

# Contents



<b>Preface</b>	<b>xxvii</b>
<b>Nomenclature</b>	<b>xxxv</b>
<b>1 ■ BASIC CONCEPTS OF THERMODYNAMICS</b>	<b>1</b>
1-1 Thermodynamics and Energy	2
1-2 A Note on Dimensions and Units	3
1-3 Closed and Open Systems	8
1-4 Forms of Energy	9
1-5 Properties of a System	15
1-6 State and Equilibrium	16
1-7 Processes and Cycles	17
1-8 The State Postulate	18
1-9 Pressure	19
1-10 Temperature and the Zeroth Law of Thermodynamics	23
1-11 Thermodynamic Aspects of Biological Systems	27
1-12 Summary	34
References and Suggested Reading	36
Problems	36

2	PROPERTIES OF PURE SUBSTANCES	47
2-1	Pure Substance	48
2-2	Phases of a Pure Substance	48
2-3	Phase-Change Processes of Pure Substances	49
2-4	Property Diagrams for Phase-Change Processes	55
2-5	Vapor Pressure and Phase Equilibrium	62
2-6	Property Tables	66
2-7	The Ideal-Gas Equation of State	77
2-8	Compressibility Factor-A Measure of Deviation from Ideal-Gas Behavior	79
2-9	Other Equations of State	84
2-10	Summary	88
	References and Suggested Reading	90
	Problems	90
3	THE FIRST LAW OF THERMODYNAMICS: CLOSED SYSTEMS	103
3-1	Introduction	104
3-2	Heat Transfer	104
3-3	Work	111
3-4	Mechanical Forms of Work	115
3-5	The First Law of Thermodynamics	127
3-6	A Systematic Approach to Problem Solving	133
3-7	Specific Heats	140
3-8	Internal Energy, Enthalpy, and Specific Heats of Ideal Gases	142
3-9	Internal Energy, Enthalpy, and Specific Heats of Solids and Liquids	151
3-10	Refrigeration and Freezing of Foods	155
3-11	Summary	166
	References and Suggested Reading	168
	Problems	168
4	THE FIRST LAW OF THERMODYNAMICS: CONTROL VOLUMES	193
4-1	Thermodynamic Analysis of Control Volumes	194
4-2	The Steady-Flow Process	200

4-3	Some Steady-Flow Engineering Devices	204
4-4	Unsteady-Flow Processes	220
4-5	Summary	228
	References and Suggested Reading	230
	Problems	230
5	THE SECOND LAW OF THERMODYNAMICS	251
5-1	Introduction to the Second Law of Thermodynamics	252
5-2	Thermal Energy Reservoirs	253
5-3	Heat Engines	254
5-4	Energy Conversion Efficiencies	260
5-5	Refrigerators and Heat Pumps	265
5-6	Perpetual-Motion Machines	271
5-7	Reversible and Irreversible Processes	273
5-8	The Carnot Cycle	278
5-9	The Carnot Principles	281
5-10	The Thermodynamic Temperature Scale	282
5-11	The Carnot Heat Engine	284
5-12	The Carnot Refrigerator and Heat Pump	288
5-13	Household Refrigerators	291
5-14	Summary	295
	References and Suggested Reading	297
	Problems	297
6	ENTROPY: A MEASURE OF DISORDER	319
6-1	Entropy	320
6-2	The Increase of Entropy Principle	324
6-3	Entropy Change of Pure Substances	327
6-4	Isentropic Processes	331
6-5	What Is Entropy?	333
6-6	Property Diagrams Involving Entropy	337
6-7	The $T ds$ Relations	339
6-8	Entropy Change of Liquids and Solids	341
6-9	The Entropy Change of Ideal Gases	344
6-10	Reversible Steady-Flow Work	352
6-11	Minimizing the Compressor Work	356

6-12	Reducing the Cost of Compressed Air	360
6-13	Isentropic Efficiencies of Steady-Flow Devices	370
6-14	Entropy Balance	378
6-15	Summary	392
	References and Suggested Reading	395
	Problems	396
<b>7</b>	<b>EXERGY: A MEASURE OF WORK POTENTIAL</b>	<b>419</b>
7-1	Exergy: Work Potential of Energy	420
7-2	Reversible Work and Irreversibility	423
7-3	Second-Law Efficiency $\eta_{II}$	427
7-4	Exergy Associated with $ke$ , $pe$ , $u$ , $Pv$ , and $h$	430
7-5	Exergy Change of a System	434
7-6	Exergy Transfer by Heat, Work, and Mass	438
7-7	The Decrease of Exergy Principle and Exergy Destruction	441
7-8	Exergy Balance: Closed Systems	442
7-9	Exergy Balance: Control Volumes	455
7-10	Second-Law Aspects of Daily Life	463
7-11	Summary	467
	References and Suggested Reading	469
	Problems	470
<b>8</b>	<b>GAS POWER CYCLES</b>	<b>487</b>
8-1	Basic Considerations in the Analysis of Power Cycles	488
8-2	The Carnot Cycle and Its Value in Engineering	490
8-3	Air-Standard Assumptions	492
8-4	An Overview of Reciprocating Engines	493
8-5	Otto Cycle: The Ideal Cycle for Spark-Ignition Engines	494
8-6	Diesel Cycle: The Ideal Cycle for Compression-Ignition Engines	500
8-7	Stirling and Ericsson Cycles	504
8-8	Brayton Cycle: The Ideal Cycle for Gas-Turbine Engines	508
8-9	The Brayton Cycle with Regeneration	516
8-10	The Brayton Cycle with Intercooling, Reheating, and Regeneration	519
8-11	Ideal Jet-Propulsion Cycles	523

