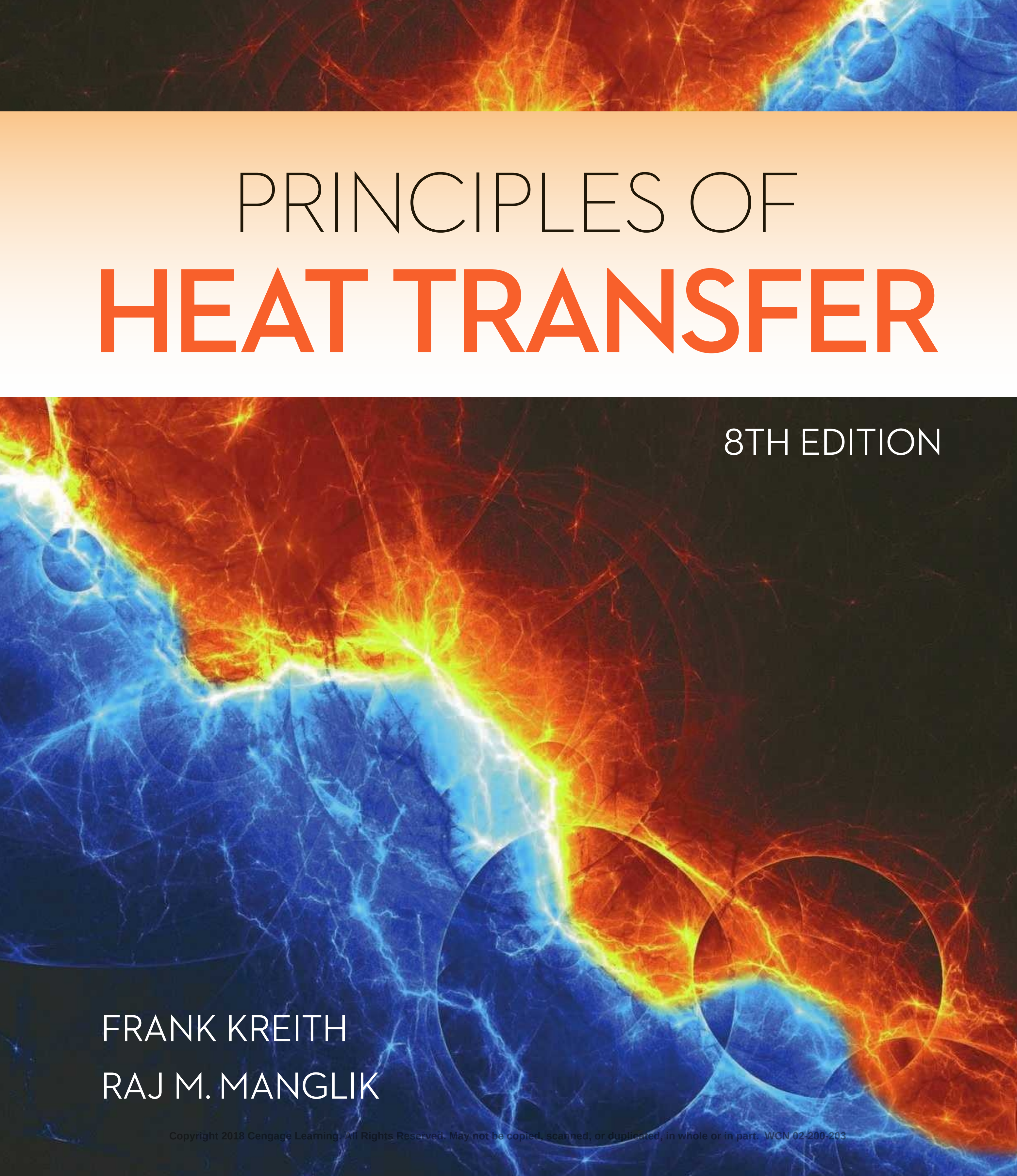

PRINCIPLES OF
HEAT TRANSFER

8TH EDITION

FRANK KREITH

RAJ M. MANGLIK

Conversion Factors for Commonly Used Quantities in Heat Transfer

Quantity	**SI → English**	**English → SI***
Area	1 m^2 = 10.764 ft^2 = 1550.0 in^2	1 ft^2 = 0.0929 m^2 1 in^2 = 6.452×10^{-4} m^2
Density	1 kg/m^3 = 0.06243 lb_m/ft^3	1 lb_m/ft^3 = 16.018 kg/m^3 1 $slug/ft^3$ = 515.38 kg/m^3
Energy†	1 J = 9.4787×10^{-4} Btu	1 Btu = 1055.06 J 1 cal = 4.1868 J 1 $lb_f \cdot ft$ = 1.3558 J 1 hp · h = 2.685×10^6 J
Energy per unit mass	1 J/kg = 4.2995×10^{-4} Btu/lb_m	1 Btu/lb_m = 2326 J/kg
Force	1 N = 0.22481 lb_f	1 lb_f = 4.448 N
Heat flux	1 W/m^2 = 0.3171 $Btu/(h \cdot ft^2)$	1 $Btu/(h \cdot ft^2)$ = 3.1525 W/m^2 1 $kcal/(h \cdot m^2)$ = 1.163 W/m^2
Heat generation per unit volume	1 W/m^3 = 0.09665 $Btu/(h \cdot ft^3)$	1 $Btu/(h \cdot ft^3)$ = 10.343 W/m^3
Heat transfer coefficient	1 $W/(m^2 \cdot K)$ = 0.1761 $Btu/(h \cdot ft^2 \cdot °F)$	1 $Btu/(h \cdot ft^2 \cdot °F)$ = 5.678 $W/(m^2 \cdot K)$
Heat transfer rate	1 W = 3.412 Btu/h	1 Btu/h = 0.2931 W 1 ton = 12,000 Btu/h = 3517.2 W
Length	1m = 3.281 ft = 39.37 in	1 ft = 0.3048 m 1 in = 0.0254 m
Mass	1 kg = 2.2046 lb_m	1 lb_m = 0.4536 kg 1 slug = 14.594 kg
Mass flow rate	1 kg/s = 7936.6 lb_m/h = 2.2046 lb_m/s	1 lb_m/h = 0.000126 kg/s 1 lb_m/s = 0.4536 kg/s
Power	1 W = 3.4123 Btu/h	1 Btu/h = 0.2931 W 1 Btu/s = 1055.1 W 1 $lb_f \cdot ft/s$ = 1.3558 W 1 hp = 745.7 W
Pressure and stress (*Note*: 1 Pa = 1N/m^2)	1 N/m^2 = 0.02089 lb_f/ft^2 = 1.4504×10^{-4} lb_f/in^2 = 4.015×10^{-3} in water = 2.953×10^{-4} in Hg	1 lb_f/ft^2 = 47.88 N/m^2 1 psi = 1 lb_f/in^2 = 6894.8 N/m^2 1 standard atmosphere = 1.0133×10^5 N/m^2 1 bar = 1×10^5 N/m^2

