

# ENGINEERING THERMODYNAMICS

JUI SHENG HSIEH

TK123  
H873

9561541

# Engineering Thermodynamics

Jui Sheng Hsieh

New Jersey Institute of Technology



E9561541



PRENTICE HALL, Englewood Cliffs, NJ 07632

**Library of Congress Cataloging-in-Publication Data**

Hsieh, Jui Sheng

Engineering thermodynamics / Jui Sheng Hsieh.  
p. cm.

Includes bibliographical references and index.

ISBN 0-13-275702-8

1. Thermodynamics. I. Title.

TJ265.H76 1993

621.402'1--dc20

91-38933

CIP

Acquisitions editor: **DOUG HUMPHREY**  
Editorial/production supervision and  
interior design: **RICHARD DeLORENZO**  
Copy editor: **PETER ZURITA**  
Cover design: **WANDA LUBELSKA**  
Prepress buyer: **LINDA BEHRENS**  
Manufacturing buyer: **DAVID DICKEY**  
Editorial assistant: **JAIME ZAMPINO**  
Supplements editor: **ALICE DWORKIN**



© 1993 by Prentice-Hall, Inc.  
A Simon & Schuster Company  
Englewood Cliffs, New Jersey 07632

All rights reserved. No part of this book may be  
reproduced, in any form or by any means,  
without permission in writing from the publisher.

Printed in the United States of America

10 9 8 7 6 5 4 3 2 1

ISBN 0-13-275702-8

Prentice-Hall International (UK) Limited, London  
Prentice-Hall of Austria Pty. Limited, Sydney  
Prentice-Hall Canada Inc., Toronto  
Prentice-Hall Hispanoamericana, S.A., Mexico  
Prentice-Hall of India Private Limited, New Delhi  
Prentice-Hall of Japan, Inc., Tokyo  
Simon & Schuster Asia Pte. Ltd., Singapore  
Editora Prentice-Hall do Brasil, Ltda., Rio de Janeiro

**TABLE A-2 CONVERSION FACTORS**

Length	$1 \text{ m} = 3.28084 \text{ ft}$ $1 \text{ ft} = 0.3048 \text{ m}$ $1 \text{ in.} = 2.54 \text{ cm}$ $1 \text{ mile} = 5280 \text{ ft} = 1.60934 \text{ km}$ $1 \text{ micron } (\mu) = 10^{-6} \text{ m} = 3.28084 \times 10^{-6} \text{ ft}$
Volume	$1 \text{ m}^3 = 35.31 \text{ ft}^3 = 1000 \text{ liter}$ $1 \text{ in.}^3 = 16.387 \text{ cm}^3$ $1 \text{ liter} = 1000 \text{ cm}^3 = 0.03531 \text{ ft}^3$ $1 \text{ gal} = 231 \text{ in.}^3$
Mass	$1 \text{ kg} = 2.20462 \text{ lbm}$ $1 \text{ lbm} = 0.453592 \text{ kg}$ $1 \text{ slug} = 32.174 \text{ lbm}$
Density	$1 \text{ kg/m}^3 = 0.062428 \text{ lbm/ft}^3$ $1 \text{ lbm/ft}^3 = 16.0185 \text{ kg/m}^3$
Specific volume	$1 \text{ m}^3/\text{kg} = 16.0185 \text{ ft}^3/\text{lbm} = 1 \text{ liter/g}$ $1 \text{ ft}^3/\text{lbm} = 0.062428 \text{ m}^3/\text{kg}$ $1 \text{ liter/gmole} = 1 \text{ m}^3/\text{kgmole}$
Force	$1 \text{ N} = 1 \text{ kg}\cdot\text{m/s}^2 = 0.224809 \text{ lbf}$ $1 \text{ dyne} = 1 \text{ g}\cdot\text{cm/s}^2 = 1 \times 10^{-5} \text{ N}$ $1 \text{ lbf} = 1 \text{ slug}\cdot\text{ft/s}^2 = 4.44822 \text{ N} = 4.44822 \times 10^5 \text{ dynes}$
Pressure	$1 \text{ Pa} = 1 \text{ N/m}^2$ $1 \text{ lbf/in.}^2 = 6894.76 \text{ N/m}^2$ $1 \text{ bar} = 10^5 \text{ Pa} = 0.986923 \text{ atm}$ $1 \text{ atm} = 14.6959 \text{ lbf/in.}^2 = 1.01325 \text{ bars}$ $\quad = 760 \text{ mmHg at } 32^\circ\text{F} = 29.92 \text{ in. Hg at } 32^\circ\text{F}$
Temperature	$T(^{\circ}\text{R}) = 1.8 T(^{\circ}\text{K}) \text{ or } 1 \text{ K} = 1.8 ^{\circ}\text{R}$ $T(^{\circ}\text{F}) = 1.8 T(^{\circ}\text{C}) + 32$ $T(^{\circ}\text{K}) = T(^{\circ}\text{C}) + 273.15$ $T(^{\circ}\text{R}) = T(^{\circ}\text{F}) + 459.67$
Energy	$1 \text{ J} = 1 \text{ N}\cdot\text{m} = 10^7 \text{ ergs}$ $1 \text{ kJ} = 0.947817 \text{ Btu}$ $1 \text{ Btu} = 778.169 \text{ ft}\cdot\text{lbf} = 1.055056 \text{ kJ}$ $\quad \text{(International Table)} = 4.1868 \text{ J}$ $1 \text{ atm}\cdot\text{cm}^3 = 1.01325 \times 10^{-10} \text{ J}$
Specific energy	$1 \text{ Btu/lbm} = 2536.9 \text{ ft}\cdot\text{lbf/lbm}$ $1 \text{ kJ/kg} = 0.429929 \text{ Btu/lbm}$
Power	$1 \text{ W} = 1 \text{ J/s} = 3.41214 \text{ Btu/h}$ $1 \text{ hp} = 550 \text{ ft}\cdot\text{lbf/s} = 745.7 \text{ W}$
Specific entropy, specific heat, gas constant	
Velocity	

