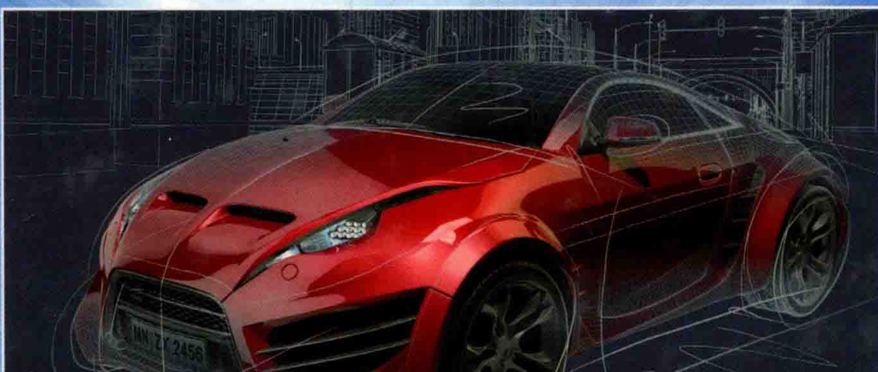
Eighth Edition

Thermodynamics and Heat Power



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Eighth Edition

Thermodynamics and Heat Power

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Thermodynamics and Heat Power

This book is dedicated to the memory of Irving Granet

Preface

It has been over ten years since this textbook was last revised. There have been many advancements in technology during this time, especially in the area of direct energy conversion. There has also been a need to expand on concepts in the areas of ideal gas flow, engine analysis, air conditioning, and heat transfer. This new edition marks a joining with the Taylor & Francis Group, including CRC Press, to continue what has been a 40-year process of providing students with an understanding of basic concepts in thermodynamics. Specifically, the following material has been added in this eighth edition:

- An emphasis on a system approach to problems
- More discussion of the types of heat and of entropy
- Added explanations for understanding pound mass and the mole
- Analysis of steady-flow gas processes, replacing the compressible flow section
- The concept of paddle work to illustrate how frictional effects can be analyzed
- A clearer discussion of the psychrometric chart and its usage in analyzing air conditioning systems
- Updates of the status of direct energy conversion systems
- A description of how the cooling tower is utilized in high-rise buildings
- Practical automotive engine analysis
- Expanded Brayton cycle analysis including intercooling, reheat, and regeneration and their effect on gas turbine efficiency
- A description of fins and how they improve heat transfer rates
- Added illustrative problems and new homework problems
- Availability of a publisher's website for fluid properties and other reference materials
- Properties of the latest in commercial refrigerants

To make room for these additions, out-of-date photographs have been removed as they were felt to lend little to the understanding of the basic concepts. Many of these changes have resulted from the input of reviewers. A special thanks to Professor Herbert Crosby of the University of Maine and Professor M. David Burghardt of Hofstra University for supplying new, challenging problems. I thank Professor Mohammad Hossain of York Technical College for his suggestions.

My thanks to the staff at Taylor & Francis for their help with this new edition: Jonathan Plant, Arlene Kopeloff, Cynthia Klivecka, Florence Kizza, and especially Amber Donley. I thank my family, somewhat expanded since the last edition, for their support and encouragement: Maris, Karen, Richard, Jennifer, Michaelbarry, Chris, Jaxanna, and Bennett.

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Symbols

Symbol	Definition	Units	
		British Engineering	SI
a	Acceleration	ft./s^2	m/s^2
a, A	Area	ft.^{2}	m^2
A, B, C, D, E	Constants		
c	Clearance	dimensionless	
c	Specific heat	Btu/lb$_m$·°R	kJ/kg·K
C_D	Discharge coefficient	dimensionless	
C_n	Specific heat of any process	Btu/lb$_m$·°R	kJ/kg·K
C_p	Specific heat at constant pressure	Btu/lb$_m$·°R	kJ/kg·K
C_p	Total specific heat at constant pressure	Btu/°R	kJ/K
c_v	Specific heat at constant volume	Btu/lb$_m$·°R	kJ/kg·K
C_v	Total specific heat at constant volume	Btu/°R	kJ/K
C_v	Velocity coefficient	dimensionless	
COP	Coefficient of performance	dimensionless	
d, D	Diameter	ft.	m
e	Base of natural logarithms	dimensionless	
F	Force	lb$_f$	N
F_A	Geometric factor	dimensionless	
F_e	Emissivity factor	Dimensionless	
g	Acceleration of gravity	ft./s^2	m/s^2
g_c	Gravitational constant	32.174 ft.·lb$_m$/lb$_f$·s^2	
Gr	Grashof number	dimensionless	
H	Enthalpy	Btu	kJ
h	Heat-transfer coefficient	Btu/h·ft.^{2}·°F	kW/m^2·K
h	Height	ft.	m
h	Specific enthalpy	Btu/lb$_m$	kJ/kg
h_f	Specific enthalpy—saturated liquid	Btu/lb$_m$	kJ/kg
h_{fg}	Specific enthalpy of vaporization ($h_g - h_f$)	Btu/lb$_m$	kJ/kg
h_g	Specific enthalpy—saturated vapor	Btu/lb$_m$	kJ/kg
h_r	Heat-transfer coefficient—radiation	Btu/h·ft.^{2}·°F	kW/m^2·K
h^0	Stagnation enthalpy	Btu/lb$_m$	kJ/kg
i	Current	amperes	amperes
J	Mechanical equivalent of heat	778 ft.·lb$_f$/Btu	
k	c_p/c_v	dimensionless	
K	Proportionality constant		
k	Spring constant	lb$_f$/in.	N/m
k	Thermal conductivity	Btu/h·ft.·°F	kW/$_m$·K
K.E.	Kinetic energy	ft.·lb$_f$/lb$_m$	kJ/kg
l, L	Length	ft.	m
M	Mach number	dimensionless	
m	Mass	lb$_m$	kg
$\dot{m}$	Mass flow rate	lb$_m$/s	kg/s
mep	Mean effective pressure	lb$_f$/in.^{2}	kPa

