERGY 421

8–1 Exergy: Work Potential of Energy 422
Exergy (Work Potential) Associated with Kinetic and Potential Energy 423
8–2 Reversible Work and Irreversibility 425

8–3 Second-Law Efficiency 430

8–4 Exergy Change of a System 433

Exergy of a Fixed Mass: Nonflow (or Closed System) Exergy 433

Exergy of a Flow Stream: Flow (or Stream) Exergy 436

8–5 Exergy Transfer by Heat, Work, And Mass 438

Exergy by Heat Transfer, Q 439

Exergy Transfer by Work, W 440

Exergy Transfer by Mass, m 440

8–6 The Decrease of Exergy Principle and Exergy Destruction 441

Exergy Destruction 442

8–7 Exergy Balance: Closed Systems 443

8–8 Exergy Balance: Control Volumes 454

Exergy Balance for Steady-Flow Systems 455

Reversible Work 456

Second-Law Efficiency of Steady-Flow Devices 456

Topic of Special Interest: Second-Law Aspects of Daily Life 463

Summary 467

References and Suggested Readings 468

Problems 468

CHAPTER NINE

GAS POWER CYCLES 485

9–1 Basic Considerations in the Analysis of Power Cycles 486

9–2 The Carnot Cycle and its Value in Engineering 488

9–3 Air-Standard Assumptions 490

9–4 An Overview of Reciprocating Engines 490

9–5 Otto Cycle: The Ideal Cycle for Spark-Ignition Engines 492

9–6 Diesel Cycle: The Ideal Cycle for Compression-Ignition Engines 499

9–7 Stirling and Ericsson Cycles 502

9–8 Brayton Cycle: The Ideal Cycle for Gas-Turbine Engines 506

Development of Gas Turbines 509

Deviation of Actual Gas-Turbine Cycles from Idealized Ones 512

9–9 The Brayton Cycle with Regeneration 513

9–10 The Brayton Cycle with Intercooling, Reheating, and Regeneration 516

9–11 Ideal Jet-Propulsion Cycles 520

Modifications to Turbojet Engines 524

9–12 Second-Law Analysis of Gas Power Cycles 526

Topic of Special Interest: Saving Fuel and Money by Driving Sensibly 530

Summary 536

References and Suggested Readings 538

Problems 538

CHAPTER TEN

VAPOR AND COMBINED POWER CYCLES 553

10–1 The Carnot Vapor Cycle 554

10–2 Rankine Cycle: The Ideal Cycle for Vapor Power Cycles 555

Energy Analysis of the Ideal Rankine Cycle 555

10–3 Deviation of Actual Vapor Power Cycles from Idealized Ones 558

10–4 How Can We Increase the Efficiency of the Rankine Cycle? 561

Lowering the Condenser Pressure (*Lowers* $T_{low,avg}$) 561

Superheating the Steam to High Temperatures (*Increases* $T_{high,avg}$) 562

Increasing the Boiler Pressure (*Increases* $T_{high,avg}$) 562

10–5 The Ideal Reheat Rankine Cycle 565

10–6 The Ideal Regenerative Rankine Cycle 569

Open Feedwater Heaters 569

Closed Feedwater Heaters 571

10–7 Second-Law Analysis of Vapor Power Cycles 577

10–8 Cogeneration 579

10–9 Combined Gas–Vapor Power Cycles 584

Topic of Special Interest: Binary Vapor Cycles 587

Summary 589

References and Suggested Readings 590

Problems 590

CHAPTER ELEVEN
REFRIGERATION CYCLES 607

11–1 Refrigerators and Heat Pumps 608
11–2 The Reversed Carnot Cycle 609
11–3 The Ideal Vapor-Compression Refrigeration Cycle 610
11–4 Actual Vapor-Compression Refrigeration Cycle 613
11–5 Second-Law Analysis of Vapor-Compression Refrigeration Cycle 615
11–6 Selecting the Right Refrigerant 620
11–7 Heat Pump Systems 622
11–8 Innovative Vapor-Compression Refrigeration Systems 623
Cascade Refrigeration Systems 624
Multistage Compression Refrigeration Systems 626
Multipurpose Refrigeration Systems with a Single Compressor 628
Liquefaction of Gases 629
11–9 Gas Refrigeration Cycles 630
11–10 Absorption Refrigeration Systems 633
Topic of Special Interest: Thermoelectric Power Generation and Refrigeration Systems 636
Summary 638
References and Suggested Readings 639
Problems 639

CHAPTER TWELVE
THERMODYNAMIC PROPERTY RELATIONS 655

12–1 A Little Math—Partial Derivatives and Associated Relations 656
Partial Differentials 657
Partial Differential Relations 659
12–2 The Maxwell Relations 661
12–3 The Clapeyron Equation 662
12–4 General Relations For du, dh, ds, c_v, and c_p 665
Internal Energy Changes 666
Enthalpy Changes 666
Entropy Changes 667
Specific Heats c_v and c_p 668
12–5 The Joule-Thomson Coefficient 672
12–6 The Δh, Δu, and Δs of Real Gases 674
Enthalpy Changes of Real Gases 674
Internal Energy Changes of Real Gases 675
Entropy Changes of Real Gases 676
Summary 679
References and Suggested Readings 680
Problems 680

CHAPTER THIRTEEN
GAS MIXTURES 687

13–1 Composition of a Gas Mixture: Mass and Mole Fractions 688
13–2 P-v-T Behavior of Gas Mixtures: Ideal and Real Gases 690
Ideal-Gas Mixtures 691
Real-Gas Mixtures 692
13–3 Properties of Gas Mixtures: Ideal and Real Gases 695
Ideal-Gas Mixtures 696
Real-Gas Mixtures 700
Topic of Special Interest: Chemical Potential and the Separation Work of Mixtures 704
Summary 714
References and Suggested Readings 715
Problems 716

CHAPTER FOURTEEN
GAS–VAPOR MIXTURES AND AIR-CONDITIONING 725

14–1 Dry and Atmospheric Air 726
14–2 Specific and Relative Humidity of Air 727
14–3 Dew-Point Temperature 729
14–4 Adiabatic Saturation and Wet-Bulb Temperatures 731
14–5 The Psychrometric Chart 734
14–6 Human Comfort and Air-Conditioning 735
14–7 Air-Conditioning Processes 737
Simple Heating and Cooling (ω = constant) 738
Heating with Humidification 739
Cooling with Dehumidification 740
Evaporative Cooling 742

Adiabatic Mixing of Airstreams 743
Wet Cooling Towers 745

Summary 747
References and Suggested Readings 748
Problems 749

CHAPTER FIFTEEN
CHEMICAL REACTIONS 759

15–1 Fuels and Combustion 760

15–2 Theoretical and Actual Combustion Processes 764

15–3 Enthalpy of Formation and Enthalpy of Combustion 771

15–4 First-Law Analysis of Reacting Systems 774

Steady-Flow Systems 775
Closed Systems 776

15–5 Adiabatic Flame Temperature 780

15–6 Entropy Change of Reacting Systems 782

15–7 Second-Law Analysis of Reacting Systems 784

Topic of Special Interest: Fuel Cells 790
Summary 792
References and Suggested Readings 793
Problems 793

