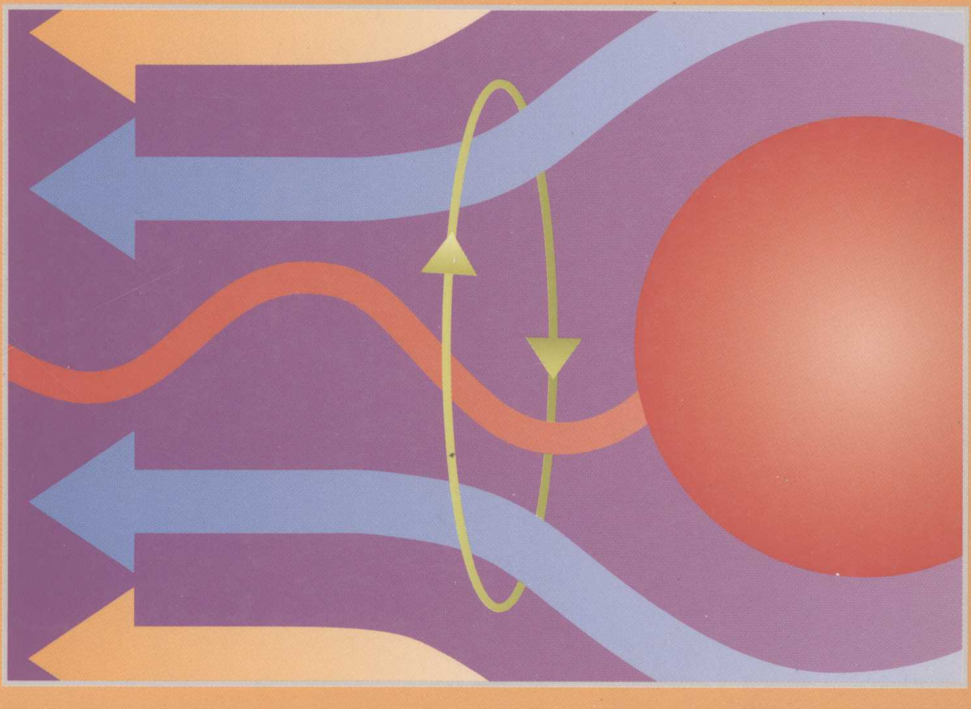
Wiley Asia Student Edition

Fundamentals of

Heat and Mass Transfer



SIXTH EDITION

Incropera DeWitt Bergmann Lavine

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Fundamentals of Heat and Mass Transfer

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In Memory

David P. DeWitt

March 2, 1934–May 17, 2005

The year 2005 was marked by the loss of Dr. David P. DeWitt, a dear friend and colleague who contributed significantly to heat transfer technology and pedagogy throughout a distinguished 45-year career. Dave was educated as a mechanical engineer, receiving a BS degree from Duke University, an MS from MIT, and the PhD degree from Purdue University. His graduate studies at Purdue nucleated a strong interest in the fields of thermal physics and radiometry, in which he worked until illness made it impossible to continue. Dave was instrumental in developing radiometric measurement standards at Purdue's Thermophysical Properties Research Center, eventually becoming its deputy director and president of Technometrics Inc., an optical and thermal instrument design company. In 1973 he joined Purdue's School of Mechanical Engineering at the rank of professor, where he taught and conducted research until his retirement in 2000. From 2000 to 2004, he worked in the Optical Technology Division of the National Institute of Technology and Standards.

Dave was an excellent and demanding teacher, a good researcher and a superb engineer. In our nearly thirty-year collaboration, he provided complementary skills that contributed significantly to the success of the books we have co-authored. However, it is much more on a personal than a professional level that I have my fondest memories of this very special colleague.

As co-authors, Dave and I spent thousands of hours working together on all facets of our books, typically in blocks of three to five hours. This time often involved spontaneous diversions from the task at hand, typically marked by humor or reflections on our personal lives.

Dave and I each have three daughters of comparable ages, and we would often share stories on the joys and challenges of nurturing them. It's hard to think about Dave without reflecting on the love and pride he had for his daughters (Karen, Amy, and Debbie). In 1990 Dave lost his first wife Jody due to cancer, and I witnessed first hand his personal character and strength as he supported her in battling this terrible disease. I also experienced the joy he felt in the relationship he developed with his second wife Phyllis, whom he married in 1997.

I will always remember Dave as a sensitive and kind person of good humor and generosity. Dear friend, we miss you greatly, but we are comforted by the knowledge that you are now free of pain and in a better place.

