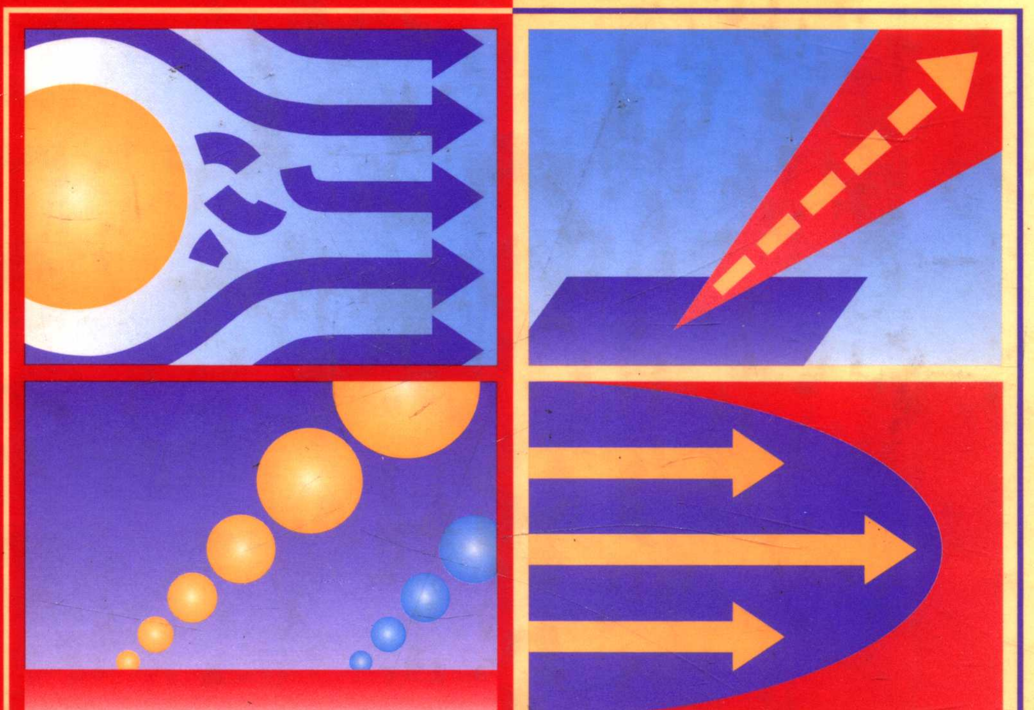
FIFTH EDITION

FUNDAMENTALS OF

Heat and Mass Transfer



Frank P. Incropera
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FIFTH EDITION

Fundamentals of Heat and Mass Transfer

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Dedicated to our wives, ***Andrea and Phyllis,*** and to our extended families and their children,

Nicholas DeWitt and Alexandra Joanne Bifano; John Wallace, Michael Anthony, and Mallory Renee Dant; Patricia Ann and David Andrew Foley; Michael DeWitt and Sarah Joanne Frederick; and Brandon Patrick and Kyle James Tafelski

who have brought a new level of love, patience,
and understanding into our lives.

Preface

In the decade of the nineties, a good deal of attention was given to critically assessing traditional pedagogy and to exploring means by which *student learning* may be enhanced. With respect to the development of educational tools and curricula, this assessment has stimulated serious consideration of *learning objectives* and means of determining the extent to which prescribed objectives are being met.

The foregoing trend prompts the following questions. What are appropriate learning objectives for a first course in heat transfer? Is the structure of the course, as well as the textbook for the course, consonant with these objectives?

From our perspective, the following four learning objectives are desired attributes of any first course in heat transfer.

(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 to draw conclusions concerning process/system design or performance from the attendant analysis.

The **first objective** constitutes a **primary level** of learning that must be achieved if the remaining objectives are to be realized. It is precisely what we have in mind when we tell our students that they must *learn the fundamentals.* And, we might add, it is the source of one of our greatest frustrations when we discover that they are not meeting our expectations. In such cases, where does the fault lie?

Certainly, some students do not put forth the effort needed to assimilate knowledge of the fundamentals. Or, perhaps their efforts are disproportionately directed to solving *the problem of the day,* and they do not take the time to read carefully or to think at any more than a superficial level about the subject matter. However, some of the fault may lie with us, their teachers. Perhaps we are too quick to move to analysis and problem solving and thereby devote insufficient time to concepts.

Both the richness of the heat transfer discipline and the learning difficulties that it often poses to students are attributable to the great diversity of its physical concepts. Consider just a few.