CHAPTER SIXTEEN
CHEMICAL AND PHASE EQUILIBRIUM 805

16–1 Criterion for Chemical Equilibrium 806

16–2 The Equilibrium Constant for Ideal-Gas Mixtures 808

16–3 Some Remarks about the K_p of Ideal-Gas Mixtures 812

16–4 Chemical Equilibrium for Simultaneous Reactions 816

16–5 Variation of K_p with Temperature 818

16–6 Phase Equilibrium 820

Phase Equilibrium for a Single-Component System 820
The Phase Rule 822
Phase Equilibrium for a Multicomponent System 822

Summary 828
References and Suggested Readings 829
Problems 829

CHAPTER SEVENTEEN
COMPRESSIBLE FLOW 839

17–1 Stagnation Properties 840

17–2 Speed of Sound and Mach Number 843

17–3 One-Dimensional Isentropic Flow 845

Variation of Fluid Velocity with Flow Area 847
Property Relations for Isentropic Flow of Ideal Gases 849

17–4 Isentropic Flow Through Nozzles 851

Converging Nozzles 852
Converging–Diverging Nozzles 856

17–5 Shock Waves and Expansion Waves 860

Normal Shocks 860
Oblique Shocks 866
Prandtl–Meyer Expansion Waves 870

17–6 Duct Flow with Heat Transfer and Negligible Friction (Rayleigh Flow) 875

Property Relations for Rayleigh Flow 881
Choked Rayleigh Flow 882

17–7 Steam Nozzles 884

Summary 887
References and Suggested Readings 888
Problems 889

CHAPTER EIGHTEEN (WEB CHAPTER)
RENEWABLE ENERGY

18–1 Introduction

18–2 Solar Energy

Solar Radiation
Flat-Plate Solar Collector
Concentrating Solar Collector
Linear Concentrating Solar Power Collector
Solar-Power Tower Plant
Solar Pond
Photovoltaic Cell
Passive Solar
Applications
Solar Heat Gain through Windows

18-3 Wind Energy
Wind Turbine Types and Power Performance Curve
Wind Power Potential
Wind Power Density
Wind Turbine Efficiency
Betz Limit for Wind Turbine Efficiency
18-4 Hydropower
Analysis of Hydroelectric Power Plant
Turbine Types
18-5 Geothermal Energy
Geothermal Power Production
18-6 Biomass Energy
Biomass Resources
Conversion of Biomass to Biofuel
Biomass Products
Electricity and Heat Production by Biomass
Solid Municipality Waste
Summary
References and Suggested Readings
Problems

APPENDIX

PROPERTY TABLES AND CHARTS 897

Table A–1 Molar mass, gas constant, and critical-point properties 898
Table A–2 Ideal-gas specific heats of various common gases 899
Table A–3 Properties of common liquids, solids, and foods 902
Table A–4 Saturated water—Temperature table 904
Table A–5 Saturated water—Pressure table 906
Table A–6 Superheated water 908
Table A–7 Compressed liquid water 912
Table A–8 Saturated ice–water vapor 913
Figure A–9 *T-s* diagram for water 914
Figure A–10 Mollier diagram for water 915
Table A–11 Saturated refrigerant-134a—Temperature table 916
Table A–12 Saturated refrigerant-134a—Pressure table 918
Table A–13 Superheated refrigerant-134a 919
Figure A–14 *P-h* diagram for refrigerant-134a 921
Figure A–15 Nelson–Obert generalized compressibility chart 922
Table A–16 Properties of the atmosphere at high altitude 923
Table A–17 Ideal-gas properties of air 924
Table A–18 Ideal-gas properties of nitrogen, N_2 926
Table A–19 Ideal-gas properties of oxygen, O_2 928
Table A–20 Ideal-gas properties of carbon dioxide, CO_2 930
Table A–21 Ideal-gas properties of carbon monoxide, CO 932
Table A–22 Ideal-gas properties of hydrogen, H_2 934
Table A–23 Ideal-gas properties of water vapor, H_2O 935
Table A–24 Ideal-gas properties of monatomic oxygen, O 937
Table A–25 Ideal-gas properties of hydroxyl, OH 937
Table A–26 Enthalpy of formation, Gibbs function of formation, and absolute entropy at 25°C, 1 atm 938
Table A–27 Properties of some common fuels and hydrocarbons 939
Table A–28 Natural logarithms of the equilibrium constant K_p 940
Figure A–29 Generalized enthalpy departure chart 941
Figure A–30 Generalized entropy departure chart 942
Figure A–31 Psychrometric chart at 1 atm total pressure 943
Table A–32 One-dimensional isentropic compressible-flow functions for an ideal gas with $k = 1.4$ 944
Table A–33 One-dimensional normal-shock functions for an ideal gas with $k = 1.4$ 945
Table A–34 Rayleigh flow functions for an ideal gas with $k = 1.4$ 946

INDEX 947

INDEX

Absolute entropy, 344, 783
Absolute gas temperature scale, 19
Absolute pressure, 23
Absolute temperatures, 300
Absorption refrigeration systems, 633–635
Absorptivity, 94
Acid rain, 87–88
Actual vapor compression refrigeration cycle, 613–615
Adiabatic flame temperature, 780–782
Adiabatic mixing of airstreams, 743–745
Adiabatic process, 60–61
Adiabatic saturation temperature, 731–734
Afterburner, 526
Air-conditioning processes, 737–747
  adiabatic mixing of airstreams, 743–745
  cooling with dehumidification, 740–742
  evaporative cooling, 742–743
  heating with humidification, 739–740
  simple heating and cooling, 738
  wet cooling towers, 745–747
Air-fuel ratio, 763
Air-standard assumptions, 480
Amagat's law of additive volumes, 690
Ampere (A), 5
Annual fuel utilization efficiency (AFUE), 79
Atmospheric air, 726–727
Average velocity, 214

Back pressure, 851
Back work ratio, 508–509
Barometer, 27
Barometric pressure, 27
Beattie-Bridgeman equation of state, 142–143
Benedict-Webb-Rubin equation of state, 143–144
Bernoulli equation, 360
Binary vapor cycles, 587–589
Biological systems, 187–194
  thermodynamic aspects of, 187–194
Blackbody, 94
Blackbody radiation, 94
Body mass index, 193
Boiler pressure, 562–565
Boiling, 148–149
Boltzmann constant, 94, 344
Boltzmann relation 344
Bore, 491
Bottom dead center (BDC), 491
Boundary, 10
Bourdon tube, 33
Bow wave, 868
Brayton cycle, 506–513, 513–515, 516–520
  actual gas-turbine cycles versus idealized, 512–513
  back work ratio, 508–509
  closed cycle, 506
  effectiveness ε, 514
  efficiency, 509–510
  gas turbines, development, 509–511
  with intercooling, reheating, and regeneration, 516–520
  open cycle, 506
  pressure ratio, 507
  with regeneration, 513–515
British thermal unit (Btu), 7