Frank P. Incropera
Notre Dame, Indiana

Forward to Preface

Not too long after finishing the previous editions of *Fundamentals of Heat and Mass Transfer* and *Introduction to Heat Transfer*, Dave DeWitt and I felt the need to plan for that time when we would no longer be able to add appropriate value to future editions. There were two matters of special concern. First, we were advancing in years, and the potential for disruption due to declining health or our own mortality could not be ignored. But, perhaps more pertinent to maintaining freshness and vitality to the text books, we also recognized that we were becoming ever more distant from leading-edge activities in the field.

In 2002, we concluded that we should proactively establish a succession plan involving the participation of additional co-authors. In establishing desired attributes of potential candidates, we placed high priority on the following: a record of success in teaching heat and mass transfer, active involvement with research in the field, a history of service to the heat transfer community, and the ability to *sustain* an effective collaborative relationship. A large weighting factor was attached to this last attribute, since it was believed to have contributed significantly to whatever success Dave DeWitt and I have enjoyed with the previous editions.

After reflecting long and hard on the many excellent options, Dave and I invited Ted Bergman and Adrienne Lavine, professors of Mechanical Engineering at the University of Connecticut and the University of California, Los Angeles, respectively, to join us as co-authors. We were grateful for their acceptance. Ted and Adrienne are listed as third and fourth authors for this edition, will move to first and second authors on the next edition, and will thereafter appear as sole authors.

Ted and Adrienne have worked extremely hard on the current edition, and you will see numerous enhancements from their efforts, particularly in modern applications related to subjects such as nano and biotechnology. It is therefore most appropriate for Ted and Adrienne to share their thoughts in the following preface.

Frank P. Incropera
Notre Dame, Indiana

Preface

Since the last edition, fundamental changes have occurred, both nationally and globally, in how engineering is practiced, with questions raised about the future of the profession. How will the practice of engineering evolve over the next decade? Will tomorrow's engineer be more valued if he is a specialist, or more handsomely rewarded if she has knowledge of greater breadth but less depth? How will engineering educators respond to changing *market forces*? Will the traditional boundaries that separate the engineering disciplines in the typical college or university remain in place?

We believe that, because technology provides the foundation for improving the standard of living of all humankind, the future of engineering is bright. But, in light of the tension between *external demand for generalization* and *intellectual satisfaction of specialization*, how will the discipline of heat transfer remain relevant? What will the value of this discipline be in the future? To what new problems will the knowledge of heat transfer be applied?

In preparing this edition, we attempted to identify emerging issues in technology and science in which heat transfer is *central* to the realization of new products in areas such as information technology, biotechnology and pharmacology, alternative energy, and nanotechnology. These new applications, along with traditional applications in energy generation, energy utilization, and manufacturing, suggest that the discipline of heat transfer is healthy. Furthermore, when applied to problems that transcend traditional boundaries, heat transfer will be a vital and *enabling discipline* of the future.

We have strived to remain true to the fundamental pedagogical approach of previous editions by retaining a rigorous and systematic methodology for problem solving, by including examples and problems that reveal the richness and beauty of the discipline, and by providing students with opportunities to meet the learning objectives.

Approach and Organization

From our perspective, the four learning objectives desired in any first course in heat transfer, detailed in the previous edition, remain as follows:

1. The student should internalize the meaning of the terminology and physical principles associated with the subject.
2. The student should be able to delineate pertinent transport phenomena for any process or system involving heat transfer.
3. The student should be able to use requisite inputs for computing heat transfer rates and/or material temperatures.
4. The student should be able to develop representative models of real processes and systems and draw conclusions concerning process/system design or performance from attendant analysis.

As in the previous edition, learning objectives for each chapter are clarified to enhance the means by which they are achieved, as well as means by which achievement may be assessed. The summary of each chapter highlights key terminology and concepts developed in the chapter, and poses questions to test and enhance student comprehension.

For problems involving complex models and/or *exploratory, what-if*, and *parameter sensitivity* considerations, it is recommended that they be addressed by using a computational equation-solving package. To this end, the *Interactive Heat Transfer* (IHT) package developed by Intellipro, Inc. (New Brunswick, New Jersey) and available in the previous edition has been updated. The seasoned user will find the technical content of IHT to be largely unchanged, but the computational capability and features have been improved significantly. Specifically, IHT is now capable of solving 300 or more simultaneous equations. The user interface has been updated to include a full-function workspace editor with complete control over formatting of text, copy and paste functionality, an equation editor, a new graphing subsystem, and enhanced syntax checking. In addition, the software now has the capability to export IHT-specific functions (e.g. properties and correlations) as Microsoft Excel add-ins. A second software package, *Finite Element Heat Transfer* (FEHT), developed by F-Chart Software of Middleton, Wisconsin, provides enhanced capabilities for solving two-dimensional conduction heat transfer problems.