MW	Molecular weight	$lb_m/lb_m \cdot mol$	kg/kg·mol
n	Number of moles	dimensionless	
n	Number of moles	mass/MW	mass/MW
n	Number of particles	dimensionless	
n	Polytropic exponent	dimensionless	
Nu	Nusselt number	dimensionless	
p	Pressure	$lb_f/in.^2$	kPa
p_m	Mean effective pressure	$lb_f/in.^2$	kPa
p_m	Mixture pressure	$lb_f/in.^2$	kPa
p_r	Reduced pressure	dimensionless	
p_r	Relative pressure	dimensionless	
P.E.	Potential energy	$ft. lb_f/lb_m$	kJ/g
Pr	Prandtl number	dimensionless	
Q	Heat interchange	Btu	kJ
$\dot{Q}$	Heat transfer rate	Btu/h	kW
q	Specific heat interchange	Btu/lb_m	kJ/kg
$\dot{Q}_r$	Radiant heat transfer rate	Btu/h	kW
R	Electrical resistance	ohms	ohms
r	Radius	ft.	m
R	Universal gas constant	$ft. lb_f/lb_m \cdot °R$	kJ/kg·K
r_c	Compression ratio	dimensionless	
$r_{c.o.}$	Cutoff ratio	dimensionless	
r_e	Expansion ratio	dimensionless	
r_p	Pressure ratio	dimensionless	
R_t	Thermal resistance	°F·h/Btu	°C/W
Re	Reynolds number	dimensionless	
s	Specific entropy	$Btu/lb_m \cdot °R$	kJ/kg·K
s	Total entropy	Btu/°R	kJ/K
s_f	Specific entropy of saturated liquid	$Btu/lb_m \cdot °R$	kJ/kg·K
s_{fg}	Specific entropy of vaporization ($s_g - s_f$)	$Btu/lb_m \cdot °R$	kJ/kg·K
s_g	Specific entropy of saturated vapor	$Btu/lb_m \cdot °R$	kJ/kg·K
s_g	Specific gravity	dimensionless	
t	Temperature	°F	°C
T	Temperature, absolute	°R	K
t	Time	s (seconds)	s
T_r	Reduced temperature	dimensionless	
Tc	Critical temperature	°R	K
$(\Delta t)_m$	Logarithmic temperature difference	°F	°C
U	Internal energy	Btu	kJ
U	Overall heat transfer coefficient	$Btu/h \cdot ft.^2 \cdot °F$	$kW/m^2 \cdot K$
u	Specific internal energy	Btu/lb_m	kJ/kg
u_f	Specific internal energy—saturated liquid	Btu/lb_m	kJ/kg
u_{fg}	Specific internal energy of vaporization ($u_g - u_f$)	Btu/lb_m	kJ/kg
u_g	Specific internal energy—saturated liquid	Btu/lb_m	kJ/kg
v	Specific volume	$ft.^3/lb_m$	m^3/kg
V	Velocity	ft./s	m/s
V	Volume	$ft.^3$	m^3
$\dot{V}$	Volume flow rate	$ft.^3/min$	m^3/s

V_a	Acoustic velocity	ft./s	m/s
v_c	Critical specific volume	$ft.^3/lb_m$	m^3/kg
v_f	Specific volume of saturated liquid	$ft.^3/lb_m$	m^3/kg
v_{fg}	Specific volume of vaporization ($v_g - v_f$)	$ft.^3/lb_m$	m^3/kg
v_g	Specific volume of saturated vapor	$ft.^3/lb_m$	m^3/kg
v_r	Reduced specific volume	dimensionless	
v_r	Relative specific volume	dimensionless	
W	Humidity ratio	dimensionless	
$\dot{W}$	Power	Btu/min	kW
W	Weight	lb_f	kN
w	Weight	lb_f	N
W	Work	ft. lb_f	kJ
w	Work per unit mass	ft. lb_f/lb_m	kJ/kg
x	Length	ft.	m
x	Mole fraction	dimensionless	
x	Quality	dimensionless	
Z	Compressibility factor	dimensionless	
z	Elevation above reference plane	ft.	m
α	Absorptivity	dimensionless	
Δ	Small change of variable	dimensionless	
ε	Emissivity	dimensionless	
ϕ	Relative humidity	dimensionless	
γ	Specific weight	$lb_f/ft.^3$	kn/m^3
η	Efficiency	dimensionless	
η_v	Volumetric efficiency	dimensionless	
μ	Viscosity	$lb_m/ft.^2 \cdot h$	$N \cdot s/m^2$
θ	A function of	dimensionless	
ρ	Density	$lb_m/ft.^3$	kg/m^3
ρ	Reflectivity	dimensionless	
σ	Stefan–Boltzmann constant	$Btu/h \cdot ft.^2 \cdot {}^\circ R^4$	$W/m^2 \cdot K^4$
τ	Transmissivity	dimensionless	