8-12	Second-Law Analysis of Gas Power Cycles	530
8-13	Summary	533
	References and Suggested Reading	535
	Problems	536
9	VAPOR AND COMBINED POWER CYCLES	555
9-1	The Carnot Vapor Cycle	556
9-2	Rankine Cycle: The Ideal Cycle for Vapor Power Cycles	557
9-3	Deviation of Actual Vapor Power Cycles from Idealized Ones	561
9-4	How Can We Increase the Efficiency of the Rankine Cycle?	564
9-5	The Ideal Reheat Rankine Cycle	568
9-6	The Ideal Regenerative Rankine Cycle	571
9-7	Second-Law Analysis of Vapor Power Cycles	580
9-8	Cogeneration	582
9-9	Binary Vapor Cycles	587
9-10	Combined Gas-Vapor Power Cycles	589
9-11	Summary	592
	References and Suggested Reading	594
	Problems	595
10	REFRIGERATION CYCLES	615
10-1	Refrigerators and Heat Pumps	616
10-2	The Reversed Carnot Cycle	617
10-3	The Ideal Vapor-Compression Refrigeration Cycle	619
10-4	Actual Vapor-Compression Refrigeration Cycles	623
10-5	Selecting the Right Refrigerant	625
10-6	Heat Pump Systems	627
10-7	Innovative Vapor-Compression Refrigeration Systems	628
10-8	Gas Refrigeration Cycles	637
10-9	Absorption Refrigeration Systems	640
10-10	Thermoelectric Power Generation and Refrigeration Systems	644
10-11	Summary	646
	References and Suggested Reading	647
	Problems	648

11	THERMODYNAMIC PROPERTY RELATIONS	663
11-1	A Little Math-Partial Derivatives and Associated Relations	664
11-2	The Maxwell Relations	669
11-3	The Clapeyron Equation	670
11-4	General Relations for $du$ , $dh$ , $ds$ , $C_v$ , and $C_p$	673
11-5	The Joule-Thompson Coefficient	680
11-6	The $A_h$ , $A_u$ , and $A_s$ of Real Gases	682
11-7	Summary	687
	References and Suggested Reading	689
	Problems	689
12	GAS MIXTURES	697
12-1	The Composition of a Gas Mixture: Mass and Mole Fractions	698
12-2	$P$ - $v$ - $T$ Behavior of Gas Mixtures: Ideal and Real Gases	700
12-3	Properties of Gas Mixtures: Ideal and Real Gases	705
12-4	Summary	713
	References and Suggested Reading	715
	Problems	715
13	GAS-VAPOR MIXTURES AND AIR-CONDITIONING	723
13-1	Dry and Atmospheric Air	724
13-2	Specific and Relative Humidity of Air	725
13-3	Dew-Point Temperature	727
13-4	Adiabatic Saturation and Wet-Bulb Temperatures	729
13-5	The Psychrometric Chart	732
13-6	Human Comfort and Air-Conditioning	733
13-7	Air-Conditioning Processes	735
13-8	Summary	748
	References and Suggested Reading	750
	Problems	751
14	CHEMICAL REACTIONS	763
14-1	Fuels and Combustion	764
14-2	Theoretical and Actual Combustion Processes	767
14-3	Enthalpy of Formation and Enthalpy of Combustion	772
14-4	First-Law Analysis of Reacting Systems	776