Conversion Factors for Commonly Used Quantities in Heat Transfer (*Continued*)

Quantity	**SI → English**	**English → SI**[*]
Specific heat	$1\ \text{J/(kg}\cdot\text{K)} = 2.3886 \times 10^{-4}\ \text{Btu/(lb}_m \cdot {}^\circ\text{F)}$	$1\ \text{Btu/(lb}_m \cdot {}^\circ\text{F)} = 4187\ \text{J/(kg}\cdot\text{K)}$
Surface tension	$1\ \text{N/m} = 0.06852\ \text{lb}_f\text{/ft}$	$1\ \text{lb}_f\text{/ft} = 14.594\ \text{N/m}$ $1\ \text{dyne/cm} = 1 \times 10^{-3}\ \text{N/m}$
Temperature	$T(\text{K}) = T({}^\circ\text{C}) + 273.15$ $= T({}^\circ\text{R})/1.8$ $= [T({}^\circ\text{F}) + 459.67]/1.8$ $T({}^\circ\text{C}) = [T({}^\circ\text{F}) - 32]/1.8$	$T({}^\circ\text{R}) = 1.8T(\text{K})$ $= T({}^\circ\text{F}) + 459.67$ $T({}^\circ\text{F}) = 1.8T({}^\circ\text{C}) + 32$ $= 1.8[T(\text{K}) - 273.15] + 32$
Temperature difference	$1\ \text{K} = 1{}^\circ\text{C}$ $= 1.8{}^\circ\text{R}$ $= 1.8{}^\circ\text{F}$	$1{}^\circ\text{R} = 1{}^\circ\text{F}$ $= (5/9)\text{K}$ $= (5/9){}^\circ\text{C}$
Thermal conductivity	$1\ \text{W/(m}\cdot\text{K)} = 0.57782\ \text{Btu/(h}\cdot\text{ft}\cdot{}^\circ\text{F)}$	$1\ \text{Btu/(h}\cdot\text{ft}\cdot{}^\circ\text{F)} = 1.731\ \text{W/m}\cdot\text{K}$ $1\ \text{kcal/(h}\cdot\text{m}\cdot{}^\circ\text{C)} = 1.163\ \text{W/m}\cdot\text{K}$
Thermal diffusivity	$1\ \text{m}^2\text{/s} = 10.7639\ \text{ft}^2\text{/s}$	$1\ \text{ft}^2\text{/s} = 0.0929\ \text{m}^2\text{/s}$ $1\ \text{ft}^2\text{/h} = 2.581 \times 10^{-5}\ \text{m}^2\text{/s}$
Thermal resistance	$1\ \text{K/W} = 0.5275{}^\circ\text{F}\cdot\text{h/Btu}$	$1{}^\circ\text{F}\cdot\text{h/Btu} = 1.896\ \text{K/W}$
Velocity	$1\ \text{m/s} = 3.2808\ \text{ft/s}$	$1\ \text{ft/s} = 0.3048\ \text{m/s}$
Viscosity (dynamic)	$1\ \text{N}\cdot\text{s/m}^2 = 0.672\ \text{lb}_m\text{/(ft}\cdot\text{s)}$ $= 2419.1\ \text{lb}_m\text{/(ft}\cdot\text{h)}$ $= 5.8016 \times 10^{-6}\ \text{lb}_f\cdot\text{h/ft}^2$	$1\ \text{lb}_m\text{/(ft}\cdot\text{s)} = 1.488\ \text{N}\cdot\text{s/m}^2$ $1\ \text{lb}_m\text{/(ft}\cdot\text{h)} = 4.133 \times 10^{-4}\ \text{N}\cdot\text{s/m}^2$ $1\ \text{centipoise} = 0.001\ \text{N}\cdot\text{s/m}^2$
Viscosity (kinematic)	$1\ \text{m}^2\text{/s} = 10.7639\ \text{ft}^2\text{/s}$	$1\ \text{ft}^2\text{/s} = 0.0929\ \text{m}^2\text{/s}$ $1\ \text{ft}^2\text{/h} = 2.581 \times 10^{-5}\ \text{m}^2\text{/s}$
Volume	$1\text{m}^3 = 35.3134\ \text{ft}^3$	$1\ \text{ft}^3 = 0.02832\ \text{m}^3$ $1\ \text{in}^3 = 1.6387 \times 10^{-5}\ \text{m}^3$ $1\ \text{gal (U.S. liq.)} = 0.003785\ \text{m}^3$
Volume flow rate	$1\ \text{m}^3\text{/s} = 35.3134\ \text{ft}^3\text{/s}$ $= 1.2713 \times 10^5\ \text{ft}^3\text{/h}$	$1\ \text{ft}^3\text{/h} = 7.8658 \times 10^{-6}\ \text{m}^3\text{/s}$ $1\ \text{ft}^3\text{/s} = 2.8317 \times 10^{-2}\ \text{m}^3\text{/s}$

[*] Some units in this column belong to the cgs and mks metric systems.

[†] Definitions of the units of energy which are based on thermal phenomena:

