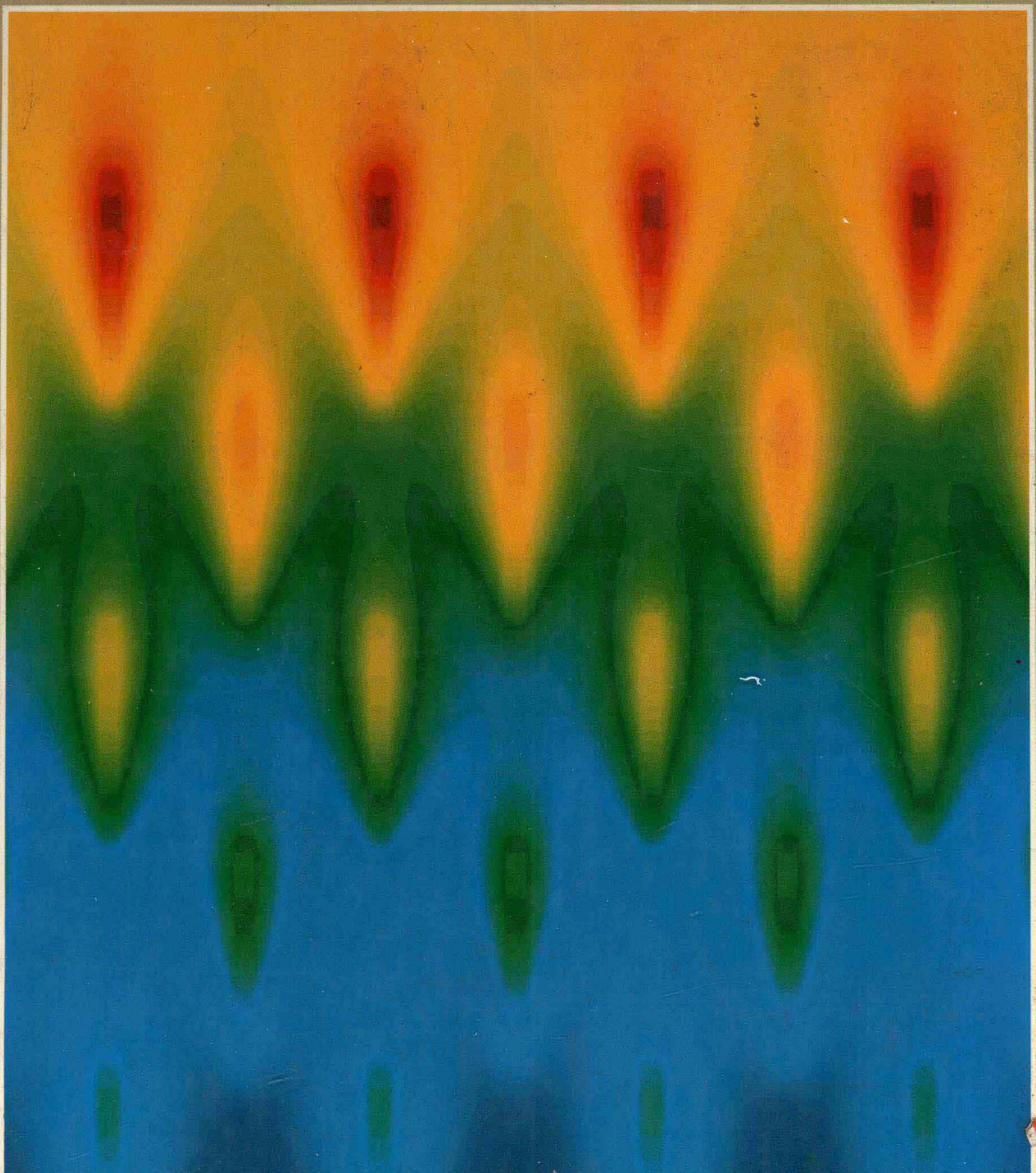
HEAT TRANSFER



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Other books by Adrian Bejan:

Entropy Generation through Heat and Fluid Flow, Wiley, 1982, 248 pages.
(*Solutions Manual*, Wiley, 1984, 50 pages, available from the author.)
Convection Heat Transfer, Wiley, 1984, 477 pages.
(*Solutions Manual*, Wiley, 1984, 218 pages, available from the publisher and from the author.)
Advanced Engineering Thermodynamics, Wiley, 1988, 759 pages.
(*Solutions Manual*, Wiley, 1988, 153 pages, available from the publisher and from the author.)
Convection in Porous Media, with D. A. Nield, Springer-Verlag, 1992, 425 pages.