14-5	Adiabatic Flame Temperature	781
14-6	Entropy Change of Reacting Systems	784
14-7	Second-Law Analysis of Reacting Systems	786
14-8	Summary	792
	References and Suggested Reading	795
	Problems	795
<b>15</b>	<b>▣ CHEMICAL AND PHASE EQUILIBRIUM</b>	<b>809</b>
15-1	Criterion for Chemical Equilibrium	810
15-2	The Equilibrium Constant for Ideal-Gas Mixtures	812
15-3	Some Remarks About the $K_p$ of Ideal-Gas Mixtures	815
15-4	Chemical Equilibrium for Simultaneous Reactions	820
15-5	Variation of $K_p$ with Temperature	822
15-6	Phase Equilibrium	823
15-7	Summary	832
	References and Suggested Reading	834
	Problems	834
<b>16</b>	<b>▣ THERMODYNAMICS OF HIGH-SPEED GAS FLOW</b>	<b>843</b>
16-1	Stagnation Properties	844
16-2	Velocity of Sound and Mach Number	848
16-3	One-Dimensional Isentropic Flow	852
16-4	Isentropic Flow through Nozzles	859
16-5	Normal Shocks in Nozzle Flow	867
16-6	Flow through Actual Nozzle and Diffusers	873
16-7	Steam Nozzles	879
16-8	Summary	882
	References and Suggested Reading	886
	Problems	886
APPENDIX 1 PROPERTY TABLES AND CHARTS (SI UNITS)		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	917
Table A-13	Superheated Refrigerant-134a	918
Table A-14	$P$ - $h$ Diagram for Refrigerant-134a	920
Table A-15	One-Dimensional Isentropic Compressible-Flow Functions for an Ideal Gas with Constant Specific Heats and Molar Mass, and $k = 1.4$	921
Table A-16	One-Dimensional Normal-Shock Functions for an Ideal Gas with Constant Specific Heats and Molar Mass, and $k = 1.4$	922
Table A-17	Ideal-Gas Properties of Air	923
Table A-18	Ideal-Gas Properties of Nitrogen, $N_2$	925
Table A-19	Ideal-Gas Properties of Oxygen, $O_2$	927
Table A-20	Ideal-Gas Properties of Carbon Dioxide, $CO_2$	929
Table A-21	Ideal-Gas Properties of Carbon Monoxide, $CO$	931
Table A-22	Ideal-Gas Properties of Hydrogen, $H_2$	933
Table A-23	Ideal-Gas Properties of Water Vapor, $H_2O$	934
Table A-24	Ideal-Gas Properties of Monatomic Oxygen, $O$	936
Table A-25	Ideal-Gas Properties of Hydroxyl, $OH$	936
Table A-26	Enthalpy of Formation, Gibbs Function of Formation, and Absolute Entropy at $25^\circ C$ , 1 atm	937
Table A-27	Enthalpy of Combustion and Enthalpy of Vaporization at $25^\circ C$ , 1 atm	938
Table A-28	Logarithms to the Base $e$ of the Equilibrium Constant $K_p$	939
Table A-29	Constants that Appear in the Beattie–Bridgeman and the Benedict–Webb–Rubin Equations of State	940
Figure A-30	Nelson–Obert Generalized Compressibility Charts	941



Figure A-3 I	Generalized Enthalpy Departure Chart	944
Figure A-32	Generalized Entropy Departure Chart	945
Figure A-33	Psychrometric Chart at 1 atm Total Pressure	946
APPENDIX 2	PROPERTY TABLES AND CHARTS (ENGLISH UNITS)	947
Table A-1E	Molar Mass, Gas Constant, and Critical-Point Properties	948
Table A-2E	Ideal-Gas Specific Heats of Various Common Gases	949
Table A-3E	Properties of Common Liquids, Solids, and Foods	952
Table A-4E	Saturated Water-Temperature Table	954
Table A-5E	Saturated Water-Pressure Table	955
Table A-6E	Superheated Water	957
Table A-7E	Compressed Liquid Water	961
Table A-8E	Saturated Ice—Water Vapor	962
Table A-9E	<i>T-s</i> Diagram for Water	963
Table A-10E	Mollier Diagram for Water	964
Table A-11E	Saturated Refrigerant-134a—Temperature Table	965
Table A-12E	Saturated Refrigerant-134a—Pressure Table	966
Table A-13E	Superheated Refrigerant-134a	967
Figure A-14E	<i>P-h</i> Diagram for Refrigerant-134a	969
Table A-17E	Ideal-Gas Properties of Air	970
Table A-18E	Ideal-Gas Properties of Nitrogen, N <sub>2</sub>	972
Table A-19E	Ideal-Gas Properties of Oxygen, O <sub>2</sub>	974
Table A-20E	Ideal-Gas Properties of Carbon Dioxide, CO <sub>2</sub>	976
Table A-21E	Ideal-Gas Properties of Carbon Monoxide, CO	978
Table A-22E	Ideal-Gas Properties of Hydrogen, H <sub>2</sub>	980
Table A-23E	Ideal-Gas Properties of Water Vapor, H <sub>2</sub> O	981
Table A-26E	Enthalpy of Formation, Gibbs Function of Formation, and Absolute Entropy at 77°F, 1 atm	983
Table A-27E	Enthalpy of Combustion and Enthalpy of Vaporization at 77°F, 1 atm	984
Table A-29E	Constants that Appear in the Beattie-Bridgeman and the Benedict-Webb-Rubin Equations of State	985
Table A-33E	Psychrometric Chart at 1 atm Total Pressure	986

APPENDIX 3 ABOUT THE SOFTWARE: INTRODUCTION TO EES	987
Overview	987
Background Information	987
A Thermodynamics Example Problem	991
Loading a Textbook File	998
<b>INDEX</b>	1001