Caloric theory, 61–62
Candela (cd), 5
Carnot cycle, 295–297, 488–490
  Carnot heat engine, 295
  Carnot refrigeration cycle, 297
  definition, 295
  reversed Carnot cycle, 297
  reversible adiabatic compression, 296
  reversible adiabatic expansion, 296
  reversible isothermal compression, 296
  reversible isothermal expansion, 296
Carnot efficiency, 301
Carnot heat engine, 295, 301–304
  Carnot efficiency, 301
  quality, 302–303
  quantity versus quality, daily life, 303–304
  thermal efficiency, 302
Carnot principles, 297–298
Carnot refrigeration cycle, 297
Carnot refrigerator and heat pump, 304–307, 609–610
Carnot vapor cycle, 554
Cascade refrigeration systems, 624–626
Celsius scale, 18
Change of system, 374
Chemical energy, 55
Chemical equilibrium, 15, 806–837
  criterion, 806–808
  ideal-gas mixtures constant, 808–812, 812–816
  multicomponent system, 822–828
  phase equilibrium, 820–828
  phase rule, 822
  simultaneous reactions, 816–818
  single component system, 820–822
  temperature, variations of constant with, 818–820
Chemical potential, 705
Chemical reactions, 759–803
  adiabatic flame temperature, 780–782
  closed systems, 776–779
  enthalpy, formation and combustion, 771–774
  entropy change of reacting systems, 782–784
  first-law analysis of reacting systems, 774–779
  fuel cells, 790–791
  fuels and combustion, 760–764
  second-law analysis of reacting systems, 784–790
  steady-flow systems, 775–776
  theoretical and actual combustion processes, 764–770
Choke, 855
Clapeyron-Clausius equation, 664–665
Clapeyron equation, 662–665
Classical thermodynamics, 3
Clausius inequality, 330–333
Clausius statement, 288–289
  equivalency with Kelvin-Planck statement, 289–290
Clearance volume, 491
Closed cycle, 506
Closed feedwater heater, 571
Closed system, 10, 377–378, 435, 443–454
  chemical reactions, 776–779
  exergy balance, 443–454
Coefficient of performance, 284–285
Cogeneration, 579–584
Combined gas-vapor power cycles, 584–587
Combustion processes, theoretical and actual, 764–770
  deficiency of air, 765
  equivalence ratio, 765
  excess air, 765
  percent deficiency of air, 765
  percent excess air, 765
  percent theoretical air, 765
  stoichiometric air, 764
  theoretical air, 764
Component pressure, 691
Component volume, 691
Compressed air, 386–394
Compressed liquid and saturated liquid, 114
Compressed liquid property tables of pure substances, 131–132
Compressed liquid water property tables, 912, 962
Compressibility factor (Z), 138–141
  definition, 138
  principle of corresponding states, 138–139
  reduced pressure, 138
  reduced temperature, 138
Compressible flow, 839–896
  converging-diverging nozzles, 856–860
  converging nozzles, 852–856
  duct flow, heat transfer, negligible friction (Rayleigh flow), 875–884
  isentropic flow through nozzles, 851–860
  normal shock waves, 860–866
  oblique shock waves, 866–870
  one-dimensional isentropic flow, 845–851
  Prandtl-Meyer expansion waves, 870–875
  property relations, isentropic flow of ideal gases, 849–851
  Rayleigh flow, property relations, 881–882
  Rayleigh flow, choked, 882–884
  shock waves, 860–870
  speed of sound and Mach number, 843–845
  stagnation properties, 840–843
  steam nozzles, 884–887
  variation of fluid velocity with flow area, 847–849
Compressing flow, 870
Compression ignition (CI) engines, 491
Compression ratio, 495
Compressors, 363–366
Condenser pressure, 561
Conduction, 62, 91

Consequences of T_{sat} and P_{sat} dependence, 116–118
package icing, 118
vacuum cooling, 117
vacuum freezing, 118
Conservation of energy principle, 2, 70, 71, 247
Conservation of mass, 214–221
average velocity, 214
conservation of mass principle, 216–218
incompressible flow, 219–221
mass and volume flow rates, 214–216
mass balance for steady-flow processes, 218–219
moving or deforming control volumes, 218
Conservation of mass principle, 216–218, 762
definition, 216
mass balance, 216, 762
Constant-pressure quasi-equilibrium process, 172
Constant specific heat, 353, 355–356
Constant volume gas thermometer, 19
Continuum, 12–13
Control mass, 10
Control surface, 11
Control volume, 10–13, 213–256, 378–385, 454–463
conservation of mass, 214–221
conservation of mass principle, 216–218
definition, 11
energy transport by mass, 223–225
entropy, 378–385
exergy balance, 454–463
flow work, 221–225
general energy equation, 247–250
heat exchangers, 238–240
incompressible flow, 219–221
mass and volume control rates, 214–216
mass balance for steady-flow processes, 218–219
mixing chambers, 236–237
moving or deforming control volumes, 218
nozzles and diffusers, 229–231
pipe and duct flow, 240–242
steady flow engineering devices, 228–242
steady flow systems, 225–228
systems, 10–12
throttling valves, 234–236
total energy, flowing fluid, 222–223
turbines and compressors, 231–234
unsteady-flow processes, 242–247
Convection, 62, 92
Convection heat transfer coefficient, 93
Converging-diverging nozzles, 847, 856–860
Converging nozzles, 852–856
Conversion efficiencies, 78–85
annual fuel utilization efficiency (AFUE), 79
cooking appliance, 80
environment, 81
generator, 79, 83
higher heating value (HHV), 79
lighting efficacy, 80
lower heating value (LHV), 78
mechanical and electrical devices, 82–84
motor, 83
pump, 82
turbine, 82
water heater, 78
Conversion ratios, units, 9–10
Cooking appliance efficiency, 80
Cooling pond, 746
Cooling with dehumidification, 740–742
Coulomb repulsion, 57
Criterion for chemical equilibrium, 806–808
Critical properties, 850
Critical ratios, 850
Cycle, 16

Daily calorie needs, 190
Dalton's law of additive pressures, 690
Dead state, 422
Deadweight tester, 34
Decrease of exergy principle, 441–442
Deficiency of air, 765
Deflection angle, 866
Degree Kelvin (°K), 5
Density, 13
Density and specific gravity, 13–14
density, 13
relative density, 14
specific gravity, 14
specific weight, 14
Desalination processes, 712–714
osmotic pressure, 712
osmotic rise, 712
Destruction, exergy, 441–442
Detached oblique shock wave, 868
Mach angle, 870
Mach wave, 870
Dew-point temperature, 729–731
Diesel cycle, 499–502
dual cycle, 500
Diffusers, 229–231
Dimensional homogeneity, 8
Dimensions, 3–10
primary (fundamental), 3
secondary (derived), 3
Direct-contact feedwater heater, 569
Displacement volume, 491
Dry air, 726–727
Duct flow, heat transfer, negligible friction (Rayleigh flow), 875–884
Rayleigh flow, 875
Rayleigh flow, choked, 882–884
Rayleigh flow property relations, 881–882
Rayleigh line, 877
Dynamic temperature, 841