To our William

PREFACE

The principal objective in writing this textbook for a first course in heat transfer is to present a rigorous and refreshing treatment of the subject, and to relate heat transfer to other disciplines, in particular, thermodynamics and fluid mechanics. This book is about "modern" heat transfer, that is, it is intended to reflect the changes currently taking place in the engineering profession and in engineering education.

Engineering Design

Engineering work and research are driven not only by human curiosity but also by the real needs of our society. For this reason, this book emphasizes design, or the synthesizing of two or more issues (i.e., engineering disciplines) into an answer with a practical meaning. The student is called on to recognize that there is more than one way in which to design a heat transfer apparatus—and to understand that knowing the worst design (the greatest pitfall, or trap) is often as important as knowing the optimal solution and all of the other options in between.

Design questions are drawn from many diverse areas. They include, for instance, insulations for walls with nonuniform temperature, insulations that must provide mechanical rigidity and support, the safe disposal of hot ash, the stabilization of superconductors, optimal packing of fibrous insulation, fins subjected to material constraint, and several applications covering the packaging and cooling of integrated electronic circuits. Each design question is presented in a fundamental way, so that (1) the answer can be used in more than one application, and (2) the work of arriving at the answer has the greater educational value.

Interdisciplinary Approach

This book teaches heat transfer as a discipline that works hand-in-hand with other disciplines in the evolution of a process, or in the successful performance of a device. Throughout its discussion emphasizes that real applications tend to be interdisciplinary, and that good work requires a solid foundation in all of the compartments of engineering education. The material presented in the chapter discussions and in the problems at the end of each chapter illustrates extensively the interfaces between heat transfer and other disciplines, such as metallurgy, structural mechanics, tribology, electrical engineering, superconductivity, cryogenics, and solar and geothermal energy production.

The emphasis of this book on the interdisciplinary character of real-life thermal engineering, however, does not detract from the teaching of heat transfer first as a self-standing *discipline*, that is, a field with its own scope, language, and rules. Interdisciplinary engineering can only be practiced by the engineer who is solidly grounded in the fundamentals of each discipline. To gloss over the fundamentals in the quick and currently popular pursuit of "interdisciplinary" topics would be to promote shallowness in the name of erudition and modernism.

Student Oriented

Early in my career, I discerned a need to present a course that treats each student as an intelligent human being, regardless of his or her background or aspirations. In this book, my goal is to reach simultaneously the curious, who are attuned to asking more questions, and the pragmatic, who prefer to get on with their calculations based on well-defined formulas.

Relationship to Fluid Mechanics, Thermodynamics, and History of Engineering

The book stresses the importance of fluid mechanics as a prerequisite for heat transfer analysis. To understand the flow configuration and its regime (laminar versus turbulent) is tremendously important not only in convection heat transfer calculations but also in *conjugate* situations in which convection is accompanied by conduction and radiation.

The role of thermodynamics in heat transfer is presented with great care. This begins with the calorimetric terminology, which is shared by both disciplines, and continues with the thermodynamic meaning of heat transfer engineering concepts, such as natural ("free") convection, heat exchanger pressure drop, and solar collector optimization.

Throughout the book I explain where each concept and formula comes from. In many instances, I provide the history of the concept and, sometimes, even the origin of the words that are used to name that concept.