As in the previous edition, many homework problems that involve a computer-based solution appear as extensions to problems that can be solved by hand calculation. This approach is time tested and allows students to validate their computer predictions by checking the predictions with their hand solutions. They may then proceed with parametric studies that explore related design and operating conditions. Such problems are identified by enclosing the exploratory part in a red rectangle, as, for example (b), (c), or (d). This feature also allows instructors who wish to limit their assignments of computer-based problems to benefit from the richness of these problems. Solutions to problems for which the number itself is highlighted, as, for example, 1.26, should be entirely computer based.

We are aware that some instructors who use the text have not utilized IHT in their courses. We encourage our colleagues to dedicate, at a minimum, one-half hour of lecture or recitation time to demonstrate IHT as a tool for solving simultaneous equations, and for evaluating the thermophysical properties of various materials. We have found that, once students have seen its power and ease of use, they will eagerly utilize IHT's additional features on their own. This will enable them to solve problems faster, with fewer numerical errors, thereby freeing them to concentrate on the more substantive aspects of the problems.

What's New in the 6th Edition

Problem Sets This edition contains a significant number of new, revised, and renumbered end-of-chapter problems. Many of the new problems require relatively straightforward analyses, and many involve applications in nontraditional areas of science and technology. The solutions manual has undergone extensive revision.

Streamlined Presentation The text has been streamlined by moving a small amount of material to stand-alone supplemental sections that can be accessed electronically from the companion website. The supplemental sections are called out with marginal notes throughout the text. If instructors prefer to use material from the supplemental sections, it is readily available from the Wiley website (see below). Homework problem statements associated with the supplemental sections are also available electronically.

Chapter-by-Chapter Content Changes To help motivate the reader, Chapter 1 includes an expanded discussion of the *relevance of heat transfer*. The richness and pertinence of the topic are conveyed by discussion of *energy conversion devices* including fuel cells, applications in *information technology* and *biological* as well as *biomedical engineering*. The presentation of the *conservation of energy requirement* has been revised.

New material on *micro- and nanoscale conduction* has been included in Chapter 2. Because *in-depth* treatment of these effects would overwhelm most students, they are introduced and illustrated by describing the motion of *energy carriers* including *phonons* and *electrons*. Approximate expressions for the effective thermal conductivity of *thin films* are presented and are explained in terms of energy carrier behavior at physical boundaries. The thermal conductivity of *nanostructured* versus *conventional* materials is presented and used to demonstrate practical applications of recent nanotechnology research. Microscale-related *limitations of the heat diffusion equation* are explained. The *bioheat equation* is introduced in Chapter 3, and its similarity to the heat equation for extended surfaces is pointed out in order to facilitate its use and solution.

The Chapter 4 discussion of *conduction shape factors*, applied to multidimensional steady-state conduction, is embellished with recent results involving the *dimensionless conduction heat rate*. Although we have moved the graphical method to the supplemental material, discussion of two-dimensional *isotherm* and *heat flow line distributions* has been enhanced in order to assist students to conceptualize the conduction process. Use of the dimensionless conduction heat rate is extended to transient situations in Chapter 5. A new, *unified approach* to transient heat transfer is presented; easy-to-use *approximate solutions* associated with a range of geometries and time scales have been added. Recently, we have noted that few students use the graphical representations of the one-dimensional, transient conduction solutions (Heisler charts); most prefer to solve the approximate or exact analytical expressions.

Hence, we have relegated the graphical representations to the supplemental material. Because of the ease and frequency with which computational methods are used by students today, analytical solutions involving multidimensional effects have also been moved to the supplemental material. We have added a brief section on periodic heating and have demonstrated its relevance by presenting a modern method used to measure the thermophysical properties of nanostructured materials.

Introduction to the fundamentals of convection, included in Chapter 6, has been simplified and streamlined. The description of *turbulence* and *transition to turbulence* has been updated. Proper accounting of the *temperature-dependence of thermophysical properties* is emphasized. Derivation of the convection transfer equations is now relegated to the supplemental material.