1 Btu = energy required to raise 1 lb_m of water 1°F at 68°F

1 cal = energy required to raise 1 g of water 1°C at 20°C

Eighth Edition

Principles of
HEAT TRANSFER

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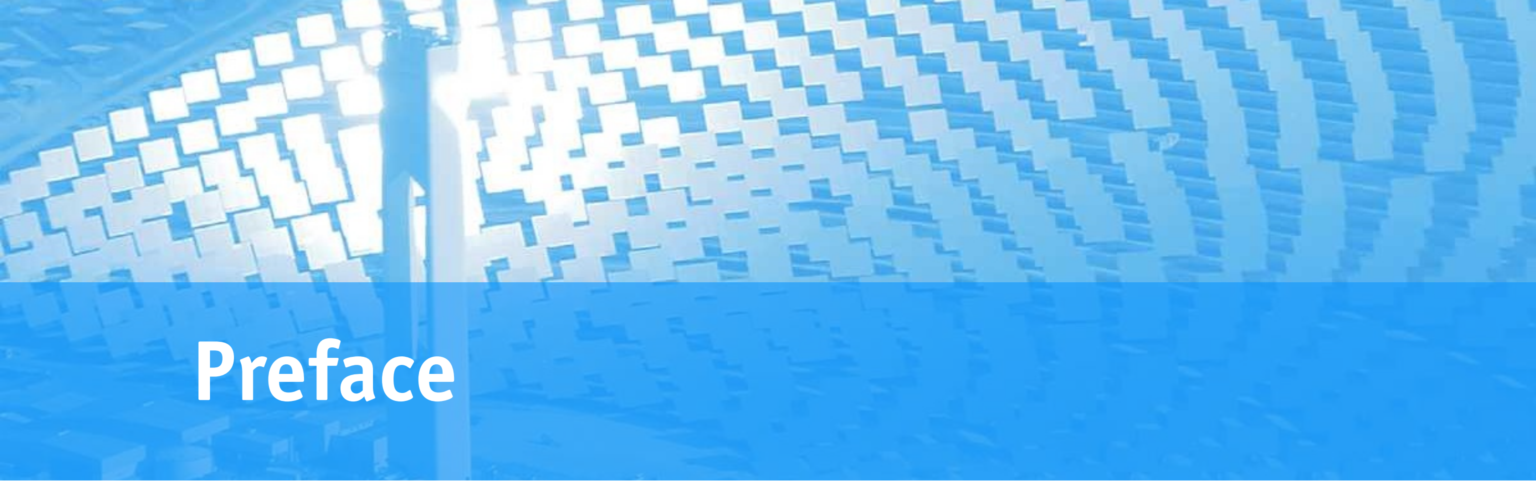
To our students
all over the world



Preface

When a textbook is published in its eighth edition, having been used by engineering students around the globe, it is natural to ask, “What has prompted the authors to revise the book?” The basic outline of how to teach the subject of heat transfer, which was pioneered by the senior author in its first edition, published almost 60 years ago, has been universally accepted by virtually all subsequent authors of heat transfer texts. Thus, while the general structure of this book has essentially remained the same over the years, newer experimental data, newer heat transfer devices and applications, especially in emerging technologies, as well as advancements in computational analyses and design methods, have necessitated reorganization, additions, and integration of contemporary engineering applications and methods of solution into the text.

The book is designed for a one-semester course in heat transfer at the junior or senior level. However, we have provided some flexibility. Sections marked with asterisks can be omitted without breaking the continuity of the presentation. If all the sections marked with an asterisk are omitted, the material in the book can be covered in a single quarter. For a full semester course, the instructor can select some of these sections and thus emphasize his or her own areas of interest and expertise.

Trusted Features

- **Open-ended problems** illustrate practical applications of heat transfer with problems similar to those faced by practicing engineers. The book emphasizes proven methods for approaching real-world engineering challenges, such as describing problems in one’s own words and providing schematic descriptions identifying known and unknown variables.
- **Learning objectives** clearly identify each chapter’s most important concepts and analyses. Helpful **Concepts and Analyses to Be Learned** sections at the beginning of each chapter link broad learning objectives to the key principles and critical material within the chapter that is most important for students to master.

- To test students' ability to absorb the main concepts in a chapter, a set of **Concept Review Questions** are provided online, with solutions available to instructors.

Supplements

Concept Review Questions and their **Solutions, Lecture Note PowerPoint** slides and a detailed **Instructor's Solution Manual** are available via the secure, password-protected Instructor Resource Center at https://login.cengage.com/.

New to the Eighth Edition

This new edition of *Principles of Heat Transfer* has significantly enhanced the presentation by incorporating new pedagogic elements and features to provide a more enriching learning experience. For example, important issues and concepts are highlighted at the beginning of each chapter to help students readily recognize these issues when they come up in the chapter and focus on them for a deeper understanding. Likewise, recapping the primary learning points at the end of each chapter helps students better assimilate the content. Another very important aspect of learning engineering science is to connect concepts and analysis methods with practical applications and the appropriate modeling of associated systems and devices. New elements of this edition include:

- **End-of-chapter summaries** recap and reiterate the key learning elements, improving comprehension and streamlining studying for exams.
- The content has been reorganized to provide a more **contemporary pedagogic structure,** and in each chapter particular attention is given to connecting modeling and analyses to current real-world engineering applications.
- Many **new examples and homework problems** have been added, which emphasize modeling and engineering applications to current technologies, such as bioengineering, micro-scale devices and microelectronics, materials processing, renewable energy, space exploration, and energy conservation. Other examples and problems have been revised to yield new solutions. Several new problems have been structured to not only provide learning experience in modeling and analysis, but also practical design optimization insights.
- Examples have been extended with **new comments sections** where the discussion expands the application context of the problem, and highlights design optimization strategies and insights.
- **Updated correlations and predictive equations** provide state-of-the-art design tools for current and emerging practical engineering applications, especially in newer applications of convection heat transfer.

Acknowledgments

The collaboration between the authors of this book, Frank Kreith and Raj M. Manglik, began with the publication of the seventh edition. We are profoundly grateful for our continued partnership and engagement in the pedagogy and instruction of heat transfer, which has resulted in the substantive updating and refreshing of the textbook. This revised edition, which is fundamentally rigorous as well as enriching with contemporary engineering applications of heat transfer, should continue to provide students a rewarding learning experience.

Frank Kreith would like to pay tribute to his lifelong friend and original co-author, the late Dr. Mark Bohn for his contributions to several previous editions of this book. This edition of the book is dedicated to our lifelong friend and great teacher of heat transfer, the late Dr. Arthur E. Bergles.

In addition, we would like to acknowledge the contributions by the reviewers of the seventh edition who have provided input and suggestions for the update leading to the new edition of the book: John R. Biddle, Cal Poly Pomona; Antonio Campo, The University of Texas at San Antonio; Michael Detamore, University of Kansas; Harry C. Hardee, New Mexico State University; Milind A. Jog, University of Cincinnati; Bassam Jubran, Ryerson University; Jungho Kim, University of Maryland; Francis A. Kulacki, University of Minnesota; Laura L. Pauley, Penn State University; and Satwindar S. Sadhal, University of Southern California.