Scale Analysis

This book makes a strong case for the use of simple and approximate analyses. Special emphasis is placed on order-of-magnitude calculations, or "scale analysis." I previously used this method in my graduate text on *Convection Heat Transfer* (Wiley, 1984). Since then, I have found that scale analysis can play an even greater role in a first course on heat transfer, where it can be used to solve conduction problems in addition to those of convection. Approximate methods, such as scale analysis and integral analysis, are emphasized because of their high rate of "return on investment." This has always been a central objective in engineering practice.

Problem-Solving Material

The emphasis on physical understanding and the freedom to choose between exact and approximate calculations is reflected also in the problem-solving material included in this course. The simplest problems are presented in the text as worked out *examples*, whereas the more challenging ones are proposed as *problems* at the end of each chapter. In later chapters, the *projects* that follow the problems require more time to solve. These projects usually have greater design content, and may be developed by the instructor into homework of longer duration.

It is always a good idea to begin solving a problem by executing a *good drawing*, and I have tried to demonstrate this to the student. Making a good drawing requires the student to explain to himself or herself the physics of the problem. Learning to take this preliminary step will be a benefit in the student's future career in engineering. The *Solutions Manual* that accompanies this book reflects the same care for problem solving (explanations, details, graphics) that is exhibited throughout the text. I wrote the solutions manual myself, as a "second book" in both content and appearance.

Looking Back at the Last Four Years

I am extremely fortunate to be and work at Duke University, which has provided me with a very friendly and supportive environment and, above all, freedom. It is a rare privilege to be allowed the freedom to think one's own thoughts.

Mary, my wife, was once again my chief collaborator and counselor. I owe every bit of my progress to her. Our family was also very supportive and a steady reminder of what is really important. I am deeply indebted to my parents-in-law, Terry Riordan and the late Bill Riordan, who actively supported my work, laboratory, and students.

Linda Hayes typed the entire manuscript while improving its English and organization. She also prepared the *Solutions Manual* on the word processor so that the manual, too, has a professional appearance. Her exquisite work is an important part of this finished project. I am very grateful to her for all of her help.

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Adrian Bejan
Durham, North Carolina
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A. B.

ABOUT THE AUTHOR

Adrian Bejan received his B.S. (1972, Honors Course), M.S. (1972, Honors Course), and Ph.D. (1975) degrees in mechanical engineering, all from the Massachusetts Institute of Technology. From 1976 until 1978, he was a Fellow of the Miller Institute for Basic Research in Science, at the University of California, Berkeley. Before coming to Duke as a full professor in 1984, he taught at the University of Colorado, Boulder.

Professor Bejan is the author of three graduate-level textbooks, *Entropy Generation through Heat and Fluid Flow, Convection Heat Transfer,* and *Advanced Engineering Thermodynamics,* and is coauthor of a research monograph on *Convection in Porous Media.* In addition, he has written 190 technical articles on a variety of topics, including natural convection, combined heat and mass transfer, convection through porous media, transition to turbulence, second-law analysis and design, solar energy conversion, melting and solidification, condensation, cryogenics, applied superconductivity, and tribology.

Adrian Bejan is the 1990 recipient of the thermodynamics award of the American Society of Mechanical Engineers (ASME), the James Harry Potter Gold Medal. He also received the Gustus L. Larson Memorial Award of the ASME in 1988, and was elected Fellow of the ASME in 1987. He was awarded the J. A. Jones chair at Duke in 1989.