Effectiveness ε, 514
Efficiency, 509–510
Efficiency, Rankine cycle
boiler pressure, 562–565
condenser pressure, 561
superheated steam, 562
Elastic solid bars, 67–68
Electrical power (W_e), 65
Electrical work, 65
Emissivity, 94
Energy, 51–110
balance, 72
change of a system, 72–73, 433–438
conservation, 52–53
conversion efficiencies, 78–85
and environment, 85–91
first law of thermodynamics, 70–77
forms, 53–59
heat transfer, 60–62, 91–96
introduction, 52–53
mechanical, 66–70
and thermodynamics, 2–3
transfer mechanisms, 73–77
work, 62–65
Energy analysis, 163–211
energy balance, 169–174
enthalpy changes, 184–187
internal energy changes, 184
internal energy, enthalpy, and specific heats of ideal gases, 176–183
internal energy, enthalpy, and specific heats of solids and liquids, 183–187
moving boundary work, 164–169
polytropic process, 168–169
specific heat, ideal gases, 178–183
specific heats, 174–176
steady flow systems, 225–228
Energy balance, 169–174
constant-pressure quasi-equilibrium process, 172
Energy efficiency ratio (EER), 286–288
Energy forms, 53–59
chemical, 55
Coulomb repulsion, 57
heat transfer, 56
internal (U), 53
kinetic (KE), 53–54
latent, 55
macroscopic, 53
mechanical, 58–59
microscopic, 53
nuclear, 55–57
potential, 54
unsteady-flow processes, 242–247
volume flow rate, 54
work, 56, 62–65
Energy transfer mechanisms, 73–77
heat transfer, 73
mass flow, 73
work transfer, 73
Engineering equation solver (EES), 37–39
Engineering software packages, 36–37
English units, 6–8
property tables, 948–987
Enthalpy, 125–126, 176–183, 183–187
changes, 184–187
internal energy and specific heats of ideal gases, 176–183
internal energy and specific heats of solids and liquids, 183–187
Enthalpy changes of real gases, 674–675
Enthalpy changes, thermodynamic property relations, 666–667
Enthalpy departure, thermodynamic property relations, 675
Enthalpy, formation and combustion, 771–774
enthalpy of reaction, 772
heating value, 773
higher heating value (HHV), 773
lower heating value (LHV), 773
Enthalpy of formation, Gibbs function of formation
and absolute entropy at 25°C, 1 atm, 937
and absolute entropy at 77°C, 1 atm, 985
Enthalpy of gas mixtures, 705
Enthalpy of reaction, 772
Enthalpy of vaporization property tables of pure substances, 126

Entropy, 329–420
absolute entropy, 344
balance, 373–386
Bernoulli equation, 360
Boltzmann constant, 344
change of pure substances, 337–340
Clausius inequality, 330–333
compressors, 363–366
constant specific heat, 353, 355–356
in daily life, 346–347
definition, 332
ideal gases, entropy change in, 352–359
increase of entropy principle, 334–337
internally reversible isothermal heat transfer processes, 333
isentropic efficiencies, 367–373
isentropic efficiency of a compressor, 369–371
isentropic efficiency of nozzles, 371–373
isentropic efficiency of turbines, 367–368
isentropic processes, 340–342, 355
liquids and solids, entropy changes in, 349–352
molecular disorder, 344–345
multistage compression with intercooling, 364–366
property diagrams, 342–343
relative pressure, 356–359
relative specific volume, 356–359
reversible adiabatic process, 341
reversible steady-flow work, 359–363
second law of thermodynamics, 330–333
T ds relations, 347–348
third law of thermodynamics, 344–345
variable specific heat, 353–355, 356
Entropy balance, 373–394
change of system, 374
closed systems, 377–378
compressed air, 386–394
control volumes, 378–385
generation of, 376–377, 385–386
heat transfer, 374–375, 385–386
mass flow, 375–376
mechanisms of transfer, 374–376
Entropy change of reacting systems, 782–784
absolute entropy, 783
third law of thermodynamics, 783
Entropy changes, thermodynamic property relations, 667–668
Entropy changes of real gases, 676–678
Entropy departure, 678
Entropy of gas mixtures, 705
Environment, 81, 85–91
acid rain, 87–88
greenhouse effect, 88–91
ozone and smog, 86–87
Equation of state, 135
Equilibrium, 14
Equivalence ratio, 765
Evaporation, 148
Evaporative coolers, 148
Evaporative cooling, 742–743
Exact differentials, 63
Excess air, 765
Exergy, 421–484
balance, 443–463
closed system (nonflow), 435
in daily life, 463–466
dead state, 422
decrease of exergy principle, 441–442
definition, 422
destruction, 441–442, 784
energy change of a system, 433–438
fixed mass, 433–435
flow (stream), 436–438
heat transfer, 439–440
irreversibility, 425–430
kinetic and potential energy, 423–425
mass transfer, 440–441
reversible work, 425–430
second law efficiency, 430–433
surroundings work, 426
transfer, 438–441
work potential, 422–425
work transfer, 440
Exergy balance, 443–463
closed systems, 443–454
control volumes, 454–463
definition, 443
rate form, 443
reversible work, 456
second-law efficiency, steady-flow devices, 456–463
steady-flow systems, 455–456
Exhaust blowdown, 492–493
Exhaust valve, 491
Expanding flow, 870
Expansion fan, 870
Extension diagrams for solid phases, 120–122
sublimation, 122
triple point, 121
Extensive properties, 12
External combustion, 506
Externally reversible, 295

Fahrenheit scale, 18
Feedwater heater (FWH), 569
closed, 571
direct-contact, 569
open, 569
First-law analysis of reacting systems, 774–779
closed systems, 776–779
steady-flow systems, 775–776
First law of thermodynamics, 2, 70–77
conservation of energy principle, 70, 71
energy balance, 72
energy change of a system, 72–73
energy transfer mechanisms, 73–77
general energy equation, 247
Fixed mass, 433–435
Flow (stream), 436–438
Flow work, 221–225
energy transport by mass, 223–225
flow energy, 221
total energy, 222–223
Force (*F*), 66
Forced convection, 93
Formal sign convention, 63
Fourier's law, 92
Four-stroke combustion engine, 492
Free (natural) convection, 93
Friction, 293
Fuel cells, 790–791
Fuel efficiency, 530–536
Fuels and combustion, 760–764
air-fuel ratio, 763
conservation of mass principle, 762
hydrocarbon fuels, 760
ignition temperature, 762
mass balance, 762
octane, 760
products, 762
reactants, 762

Gas, 113
Gas mixtures, 687–723
Amagat's law of additive volumes, 690
Dalton's law of additive pressures, 690
desalination processes, 712–714
ideal and real gas behavior, 690–695
ideal and real gas properties, 695–703
ideal-gas mixtures, 691, 696–700, 706–708
mass and mole fractions, 688–690
minimum work of separation of mixtures, 708–710
real-gas mixtures, 692–695, 700–714
reversible mixing processes, 710
second-law efficiency, 710–711
separation of a two component mixture, 711
Gas power cycles, 485–552
actual gas-turbine cycles versus idealized, 511–512
air-standard assumptions, 480
analysis, 486–488
Brayton cycle, 506–513, 513–515, 516–520
Carnot cycle, 488–490
Diesel cycle, 499–502
fuel efficiency, 530–536
gas turbine development, 509–511
idealizations and simplifications, 487
jet propulsion cycles, 520–526
Otto cycle, 492–498
reciprocating engines, 490–491
second-law analysis, 526–529
Stirling and Ericsson cycles, 502–506
Gas refrigeration cycles, 630–633
Gas turbines, development, 509–511
Gas-vapor mixtures, 725–758
absolute (specific) humidity, 727–729
adiabatic mixing of airstreams, 743–745
adiabatic saturation temperature, 731–734
air-conditioning processes, 737–747
atmospheric air, 726–727
cooling with dehumidification, 740–742
dew-point temperature, 729–731
dry air, 726–727
evaporative cooling, 742–743
heating with humidification, 739–740
human comfort and air conditioning, 735–737
psychrometric charts, 734–735
relative humidity, 727–729
saturated air, 727
simple heating and cooling, 738
specific humidity, 727–729
wet-bulb temperature, 732–734
wet cooling towers, 745–747
General Conference of Weights and Measures, 5
General energy equation, 247–250
Generalized enthalpy departure chart, 940
Generalized entropy departure chart, 941
Generation of entropy balance, 376–377, 385–386
Generator, efficiency 79, 83
Gibbs-Dalton law, 696
Gibbs equation, 348
Gibbs' formulation 344