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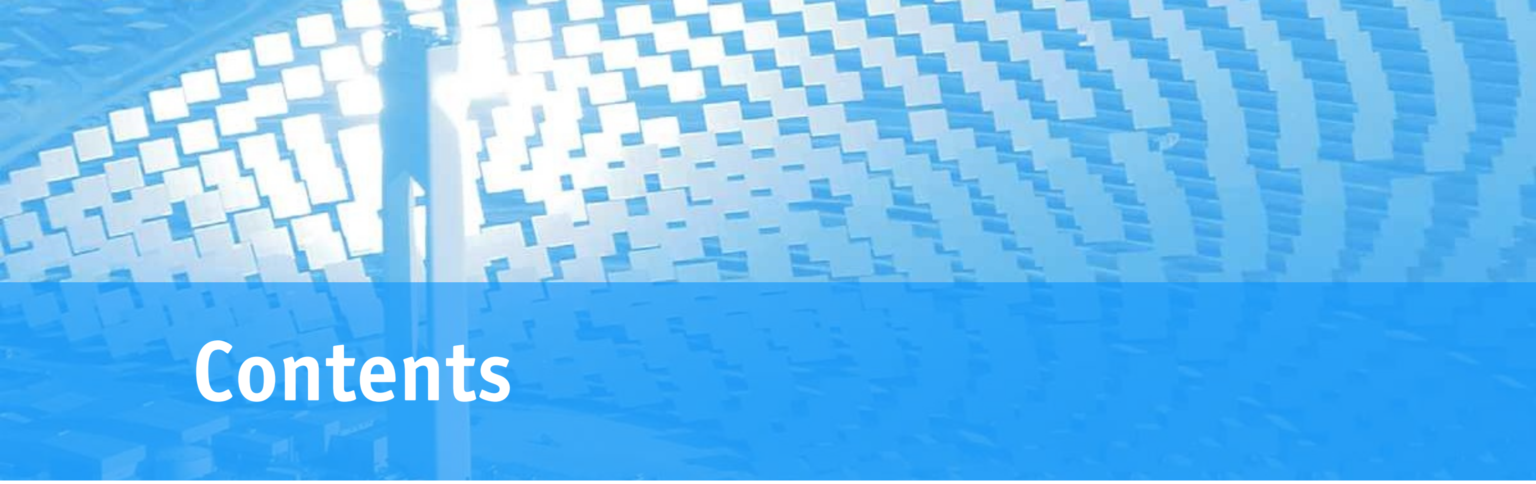
On a more personal level, Frank Kreith would like to express his appreciation to his assistant, Bev Weiler, who has supported his work in many tangible and intangible ways, and to his wife, Marion Kreith, whose forbearance with the time taken in writing books has been of invaluable help. Raj Manglik would like to express his fond gratitude to his wife, Vandana Manglik, for her patient encouragement during the long hours needed in this endeavor, and to his children, Aditi and Animaesh, for their affection and willingness to forego some of our shared time.



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Nomenclature

Symbol	Quantity	International System of Units	English System of Units
a	velocity of sound	m/s	ft/s
a	acceleration	m/s^2	ft/s^2
A	area; A_c cross-sectional area; A_p, projected area of a body normal to the direction of flow; A_q, area through which rate of heat flow is q; A_s, surface area; A_o, outside surface area; A_i, inside surface area	m^2	ft^2
b	breadth or width	m	ft
c	specific heat; c_p, specific heat at constant pressure; c_v, specific heat at constant volume	J/kg K	Btu/lb$_m$ °F
C	constant		
C	thermal capacity	J/K	Btu/°F
C	hourly heat capacity rate in Chapter 8; C_c, hourly heat capacity rate of colder fluid in a heat exchanger; C_h, hourly heat capacity rate of warmer fluid in a heat exchanger	W/K	Btu/h °F
C_D	total drag coefficient		
C_f	skin friction coefficient; Cfx, local value of Cf at distance x from leading edge; $\bar{C}_f$, average value of Cf defined by Eq. (4.31)		
d, D	diameter; D_H, hydraulic diameter; D_o, outside diameter; D_i, inside diameter	m	ft

(Continued)

Symbol	Quantity	International System of Units	English System of Units
e	base of natural or Napierian logarithm		
e	internal energy per unit mass	J/kg	Btu/lb$_m$
E	internal energy	J	Btu
E	emissive power of a radiating body; E_b, emissive power of blackbody	W/m^2	Btu/h ft^2
E_λ	monochromatic emissive power per micron at wavelength λ	W/m^2 μm	Btu/h ft^2 micron
$\mathcal{E}$	heat exchanger effectiveness defined by Eq. (8.22)		
f	Darcy friction factor for flow through a pipe or a duct, defined by Eq. (6.13)		
f	friction coefficient for flow over banks of tubes defined by Eq. (7.37)		
F	force	N	lb$_f$
F_T	temperature factor defined by Eq. (9.119)		
F_{1-2}	geometric shape factor for radiation from one blackbody to another		
$\mathcal{F}_{1-2}$	geometric shape and emissivity factor for radiation from one graybody to another		
g	acceleration due to gravity	m/s^2	ft/s^2
g_c	dimensional conversion factor	1.0 kg m/N s^2	32.2 ft lb$_m$/lb$_f$ s^2
G	mass flow rate per unit area ($G = \rho U_\infty$)	kg/m^2 s	lb$_m$/h ft^2
G	irradiation incident on unit surface in unit time	W/m^2	Btu/h ft^2
h	enthalpy per unit mass	J/kg	Btu/lb$_m$
h_c	local convection heat transfer coefficient	W/m^2 K	Btu/h ft^2°F
$\bar{h}$	combined heat transfer coefficient $\bar{h} = \bar{h}_c + \bar{h}_r$; hb, heat transfer coefficient of a boiling liquid, defined by Eq. (10.1); $\bar{h}_c$, average convection heat transfer coefficient; $\bar{h}_r$, average heat transfer coefficient for radiation	W/m2 K	Btu/h ft2°F
h_{fg}	latent heat of condensation or evaporation	J/kg	Btu/lb$_m$
i	angle between sun direction and surface normal	rad	deg

Symbol	Quantity	International System of Units	English System of Units
i	electric current	amp	amp
I	intensity of radiation	W/sr	Btu/h sr
I_λ	intensity per unit wavelength	W/sr μm	Btu/h sr micron
J	radiosity	W/m^2	Btu/h ft^2
k	thermal conductivity; k_s, thermal conductivity of a solid; k_f, thermal conductivity of a fluid	W/m K	Btu/h ft °F
K	thermal conductance; K_k, thermal conductance for conduction heat transfer; K_c, thermal conductance for convection heat transfer; K_r, thermal conductance for radiation heat transfer	W/K	Btu/h °F
l	length, general	m	ft or in.
L	length along a heat flow path or characteristic length of a body	m	ft or in.
L_f	latent heat of solidification	J/kg	Btu/lb$_m$
$\dot{m}$	mass flow rate	kg/s	lb$_m$/s or lb$_m$/h
M	mass	kg	lb$_m$
$\mathcal{M}$	molecular weight	gm/gm-mole	lb$_m$/lb-mole
N	number in general; number of tubes, etc.		
p	static pressure; p_c, critical pressure; p_A, partial pressure of component A	N/m^2	psi, lb$_f$/ft^2, or atm
P	wetted perimeter	m	ft
q	rate of heat flow; q_k, rate of heat flow by conduction; q_r, rate of heat flow by radiation; q_c, rate of heat flow by convection; q_b, rate of heat flow by nucleate boiling	W	Btu/h
$\dot{q}_G$	rate of heat generation per unit volume	W/m^3	Btu/h ft^3
q''	heat flux	W/m^2	Btu/h ft^2
Q	quantity of heat	J	Btu
$\dot{Q}$	volumetric rate of fluid flow	m3/s	ft3/h
r	radius; r_H, hydraulic radius; r_i, inner radius; r_o, outer radius	m	ft or in.