- What are the physical mechanisms associated with transport by conduction, convection, and radiation?
- What is an isothermal surface? An isoflux surface? When are such surface conditions achieved, at least to a reasonable approximation?
- What is the inherent nature of a combined conduction/convection system?
- What are the inherent features of laminar, turbulent, and separated flows? Of forced and natural convection? Of internal and external flow?
- What is the spectral and directional nature of radiation? What is a diffuse surface? A gray surface?
- What is the physical nature of terms associated with the first law of thermodynamics? How do conditions differ for application to a volume of matter and at a surface? To a steady process and a transient process?

These examples provide a very small subset of the many concepts which our students should understand and have the facility to use with confidence. If they are to develop *habits of mind* appropriate to heat transfer, they must achieve a level of comfort with the many terms and concepts intrinsic to the discipline.

The **second and third learning objectives** represent a matched pair of skills that is sequentially used in heat transfer analysis. Pertinent heat transfer processes and energy flows are first identified, and appropriate assumptions are made. Relevant rate equations, conservation laws, material properties, and coefficients are introduced, and calculations are performed. In any first course on heat transfer, it is reasonable to expect achievement of the first through the third objectives for all students.

The **fourth objective** may appear to be a restatement of the second and third objectives, but it is intended to be much more. Achievement of this level of learning implies the ability to think critically and creatively when solving complex problems with multiple transport modes. The solution methodology involves synthesis and integration of diverse inputs, as well as a good deal of judgment, in the development of models and interpretation of results. The ability to transition from modeling simple and/or highly idealized systems to real and generally complex systems is likely to be achieved by only a subset of students and then only in later stages of the course. If the first objective provides the *cornerstone* to a house of learning, the fourth objective is its *capstone.* Progression from **Level 1** to **Level 4** involves increasing familiarity with the subject matter and confidence in one's ability to obtain useful results from realistic models of process/system behavior.

In this edition of the text, we have attempted to clarify learning objectives for each chapter and to enhance means by which they are achieved, as well as means by which achievement may be assessed. The summary of each chapter has been expanded to highlight key terminology and concepts developed in the chapter, and to pose questions that test and enhance student comprehension. Recognizing the contribution that verbalization can make to learning, the questions may also be used to stimulate student discussion in and out of the classroom.

We have also attempted to simplify the introduction to convection transfer by culling derivations of the related transfer equations from Chapter 6 and relegating them to Appendix F, where they can be accessed by those interested in details of the derivations. In the streamlined version of Chapter 6, consideration is still given to physical conditions within the boundary layer(s), the nature of the boundary layer equations, and boundary layer similitude, including important analogies.

A total of 289 new problems have been developed for this edition of the book. To sharpen the focus on fundamentals, a large percentage of these problems deals more explicitly with basic principles, but in the context of simpler applications for which solutions are less onerous. Another family of new problems is linked to the examples of the text and is intended to reinforce concepts introduced by the examples, as well as to explore related issues. Many of the examples themselves have been amplified to better achieve learning objectives. In addition, a significant number of new problems deal with more complex **(Level 4)** issues and models, for which computer-based solutions facilitate parametric considerations.

For problems involving complex models and/or *exploratory, what-if,* and *parameter sensitivity* considerations, it is recommended that they be addressed by using a computer with an equation-solving package. Although students can create and solve their models using software with which they are already familiar, the Windows™-based software packages developed for this text offer distinct advantages as learning and productivity tools. Termed *Interactive Heat Transfer* (IHT) and developed by IntelliPro, Inc. of New Brunswick, New Jersey, the first software package is fully integrated with the text, using the same methodologies and nomenclature. Termed *Finite Element Heat Transfer* (FEHT) and developed by F-Chart Software of Middleton, Wisconsin, the second package provides enhanced capabilities for solving conduction heat transfer problems.

IHT provides a model-building, problem-solving environment, which includes a *pre-processor,* a *solver,* and a *post-processor.* The pre-processor encompasses a *work space,* into which equations may be entered from existing **modules** and/or **tool pads,** as well as from the keyboard. The modules include six models that deal with applications of the **first law; resistance networks; one-dimensional, steady-state conduction; extended surfaces; transient, lumped-capacitance systems;** and **transient, one-dimensional conduction.** The tool pads provide widely used **rate equations, thermal conduction resistances, finite-difference equations,** and **convection correlations,** as well as standard expressions for analyzing **heat exchangers** and **radiation exchange** between surfaces. An additional tool pad provides access to temperature-dependent **thermophysical properties** of common solids, gases, and liquids.