**TABLE A-3 PHYSICAL CONSTANTS**

Avogadro's number	$6.022169 \times 10^{26} \text{ (kgmole)}^{-1}$
Boltzmann constant	$1.380622 \times 10^{-23} \text{ J/K}$
Planck's constant	$6.626196 \times 10^{-34} \text{ J}\cdot\text{s}$
Speed of light	$2.9979250 \times 10^8 \text{ m/s}$
Electronic charge	$1.6021917 \times 10^{-19} \text{ C}$
Bohr magneton	$9.274096 \times 10^{-24} \text{ A}\cdot\text{m}^2$
Permeability of free space	$4 \times 10^{-7} \text{ N/A}^2$
Standard gravitational acceleration	$9.80665 \text{ m/s}^2 = 32.174 \text{ ft/s}^2$

**TABLE A-4 UNIVERSAL GAS CONSTANT**

8314.29 J/kgmole·K
8.31429 kJ/kgmole·K
0.0820560 atm·m <sup>3</sup> /kgmole·K
1.98583 kcal/kgmole·K
1545.31 ft·lbf/lbmole·°R
1.98583 Btu/lbmole·°R
0.730225 atm·ft <sup>3</sup> /lbmole·°R



# Preface

Thermodynamics is the science of energy. This book provides a rigorous and comprehensive treatment of the basic principles and engineering applications of thermodynamics. The presentation of the subject follows the traditional classical, or macroscopic, approach. It is intended to fit undergraduate engineering curricula and contains enough material for a two-semester thermodynamics course. With proper selection of materials it can be used for a single course given in one semester.

Throughout the preparation of this book the student has been foremost in the author's mind. Sufficient detail is given in the presentation of the subject matter. Important derivations and calculations are not left to the student but are contained in the main body of the text. A large number of completely solved examples are provided to illustrate the theories and applications. There are many end-of-chapter problems which model practical engineering situations, with accompanying schematics to enhance the student's understanding of the problem.

Chapter 1 presents basic definitions, concepts, and schematics of some typical engineering applications. The first law of thermodynamics is introduced in Chapter 2 along with the formulation of various work modes. Thermodynamic properties of pure substances are discussed in Chapter 3 with emphasis on the use of tabulated property data in energy analyses. The concept of ideal gas and its use as a simple model of the actual behavior of a pure substance is introduced in Chapter 4. The conservation-of-mass and conservation-of-energy equations are presented in Chapter 5, including steady-flow and uniform-flow typical processes of application.

Chapters 6 and 7 are devoted to a thorough treatment of the second law of thermodynamics and its consequences. The property "entropy" is developed from the macroscopic viewpoint, with a microscopic interpretation added as an aid to understanding the nature of this property. The concepts of availability and irreversibility are developed in Chapter 8, laying the foundation for the study of second-law analysis and second-law effectiveness.

