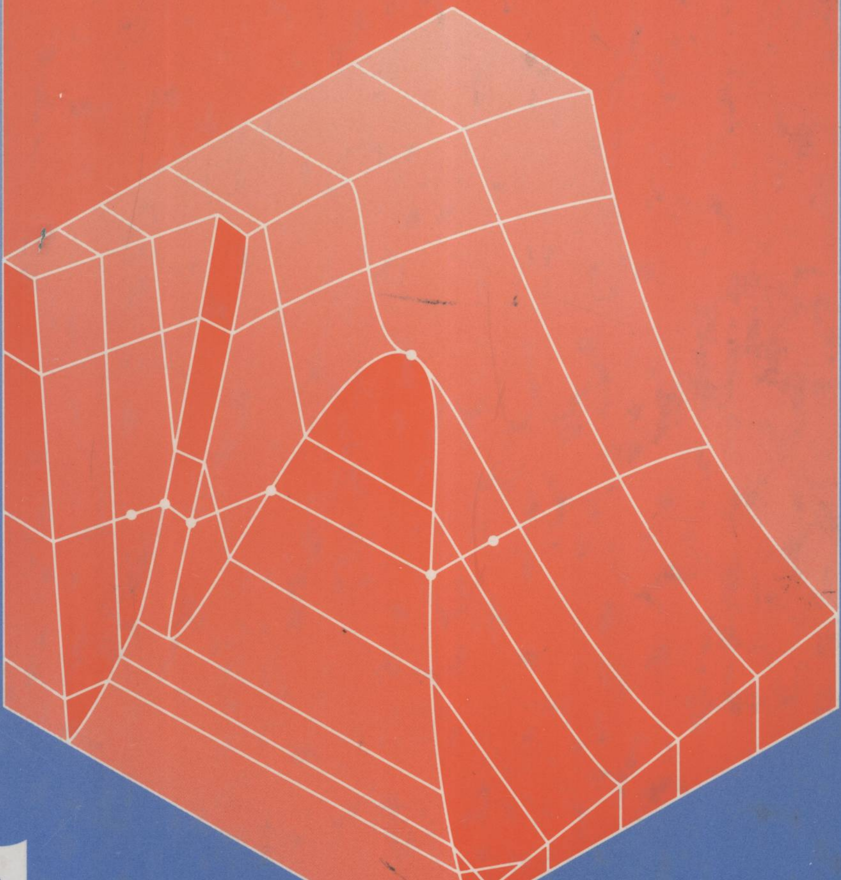

ENGINEERING THERMODYNAMICS

JUI SHENG HSIEH

Engineering Thermodynamics

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TABLE A-2 CONVERSION FACTORS

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

TABLE A-3 PHYSICAL CONSTANTS

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

TABLE A-4 UNIVERSAL GAS CONSTANT

8314.29 J/kgmole·K
8.31429 kJ/kgmole·K
0.0820560 atm·m^3/kgmole·K
1.98583 kcal/kgmole·K
1545.31 ft·lbf/lbmole·°R
1.98583 Btu/lbmole·°R
0.730225 atm·ft^3/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
a, A	Specific Helmholtz function, Helmholtz function
A	Area
AF	Air-fuel ratio
c	Specific heat
c_p	Constant-pressure specific heat
c_v	Constant-volume specific heat
C_c	Curie constant
COP	Coefficient of performance
COP_{ref}	Coefficient of performance of a refrigerator
$COP_{H.P.}$	Coefficient of performance of a heat pump
C_H	Heat capacity at constant magnetic field
C_M	Heat capacity at constant magnetic moment
d	Differential change in a property
đ	Differential change in a path function
e	Base of natural logarithm
e, E	Specific total energy, total energy
E	Electric field strength
$\mathscr{E}$	Electrical potential
f	Functional relation
F	Degree of freedom
F	Force
g	gravitational acceleration
g, G	Specific Gibbs function, Gibbs function
g_c	$g_c = 32.174$ ft · lbm/lbf · s^2
Δg_f°	Gibbs function of formation at standard state
ΔG_R	Gibbs-function change of reaction
h	Vertical height
h, H	Specific enthalpy, enthalpy
Δh_f°	Enthalpy of formation at standard state
ΔH_R°	Enthalpy of reaction at standard state
HHV	Higher heating value
H	Magnetic field streagth
i	Electric current
i, I	Specific irreversibility, irreversibility
k	Boltzmann constant
k	Specific heat ratio, c_p/c_v
K_p	Diffuser pressure coefficient
K_p	Equilibrium constant
KE	Kinetic energy
l, L	Length
L	Latent heat
LHV	Lower heating value
m	Mass
M	Molar mass or molecular weight
mep	Mean effective pressure
M	Magnetization or magnetic moment per unit volume
n	Number of moles
n	Polytropic exponent
p	Pressure
p_c	Critical pressure
p_i	Partial pressure of component i
p_r	Reduced pressure p/p_c
p_r	Relative pressure as used in gas tables
PE	Potential energy
P	Electric polarization or electric dipole moment per unit volume
q, Q	Heat transfer per unit mass, heat transfer
Q_{av}	Available energy
Q_{unav}	Unavailable energy
r	Compression ratio
r_c	Cutoff ratio
r_p	Pressure ratio
R	Gas constant
$\mathscr{R}$	Universal gas constant
s, S	Specific entropy, entropy
ΔS_R	Entropy change of reaction
S_{prod}	Entropy production
t	Time
T	Temperature
T_c	Critical temperature
T_{db}	Dry-bulb temperature
T_{dp}	Dew-point temperature
T_{wb}	Wet-bulb temperature
T_r	Reduced temperature T/T_c
u, U	Specific internal energy, internal energy
ΔU_R°	Internal energy of reaction at standard state
v, V	Specific volume, volume
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
$\mathbf{V}$	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