(Continued)

Symbol	Quantity	International System of Units	English System of Units
R	thermal resistance; R_c, thermal resistance to convection heat transfer; R_k, thermal resistance to conduction heat transfer; R_r, thermal resistance to radiation heat transfer	K/W	h °F/Btu
R_e	electrical resistance	ohm	ohm
$\mathcal{R}$	perfect gas constant	8.314 J/K kg-mole	1545 ft lb_f/lb-mole °F
S	shape factor for conduction heat flow		
S	spacing	m	ft
S_L	distance between centerlines of tubes in adjacent longitudinal rows	m	ft
S_T	distance between centerlines of tubes in adjacent transverse rows	m	ft
t	thickness	m	ft
T	temperature; T_b, temperature of bulk of fluid; T_f, mean film temperature; T_s, surface temperature; T_∞, temperature of fluid far removed from heat source or sink; T_m, mean bulk temperature of fluid flowing in a duct; T_{sv}, temperature of saturated vapor; T_{sl}, temperature of a saturated liquid; T_{fr}, freezing temperature; T_l, liquid temperature; T_{as}, adiabatic wall temperature	K or °C	R or °F
u	internal energy per unit mass	J/kg	Btu/lb_m
u	time average velocity in x direction; u', instantaneous fluctuating x component of velocity; $\bar{U}$, average velocity	m/s	ft/s or ft/h
U	overall heat transfer coefficient	W/m^2 K	Btu/h ft^2 °F
U_∞	free-stream velocity	m/s	ft/s
υ	specific volume	m^3/kg	ft^3/lb_m
υ	time average velocity in y direction; υ', instantaneous fluctuating y component of velocity	m/s	ft/s or ft/h
V	volume	m^3	ft^3
w	time average velocity in z direction; w', instantaneous fluctuating z component of velocity	m/s	ft/s

Symbol	Quantity	International System of Units	English System of Units
w	width	m	ft or in.
$\dot{W}$	rate of work output	W	Btu/h
x	distance from the leading edge; x_c, distance from the leading edge where flow becomes turbulent	m	ft
x	coordinate	m	ft
x	quality		
y	coordinate	m	ft
y	distance from a solid boundary measured in direction normal to surface	m	ft
z	coordinate	m	ft
Z	ratio of hourly heat capacity rates in heat exchangers		
	Greek Letters		
α	absorptivity for radiation; α_λ, monochromatic absorptivity at wavelength λ		
α	thermal diffusivity $= k/\rho c$	m^2/s	ft^2/s
β	temperature coefficient of volume expansion	1/K	1/R
β_k	temperature coefficient of thermal conductivity	1/K	1/R
γ	specific heat ratio, c_p/c_v		
Γ	body force per unit mass	N/kg	lb_f/lb_m
Γ_c	mass rate of flow of condensate per unit breadth for a vertical tube	kg/s m	lb_m/h ft
δ	boundary-layer thickness; δ_h, hydrodynamic boundary-layer thickness; δ_{th}, thermal boundary-layer thickness	m	ft
Δ	difference between values		
ε	packed bed void fraction		

(Continued)

Symbol	Quantity	International System of Units	English System of Units
ε	emissivity for radiation; ε_λ, monochromatic emissivity at wavelength λ; ε_ϕ, emissivity in direction of ϕ		
ε_H	thermal eddy diffusivity	m^2/s	ft^2/s
ε_M	momentum eddy diffusivity	m^2/s	ft^2/s
ζ	ratio of thermal to hydrodynamic boundary-layer thickness, δ_{th}/δ_h		
η_f	fin efficiency		
θ	time	s	h or s
λ	wavelength; λ_{max}, wavelength at which monochromatic emissive power $E_{b\lambda}$ is a maximum	μm	micron
λ	latent heat of vaporization	J/kg	Btu/lb_m
μ	absolute viscosity	$N\ s/m^2$	$lb_m/ft\ s$
ν	kinematic viscosity, μ/ρ	m^2/s	ft^2/s
ν_r	frequency of radiation	1/s	1/s
ρ	mass density, $1/v$; ρ_l, density of liquid; ρ_v, density of vapor	kg/m^3	lb_m/ft^3
ρ	reflectivity for radiation		
τ	shearing stress; τ_s, shearing stress at surface; τ_w, shear at wall of a tube or a duct	N/m^2	lb_f/ft^2
τ	transmissivity for radiation		
σ	Stefan–Boltzmann constant	$W/m^2\ K^4$	$Btu/h\ ft^2\ R^4$
σ	surface tension	N/m	lb_f/ft
ϕ	angle	rad	rad
ω	angular velocity	rad/s	rad/s
ω	solid angle	sr	steradian
	Dimensionless Numbers		
Bi	Biot Number $= \bar{h}L/k_s$ or $\bar{h}r_o/k_s$		
Fo	Fourier modulus $= a\theta/L^2$ or $a\theta/r_o^2$		
Gz	Graetz number $= (\pi/4)\mathrm{RePr}(D/L)$		

Symbol	Quantity	International System of Units	English System of Units
Gr	Grashof number $= \beta_g L^3 \, \Delta T/\nu^2$		
Ja	Jakob number $= (T_\infty - T_{\text{sat}})c_{pl}/h_{fg}$		
M	Mach number $= U_\infty/a$		
Nu_x	local Nusselt number at a distance x from leading edge, $h_c x/k_f$		
$\overline{Nu}_L$	average Nusselt number for blot plate, $\bar{h}_c L/k_f$		
$\overline{Nu}_D$	average Nusselt number for cylinder, $\bar{h}_c D/k_f$		
Pe	Peclet number = RePr		
Pr	Prandtl number $= c_p\mu/k$ or ν/α		
Ra	Rayleigh number = GrPr		
Re_L	Reynolds number $= U_\infty \rho L/\mu$;		
$\text{Re}_x = U_\infty \rho x/\mu$	Local value of Re at a distance x from leading edge		
$\text{Re}_D = U_\infty \rho D/\mu$	Diameter-based Reynolds number		
$\text{Re}_b = D_b G_b/\mu_l$	Bubble Reynolds number		
θ	Boundary Fourier modulus $= \bar{h}^2 a\theta/k_s^2$		
St	Stanton number $= \bar{h}_c/\rho U_{\infty c_p}$ or $\overline{Nu}$/RePr		
	Miscellaneous		
$a > b$	a greater than b		
$a < b$	a smaller than b		
$\propto$	proportional sign		
$\simeq$	approximately equal sign		
∞	infinity sign		
Σ	summation sign		

Eighth Edition

Principles of
HEAT TRANSFER

CHAPTER 1

Basic Modes of Heat Transfer

A typical solar power plant with its arrays or field of heliostats and the solar power tower in the left center; such a system involves all modes of heat transfer–radiation, conduction, and convection, including boiling and condensation.