Chapters 9 through 12 illustrate the engineering applications concerning air-conditioning, gas power, vapor power, and refrigeration. Innovative energy systems, such as combined cycles, cogeneration systems, and low-temperature Rankine cycles, are included in the study. Also included is the subject of cryogenics, with an emphasis on gas liquefaction.

Thermodynamic relations for simple compressible systems are presented in Chapter 13, including general equations for specific heats, internal energy, enthalpy, entropy, Helmholtz function, Gibbs function, and Maxwell relations. In addition, general equations for simple paramagnetic systems are included in this chapter to lay the basis for the study of magnetic cooling in cryogenics for attaining extremely low temperatures, approaching the absolute zero as a limit. Analytical and graphical equations of state for real gases and real-gas mixtures are treated in Chapter 14, with detailed numerical illustrations on the use of these equations along with the general equations developed in Chapter 13 to evaluate various thermodynamic properties and heat and work interactions.

Chemical reactions, with emphasis on the first-law analysis of combustion processes are given in Chapter 15. Whereas second-law analyses of reactive systems are presented in Chapter 16 when the absolute entropy and Gibbs function of formation are studied. In addition to availability analysis of reactive systems, Chapter 16 covers the topics of stability, phase and reaction equilibrium, equilibrium constant, and the third law of thermodynamics. A detailed study of absorption refrigeration analysis is presented as an illustration of phase equilibrium of binary vapor-liquid mixtures.

The presentation of the second-law analysis and second-law effectiveness in the main body of the text and in the end-of-chapter problems are arranged in such a way that give the instructor the choice of covering the first-law and second-law analyses together or separately. The structure of the book can be easily adopted to the case where a brief coverage of the second-law analysis in one thermodynamics course and a thorough coverage of this material in another thermodynamics course are called for.

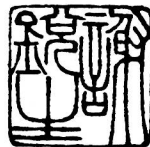
A simplified, but comprehensive, summary is included at the end of each chapter. These summaries can be used for review classes by the instructor. They can serve as the last-minute quick review materials by the student before taking an examination. They can also be used by the student as formula sheets during exams if the instructor prefers closed-book tests and yet wants to make the important equations available to the students.

A bibliography at the end of the book gives a selected group of references that can be helpful to the students for their current and future study of thermodynamics. It should be noted that the number in square brackets in the text refers to the number in the Bibliography.

Most countries in the world use the metric system of units. Old English units, however, are still widely used in some industries and everyday life in the United States. This book uses both SI and English units, with an emphasis on SI. There are more examples and chapter-end-problems which use SI than English units, the ratio of examples written in English units to that in SI being about 3 to 5. This book can be covered using combined SI and English units or SI units alone, depending on the preference of the instructor. Tables and charts of properties are provided in both sets of units. A table of unit conversion is included.

It is a great pleasure to acknowledge my indebtedness to Dr. E. M. Sparrow of University of Minnesota for his detailed review and invaluable suggestions on the manuscript. It is with deep appreciation that I express thanks to the numerous and valuable comments, suggestions, criticism, and praise of the following academic reviewers: Dr. P. S. Ayyaswamy of University of Pennsylvania, Dr. J. E. Drummond of University of Akron, Dr. S. Goplen of North Dakota State University, Dr. G. S. Jakubowski of Memphis State University, Dr. J. E. Peters of University of Illinois-Chicago, Dr. C. S. Reddy of Union College, and Dr. J. W. Sheffield of University of Missouri-Rolla. Thanks are also due to Dr. R. P. Kirchner of New Jersey Institute of Technology for using the manuscript in his thermodynamics class at NJIT. Finally, I wish to express my thanks and appreciation to my wife Mary, my son Lawrence, and my daughters Esther and Vivian for their encouragement, support, and typing efforts throughout the preparation of this text.