α	Coefficient of thermal expansion
γ	Specific weight
γ	Surface (or interfacial) tension
δ	Virtual variation
Δ	Finite change = final minus initial
ϵ	Second-law effectiveness
ϵ	Strain
ϵ_0	Permittivity of free space
η	Efficiency
η_{th}	Thermal efficiency
η_T	Turbine efficiency
θ	Angle
κ	Isothermal compressibility
κ_s	Adiabatic compressibility
μ	Chemical potential
μ_J	Joule-Thomson coefficient
μ_0	Permeability of free space
ν	Stoichiometric coefficient
π	$\pi = 3.14159$
ρ	Density
σ	Stress
Σ	Summation
τ	Torque
ϕ	$\phi = \int_0^T c_p \frac{dT}{T}$ as defined in gas tables
ϕ	Relative humidity
φ, Φ	Closed system specific availability, availability
ψ, Ψ	Open system specific stream availability, stream availability
ω	Specific humidity
Ω	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	ith 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	Reheator
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

1

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-

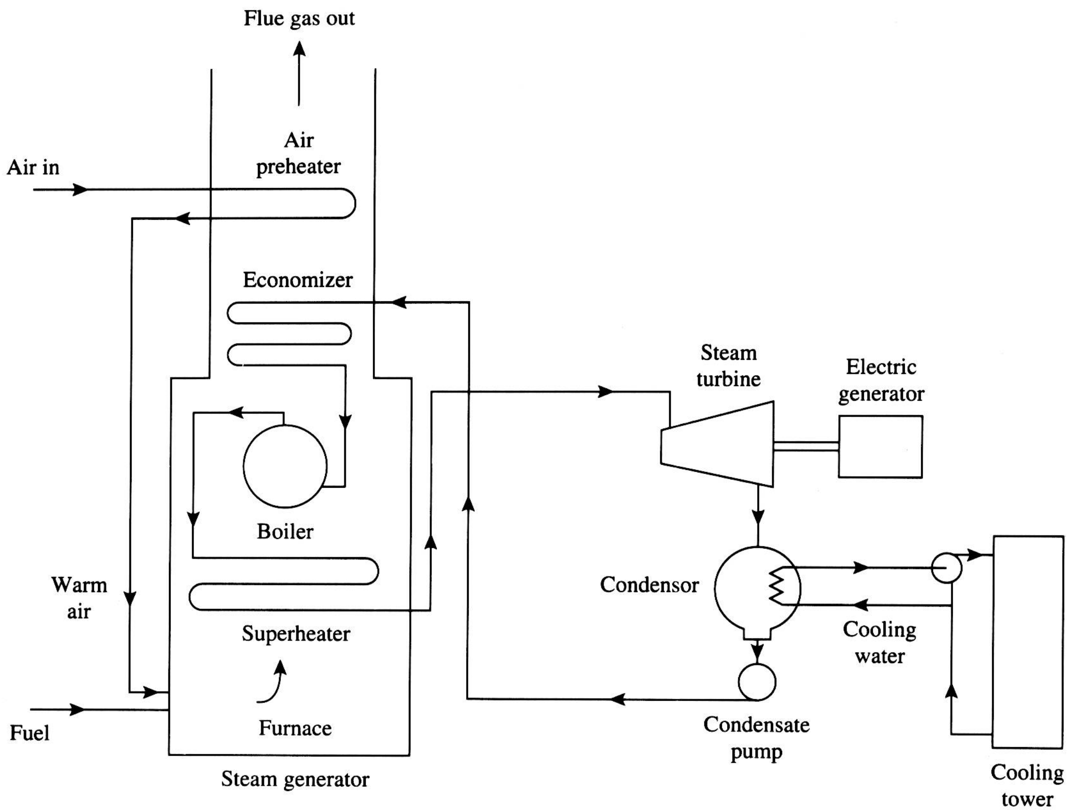

Figure 1-1 Schematic of a steam power plant.

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.