The IHT solver provides comprehensive, equation-solving capabilities, while the post-processor includes an *explore option* for parameter sensitivity studies, a *browser* for tabulating results, and a *graphical option* for plotting results. The model-building, problem-solving capabilities of IHT facilitate implementation of the methodologies espoused in the text, as well as execution of *design* and *what-if* considerations.

FEHT provides enhanced capabilities for treating steady-state and transient one- and two-dimensional conduction problems. It includes a *Problem Defini-*

tion function that is used to establish the geometrical features, the corresponding finite-element mesh, and the boundary and initial conditions of the problem. A *Run* function checks for proper discretization of the problem before executing a numerical solution. The *Output* function provides several options for representing results of the calculations, including tabulated temperature fields, temperature contours, and heat flow lines.

IHT and FEHT have *tutorials, examples,* and *help menus* that are user friendly and enable implementation of the software with minimal learning requirements. However, in using the software, it is important to recognize that it is not a collection of pre-solved problems to be exercised for different input conditions. Rather, each should be viewed as a productivity tool that facilitates model development and solution for the broad range of problems embodied in the topical coverage of this text.

To minimize frustrations associated with obtaining *incorrect results from an incorrect computer model,* many of the computer-based problems of this text appear as extensions to problems that can be solved by performing *hand calculations.* In this way students may first develop and solve their models under prescribed conditions for which there is a single solution. They may then use this solution to validate their computer model and to proceed with parametric studies that explore related design or 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 permits instructors wishing to limit the assignment of computer-based problems to still benefit from the richness of these problems by assigning all but the highlighted versions. Solutions to problems for which the number itself is highlighted, as, for example, 1.26, should be entirely computer-based.

We continue to be indebted to numerous colleagues around the world who have provided ideas and suggestions that, in no small way, have contributed to the fabric of this text. We have always strived to remain cognizant of student learning needs and difficulties, and we are grateful to the many students, at Purdue, Notre Dame, and elsewhere, who have provided positive reinforcement for our efforts.

Finally, we would be remiss if we did not acknowledge the Herculean effort of Andrea Incropera, who processed the solutions to the end-of-chapter problems in this text. She did so with great care and patience, for which, we are both grateful.

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Symbols

A	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
c	specific heat, J/kg · K; speed of light, m/s
c_p	specific heat at constant pressure, J/kg · K
c_v	specific heat at constant volume, J/kg · K
D	diameter, m
D_{AB}	binary mass diffusion coeffeicient, m^2/s
D_h	hydraulic diameter, m
E	thermal (sensible) internal energy, J; electric potential, V; emissive power, W/m^2
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
f	friction factor; similarity variable
G	irradiation, W/m^2; mass velocity, kg/s · m^2
Gr	Grashof number
Gz	Graetz number
g	gravitational acceleration, m/s^2
g_c	gravitational constant, 1 kg · m/N · s^2 or 32.17 ft · lb_m/lb_f · s^2
H	nozzle height, m
h	convection heat transfer coefficient, W/m^2 · K; Planck's constant
h_{fg}	latent heat of vaporization, J/kg
h_m	convection mass transfer coefficient, m/s
h_{rad}	radiation heat transfer coefficient, W/m^2 · K
I	electric current, A; radiation intensity, W/m^2 · 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 · 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
$\dot{M}_{\text{in}}$ rate at which mass enters a control volume, kg/s
$\dot{M}_{\text{out}}$ rate at which mass leaves a control volume, kg/s
$\dot{M}_{\text{st}}$ 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
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, 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
$x_{\text{fd},c}$ concentration entry length, m
$x_{\text{fd},h}$ hydrodynamic entry length, m
$x_{\text{fd},t}$ 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 · m
δ	hydrodynamic boundary layer thickness, m
δ_c	concentration boundary layer thickness, m
δ_t	thermal boundary layer thickness, m
ε	emissivity; porosity of a packed bed; heat exchanger effectiveness
ε_f	fin effectiveness
ε_H	turbulent diffusivity for heat transfer, m^2/s
ε_M	turbulent diffusivity for momentum transfer, m^2s
ε_m	turbulent diffusivity for mass transfer, m^2/s
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
μ	viscosity, kg/s · 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

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
evap	evaporation
f	fluid properties; fin conditions; saturated liquid conditions
fd	fully developed conditions
g	saturated vapor conditions
H	heat transfer conditions
h	hydrodynamic; hot fluid
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	mass transfer condition; mean value over a tube cross section
max	maximum fluid velocity
o	center or midplane condition; tube outlet condition; outer
R	reradiating surface
r, ref	reflected radiation
rad	radiation
S	solar conditions
s	surface conditions; solid properties
sat	saturated conditions
sky	sky conditions
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

—	surface average conditions; time mean

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