Source: Photo courtesy of Abengoa Solar.

Concepts and Analyses to Be Learned

Heat is fundamentally transported, or “moved,” by a temperature gradient; it *flows* or is *transferred* from a higher temperature region to a lower temperature one. An understanding of this process and its different mechanisms requires you to connect principles of thermodynamics and fluid flow with those of heat transfer. The latter has its own set of concepts and definitions, and the foundational principles among these are introduced in this chapter along with their mathematical descriptions and some typical engineering applications. A study of this chapter will teach you:

- How to apply the basic energy conservation principles that stem from the relationship between thermodynamics and heat transfer.
- How to model the concepts of different modes or mechanisms of heat transfer for practical engineering applications.
- How to use the analogy between heat and electric current flow, as well as thermal and electrical resistance, in engineering analysis.
- How to identify the difference between steady state and transient modes of heat transfer.

1.1 The Relation of Heat Transfer to Thermodynamics

Whenever a temperature gradient exists within a system, or whenever two systems at different temperatures are brought into contact, energy is transferred. The process by which the energy transport takes place is known as *heat transfer*. The thing in transit, called heat, cannot be observed or measured directly. However, its effects are identified and quantified through measurements and analysis. The flow of heat, like the performance of work, is a process by which the initial energy of a system is changed.

The branch of science that deals with the relation between heat and other forms of energy, including mechanical work in particular, is called *thermodynamics*. Its principles, like all laws of nature, are based on observations and have been generalized into laws that are believed to hold for all processes occurring in nature because no exceptions have ever been found. For example, the first law of thermodynamics states that energy can be neither created nor destroyed but only changed from one form to another. It governs all energy transformations quantitatively, but places no restrictions on the direction of the transformation. It is known, however, from experience that no process is possible whose sole result is the net transfer of heat from a region of lower temperature to a region of higher temperature. This statement of experimental truth is known as the second law of thermodynamics.

All heat transfer processes involve the exchange and/or conversion of energy. They must, therefore, obey the first as well as the second law of thermodynamics. At first glance, one might therefore be tempted to assume that the principles of heat transfer are derived from the basic laws of thermodynamics. This conclusion, however, is erroneous, because classical thermodynamics is restricted primarily to the study of equilibrium states including mechanical, chemical, and thermal equilibriums, and is therefore, by itself, of little help in determining quantitatively the transformations that occur from a lack of equilibrium in engineering processes. Since heat flow is the result of temperature nonequilibrium, its quantitative treatment must be based on other branches of science. The same reasoning applies to other types of transport processes such as mass transfer and diffusion.

Limitations of Classical Thermodynamics Classical thermodynamics deals with the states of systems from a macroscopic view and makes no hypotheses about the structure of matter. To perform a thermodynamic analysis it is necessary to describe the state of a system in terms of gross characteristics, such as pressure, volume, and temperature, which are measured directly and involves no special assumptions regarding the structure of matter. These variables (or thermodynamic properties) are of significance for the system as a whole only when they are uniform throughout it, that is, when the system is in equilibrium. Thus, classical thermodynamics is not concerned with the details of a process but rather with equilibrium states and the relations among them. The processes employed in a thermodynamic analysis are idealized processes devised to give information concerning equilibrium states.

The schematic example of an automobile engine in Fig. 1.1 is illustrative of the distinctions between thermodynamic and heat transfer analysis. While the basic law of energy conservation is applicable in both, from a thermodynamic viewpoint, the amount of heat transferred during a process simply equals the difference between the energy change of the system and the work done. It is evident that this type of analysis considers neither the mechanism of heat flow nor the time required to transfer the heat. It simply prescribes how much heat to supply to or reject from a system during a process between specified end states without considering whether, or how, this is accomplished. The question of how long it takes to transfer a specified amount of heat, via different mechanisms or modes of heat transfer and their processes (both in terms of space and time) by which