*J. S. Hsieh*



# Symbols

$a$	Acceleration	KE	Kinetic energy
$a, A$	Specific Helmholtz function, Helmholtz function	$l, L$	Length
$A$	Area	$L$	Latent heat
$AF$	Air-fuel ratio	LHV	Lower heating value
$c$	Specific heat	$m$	Mass
$c_p$	Constant-pressure specific heat	$M$	Molar mass or molecular weight
$c_v$	Constant-volume specific heat	mep	Mean effective pressure
$C_c$	Curie constant	$\mathbf{M}$	Magnetization or magnetic moment per unit volume
COP	Coefficient of performance	$n$	Number of moles
COP <sub>ref</sub>	Coefficient of performance of a refrigerator	$n$	Polytropic exponent
COP <sub>H.P.</sub>	Coefficient of performance of a heat pump	$p$	Pressure
$C_H$	Heat capacity at constant magnetic field	$p_c$	Critical pressure
$C_M$	Heat capacity at constant magnetic moment	$p_i$	Partial pressure of component $i$
$d$	Differential change in a property	$p_r$	Reduced pressure $p/p_c$
$\bar{d}$	Differential change in a path function	$p_r$	Relative pressure as used in gas tables
$e$	Base of natural logarithm	PE	Potential energy
$e, E$	Specific total energy, total energy	$\mathbf{P}$	Electric polarization or electric dipole moment per unit volume
$\mathbf{E}$	Electric field strength	$q, Q$	Heat transfer per unit mass, heat transfer
$\mathcal{E}$	Electrical potential	$Q_{av}$	Available energy
$f$	Functional relation	$Q_{unav}$	Unavailable energy
$F$	Degree of freedom	$r$	Compression ratio
$F$	Force	$r_c$	Cutoff ratio
$g$	gravitational acceleration	$r_p$	Pressure ratio
$g, G$	Specific Gibbs function, Gibbs function	$R$	Gas constant
$g_c$	$g_c = 32.174 \text{ ft} \cdot \text{lbm}/\text{lbf} \cdot \text{s}^2$	$\mathcal{R}$	Universal gas constant
$\Delta g_f^\circ$	Gibbs function of formation at standard state	$s, S$	Specific entropy, entropy
$\Delta G_R$	Gibbs-function change of reaction	$\Delta S_R$	Entropy change of reaction
$h$	Vertical height	$S_{prod}$	Entropy production
$h, H$	Specific enthalpy, enthalpy	$t$	Time
$\Delta h_f^\circ$	Enthalpy of formation at standard state	$T$	Temperature
$\Delta H_R^\circ$	Enthalpy of reaction at standard state	$T_c$	Critical temperature
HHV	Higher heating value	$T_{db}$	Dry-bulb temperature
$\mathbf{H}$	Magnetic field strength	$T_{dp}$	Dew-point temperature
$i$	Electric current	$T_{wb}$	Wet-bulb temperature
$i, I$	Specific irreversibility, irreversibility	$T_r$	Reduced temperature $T/T_c$
$k$	Boltzmann constant	$u, U$	Specific internal energy, internal energy
$k$	Specific heat ratio, $c_p/c_v$	$\Delta U_R$	Internal energy of reaction at standard state
$K_p$	Diffuser pressure coefficient	$v, V$	Specific volume, volume
$K_p$	Equilibrium constant	$v_c$	Critical volume
		$v_i$	Partial volume of component $i$
		$v_r$	Reduced volume $v/v_c$



$v_r$	Relative volume as used in gas tables
$V$	Velocity
$w, W$	Work per unit mass, Work
$x$	Mole fraction
$x$	Quality
$y$	Mass fraction
$z$	Elevation
$Z$	Compressibility factor
$Z$	Electric charge
$Z_c$	Critical compressibility factor

### Greek Letters

$\alpha$	Coefficient of thermal expansion
$\gamma$	Specific weight
$\gamma$	Surface (or interfacial) tension
$\delta$	Virtual variation
$\Delta$	Finite change = final minus initial
$\epsilon$	Second-law effectiveness
$\epsilon$	Strain
$\epsilon_0$	Permittivity of free space
$\eta$	Efficiency
$\eta_{th}$	Thermal efficiency
$\eta_T$	Turbine efficiency
$\theta$	Angle
$\kappa$	Isothermal compressibility
$\kappa_s$	Adiabatic compressibility
$\mu$	Chemical potential
$\mu_J$	Joule-Thomson coefficient
$\mu_0$	Permeability of free space
$\nu$	Stoichiometric coefficient
$\pi$	$\pi = 3.14159$
$\rho$	Density
$\sigma$	Stress
$\Sigma$	Summation
$\tau$	Torque
$\phi$	$\phi = \int_0^T c_p \frac{dT}{T}$ as defined in gas tables
$\phi$	Relative humidity
$\varphi, \Phi$	Closed system specific availability, availability
$\psi, \Psi$	Open system specific stream availability, stream availability
$\omega$	Specific humidity
$\Omega$	Thermodynamic probability