The treatment of *external flow* in Chapter 7 is largely unchanged. Chapter 8 correlations for the *entrance regions* of *internal flow* have been updated, while the discussion of heat transfer enhancement has been expanded by adding correlations for flow in *curved tubes*. Microsale-related *limitations of the convective correlations* for internal flow are presented. Chapter 9 correlations for the effective thermal conductivity associated with *free convection* in enclosures have been revised in order to more directly relate these correlations to the conduction results of Chapter 3.

Presentation of *boiling heat transfer* in Chapter 10 has been modified to improve student understanding of the boiling curve by relating aspects of boiling phenomena to forced convection and free convection concepts from previous chapters. Values of the constants used in the boiling correlations have been modified to reflect the current literature. Reference to refrigerants that are no longer used has been eliminated, and replacement refrigerant properties have been added. Heat transfer correlations for *internal two-phase flow* are presented. Microscale-related *limitations of the correlations* for internal two-phase flow are discussed. A much-simplified method for solution of condensation problems is presented.

The use of the log mean temperature difference (*LMTD*) method is retained for developing correlations for concentric tube heat exchangers in Chapter 11, but, because of the flexibility of the *effectiveness-NTU* method, the LMTD-based analysis of heat exchangers of other types has been relegated to the supplemental material. Again, the supplemental sections can be accessed at the companion website. Treatment of radiation heat transfer in Chapter 12 and 13 has undergone modest revision and streamlining.

The coverage of mass transfer, Chapter 14, has been revised extensively. The chapter has been reorganized so that instructors can either cover the entire content or *seamlessly* restrict attention to mass transfer in stationary media. The latter approach is recommended if time is limited, and/or if interest is limited to mass transfer in liquids or solids. The new example problems of Chapter 14 reflect contemporary applications. Discussion of the various boundary conditions used in mass transfer has been clarified and simplified.

Acknowledgments

We are immensely indebted to Frank Incropera and Dave DeWitt who entrusted us to join them as co-authors. We are especially thankful to Frank for his patience, thoughtful advice, detailed critique of our work, and kind encouragement as this edition was being developed.

Appreciation is extended to our colleagues at the University of Connecticut and UCLA who provided valuable input. Eric W. Lemmon of the National Institute of Standards and Technology is acknowledged for his generosity in providing properties of new refrigerants.

We are forever grateful to our wonderful spouses and children, Tricia, Nate, Tico, Greg, Elias, and Jacob for their love, support, and endless patience. Finally, we both extend our appreciation to Tricia Bergman who, despite all her responsibilities, somehow found the time to expertly and patiently process the solutions for the new end-of-chapter problems.

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Supplemental and Website Material

The companion website for the text is www.wiley.com/college/incropera. By clicking on the 'student companion site' link, *students* may access the answers to the homework problems and the Supplemental Sections of the text.

Material available *for instructors only* includes the instructor Solutions Manual, Powerpoint slides that can be used by instructors for lectures, and electronic versions of figures from the texts for those wishing to prepare their own materials for electronic classroom presentation. The instructor Solutions Manual is for use by instructors who are requiring use of the text for their course. *Copying or distributing all or part of the Solutions Manual in any form without the Publisher's permission is a violation of copyright law.*

Interactive Heat Transfer v3.0/FEHT with User's Guide is available either with the text or as a separate purchase. This software tool provides modeling and computational features useful in solving many problems in the text, and enables *what-if* and *exploratory analysis* of many types of heat transfer problems. The CD/booklet package is available as a stand-alone purchase from the Wiley website, www.wiley.com, or through your local bookstore. Faculty interested in using this tool in their course may order the software shrinkwrapped to the text at a significant discount. Contact your local Wiley representative for details.

Symbols

A area, m^2

A_b area of prime (unfinned) surface, m^2

A_c cross-sectional area, m^2

A_{ff} free-flow area in compact heat exchanger core (minimum cross-sectional area available for flow through the core), m^2

A_{fr} heat exchanger frontal area, m^2

A_p fin profile area, m^2

A_r nozzle area ratio

a acceleration, m/s^2

Bi Biot number

Bo Bond number

C molar concentration, $kmol/m^3$; heat capacity rate, W/K

C_D drag coefficient

C_f friction coefficient

C_t thermal capacitance, J/K

Co Confinement number

c specific heat, $J/kg \cdot K$; speed of light, m/s

c_p specific heat at constant pressure, $J/kg \cdot K$

c_v specific heat at constant volume, $J/kg \cdot K$

D diameter, m

D_{AB} binary mass diffusivity, m^2/s

D_b bubble diameter, m

D_h hydraulic diameter, m

E thermal plus mechanical energy, J; electric potential, V; emissive power, W/m^2