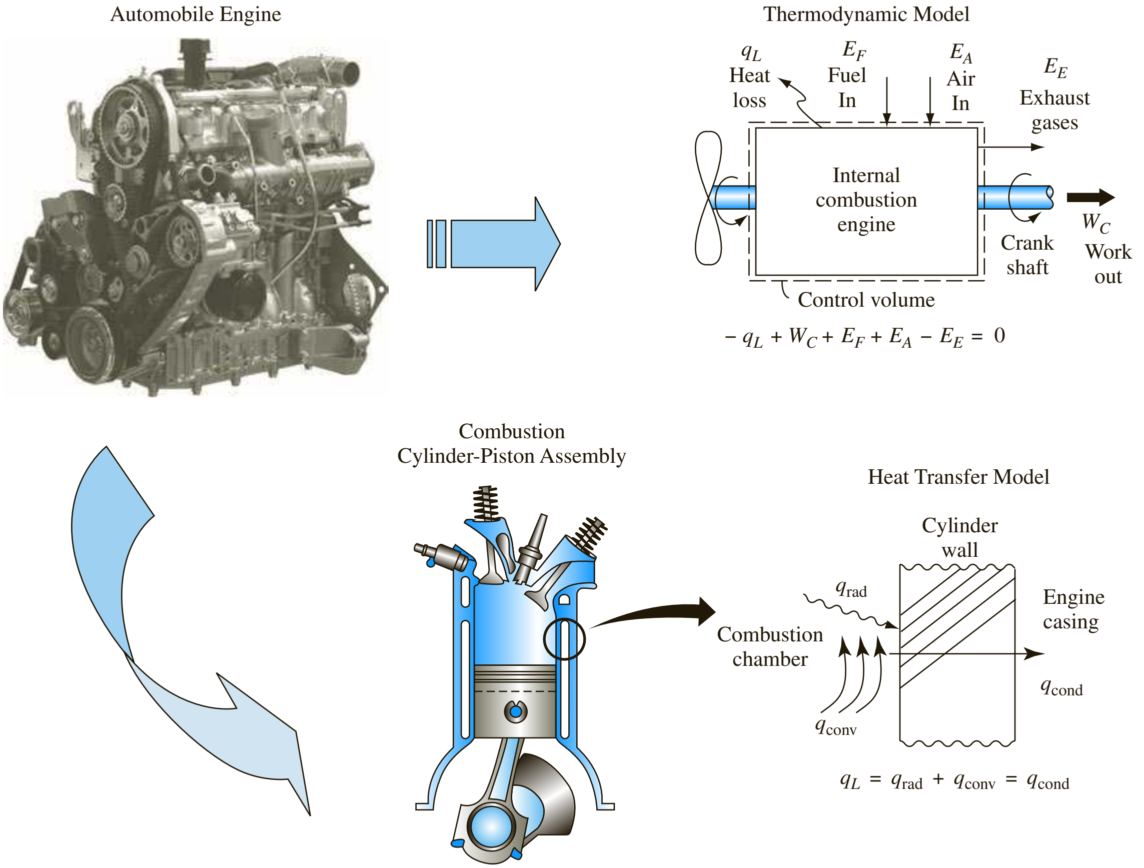

FIGURE 1.1 A classical thermodynamics model and a heat transfer model of a typical automobile (spark-ignition internal combustion) engine.

Source: AJancso/Shutterstock.com

they occur, although of great practical importance, does not usually enter into the thermodynamic analysis.

Engineering Heat Transfer From an engineering viewpoint, the key problem is the determination of the *rate of heat transfer at a specified temperature difference*. To estimate the cost, the feasibility, and the size of equipment necessary to transfer a specified amount of heat in a given time, a detailed heat transfer analysis must be made. The dimensions of boilers, heaters, refrigerators, and heat exchangers depend not only on the amount of heat to be transmitted but also on the rate at which the heat is to be transferred under given conditions. The successful operation of equipment components, such as turbine blades or the walls of combustion chambers, depends on the possibility of cooling certain metal parts by continuously removing heat from a surface at a rapid rate. A heat transfer analysis is also made in the design of electric machines, transformers, and bearings to avoid conditions that will overheat and damage the equipment. The listing in Table 1.1, which by no means is comprehensive, gives an indication of the extensive significance of heat transfer and its different practical applications. These examples show that almost every branch of engineering encounters heat transfer problems, which shows that they are not capable of solution by thermodynamic reasoning alone but require an analysis based on the science of heat transfer.

In heat transfer, as in other branches of engineering, the successful solution of a problem requires assumptions and idealizations. It is almost impossible to describe physical phenomena exactly, and in order to express a problem in the

TABLE 1.1 Significance and diverse practical applications of heat transfer

Chemical, petrochemical, and process industry: Heat exchangers, reactors, reboilers, etc.

Power generation and distribution: Boilers, condensers, cooling towers, feed heaters, transformer cooling, transmission cable cooling, etc.

Aviation and space exploration: Gas turbine blade cooling, vehicle heat shields, rocket engine/nozzle cooling, space suits, space power generation, etc.

Electrical machines and electronic equipment: Cooling of motors, generators, computers and microelectronic devices, etc.

Manufacturing and material processing: Metal processing, heat treating, composite material processing, crystal growth, micromachining, laser machining, etc.

Transportation: Engine cooling, automobile radiators, climate control, mobile food storage, etc.

Fire and combustion

Health care and biomedical applications: Blood warmers, organ and tissue storage, hypothermia, etc.

Comfort heating, ventilation, and air-conditioning: Air conditioners, water heaters, furnaces, chillers, refrigerators, etc.

Weather and environmental changes: Temperature rise of oceans.

Renewable Energy System: Flat plate collectors, thermal energy storage, PV module cooling, etc.

form of an equation that can be solved, it is necessary to make some approximations. In electrical circuit calculations, for example, it is usually assumed that the values of the resistances, capacitances, and inductances are independent of the current flowing through them. This assumption simplifies the analysis but *may* in certain cases severely limit the accuracy of the results.

It is important to keep in mind the assumptions, idealizations, and approximations made in the course of an analysis when the final results are interpreted. Sometimes insufficient information on physical properties make it necessary to use engineering approximations to solve a problem. For example, in the design of machine parts for operation at elevated temperatures, it may be necessary to estimate the proportional limit or the fatigue strength of the material from low-temperature data. To assure satisfactory operation of a particular part, the designer should apply a factor of safety to the results obtained from the analysis. Similar approximations are also necessary in heat transfer problems. Physical properties such as thermal conductivity or viscosity change with temperature, but if suitable average values are selected, the calculations are considerably simplified without introducing an appreciable error in the final result. When heat is transferred from a fluid to a wall, as in a boiler, a scale forms under continued operation and reduces the rate of heat flow. To assure satisfactory operation over a long period of time, a factor of safety must be applied to provide for this contingency.

When it becomes necessary to make an assumption or approximation in the solution of a problem, the engineer must rely on ingenuity and past experience. There are no simple guides to new and unexplored problems, and an assumption valid for one problem may be misleading in another. Experience has shown, however, that the first requirement for making sound engineering assumptions or approximations is a complete and thorough physical understanding of the problem at hand. In the field of heat transfer, this means having familiarity not only with the laws and physical mechanisms of heat flow but also with those of fluid mechanics, physics, and mathematics.

Heat transfer is defined as the transmission of energy from one region to another as a result of a temperature difference between them. Since differences in temperatures exist all over the universe, the phenomena of heat flow are as universal as those associated with gravitational attractions. Unlike gravity, however, heat flow is governed not by a unique relationship but rather by a combination of various independent laws of physics.

Mechanisms of Heat Transfer The literature of heat transfer generally recognizes three distinct modes of heat transmission: conduction, radiation, and convection. Strictly speaking, only conduction and radiation should be classified as heat transfer processes, because only these two mechanisms depend for their operation on the mere existence of a temperature difference. The last of the three, convection, does not strictly comply with the definition of heat transfer because its operation also depends on mechanical mass transport. But since convection also accomplishes transmission of energy from regions of higher temperature to regions of lower temperature, the term “heat transfer by convection” has become generally accepted.

In Sections 1.3–1.5, we survey the basic equations governing each of the three modes of heat transfer. Our initial aim is to obtain a broad perspective of the field without becoming involved in details. We therefore consider only simple cases. Yet it should be emphasized that in most natural situations heat is transferred not by one but by several mechanisms operating simultaneously. Hence, in Section 1.6 we show how to combine the simple relations in situations when several heat transfer modes occur simultaneously, and in Section 1.7 we show how to reduce heat flow by insulation. And finally, in Section 1.8, we illustrate how to use the laws of thermodynamics in heat transfer analyses.