LIST OF SYMBOLS

a_i	impurity-scattering resistivity coefficient ($m \cdot K^2/W$), eq. (1.30)
a_n	dimensionless characteristic values, eq. (3.43) and Table 3.1
a_p	phonon-scattering resistivity coefficient ($m/W \cdot K$), eq. (1.30)
A	area (m^2)
A_c	cross-sectional area (m^2)
A_c	minimum free-flow area (m^2), eq. (9.65)
A_{exp}	fin surface exposed to the fluid (m^2)
A_f	finned area (m^2), contributed by the exposed surfaces of the fins, Chapter 9
A_{fr}	frontal area (m^2), eq. (9.65)
A_n	normal or projected area (m^2)
A_u	unfinned area (portions) of the wall (m^2), Chapter 9
A_0	bare surface, projected surface (m^2), Fig. 2.10
$A_{0,f}$	finned portion of bare surface (m^2), Fig. 2.10
$A_{0,u}$	unfinned portion of bare surface (m^2), Fig. 2.10
b	thermal stratification parameter, eq. (7.71)
b, b_T	transversal length scales (m), eqs. (5.148)–(5.149)
b_n	dimensionless characteristic values, Table 4.1
B	cross-section shape number, eq. (6.30)
B	driving parameter for film condensation, eq. (8.26)
Bi	Biot number, eq. (2.63)
Bo_y	Boussinesq number, $\mathrm{Bo}_y = \mathrm{Ra}_y \mathrm{Pr}$
c	specific heat of incompressible substance ($J/kg \cdot K$)
c	speed of light in vacuum, Appendix A
c_v	specific heat at constant volume ($J/kg \cdot K$)
c_P	specific heat at constant pressure ($J/kg \cdot K$)
C	capacity rate (W/K), or $\dot{m}c_P$
C_c	correction factor, Fig. 10.27
C_i	molar concentration of species i ($kmol/m^3$)
C_D	drag coefficient, eq. (5.138)
$C_{f,x}$	local skin friction coefficient, eq. (5.39)
$\overline{C}_{f,x}$	average skin friction coefficient, eq. (5.55)
C_{sf}	empirical constant for liquid–surface combination, Table 8.1
C_w	correction factor, Fig. 10.29

d	diameter (m)
D	diameter (m)
D	mass diffusivity, diffusion coefficient, or diffusion constant (m^2/s)
D_h	hydraulic diameter (m), eq. (6.28)
D_i	inner diameter (m)
D_o	outer diameter (m)
D_{12}	mass diffusivity of species 1 into species 2 (m^2/s)
e	specific internal energy (J/kg), eq. (5.12)
E	energy (J)
E	modulus of elasticity (N/m^2)
E	total hemispherical emissive power (W/m^2)
E_b	total hemispherical blackbody emissive power (W/m^2)
$E_{b,\lambda}$	monochromatic hemispherical blackbody emissive power ($W/m \cdot m^2$)
Ec	Eckert number, Appendix A
E_λ	monochromatic hemispherical emissive power ($W/m \cdot m^2$)
f	factor, Figs. 9.37–9.38
f	friction factor, eq. (6.24)
f_v	vortex shedding frequency (s^{-1}), eqs. (5.137) and (F.9)
f_v	fire pulsating frequency, eq. (F. 10)
F	correction factor, Figs. 9.16–9.20
F	force (N)
F	similarity streamfunction profile, eq. (7.45)
F_D	drag force (N)
F_n	normal force (N)
Fo	Fourier number (dimensionless time), eqs. (4.63)
F_r, F_θ, F_z	body forces per unit volume (N/m^3), Table 5.2
F_r, F_ϕ, F_θ	body forces per unit volume (N/m^3), Table 5.3
F_t	tangential force (N)
F_{12}	geometric view factor, eq. (10.33)
g	gravitational acceleration (m/s^2)
G	mass velocity ($kg/m^2 \cdot s$), eq. (9.58)
G	similarity vertical velocity profile, eq. (7.43)
G	total irradiation (W/m^2)
Gr_y	Grashof number based on temperature difference and height y, $Gr_y = g\beta y^3 \, \Delta T/\nu^2 = Ra_y/Pr$
Gz	Graetz number, eq. (6.53)
$G_{\mathcal{L}}$	constant, Table 7.1
G_λ	monochromatic irradiation ($W/m^2 \cdot m$)
h	heat transfer coefficient for external flow ($W/m^2 \cdot K$), eq. (1.54)
h	heat transfer coefficient for internal flow ($W/m^2 \cdot K$), eq. (1.55)
h	Planck's constant ($J \cdot s$), Appendix A
h	specific enthalpy (J/kg)
h_e	effective heat transfer coefficient ($W/m^2 \cdot K$), eq. (9.7)
h_f	specific enthalpy of saturated liquid (J/kg)
h_{fg}	latent heat of condensation (J/kg), $h_g - h_f$
h'_{fg}	augmented latent heat of condensation (J/kg), eqs. (8.10) and (8.17)
h''_{fg}	augmented latent heat of condensation (J/kg), eq. (8.41)
h_g	specific enthalpy of saturated vapor (J/kg)
h_m	local mass transfer coefficient (m/s), eq. (11.57)
h_s	specific enthalpy of saturated solid (J/kg)
h_{sf}	latent heat of melting, or of solidification (J/kg), $h_f - h_s$
h_x	local heat transfer coefficient ($W/m^2 \cdot K$) at position x
$\overline{h}_x$	average heat transfer coefficient ($W/m^2 \cdot K$) averaged over length x
$\overline{h}_D$	heat transfer coefficient ($W/m^2 \cdot K$) averaged over cylinder or sphere of diameter D
H	enthalpy (J)
H	enthalpy flowrate per unit length (W/m), eq. (8.5)
H	height (m)
H	Henry's constant (bar), Table 11.5
i	specific enthalpy (J/kg), eq. (5.16)
I_b	total intensity of blackbody radiation ($W/m^2 \cdot sr$)