Note: In addition to the symbols listed above, the following notation is used: Subscript $_m$ refers to the mixture property.

Contents

1

Fundamental Concepts

LEARNING GOALS

After reading and studying the material in this chapter, you should be able to

1. Define thermodynamics as the study of energy and the conversion of energy from one form to another
2. Use the observable external characteristics that are known as properties to describe a system
3. Establish and convert from one system of temperature measurement to another and understand the four methods of measuring temperature
4. Use both the English and SI systems of units
5. Use the elementary kinetic theory of gases to establish the concepts of pressure, temperature, density, specific weight, specific volume, and Avogadro's law
6. Use the concept of pressure in both English and SI units (Gauge and absolute pressure definitions are important ideas that are necessary in engineering applications.)
7. Use the concept that fluids exert pressures that can be expressed in terms of the height and specific weight of the column of fluid
8. Describe the various methods of measuring pressure and the methods used to calibrate pressure-measuring devices

1.1 Introduction

Thermodynamics is the study of energy, heat, work, the properties of the media employed, and the processes involved. Thermodynamics is also the study of the conversion of one form of energy to another. Because energy can be derived from electrical, chemical, nuclear, or other means, thermodynamics plays an important role in all branches of engineering, physics, chemistry, and the biological sciences.

In defining the word *thermodynamics*, we have used the terms *energy*, *heat*, and *work*. It is necessary to examine these terms in detail, and this will be done in subsequent chapters. In this chapter, certain fundamental concepts are defined, and basic ideas are developed for future use.

Even in our modern age, which has seen changes in our understanding of how the world works, the basics of thermodynamics remain valid. Even as Newton's laws have been shown not to apply in all cases, the fundamental laws of thermodynamics are always applicable. They apply to biological, chemical, electromagnetic, and mechanical systems. They apply to microscopic as well as macroscopic systems. In this textbook, the emphasis is on practical mechanical systems, including engines and heat transfer devices.

1.2 Thermodynamic Systems

In physics, when studying the motion of a rigid body (i.e., a body that is not deformed or only slightly deformed by the forces acting on it), extensive use is made of *free-body diagrams*. Briefly, a free-body diagram is an outline of a body (or a portion of a body) showing *all* the external forces acting on it. A free-body diagram is one example of the concept of a system. As a general concept applicable to all situations, we can define a system as a grouping of matter taken in any convenient or arbitrary manner. We can consider a fixed amount of mass and follow it as it changes shape, volume, or position. The mass will have a boundary that prevents any portion of mass from entering or leaving; this is called a *closed system*. It still permits energy (i.e., heat and/or work) to cross the boundary. On the other hand, we can choose as our system a region in space with a geographic boundary. Such a system permits mass to enter or leave the system across the boundary. It too allows for the movement of energy across the boundary. This is called an *open system*. In either case, a thermodynamic system will invariably have energy transferred from it or to it and can also have energy stored in it. From this definition, it will be noted that we are at liberty to choose the grouping, but once having made a choice, we must take into account *all* energies involved. An example of a closed system is the refrigerant fluid inside an air conditioner. An example of an open system is an automobile engine cylinder.

1.2.1 Application of System Concept

Thermodynamic equipment is best analyzed by rigorously applying the concept of a system. It can be applied to a volume in space, to a single body or a body of components, and even to a series of processes. To see how effective such a system analysis can be, consider as an example a well-insulated closed room with only a refrigerator in it. There is an electrical outlet in the wall to power the refrigerator. The room is so well insulated that no work or heat can pass through the walls except for electrical energy through the outlet. The refrigerator is plugged in and its door left open. What will happen to the temperature of the air inside the room? Will it rise, fall, or remain constant? The room air represents a closed system. There is an inflow of energy to the system through the outlet and the refrigerator. No other energy or mass change occurs; thus, the air temperature must rise.

This concept of the system should be remembered when considering alternative energy sources for transportation. In an attempt to find substitutes for our dependence on foreign oil, electric vehicles have been developed and ethanol has been added to gasoline. All too often, such measures ignore the system cost for developing those energy sources. In the case of electric vehicles, one must consider the source of the electricity: batteries and