Gibbs function, 661, 784, 807
Gibbs phase rule, 822
Gravitation force, 7
Greenhouse effect, 88–91

Heat engines, 278–283
  Kelvin-Planck statement, 283
  Q_{out}, 281–283
  thermal efficiency, 279–281
  working fluid, 278
Heat exchangers, 238–240
Heating value, 773
Heating with humidification, 739–740
Heat pumps, 285–286
  coefficient of performance, 608
  and refrigerators, 608–609
Heat pump systems, 622–623
Heat transfer, 56, 60–62, 73, 374–375, 385–386
  adiabatic process, 60–61
  caloric theory, 61–62
  conduction, 62
  convection, 62
  entropy, 374–375, 385–386
  exergy, 439–440
  irreversibility, 294
  kinetic energy, 61
  radiation, 62
Heat transfer, mechanisms of, 91–96
  absorptivity, 94
  blackbody, 94
  blackbody radiation, 94
  Boltzmann constant, 94
  conduction, 91
  convection, 92
  convection heat transfer coefficient, 93
  emissivity, 94
  forced convection, 93
  Fourier's law, 92
  free (natural) convection, 93
  Kirchhoff's law, 94
  Newton's law of cooling, 93
  radiation, 93
  thermal conductivity, 91
Helmholtz function, 661
Henry's constant, 824
Higher heating value (HHV), 79, 773
Human comfort and air conditioning, 735–737
Hydrocarbon fuels, 760
Hypersonic fluid flow, 843

Ice point, 20
Ideal and real gas behavior, 690–695
  Amagat's law of additive volumes, 690
  component pressure, 691
  component volume, 691
  Dalton's law of additive pressures, 690
  partial pressure, 691
  partial volume, 691
Ideal and real gas properties, 695–703
  extensive properties, 696
  ideal-gas mixtures, 696–700
Ideal gases, entropy change in, 352–359
Ideal gases, internal energy and specific heats, 176–183
  property tables for, 899, 949
Ideal-gas equation of state, 134–138
  definition, 135
  equation of state, 135
  ideal-gas relation, 135
  molar mass M, 135–136
  universal gas constant R_u, 135
  water vapor, 137–138
Ideal-gas mixtures, 691, 696–700, 706–708
Ideal-gas mixtures, chemical equilibrium constant, 808–812, 812–816
Ideal-gas properties
  air, 923, 972
  carbon monoxide, 929, 978
  hydrogen, 933, 982
  hydroxyl, 936
  monatomic oxygen, 936
  nitrogen, 925, 974
  oxygen, 927, 976
  water vapor, 934, 983
Ideal-gas relation, 135
Ideal-gas specific heats of various common gases, 899, 949
Ideal-gas temperature scale, 18–19
Idealizations and simplifications, power cycles, 487
Ideal power cycle, 486
Ideal vapor-compression refrigeration cycle, 610–613
Ignition temperature, 762
Inclined manometer, 31
Incompressible flow, 219–221
Incompressible substance, 183
Increase of entropy principle, 334–337
Independent properties, 15
Inexact differentials, 63
Innovative vapor-compression systems, 623–630
  cascade refrigeration systems, 624–626
  liquefaction of gases, 629–630
  multipurpose refrigeration systems, single compressor, 628–629
  multistage compression refrigeration systems, 626–628
Intensive properties, 12
Internal (U) energy, 53, 176–183, 183–187
  changes, 184
  enthalpy and specific heats of ideal gases, 176–183
  enthalpy and specific heats of solids and liquids, 183–187
Internal energy changes, thermodynamic property relations, 666
Internal energy changes of real gases, 675
Internally and externally reversible processes, 294–295
  externally reversible, 295
  internally reversible, 294–295
  totally reversible, 295
Internally reversible, 294–295
Internally reversible isothermal heat transfer processes, 333
International Temperature Scale of 1990, 20–21
Irreversibilities, 293
Irreversible processes, 293–294, 425–430
  exergy, 425–430
  friction, 293
  heat transfer, 294
  irreversibilities, 293
  unrestrained expansion of a gas, 294
Isentropic efficiencies, 367–373
  compressor, 369–371
  nozzles, 371–373
  turbines, 367–368
Isentropic flow through nozzles, 851–860
  back pressure, 851
  choke, 855
  converging-diverging nozzles, 856–860
  converging nozzles, 852–856
  normal shock, 857
Isentropic stagnation state, 841
Isobaric process, 16
Isochoric (isometric) process, 16
Isolated system, 11
Isothermal process, 16, 340–342, 355

Jet propulsion cycles, 520–526
  afterburner, 526
  modifications, 524–526
  propjet engine, 525
  propulsive efficiency, 521
  ramjet, 526
  turbofan, 524
Joule-Thompson coefficient, 235, 672–674

Kay's rule, 692
Kelvin-Planck statement, 283
  equivalency, Kelvin-Planck statement, 289–290
Kelvin scale, 20, 300
Kilogram (kg), 5
Kinetic and potential energy, 423–425
Kinetic (KE) energy, 53–54, 61
Kirchhoff's law, 94

Latent energy, 55
Latent heat of fusion, 116
Latent heat of vaporization, 116
Liquefaction of gases, 629–630
Liquid, 113
  property tables for, 902, 952
Liquids and solids, entropy changes in, 349–352
Liquid-vapor saturation curve, 116
Lower heating value (LHV), 78, 773

Mach angle, 870
Mach number (Ma), 844
Mach wave, 870
Macroscopic energy, 53
Manometer, 30–33
Mass and mole fractions, gas mixtures, 688–690
Mass and volume flow rates, 214–216
Mass balance, 216, 762
Mass balance for steady-flow processes, 218–219
Mass flow, 73, 375–376
Mass transfer, 440–441
Maxwell relations, 661–662
Mayer relation, 669–672
Mean effective pressure (MEP), 491
Mechanical and electrical devices, efficiency, 82–84
Mechanical energy, 58–59, 66–70
  elastic solid bars, 67–68
  force (F), 66
  raising or accelerating a body, 68–69
  shaft work, 66–67
  spring work, 67
  stretching of liquid film, 68

Mechanical equilibrium, 14
Mechanisms of transfer, 374–376
Metabolism, 188
Meter (m), 5
Microscopic energy, 53
Minimum work of separation of gas mixtures, 708–710
Mixing chambers, 236–237
Molar mass M, 135–136
Molar mass, gas constant, and critical-point properties, property tables, 898, 948
Mole, 5
Molecular disorder, 344–345
Molecules, 2–3
Mollier diagram, 343
  for water, 915, 965
Motor efficiency, 83
Moving boundary work, 164–169
  definition, 164
  polytropic process, 168–169
  quasi-equilibrium process, 164
  quasi-static process, 164
Moving or deforming control volumes, 218
Multicomponent chemical equilibrium system, 822–828
  Henry's constant, 824
  solubility, 823
Multipurpose refrigeration systems, single compressor, 628–629
Multistage compression refrigeration systems, 626–628
Multistage compression with intercooling, 364–366