### Subscripts

$a$	Air, dry air
$a, act$	Actual

$abs$	Absolute
$atm$	Atmosphere
$av$	Average
$c$	Compressor
$c$	Critical point property
$cv$	Control volume
$f$	Final state
$f$	Saturated liquid
$fg$	Difference in property between saturated vapor and saturated liquid
$g$	Saturated vapor
$H$	High-temperature reservoir
$i$	Initial state
$i$	$i$ th component in a mixture
$i$	Saturated solid
$in$	Input
$irr$	Irreversible
$int rev$	Internally reversible
$L$	Low-temperature reservoir
$max$	Maximum
$min$	Minimum
$N$	Nozzle
$out$	Output
$P$	Pump
$prop$	Propulsive
$R$	Chemical reaction
$R$	Energy reservoir
$reg$	Regenerator
$reh$	Reheater
$rev$	Reversible
$s$	Isentropic
$sat$	Saturated
$surr$	Surroundings
$sys$	System
$st gen$	Steam generator
$th$	Thermal
$T$	Turbine
$v$	Water vapor
$0$	Dead state
$0$	Standard state
$1$	State 1
$1$	Component 1 in a mixture

### Superscripts

- Quantity per unit time
- Property at standard state
- Property at unit pressure
- \* Ideal gas state

---

---

---

# Contents

<b>PREFACE</b>	<b><i>ix</i></b>
----------------	------------------

<b>SYMBOLS</b>	<b><i>xi</i></b>
----------------	------------------

<b>CHAPTER 1 INTRODUCTION</b>	<b><i>1</i></b>
-------------------------------	-----------------

1-1	The Nature of Thermodynamics	1
1-2	Engineering Applications of Thermodynamics	1
1-3	Thermodynamic System, Property, State, and Process	10
1-4	Equilibrium State and Quasiequilibrium Process	12
1-5	Dimensions and Units	13
1-6	Density, Specific Weight, and Pressure	15
1-7	Temperature and Thermometry	18
1-8	Energy	22
1-9	Summary	25
	Problems	27

<b>CHAPTER 2 THE FIRST LAW OF THERMODYNAMICS</b>	<b><i>32</i></b>
--	------------------

2-1	Heat: A Form of Energy Transfer	32
2-2	Work: A Form of Energy Transfer	33
2-3	Expansion or Compression Work	34
2-4	Other Quasiequilibrium Modes of Work	39
2-5	The First Law of Thermodynamics	45
2-6	The State Postulate and Simple Systems	50
2-7	Simple Compressible Systems	51
2-8	Specific Heats	52
2-9	Summary	56
	Problems	57

- 3-1 Pure Substance and Phase Transition 63
- 3-2  $p$ - $v$ - $T$  Surface for a Substance that Contracts on Freezing 68
- 3-3  $p$ - $v$ - $T$  Surface for Water that Expands on Freezing 72
- 3-4 Tables of Thermodynamic Properties 74
- 3-5 Use of Tabular Data in Closed-System Energy Analysis 81
- 3-6 Properties of Incompressible Substances 86
- 3-7 Summary 88  
Problems 89

**CHAPTER 4 IDEAL GASES****97**

- 4-1 Ideal-Gas Equation of State 97
- 4-2 Internal Energy, Enthalpy, and Specific Heats of Ideal Gases 100
- 4-3 Variation of Specific Heats with Temperature 102
- 4-4 Polytropic Processes for Ideal Gases 105
- 4-5 Energy Analysis Involving Ideal Gases 108
- 4-6 Summary 114  
Problems 115

**CHAPTER 5 FIRST-LAW ANALYSIS FOR CONTROL VOLUMES****121**

- 5-1 Conservation of Mass for Control Volumes 121
- 5-2 Conservation of Energy for Control Volumes 124
- 5-3 Steady-Flow, Steady-State Processes 126
- 5-4 Nozzles and Diffusers 126
- 5-5 Steam and Gas Turbines 131
- 5-6 Compressors and Pumps 132
- 5-7 Heat Exchangers and Mixing Chambers 134
- 5-8 Throttling Process and Pipe Flow 140
- 5-9 Uniform-Flow, Uniform-State Transient Analysis 144
- 5-10 Charging and Discharging Rigid Tanks 145
- 5-11 Transient Process Involving Boundary Work 150
- 5-12 Summary 152  
Problems 153

**CHAPTER 6 THE SECOND LAW OF THERMODYNAMICS****167**

- 6-1 The Second Law of Thermodynamics 167
- 6-2 Reversible Processes 170
- 6-3 The Carnot Cycle—a Totally Reversible Cycle 172
- 6-4 The Reversed Carnot Cycle 174
- 6-5 The Carnot Principle 175
- 6-6 Thermodynamic Temperature Scale 176