E^{tot} total energy, J

Ec Eckert number

$\dot{E}_g$ rate of energy generation, W

$\dot{E}_{in}$ rate of energy transfer into a control volume, W

$\dot{E}_{out}$ rate of energy transfer out of control volume, W

$\dot{E}_{st}$ rate of increase of energy stored within a control volume, W

e thermal internal energy per unit mass, J/kg; surface roughness, m

F force, N; heat exchanger correction factor; fraction of blackbody radiation in a wavelength band; view factor

Fo Fourier number

Fr Froude number

f friction factor; similarity variable

G irradiation, W/m^2; mass velocity, $kg/s \cdot m^2$

Gr Grashof number

Gz Graetz number

g gravitational acceleration, m/s^2

g_c gravitational constant, $1\ kg \cdot m/N \cdot s^2$ or $32.17\ ft \cdot lb_m/lb_f \cdot s^2$

H nozzle height, m; Henry's constant, bars

h convection heat transfer coefficient, $W/m^2 \cdot K$; Planck's constant

h_{fg} latent heat of vaporization, J/kg

h_{sf} latent heat of fusion, J/kg

h_m convection mass transfer coefficient, m/s

h_{rad} radiation heat transfer coefficient, $W/m^2 \cdot K$

I electric current, A; radiation intensity, $W/m^2 \cdot sr$

i electric current density, A/m^2; enthalpy per unit mass, J/kg

J radiosity, W/m^2

Ja Jakob number

J_i^* diffusive molar flux of species i relative to the mixture molar average velocity, $kmol/s \cdot m^2$

j_i	diffusive mass flux of species *i* relative to the mixture mass average velocity, kg/s · m^2
j_H	Colburn *j* factor for heat transfer
j_m	Colburn *j* factor for mass transfer
k	thermal conductivity, W/m · K; Boltzmann's constant
k_0	zero-order, homogeneous reaction rate constant, kmol/s · m^3
k_1	first-order, homogeneous reaction rate constant, s^{-1}
k_1''	first-order, homogeneous reaction rate constant, m/s
L	characteristic length, m
Le	Lewis number
M	mass, kg; number of heat transfer lanes in a flux plot; reciprocal of the Fourier number for finite-difference solutions
$\dot{M}_i$	rate of transfer of mass for species, *i*, kg/s
$\dot{M}_{i,g}$	rate of increase of mass of species *i* due to chemical reactions, kg/s
$\dot{M}_{in}$	rate at which mass enters a control volume, kg/s
$\dot{M}_{out}$	rate at which mass leaves a control volume, kg/s
$\dot{M}_{st}$	rate of increase of mass stored within a control volume, kg/s
$\mathcal{M}_i$	molecular weight of species *i*, kg/kmol
m	mass, kg
$\dot{m}$	mass flow rate, kg/s
m_i	mass fraction of species *i*, ρ_i/ρ
N	number of temperature increments in a flux plot; total number of tubes in a tube bank; number of surfaces in an enclosure
N_L, N_T	number of tubes in longitudinal and transverse directions
Nu	Nusselt number
NTU	number of transfer units
N_i	molar transfer rate of species *i* relative to fixed coordinates, kmol/s
N''_i	molar flux of species *i* relative to fixed coordinates, kmol/s · m^2
$\dot{N}_i$	molar rate of increase of species *i* per unit volume due to chemical reactions, kmol/s · m^3
$\dot{N}''_i$	surface reaction rate of species *i*, kmol/s · m^2
n''_i	mass flux of species *i* relative to fixed coordinates, kg/s · m^2
$\dot{n}_i$	mass rate of increase of species *i* per unit volume due to chemical reactions, kg/s · m^3
P	perimeter, m; general fluid property designation
P_L, P_T	dimensionless longitudinal and transverse pitch of a tube bank