Natural-draft cooling tower, 746
Natural logarithms of equilibrium constant K_p, 939
Nelson-Obert generalized compressibility chart, 921
Newton (N), 5
Newton's law of cooling, 93
Nonmechanical forms of work, 70
Normal shock, 857
Nozzles, 229–231
  converging-diverging, 856–860
  converging, 852–856
  and diffusers, 229–231
  isentropic efficiency of, 371–373
  isentropic flow through, 851–860
  steam, 884–887
Nuclear energy, 55–57

Oblique shock waves, 866–870
  bow wave, 868
  deflection angle, 866
  detached oblique shock wave, 868
  Mach angle, 870
  Mach wave, 870
  shock angle, 866
  strong oblique shocks, 869
  turning angle, 866
  wave angle, 866
  weak oblique shocks, 869
Octane, 760
One-dimensional isentropic compressible-flow functions for an ideal gas with $k = 1.4$, 943
  One-dimensional isentropic flow, 845–851
  converging-diverging nozzles, 847
  property relations, isentropic flow of ideal gases, 849–851
  throat, 847
  variation of fluid velocity with flow area, 847–849, 943
One-dimensional normal shock functions for an ideal gas with $k = 1.4$, 944
Open cycle, 506
Open feedwater heater, 569
Open system, 11
Osmotic pressure, 712
Osmotic rise, 712
Otto cycle, 492–498
  compression ratio, 495
  exhaust blowdown, 492–493
  four-stroke combustion engine, 492
  two-stroke engine, 493
Ozone and smog, 86–87

Package icing, 118
Partial derivatives and associated thermodynamic property relations, 656–660
Partial differential thermodynamic property relations, 659–660
Partial differentials, 657–659
Partial molar properties, 705
Partial pressure, 691
Partial volume, 691
Pascal's law, 26, 32
Path, 15
Path functions, 63
Peltier effect, 637
Percent deficiency of air, 765
Percent excess air, 765
Percent theoretical air, 765
Perpetual motion machines, 290–292
  perpetual motion machine of the first kind (PMM1), 290
  perpetual motion machine of the second kind (PMM2), 290
P-h diagram for refrigerant, 918, 968
Phase-change processes of pure substances, 113–118
  compressed liquid and saturated liquid, 114
  consequences of T_{sat} and P_{sat} dependence, 116–118
  saturated vapor and superheated vapor, 114–115
  saturation temperature and saturation pressure, 115–116
  vacuum cooling, 117
Phase chemical equilibrium, 820–828
  Gibbs phase rule, 822
  multicomponent system, 822–828
  phase rule, 822
  single component system, 820–822
Phase equilibration, 148
Phase equilibrium, 15
Phases of pure substances, 112–113
  gas, 113
  liquid, 113
  solid, 112
Phase rule, chemical equilibrium, 822
Piezoelectric transducers, 34
Pipe and duct flow, 240–242
Polytropic process, 168–169
Potential energy, 54

Pound (lb), 6
Pound-force (lbf), 6
Power, 227
Power cycles, analysis, 486–488
  ideal cycle, 486
  idealizations and simplifications, 487
  property diagrams, 487–488
  thermal efficiency, 486
Prandtl-Meyer expansion waves, 870–875
  compressing flow, 870
  expanding flow, 870
  expansion fan, 870
  Prandtl-Meyer function, 871
Pressure, 22–26
  absolute pressure, 23
  definition, 22
  Pascal's law, 26
  vacuum pressure, 23
  variation with depth, 24–26
Pressure measurement devices, 27–34
  barometer, 27
  barometric pressure, 27
  Bourdon tube, 33
  deadweight tester, 34
  inclined manometer, 31
  manometer, 30–33
  piezoelectric transducers, 34
  pressure transducer, 33
  standard atmosphere, 27
  strain-gage pressure transducers, 34
Pressure ratio, 507
Pressure transducer, 33
Primary (fundamental) dimensions, 3
Principle of corresponding states, 138–139
Problem-solving technique, 34–36
Process, 15
Products, 762
Properties of atmosphere at high altitude, 922, 971
Properties of common liquids, solids, and foods, 902, 952
Properties of some common fuels and hydrocarbons, 938, 986
Property diagrams, entropy, 342–343
  Mollier diagram, 343
Property diagrams of pure substances, 118–124
  extension for solid phases, 120–122
  P-T diagram, 122–123
  P-v diagram, 120
  P-v-T surface, 123
  T-v diagram, 118–119
Property diagrams, power cycles, 487–488
Property relations, isentropic flow of ideal gases, 849–851
  critical properties, 850
  critical ratios, 850
Property tables and charts
  enthalpy of formation, Gibbs function of formation, and absolute entropy at 25°C, 1 atm, 937
  compressed liquid water property tables, 912, 962
  enthalpy of formation, Gibbs function of formation, and absolute entropy at 77°C, 1 atm, 985
  generalized enthalpy departure chart, 940
  generalized entropy departure chart, 941
  ideal-gas properties of air, 923, 972
  ideal-gas properties of carbon monoxide, 929, 978

Property tables and charts (*continued*)
ideal-gas properties of hydrogen, 933, 982
ideal-gas properties of hydroxyl, 936
ideal-gas properties of monatomic oxygen, 936
ideal-gas properties of nitrogen, 925, 974
ideal-gas properties of oxygen, 927, 976
ideal-gas properties of water vapor, 934, 983
ideal-gas specific heats of various common gases, 899, 949
molar mass, gas constant, and critical-point properties, property tables, 898, 948
Mollier diagram for water, 915, 965
natural logarithms of equilibrium constant K_p, 939
one-dimensional isentropic compressible-flow functions for an ideal gas with $k = 1.4$, 943
one-dimensional normal shock functions for an ideal gas with $k = 1.4$, 944
properties of atmosphere at high altitude, 922, 971
properties of common liquids, solids, and foods, 902, 952
properties of some common fuels and hydrocarbons, 938, 986
psychometric chart at 1 atm total pressure, 942, 987
Rayleigh flow functions for an ideal gas with $k = 1.4$, 945
saturated ice-water vapor property table, 913, 963
saturated refrigerant pressure table, 917, 967
saturated refrigerant temperature table, 916, 966
saturated water pressure table, 906, 956
saturated water temperature table, 904, 954
superheated water, property tables, 908, 958
T-s diagram for water, 914, 964
Property tables of pure substances, 124–134
compressed liquid, 131–132
enthalpy, 125–126
enthalpy of vaporization, 126
reference state and reference values, 132–134
saturated liquid and saturated vapor states, 125–126
saturated liquid-vapor mixture, 127–130
superheated vapor, 130–131
Propjet engine, 525
Psychometric chart at 1 atm total pressure, 942, 987
Psychrometric charts, 734–735
P-T diagram, 122–123
Pump efficiency, 82
Pure substances, 111–161, 337–340
Beattie-Bridgeman equation of state, 142–143
Benedict-Webb-Rubin equation of state, 143–144
compressed liquid and saturated liquid, 114
compressibility factor (Z), 138–141
consequences of T_{sat} and P_{sat} dependence, 116–118
definition, 112
ideal-gas equation of state, 134–138
phase-change processes of, 113–118
phases of, 112–113
property diagrams, 118–124
property tables, 124–134
saturated vapor and superheated vapor, 114–115
saturation temperature and saturation pressure, 115–116
van der Walls equation of state, 142
vapor pressure and phase equilibrium, 146–150
virial equation of state, 144–145
water vapor as ideal gas, 137–138
P-v diagram, 120
P-v-T surface, 123