$I_{b,\lambda}$	intensity of monochromatic blackbody radiation (W/m$^3\cdot$sr)
I_λ	intensity of monochromatic radiation (W/m$^3\cdot$sr)
j_H	Colburn j_H factor, eq. (9.75)
j_i	diffusion mass flux of species i (kg/m$^2\cdot$s)
$\hat{j}_i$	diffusion molar flux of species i (kmol/m$^2\cdot$s)
J	electric current density (A/m^2)
J	radiosity (W/m^2)
Ja	Jakob number, eq. (8.19)
J_0	zeroth-order Bessel function of the first kind, Fig. 3.6 and Appendix E
J_1	first-order Bessel function of the first kind, eq. (3.63)
k	Boltzmann's constant, Appendix A
k	thermal conductivity (W/m$\cdot$K)
k_{avg}	average thermal conductivity (W/m$\cdot$K), eq. (2.55)
k_e	thermal conductivity due to conduction electrons (W/m$\cdot$K)
k_l	thermal conductivity due to lattice vibrations (W/m$\cdot$K)
k_i^{-1}	thermal resistivity due to impurity scattering (m$\cdot$K/W)
k_p^{-1}	thermal resistivity due to phonon scattering (m$\cdot$K/W)
k_s	sand roughness scale (mm), Fig. 6.14
K	constant coefficient
K	permeability (cm^2), Appendix B
K_c	contraction loss coefficient, Figs. 9.30 and 9.31
K_e	enlargement loss coefficient, Figs. 9.30 and 9.31
l	equivalent length (m), eq. (7.84)
l	length (m)
l	mixing length (m), eq. (5.109)
L	characteristic length (m), eq. (7.76)
L	length (m)
$\mathcal{L}$	equivalent length (m), eqs. (5.140) and (7.85)
Le	Lewis number, Le = Sc/Pr = α/D, Table 11.7
L_c	corrected fin length (m), eq. (2.112)
L_e	equivalent length (m), Table 10.5