6-7	The Clausius Inequality	181
6-8	Entropy: A Thermodynamic Property	183
6-9	The Principle of Increase in Entropy	189
6-10	Statistical Definition of Entropy	192
6-11	Entropy of a Pure Substance	194
6-12	Temperature–Entropy Diagram for Pure Substances	197
6-13	Enthalpy–Entropy or Mollier Diagram	201
6-14	Summary	203
	Problems	205

## **CHAPTER 7 ENTROPY CHANGE DURING PROCESSES**

**216**

7-1	Two Basic Relations of Properties	216
7-2	Second Law for an Open System	217
7-3	Internally Reversible Steady-State, Steady-Flow Process	222
7-4	Entropy Change of Ideal Gases	225
7-5	Internally Reversible Adiabatic Process for an Ideal Gas with Constant Specific Heats	226
7-6	Ideal Gases with Variable Specific Heats	232
7-7	Entropy Change of Incompressible Substances	236
7-8	Efficiencies of Steady-Flow Devices	238
7-9	Available and Unavailable Energy	246
7-10	Summary	250
	Problems	252

## **CHAPTER 8 AVAILABILITY AND IRREVERSIBILITY**

**265**

8-1	Maximum Work	265
8-2	Irreversibility	270
8-3	Availability of a Closed System	280
8-4	Availability of a Steady-Flow System	283
8-5	Effectiveness of Processes and Cycles	286
8-6	Summary	297
	Problems	300

## **CHAPTER 9 IDEAL-GAS AND GAS–VAPOR MIXTURES**

**316**

9-1	Mass Analysis of Gas Mixtures	316
9-2	$p$ – $v$ – $T$ Properties of Ideal-Gas Mixtures	318
9-3	Energy Properties of Ideal-Gas Mixtures	321
9-4	Mixing Processes	327
9-5	Properties of Air–Water Vapor Mixtures	332
9-6	Adiabatic Saturation	336
9-7	Psychrometric Chart	338
9-8	Heating and Humidification	340
9-9	Cooling and Dehumidification	343

9-10	Evaporative Cooling	345
9-11	Adiabatic Mixing	349
9-12	Wet Cooling Tower	352
9-13	Summary	356
	Problems	358

## **CHAPTER 10 GAS POWER CYCLES**

**373**

10-1	Air-Standard Analysis	373
10-2	Otto Cycle	374
10-3	Diesel Cycle	383
10-4	Dual Cycle	388
10-5	Gas-Turbine Cycle	393
10-6	Regenerative Gas-Turbine Cycle	399
10-7	Multistage Compression and Expansion	403
10-8	Gas-Turbine Cycle with Intercooling and Reheating	406
10-9	Turbojet Propulsion	411
10-10	Turboprop, Turbofan, Ramjet, and Rocket Engines	418
10-11	Stirling and Ericsson Cycles	424
10-12	Availability Analysis for Gas Power Cycles	427
10-13	Summary	434
	Problems	435

## **CHAPTER 11 VAPOR POWER CYCLES**

**445**

11-1	Rankine Cycle	445
11-2	Reheat Cycle	450
11-3	Regenerative Cycle	455
11-4	Reheat-Regenerative Cycle	463
11-5	Binary Vapor Cycle	468
11-6	Low-Temperature Rankine Cycle	468
11-7	Combined Gas and Steam Power Cycle	472
11-8	Cogeneration	476
11-9	Availability Analysis for Vapor Power Cycles	482
11-10	Summary	490
	Problems	491

## **CHAPTER 12 REFRIGERATION AND CRYOGENICS**

**510**

12-1	Vapor-Compression Refrigeration	510
12-2	Heat Pump	516
12-3	Multistage Vapor-Compression Refrigeration	520
12-4	Gas-Cycle Refrigeration	525
12-5	Absorption Refrigeration	530
12-6	Steam-Jet Refrigeration	531
12-7	Gas Liquifaction	535
12-8	Availability Analysis for Refrigeration Cycles	544
12-9	Summary	552
	Problems	553