Q_{out}, 281–283
Quality, Carnot heat engine, 302–303
Quantity versus quality, daily life, 303–304
Quasi-equilibrium process, 16, 164
Quasi-static process, 16, 164

Radiation, 62, 93
Raising or accelerating a body, 68–69
Ramjet, 526
Rankine cycle, 555–558, 558–560, 561–565, 565–568, 569–577
actual versus idealized, 555–560
analysis, 558–560
efficiency, 561–565
feedwater heater (FWH), 569
ideal regenerative, 569–577
ideal reheat, 565–568
regenerator, 569
Rankine scale, 20
Rate form, 443
Rate of heat transfer, 227
Rayleigh flow, 875
choked, 882–884
line, 877
property relations, 881–882
Rayleigh flow functions for an ideal gas with $k = 1.4$, 945
Reactants, 762
Real-gas mixtures, 692–695, 700–714
chemical potential, 705
desalination processes, 712–714
enthalpy of mixing, 705
entropy of mixing, 705
ideal-gas mixtures and ideal solutions, 706–708
Kay's rule, 692
minimum work of separation of gas mixtures, 708–710
partial molar properties, 705
reversible mixing processes, 710
second-law efficiency, gas mixtures, 710–711
separation of a two component gas mixture, 711
Reciprocating engines, 490–491
bore, 491
bottom dead center (BDC), 491
clearance volume, 491
compression ignition (CI) engines, 491
displacement volume, 491
exhaust valve, 491
mean effective pressure (MEP), 491
spark ignition (SI) engines, 491
stroke, 491
top dead center (TDC), 491
Reduced pressure, 138
Reduced temperature, 138
Reference state and reference values property tables of pure substances, 132–134
Refrigerant selection, 620–622
Refrigeration cycles, 607–653
absorption refrigeration systems, 633–635
actual vapor compression, 613–615
cascade refrigeration systems, 624–626
gas refrigeration cycles, 630–633
heat pump systems, 622–623
ideal vapor compression, 610–613
innovative vapor-compression systems, 623–630
liquefaction of gases, 629–630
multipurpose refrigeration systems, single compressor, 628–629
multistage compression refrigeration systems, 626–628
refrigerant selection, 620–622
refrigerators and heat pumps, 608–609
reversed Carnot cycle, 609–610
second-law analysis of vapor compression, 615–620
thermoelectric power generation, 636–637
Refrigerators and heat pumps, 283–290, 608–609
Clausius statement, 288–289
coefficient of performance, 284–285, 608
energy efficiency ratio (EER), 286–288
equivalency, Clausius and Kelvin-Planck statements, 289–290
heat pumps, 285–286
household, 307–311
performance, 286
Regeneration, 503, 513–515
Regenerator, 569
Relative density, 14
Relative humidity, 147, 727–729
Relative pressure, 356–359
Relative specific volume, 356–359
Reversed Carnot cycle, 297, 609–610
Reversibility, 295
Reversible adiabatic compression, 296
Reversible adiabatic expansion, 296
Reversible adiabatic process, 341
Reversible isothermal compression, 296
Reversible isothermal expansion, 296
Reversible mixing processes, 710
Reversible processes, 292–293
second-law efficiency, 293
Reversible steady-flow work, 359–363
Reversible work, exergy, 425–430, 456

Saturated air, 147
Saturated ice-water vapor property table, 913, 963
Saturated liquid and saturated vapor states property tables of pure substances, 125–126
Saturated liquid line, 119
Saturated liquid-vapor mixture property tables of pure substances, 127–130
Saturated liquid vapor region (wet region), 119
Saturated refrigerant
pressure table, 917, 967
temperature table, 916, 966
Saturated vapor and superheated vapor, 114–115
Saturated vapor line, 119
Saturated water
pressure table, 906, 956
temperature table, 904, 954

Saturation temperature and saturation pressure, 115–116
latent heat of fusion, 116
latent heat of vaporization, 116
liquid-vapor saturation curve, 116
Secondary (derived) dimensions, 3
Second-law analysis, gas power cycles, 526–529
Second-law analysis of reacting systems, 784–790
exergy destroyed, 784
Second-law analysis of vapor compression, 615–620
Second-law analysis, vapor power cycles, 577–579
Second-law efficiency, 293, 430–433, 456–463
Second-law efficiency, gas mixtures, 710–711
Second law of thermodynamics, 2, 275–328
Carnot cycle, 295–297
Carnot heat engine, 301–304
Carnot principles, 297–298
Carnot refrigerator and heat pump, 304–307
Clausius statement, 288–289
coefficient of performance, 284–285
entropy and, 330–333
equivalence, Kelvin-Planck and Clausius statements, 289–290
heat engines, 278–283
heat pumps, 285–286
household refrigerators, 307–311
internally and externally reversible processes, 294–295
introduction, 276–277
irreversible processes, 293–294
Kelvin-Planck statement, 283
performance, refrigerators, air conditioners, and heat pumps, 286–288
perpetual motion machines, 290–292
Q_{net}, 281–283
quantity versus quality, daily life, 303–304
refrigerators and heat pumps, 283–290
reversed Carnot cycle, 297
reversible processes, 292–293
thermal efficiency, 279–281
thermal energy reservoirs, 277–278
thermodynamic temperature scale, 299–301
Seebeck effect, 636
Separation of a two component gas mixture, 711
Set point, 192
Shaft work, 66–67
Shock angle, 866
Shock waves, 860–875
Fanno line, 861
normal shock waves, 860–866
oblique shock waves, 866–870
Prandtl-Meyer expansion waves, 870–875
Rayleigh line, 861
SI units, 6–8
property tables, 897–945
Significant digits, 39–40
Simple compressible system, 15
Simple heating and cooling, 738
Simultaneous reactions, chemical equilibrium, 816–818
Single component system, chemical equilibrium, 820–822
Solid, 112
property tables for, 902, 952
Solids and liquids, internal energy and specific heats, 183–187
Solubility, 823
Sonic fluid flow, 843
Sonic number, 843
Spark ignition (SI) engines, 491
Specific gravity, 14
Specific heats, 174–176
at constant pressure, 174
at constant volume, 174
c_v and c_p, 668–672
definition, 174
of ideal gases, 176–183
of solids and liquids, 183–187
Specific humidity, 727–729
Specific properties, 12
Specific weight, 14
Speed of sound and Mach number, 843–845
hypersonic fluid flow, 843
Mach number (Ma), 844
sonic fluid flow, 843
sonic number, 843
subsonic fluid flow, 843
supersonic fluid flow, 843
transonic fluid flow, 843
Spring work, 67
Stagnation enthalpy, 840
Stagnation pressure, 841
Stagnation properties, 840–843
dynamic temperature, 841
isentropic stagnation state, 841
stagnation enthalpy, 840
stagnation pressure, 841
stagnation properties, 840–841
stagnation temperature, 841
static enthalpy, 840
total enthalpy, 840
total temperature, 841
Stagnation temperature, 841
Standard atmosphere, 27
Standard-state Gibbs function change, 809
State of a system, equilibrium, 14–15
chemical equilibrium, 15
equilibrium, 14
mechanical equilibrium, 14
phase equilibrium, 15
thermal equilibrium, 14
State postulate, 15
Static enthalpy, 840
Steady-flow devices, second law efficiency, 456–463
Steady flow engineering devices, 228–242
heat exchangers, 238–240
mixing chambers, 236–237
nozzles and diffusers, 229–231
pipe and duct flow, 240–242
throttling valves, 234–236
turbines and compressors, 231–234
Steady-flow process, 16–17
Steady-flow systems, 225–228, 455–456
chemical reactions, 775–776
exergy balance, 455–456
power, 227
rate of heat transfer, 227
Steam point, 20
Steam nozzles, 884–887
supersaturated steam, 885
supersaturation, 885
Wilson line, 885
Stirling and Ericsson cycles, 502–506
external combustion, 506
regeneration, 503
Stoichiometric air, 764
Strain-gage pressure transducers, 34
Stretching of liquid film, 68
Stroke, 491
Strong oblique shocks, 869
Sublimation, 122
Subsonic fluid flow, 843
Superheated refrigerant property tables, 918, 968
Superheated steam, 562
Superheated vapor property tables of pure substances, 130–131
Superheated vapor region, 119
Superheated water, property tables, 908, 958
Supersaturated steam, 885
Supersaturation, 885
Supersonic fluid flow, 843
Surroundings outside system, 11
Surroundings work, 426
System processes and cycles, 15–17
cycle, 16
isobaric process, 16
isochoric (isometric) process, 16
isothermal process, 16
path, 15
process, 15
quasi-equilibrium process, 16
quasi-static process, 16
steady-flow process, 16–17
System properties, 12–13
continuum, 12–13
definition, 12
extensive properties, 12
independent properties, 15
intensive properties, 12
simple compressible system, 15
specific properties, 12
state postulate, 15
Systems and control volumes, 10–12
boundary, 10
closed system, 10
control mass, 10
control surface, 11
control volume, 11
isolated system, 11
open system, 11
surroundings outside system, 11