L_0	Lorentz constant, 2.45×10^{-8} (V/K)^2
m	fin parameter (m^{-1}), eq. (2.92)
m	integer
m	mass (kg)
$\dot{m}$	mass flowrate (kg/s)
$\dot{m}'$	mass flowrate per unit length (kg/s$\cdot$m)
$\dot{m}''$	mass flux (kg/m$^2\cdot$s)
$\dot{m}_i'''$	volumetric rate of species i generation (kg/m$^3\cdot$s), eq. (11.2)
M	dimensionless factor, eq. (6.84)
M	molar mass of mixture (kg/kmol)
M_i	molar mass of species i (kg/kmol)
n	direction normal to the boundary (m), Table 3.2
n	integer
N	number of moles in mixture sample (kmol)
N_i	number of moles of species i (kmol)
NTU	number of heat transfer units, eq. (9.27)
$\dot{N}$	molar flowrate (kmol/s)
$\dot{N}'$	molar flowrate per unit length (kmol/m$\cdot$s)
Nu_x	Nusselt number based on the local heat transfer coefficient $h_x x/k$
$\overline{Nu_D}$	overall Nusselt number based on the surface-averaged heat transfer coefficient $\bar{h}_D D/k$, where D is the diameter
$\overline{Nu^0_{\mathcal{L}}}$	constant, Table 7.1
$\overline{Nu_x}$	overall Nusselt number based on the x-averaged heat transfer coefficient $\bar{h}_x x/k$
p	number of iterations, Chapter 3
p	perimeter (m)
p	perimeter of contact with fluid (wetted perimeter) (m)
P	dimensionless parameter, Figs. 9.16–9.20
P	pressure (Pa or N/m^2)
P	mechanical power (W)
Pe_D	Peclet number based on diameter, $U_\infty D/\alpha$, UD/α
Pe_x	Peclet number based on longitudinal length, $U_\infty x/\alpha$
Pr	Prandtl number, Pr = ν/α

Pr_t	turbulent Prandtl number, $\mathrm{Pr}_t = \varepsilon_M/\varepsilon_H$
P_i	partial pressure of component i (N/m^2)
q	heat transfer rate (W)
q_b	total heat transfer rate through the fin (W)
q_{tip}	heat transfer through the tip of the fin (W)
q'	heat transfer rate per unit length (W/m)
q''	heat flux (W/m^2)
$\dot{q}$	volumetric rate of internal heat generation (W/m^3)
$q''_{w,x}$	local wall heat flux (W/m^2)
$\overline{q}''_{w,x}$	x-averaged wall heat flux (W/m^2), eq. (5.80)
$q_{1\rightarrow 2}$	one-way heat current (W) from 1 to 2
q_{1-2}	net heat current (W) from 1 to 2
Q	heat transfer (J)
Q'	heat transfer interaction per unit length (J/m)
Q''	heat transfer interaction per unit area (J/m^2)
r	radial coordinate (m), Figs. 1.8 and 1.9
r_i	inner radius (m)
r_o	outer radius (m)
$r_{o,c}$	critical outer radius (m), eqs. (2.44) and (2.47)
r_s	thermal resistance of the scale (m$^2\cdot$K/W), eq. (9.5)
R	dimensionless parameter, Figs. 9.16–9.20
R	radius (m)
R	function of r only, Chapter 3
R	ideal gas constant (kJ/kg$\cdot$K), Appendix D
$\overline{R}$	universal ideal gas constant, Appendix A
$\mathrm{Ra}_{m,y}$	mass transfer Rayleigh number, eq. (11.102)
Ra_y	Rayleigh number based on temperature difference and height y, $\mathrm{Ra}_y = g\beta y^3\,\Delta T/\alpha\nu$
Ra_y^*	Rayleigh number based on heat flux and height y, $\mathrm{Ra}_y^* = g\beta q''_w y^4/\alpha\nu k$
Re	Reynolds number $V_{\mathrm{max}}D_h/\nu$, eq. (9.70)
Re_D	Reynolds number based on diameter, $U_\infty D/\nu$, UD/ν
Re_l	local Reynolds number, Appendix F
Re_x	Reynolds number based on longitudinal length, $U_\infty x/\nu$
Re_y	condensate film Reynolds number, $4\Gamma(y)/\mu_l$, eq. (8.22)
R_i	internal radiation resistance (m^{-2}), eq. (10.78)
R_r	radition thermal resistance (m^{-2}), eq. (10.45)
R_t	thermal resistance (K/W), eq. (2.8)
s	empirical constant, Table 8.1
s_n	dimensionless characteristic values, Table 4.2
S	conduction shape factor, eq. (3.33) and the header of Table 3.3
S	entropy (J/K)
S	solubility coefficient (kmol/m$^3\cdot$bar), Table 11.6
Sc	Schmidt number, $\mathrm{Sc} = \nu/D$
Sh_x	local Sherwood number, eq. (11.65)
St	x-independent Stanton number $h/\rho c_P U$
Ste	Stefan number, eq. (4.119)
St_m	local mass transfer Stanton number, eq. (11.85)
St_x	local Stanton number $h_x/\rho c_P U_\infty$
t	thickness (m)
t	time (s)
t_c	transition time scale (s), eq. (4.9)
T	temperature (K or °C), eqs. (1.5) and Fig. 1.2
T_b	base temperature in fin analysis (K), Chapter 2
T_b	bulk, or mean temperature (K or °C)
T_c	center temperature (K), Chapter 4
T_i	initial temperature (K)
$T_{i,j}$	temperature of the control volume surrounding the node (i, j), Chapter 3
T_m	mean, or bulk temperature (K), eq. (6.33)
T_m	melting point temperature (K)