<b>CHAPTER 13</b>	<b>THERMODYNAMIC RELATIONS FOR SIMPLE COMPRESSIBLE AND SIMPLE PARAMAGNETIC SYSTEMS</b>	<b>571</b>
13-1	Fundamentals of Partial Derivatives	571
13-2	Simple Compressible Systems	574
13-3	Relations for Specific Heats	577
13-4	Relations for Entropy, Internal Energy, and Enthalpy	581
13-5	Joule–Thomson Coefficient	584
13-6	Clapeyron Equation	586
13-7	Simple Paramagnetic Systems	589
13-8	Magnetic Cooling	592
13-9	Summary	596
	Problems	600
<b>CHAPTER 14</b>	<b>REAL GASES AND REAL-GAS MIXTURES</b>	<b>605</b>
14-1	Van der Waals Equation of State	605
14-2	Beattie–Bridgeman Equation of State	609
14-3	Other Equations of State	610
14-4	Equation of State in Virial Form	611
14-5	Evaluation of Thermodynamic Properties from an Equation of State	614
14-6	Principle of Corresponding States	627
14-7	Generalized Thermodynamic Correction Charts	631
14-8	Real-Gas Mixtures	635
14-9	Summary	642
	Problems	644
<b>CHAPTER 15</b>	<b>CHEMICAL REACTIONS</b>	<b>653</b>
15-1	Combustion Reactions	653
15-2	Actual Combustion Processes	659
15-3	First-Law Analysis of Chemical Reactions	664
15-4	Enthalpy of Formation	666
15-5	Enthalpy and Internal Energy of Reaction	668
15-6	Energy Calculations for Combustion Processes	671
15-7	Adiabatic Flame Temperature	675
15-8	Summary	680
	Problems	681
<b>CHAPTER 16</b>	<b>PHASE AND CHEMICAL EQUILIBRIUM</b>	<b>689</b>
16-1	Gibbs Equations and Chemical Potential	689
16-2	Criteria of Equilibrium	692
16-3	Stability	695
16-4	Equations of Phase Equilibrium	701
16-5	Binary Vapor–Liquid Systems	706
16-6	Absorption Refrigeration Analysis	712
16-7	Gibbs Phase Rule	715



16-8	Equation of Reaction Equilibrium	719
16-9	Ideal-Gas Reaction and Equilibrium Constant	720
16-10	The Third Law of Thermodynamics and Absolute Entropy	725
16-11	Gibbs Function of Formation	728
16-12	Availability Analysis of Reacting Systems	729
16-13	Summary	736
	Problems	739
<b>APPENDIX 1</b>	<b>LAGRANGE'S METHOD OF UNDETERMINED MULTIPLIERS</b>	<b>748</b>
<b>APPENDIX 2</b>	<b>UNITS AND PHYSICAL CONSTANTS</b>	<b>750</b>
	[List of Tables for Appendix 2 on page 750.]	
<b>APPENDIX 3</b>	<b>PROPERTIES OF SUBSTANCES—TABLES</b>	<b>754</b>
	[List of Tables for Appendix 3 on page 754.]	
<b>APPENDIX 4</b>	<b>PROPERTIES OF SUBSTANCES—FIGURES</b>	<b>829</b>
	[List of Figures for Appendix 4 on page 829.]	
	<b>BIBLIOGRAPHY</b>	<b>861</b>
	<b>ANSWERS TO SELECTED QUESTIONS</b>	<b>862</b>
	<b>INDEX</b>	<b>865</b>