Pe	Peclet number *(RePr)*
Pr	Prandtl number
p	pressure, N/m^2
Q	energy transfer, J
q	heat transfer rate, W
$\dot{q}$	rate of energy generation per unit volume, W/m^3
q'	heat transfer rate per unit length, W/m
q''	heat flux, W/m^2
q^*	dimensionless conduction heat rate
R	cylinder radius, m
$\mathcal{R}$	universal gas constant
Ra	Rayleigh number
Re	Reynolds number
R_e	electric resistance, Ω
R_f	fouling factor, m^2 · K/W
R_m	mass transfer resistance, s/m^3
$R_{m,n}$	residual for the *m, n* nodal point
R_t	thermal resistance, K/W
$R_{t,c}$	thermal contact resistance, K/W
$R_{t,f}$	fin thermal resistance, K/W
$R_{t,o}$	thermal resistance of fin array, K/W
r_o	cylinder or sphere radius, m
r, ϕ, z	cylindrical coordinates
r, θ, ϕ	spherical coordinates
S	solubility, kmol/m^3 · atm; shape factor for two-dimensional conduction, m; nozzle pitch, m; plate spacing, m
S_c	solar constant
S_D, S_L, S_T	diagonal, longitudinal, and transverse pitch of a tube bank, m
Sc	Schmidt number
Sh	Sherwood number
St	Stanton number
T	temperature, K
t	time, s
U	overall heat transfer coefficient, W/m^2 · K; internal energy, J
u, v, w	mass average fluid velocity components, m/s
u^*, v^*, w^*	molar average velocity components, m/s
V	volume, m^3; fluid velocity, m/s
v	specific volume, m^3/kg
W	width of a slot nozzle, m
$\dot{W}$	rate at which work is performed, W
We	Weber number
X	vapor quality
X, Y, Z	components of the body force per unit volume, N/m^3
x, y, z	rectangular coordinates, m
x_c	critical location for transition to turbulence, m
$x_{fd,c}$	concentration entry length, m
$x_{fd,h}$	hydrodynamic entry length, m
$x_{fd,t}$	thermal entry length, m
x_i	mole fraction of species *i*, C_i/C

Greek Letters

α	thermal diffusivity, m^2/s; heat exchanger surface area per unit volume, m^2/m^3; absorptivity
β	volumetric thermal expansion coefficient, K^{-1}
Γ	mass flow rate per unit width in film condensation, $kg/s \cdot m$
δ	hydrodynamic boundary layer thickness, m
δ_c	concentration boundary layer thickness, m
δ_p	thermal penetration depth, m
δ_t	thermal boundary layer thickness, m
ε	emissivity; porosity of a packed bed; heat exchanger effectiveness
ε_f	fin effectiveness
η	similarity variable
η_f	fin efficiency
η_o	overall efficiency of fin array
θ	zenith angle, rad; temperature difference, K
κ	absorption coefficient, m^{-1}
λ	wavelength, μm
λ_{mfp}	mean free path length, nm
μ	viscosity, $kg/s \cdot m$
ν	kinematic viscosity, m^2/s; frequency of radiation, s^{-1}
ρ	mass density, kg/m^3; reflectivity
σ	Stefan-Boltzmann constant; electrical conductivity, $1/\Omega \cdot m$; normal viscous stress, N/m^2; surface tension, N/m; ratio of heat exchanger minimum cross-sectional area to frontal area
Φ	viscous dissipation function, s^{-2}
ϕ	azimuthal angle, rad
ψ	stream function, m^2/s
τ	shear stress, N/m^2; transmissivity
ω	solid angle, sr; perfusion rate, s^{-1}

Subscripts

A, B	species in a binary mixture
abs	absorbed
am	arithmetic mean
b	base of an extended surface; blackbody
c	cross-sectional; concentration; cold fluid
cr	critical insulation thickness
cond	conduction
conv	convection
CF	counterflow
D	diameter; drag
dif	diffusion
e	excess; emission; electron
evap	evaporation
f	fluid properties; fin conditions; saturated liquid conditions
fc	forced convection
fd	fully developed conditions
g	saturated vapor conditions
H	heat transfer conditions
h	hydrodynamic; hot fluid; helical
i	general species designation; inner surface of an annulus; initial condition; tube inlet condition; incident radiation
L	based on characteristic length
l	saturated liquid conditions
lat	latent energy
lm	log mean condition
M	momentum transfer condition
m	mean value over a tube cross section
max	maximum fluid velocity
mfp	mean free path
o	center or midplane condition; tube outlet condition; outer
ph	phonon
R	reradiating surface
r, ref	reflected radiation
rad	radiation
S	solar conditions
s	surface conditions; solid properties
sat	saturated conditions
sens	sensible energy
sky	sky conditions
ss	steady state
sur	surroundings
t	thermal
tr	transmitted
v	saturated vapor conditions
x	local conditions on a surface
λ	spectral
∞	free stream conditions

Superscripts

′	fluctuating quantity
*	molar average; dimensionless quantity

Overbar

$\overline{\ }$	surface average conditions; time mean

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