T_{sat}	saturation temperature (K)
T_w	wall temperature (K or °C)
T_0	surface temperature (K), Chapter 4
T_0	reference temperature (K or °C)
T_∞	free-stream or reservoir temperature (K or °C)
u	specific internal energy (J/kg)
u	velocity component in the x direction (m/s)
U	average longitudinal velocity (m/s)
U	internal energy (J)
U	mean velocity (m/s), eq. (6.1)
U	overall heat transfer coefficient ($W/m^2 \cdot K$)
U_∞	free stream velocity (m/s)
v	specific volume (m^3/kg)
v	velocity in the y direction (m/s)
v_n	normal velocity (m/s)
V	mean longitudinal velocity (m/s)
V	volume (m^3)
$\mathcal{V}$	volume (m^3), Chapter 9
w	mechanical transfer rate, or power (W)
W	width (m)
W	work transfer (J)
$\dot{W}$	work transfer rate, or power (W)

x	Cartesian coordinate (m), Fig. 1.7
x_i	mole fraction
x_{tr}	transition length (m)
X	flow entrance length (m), eqs. (6.4′) and (6.65)
X	function of x only, Chapter 3
X_C	concentration entrance length (m), eq. (11.93)
X_l	longitudinal pitch (m)
X_t	transversal pitch (m)
X_T	thermal entrance length, eqs. (6.32) and (6.65)
X_l^*	dimensionless longitudinal pitch X_l/D
X_t^*	dimensionless transversal pitch X_t/D
X, Y, Z	body forces per unit volume (N/m^3), Table 5.1
y	Cartesian coordinate (m), Fig. 1.7
Y	function of y only, Chapter 3
Y_0	zeroth-order Bessel function of the second kind, Fig. 3.6
z	axial position in cylindrical coordinates (m), Fig. 1.8
z	Cartesian coordinate (m), Fig. 1.7
Z	function of z only, Chapter 3

Greek Letters

α	heat transfer area density (m^2/m^3), eq. (9.64)
α	thermal diffusivity (m^2/s), $\alpha = k/\rho c_P$
α	total absorptivity
α	total hemispherical absorptivity
α_0	temperature coefficient of electrical resistivity ($°C^{-1}$), Appendix B
α_λ	monocromatic hemispherical absorptivity
α'_λ	directional monochromatic absorptivity
β	coefficient of volumetric thermal expansion (K^{-1}), eq. (5.18)
β_c	composition expansion coefficient (m^3/kg), eq. (11.99)
Γ	condensate mass flowrate per unit length ($kg/s \cdot m$), eq. (8.4)
δ	film thickness (m), Chapter 8

δ	skin thickness, boundary layer thickness (m)
δ	velocity boundary layer thickness (m), eq. (5.25)
δ^*	displacement thickness (m), eq. (5.58)
δ_s	thickness of shear layer (m), eq. (7.38)
δ_T	thermal boundary layer thickness (m), eq. (5.60)
δ_{99}	velocity boundary layer thickness (m), eq. (5.57)
ΔP	pressure drop (N/m^2), eq. (6.27)
ΔT	temperature difference (K)
ΔT_{lm}	log-mean temperature difference (K), eqs. (6.105) and (9.22)
$\Delta \epsilon$	correction term, Fig. 10.30
ϵ	convergence criterion, eq. (3.99)
ϵ	heat exchanger effectiveness, eq. (9.29)