---

---

---

# Introduction

## 1-1 THE NATURE OF THERMODYNAMICS

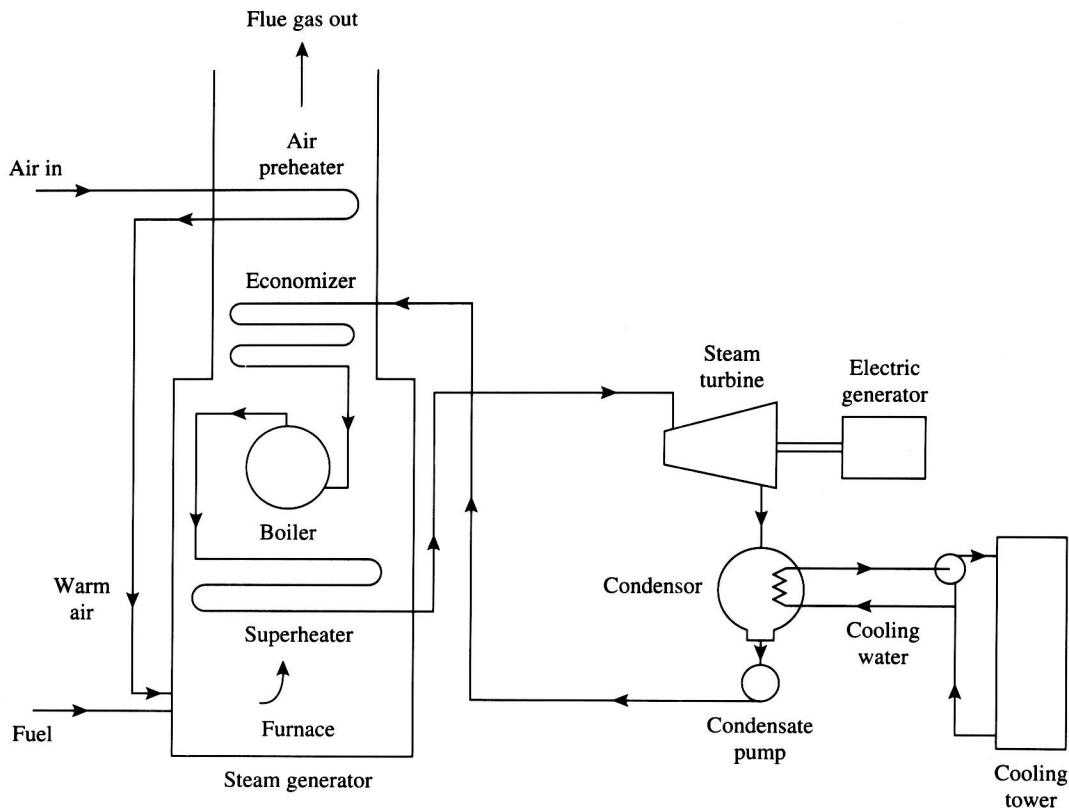
*Thermodynamics* is the basic science that deals with energy, matter, and their transformations and interactions. It is based on two general laws of nature, the first and second laws of thermodynamics. The first law is essentially the law of conservation of energy to account for the balance of thermal and other forms of energy taking part in a transformation. The second law places limitations on certain kinds of energy transformation. Based on these laws, engineers design and build various useful devices including stationary and vehicular heat engines, refrigeration and air-conditioning machines, and chemical processing plants.

The science of *classical thermodynamics* was developed without an inquiry into the structure of matter. It is concerned only with the average characteristics of large aggregations of molecules, not with the characteristics of individual molecules. In other words, classical thermodynamics takes the macroscopic point of view and deals with macroscopic phenomena. On the other hand, *statistical thermodynamics* considers the microscopic structure of matter and adopts the laws of mechanics on the statistical analysis of the individual particles. This text is based on the classical approach.

## 1-2 ENGINEERING APPLICATIONS OF THERMODYNAMICS

*Engineering thermodynamics* is a branch of thermodynamics in which emphasis is placed on the engineering analysis and design of processes, devices, and systems involving the beneficial utilization of energy and material. It covers a wide variety of applications, from the design of steam power stations and gas-liquefaction plants to the analysis of rocket engines. In order to give the students some familiarity with the processes, the equipment, and the technical terms involved in a thermodynamic analysis, we offer now a bird's-eye view of a number of engineering applications. Bear in mind, however, that what we mention here is only a few of the types of systems that can be analyzed thermodynamically.

Figure 1-1 shows a schematic diagram of a simple steam power plant. Steam at a high pressure and temperature leaves the steam generator and enters the turbine, where it expands to a lower pressure and temperature and does work to drive the electric generator, resulting in the output of electric power. The lower-pressure and lower-temper-



**Figure 1-1** Schematic of a steam power plant.

ature exhaust steam from the turbine then enters the condenser and condenses to liquid by transferring heat to the cooling water, which in turn transfers the waste heat to a river, a lake, or a cooling tower. The liquid condensate from the condenser is pumped into the steam generator to be vaporized and heated to a high temperature, thus completing a thermodynamic cycle.

Some details of the steam generator are also shown in Fig. 1-1. The economizer is a heat exchanger, where heat is transferred from the products of combustion to the condensate coming from the condensate pump, thus raising the temperature of the liquid water without evaporation. The evaporation of water occurs in the boiler section. The vapor formed in the boiler flows into the superheater, where additional heat is transferred from the hot products of combustion to increase the temperature of the vapor to a high value before entering the steam turbine. The air preheater shown in Fig. 1-1 is used to warm up the incoming outside air before entering the furnace for efficient burning of the fuel.

Although the basic components of a steam power plant are those shown in the simple drawing of Fig. 1-1, actual steam power generation systems are more complex. To help gain a general feel for what the actual equipment looks like, we include a sectional drawing of a fossil-fuel steam power station (Fig. 1-2) and a cutaway view of a steam generator (Fig. 1-3). In these figures, the names of the essential elements are indicated.