T ds relations, entropy, 347–348
Temperature, 18–22
absolute gas temperature scale, 19
Celsius scale, 18
constant volume gas thermometer, 19
Fahrenheit scale, 18
ice point, 20
ideal-gas temperature scale, 18–19
International Temperature Scale of 1990, 20–21
Kelvin scale, 20
Rankine scale, 20
steam point, 20
thermal equilibrium, 17
thermodynamic temperature scale, 18
triple point, 20
zeroeth law of thermodynamics, 18
Temperature, variations of chemical equilibrium constant with, 818–820

Theoretical air, 764
Theoretical and actual combustion processes, 764–770
deficiency of air, 765
equivalence ratio, 765
excess air, 765
percent deficiency of air, 765
percent excess air, 765
percent theoretical air, 765
stoichiometric air, 764
theoretical air, 764
Thermal conductivity, 91
Thermal efficiency, 279–281, 302, 486
Thermal energy reservoirs, 277–278
Thermal equilibrium, 14, 17
Thermodynamic property relations, 655–685
Clapeyron-Clausius equation, 664–665
Clapeyron equation, 662–665
enthalpy changes, 666–667
enthalpy changes of real gases, 674–675
enthalpy departure, 675
entropy changes, 667–668
entropy changes of real gases, 676–678
entropy departure, 678
internal energy changes, 666
internal energy changes of real gases, 675
Joule-Thomson coefficient, 672–674
Maxwell relations, 661–662
Mayer relation, 669–672
partial derivatives and associated relations, 656–560
partial differential relations, 659–660
partial differentials, 657–659
specific heats c_v and c_p, 668–672
Thermodynamics
applications of, 3
biological systems, 187–194
classical thermodynamics, 3
conservation of energy principle, 2
density and specific gravity, 13–14
and dimensions and units, 3–10
and energy, 2–3
engineering equation solver (EES) for, 37–39
engineering software packages for, 36–37
first law of thermodynamics, 2
pressure, 22–34
problem-solving technique for, 34–36
second law of thermodynamics, 2
significant digits, 39–40
state of a system, 14–15
system processes and cycles, 15–16
system properties, 12–13
systems and control volumes, 10–12
temperature and zeroeth law of thermodynamics, 17–18
third law of thermodynamics, 344–345
Thermodynamic temperature scale, 18, 299–301
absolute temperatures, 300
Kelvin scale, 300
Thermoelectric power generation, 636–637
Peltier effect, 637
refrigerator systems, 636–637
Seebeck effect, 636
Third law of thermodynamics, 344–345, 783
Throat, 847
Throttling valves, 234–236
Top dead center (TDC), 491
Total enthalpy, 840
Total temperature, 841
Transfer, exergy, 438–441
Transonic fluid flow, 843
Triple point, 20, 121
T-s diagram for water, 914, 964
Turbine efficiency, 82
Turbines and compressors, 231–234
Turbofan, 524
T-v diagram, 118–119
saturated liquid line, 119
saturated liquid vapor region (wet region), 119
saturated vapor line, 119
superheated vapor region, 119
Two-stroke engine, 493

Unit systems, 3–10
British thermal unit (Btu), 7
conversion ratios, 9–10
dimensional homogeneity, 8
English system, 3–4
kilogram (kg), 5
metric system, 4
mole, 5
newton (N), 5
pound (lb), 6
pound-force (lbf), 6
United States Customary System (USCS), 3–4
watt (W), 7
weight, 6
Universal gas constant R_u, 135
Unrestrained expansion of a gas, 294
Unsteady-flow processes, 242–247

Vacuum cooling, 117
Vacuum freezing, 118
Vacuum pressure, 23
van der Walls equation of state, 142
Vapor power cycles, 553–605
binary vapor cycles, 587–589
Carnot vapor cycle, 554
cogeneration, 579–584
combined gas-vapor power cycles, 584–587
Rankine cycle, 555–558, 558–560, 561–565, 565–568
Rankine cycle, actual versus idealized, 555–560
Rankine cycle, analysis, 558–560
Rankine cycle, efficiency, 561–565
Rankine cycle, ideal regenerative, 569–577
Rankine cycle, ideal reheat, 565–568
second-law analysis, vapor power cycles, 577–579
Vapor pressure and phase equilibrium, 146–150
boiling, 148–149
definition, 146
evaporation, 148
evaporative coolers, 148
phase equilibration, 148
relative humidity, 147
saturated air, 147
Variable specific heat, 353–355, 356
Variation of fluid velocity with flow area, 847–849
Virial equation of state, 144–145
Volume flow rate, 54

Water heater efficiency, 78
Water vapor as ideal gas, 137–138
Watt (W), 7
Wave angle, 866
Weak oblique shocks, 869
Weight, 6
Wet-bulb temperature, 732–734
Wet cooling towers, 745–747
cooling pond, 746
natural-draft cooling tower, 746
Wilson line, 885
Work, 56, 62–65
electrical work, 65
exact differentials, 63
formal sign convention, 63
inexact differentials, 63
path functions, 63
Working fluid, 278
Work potential, 422–425
Work transfer, 73, 440

Zeroeth law of thermodynamics, 18