1.2 Dimensions and Units

Before proceeding with the development of the concepts and principles governing the transmission or flow of heat, it is instructive to review the primary dimensions and units by which its descriptive variables are quantified. It is important not to confuse the meaning of the terms ***units*** and ***dimensions***. ***Dimensions*** are our basic concepts of measurements such as length, time, and temperature. For example, the distance between two points is a dimension called length. ***Units*** are the means of expressing dimensions numerically, for instance, meter or foot for length; second or hour for time. Before numerical calculations are made, ***dimensions must be quantified by units***.

Several different systems of units are in use throughout the world. The SI system (Systeme international d'unites) has been adopted by the International Organization for Standardization and is recommended by most U.S. national standard organizations. Therefore, we will primarily use the SI system of units in this book. In the United States, however, the English system of units is still widely used. It is therefore important to be able to change from one set of units to another. To be able to communicate with engineers who are still in the habit of using the English system, several examples and exercise problems in the book use the English system.

It may be recalled that the basic or fundamental SI units are expressed as length L in meter [m], mass M in kilogram [kg], time t in second [s], and temperature T in kelvin [K]. Most other units for different variables and parameters are derived from their definitions using these base units. For example, the unit of force, the newton [N], is obtained from Newton's second law of motion, which states that force is proportional to the time rate of change of momentum. For a given mass, Newton's law can be written in the form

$$F = \frac{1}{g_c} ma \tag{1.1}$$

where F is the force, m is the mass, a is the acceleration, and g_c is a constant whose numerical value and units depend on those selected for F, m, and a.

In the SI system the unit of force, the newton [N], is defined as

$$1\ \text{N} = \left(\frac{1}{g_c} \times 1\ \text{kg} \times 1\ \text{m/s}^2\right) = 1\ [\text{kg} \cdot \text{m/s}^2]$$

Thus, we see that

$$g_c = 1\ [\text{kg m/N s}^2]$$

In the English system, we have the relation

$$1\ \text{lb}_f = \left(\frac{1}{g_c} \times 1\ \text{lb} \times g\ \text{ft/s}^2\right)$$

The numerical value of the conversion constant g_c is determined by the acceleration imparted to a 1-lb mass by a 1-lb force, or

$$g_c = 32.174\ \text{ft}\ [\text{lb}_m/\text{lb}_f\,\text{s}^2]$$

The weight of a body, W, is defined as the force exerted on the body by gravity. Thus

$$W = \frac{g}{g_c} m$$

where g is the local acceleration due to gravity. Weight has the dimensions of a force and a 1-kg mass weighs 9.8 N at sea level.

It should be noted that g and g_c are not similar quantities. The gravitational acceleration g depends on the location and the altitude, whereas g_c is a constant whose value depends on the system of units. One of the great conveniences of the SI system is that g_c is numerically equal to one and therefore need not be shown specifically. In the English system, on the other hand, the omission of g_c affects the numerical answer, and it is therefore imperative that it be included and clearly displayed in analysis, especially in numerical calculations.

With the fundamental units of meter, kilogram, second, and kelvin, the units for both force and energy or heat are derived units. For quantifying heat, rate of heat transfer, its flux, and its temperature, the units employed as per the international convention are given in Table 1.2. Also listed are their counterparts in English units, along with the respective conversion factors, in cognizance of the fact that such units are still prevalent in practice in the United States. The joule (newton meter) is the only energy unit in the SI system, and the watt (joule per second)

TABLE 1.2 Dimensions and units of heat and temperature

Quantity	SI units	English units	Conversion
Q, quantity of heat	J	Btu	$1\ \text{J} = 9.4787 \times 10^{-4}$ Btu
q, rate of heat transfer	J/s or W	Btu/h	1 W = 3.4123 Btu/h
q'', heat flux	W/m^2	Btu/h·ft^2	1W/m^2 = 0.3171 Btu/h·ft^2
T, temperature	K	°R or °F	T°C = (T°F − 32)/1.8
	[K] = [°C] + 273.15	[R] = [°F] + 459.67	T K = T°R/1.8

is the corresponding unit of power. In the engineering system of units, on the other hand, the Btu (British thermal unit) is the unit for heat or energy. It is defined as the energy required to raise the temperature of 1 lb_m (454 g) of water by 1°F (0.6°C) at 60°F (15.6°C) and one atmosphere pressure (101 kPa).

The SI unit of temperature is the kelvin, but use of the Celsius temperature scale is widespread and generally considered permissible. The kelvin is based on the thermodynamic scale, while zero on the Celsius scale (0°C) corresponds to the freezing temperature of water and is equivalent to 273.15 K on the thermodynamic scale. Note, however, that temperature differences are numerically equivalent in K and °C, i.e., $\Delta T = 1.0$ K is numerically equal to $\Delta T = 1.0$°C.

In the English system of units, the temperature is usually expressed in degrees Fahrenheit (°F) or, on the thermodynamic temperature scale, in degrees Rankine (°R). Here, 1 K is equal to 1.8°R and conversions for other temperature scales are given by

$$^\circ\text{C} = \frac{^\circ\text{F} - 32}{1.8}$$

EXAMPLE 1.1

A masonry brick wall of a house has an inside surface temperature of 55°F and an average outside surface temperature of 45°F. The wall is 1.0 ft thick, and because of the temperature difference, the heat loss through the wall per square foot is 3.4 Btu/h·ft^2. Express the heat loss in SI units for a 100-ft^2 surface over a 24-h period. Also, calculate the cost of this heat loss if the house is heated by an electric resistance heater and the cost of electricity is 10 ¢/kWh.

SOLUTION

The rate of heat loss per unit surface area q in SI units is

$$q'' = 3.4\left(\frac{\text{Btu}}{\text{ft}^2\text{h}}\right) \times 0.2931\left(\frac{\text{W}}{\text{Btu/h}}\right) \times \frac{1}{0.0929}\left(\frac{\text{ft}^2}{\text{m}^2}\right) = 10.73\,[\text{W/m}^2]$$

The total heat loss Q to the environment over the specified surface area of the house wall in 24 hours is

$$Q = 3.4\left(\frac{\text{Btu}}{\text{ft}^2\text{h}}\right) \times 100(\text{ft}^2) \times 24(\text{h}) = 8160\,[\text{Btu}]$$

In SI units the heat loss Q is

$$Q = 8160 \times 0.2931 \times 10^{-3}\left(\frac{\text{kWh}}{\text{Btu}}\right) = 2.392\,[\text{kWh}]$$

At 10 ¢/kW·h, this amounts to ≈ 24 ¢ as the cost of heat loss in 24 h.