ϵ	overall surface efficiency, eq. (9.4)
ϵ	total hemispherical emissivity
ϵ_f	fin effectiveness, eq. (2.118)
ε_H	thermal eddy diffusivity (m^2/s), eq. (5.100)
ε_M	momentum eddy diffusivity (m^2/s), eq. (5.99)
ϵ_0	overall projected-surface effectiveness, eq. (2.79)
ϵ_λ	monochromatic hemispherical emissivity
ϵ'_λ	directional monochromatic emissivity
η	fin efficiency, eq. (2.115)
η	similarity variable
η_c	compressor isentropic efficiency
η_p	pump isentropic efficiency
θ	angular coordinate (rad), Figs. 1.8 and 1.9
θ	excess temperature (K), eq. (2.88)
θ	momentum thickness (m), eq. (5.59)
θ	similarity temperature profile, eq. (7.46)
θ	thermal potential function (W/m), eq. (2.51)
θ_b	excess temperature of fin base (K)
κ	von Karman's constant, eq. (5.112)
κ_λ	monochromatic extinction coefficient (m^{-1})
λ	characteristic value, Chapter 3
λ	dimensionless parameter in the Stefan solution, eq. (4.118)
λ	wavelength (m)
μ	characteristic value, Chapter 3
μ	viscosity (kg/s$\cdot$m), eq. (5.10)
ν	frequency (s^{-1})
ν	kinematic viscosity (m^2/s), $\nu = \mu/\rho$
Π	pressure drop number, $\Pi = \Delta P \cdot L^2/\mu\alpha$
ρ	density (kg/m^3)
ρ	total reflectivity
ρ_e	electrical resistivity (W$\cdot$m/A^2)
σ	contraction ratio, eq. (9.53)
σ	Stefan–Boltzmann constant, Appendix A
σ	surface tension (N/m), Table 8.2
σ_{xx}	normal stress (N/m^2), eq. (5.8)
τ	angle of enclosure inclination (rad), Fig. 7.23
τ	total transmissivity
$\tau_{w,x}$	local wall shear stress (N/m^2)
$\bar{\tau}_{w,x}$	x-averaged wall shear stress (N/m^2), eq. (5.54)
τ_{xy}	tangential stress (N/m^2), eq. (5.8)
τ_λ	monochromatic transmissivity
ϕ	angle of wall inclination (rad), Fig. 7.10
ϕ	angular coordinate (rad), Fig. 1.9
ϕ	dimensionless temperature profile, eq. (6.45)
ϕ	relative humidity, Appendix D
φ	porosity, Appendix B
Φ	viscous dissipation function (s^{-2}), eq. (5.15)
Φ_i	mass fraction ρ_i/ρ
χ	correction factor, Figs. 9.37–9.38
ψ	streamfunction (m^2/s), eq. (5.45)
ω	solid angle (sr)
ω	specific humidity, or humidity ratio, Appendix D

Subscripts

$(\ )_a$	absorbed, Chapter 10
$(\ )_a$	air, Chapter 11
$(\ )_{\mathrm{acc}}$	acceleration
$(\ )_{\mathrm{app}}$	apparent
$(\ )_{\mathrm{avg}}$	average
$(\ )_b$	base of the fin, Chapter 2
$(\ )_b$	black, Chapter 10
$(\ )_b$	bulk, mean
$(\ )_c$	carbon dioxide, Chapter 10
$(\ )_c$	centerline, center, midplane
$(\ )_c$	cold
$(\ )_c$	compressor
$(\ )_{\mathrm{eddy}}$	eddy transport
$(\ )_f$	fluid
$(\ )_g$	gas, Chapter 10
$(\ )_h$	hot
$(\ )_i$	initial
$(\ )_i$	inner