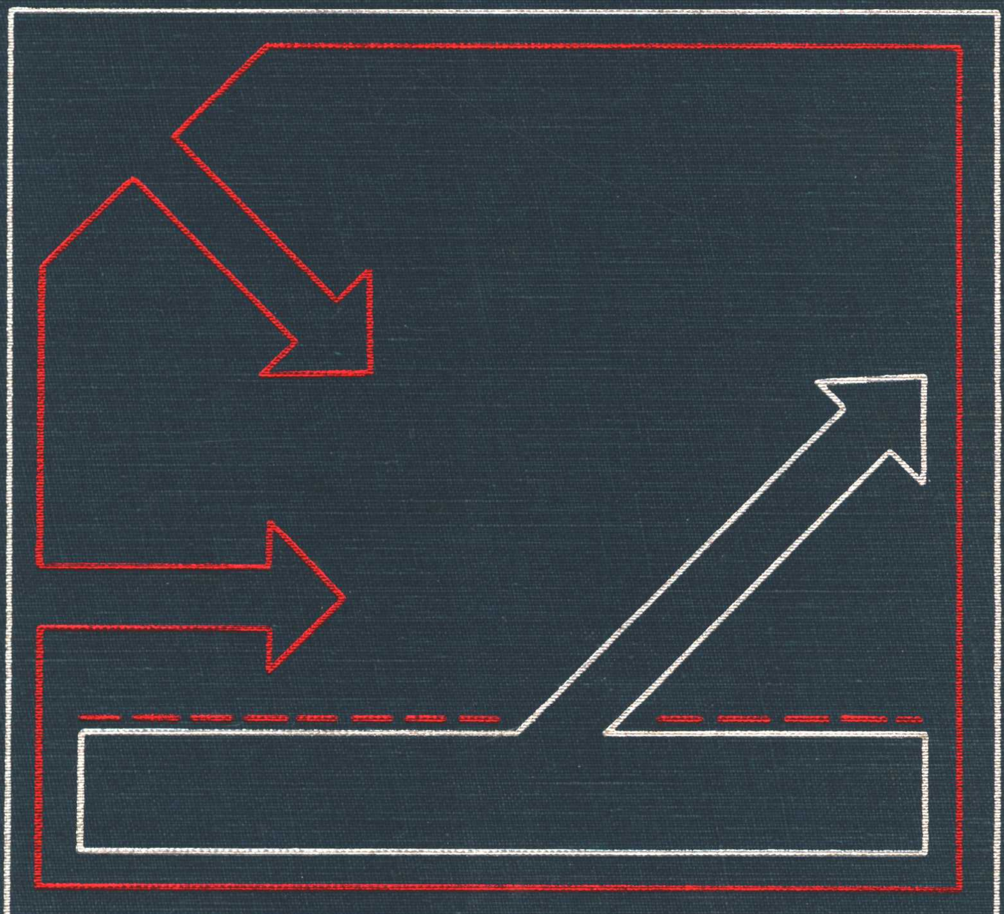
Introduction to Heat Transfer



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INTRODUCTION TO HEAT TRANSFER

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PREFACE

In preparing to revise this text, we decided to solicit feedback from colleagues who have used or were otherwise familiar with the first edition. Our solicitation was formalized by the publisher, who sent questionnaires to 119 faculty and received 82 responses. This questionnaire addressed key features of the first edition. Matters of particular interest included:

- The extent to which exact solutions, numerical methods, and computer usage should be considered in the treatment of conduction.
- The extent to which boundary layer solutions should be developed.
- Whether the treatments of heat transfer with phase change and heat exchangers were adequate.
- Whether the treatment of radiation was too detailed.
- Whether the treatments of heat and mass transfer should be integrated.

Many of the responses revealed considerable insights into (and convictions concerning) heat transfer pedagogy. Collectively, they provided an invaluable resource for planning the second edition.

Although most respondents felt that the previous edition's coverage of conduction analysis was satisfactory for a first course, 18 percent felt that more could be done to illustrate exact methods of solving multidimensional and transient forms of the heat equation. Fifty-four percent of the respondents felt that the treatment of numerical methods could be improved, and 48 percent did not object to inclusion of stock codes in the text to facilitate computer usage. However, many of the 52 percent who did object to the use of such codes voiced their opposition strongly. One group felt that stock codes fostered a superficial understanding of heat transfer, while another group held that students should (and can) write their own codes.

Although most respondents thought that the treatment of boundary layer behavior was adequate (or excessive), 18 percent felt that more should be done to obtain boundary layer solutions. Small numbers (less than 15 percent) suggested that the treatment of boiling and condensation be expanded and that compact heat exchangers be included in the discussion of heat transfer equipment. Although 71 percent of the respondents were pleased with the material on radiation, many of the others felt that the material on surface spectral and directional effects was too detailed and called for simplification. A slight majority (56 percent) favored an integrated treatment of convection heat and mass transfer, but much of the minority opinion that opposed the inclusion of mass transfer was strongly worded.

All of this input stimulated change; however, it did not cause us to alter our original objectives. In fact, these objectives were reaffirmed. Simply stated, they are:

1. To convey an appreciation for the principles of heat transfer.
2. To establish the relationship of these principles to thermal system behavior and to develop methodologies for predicting this behavior.

Implicit in the first objective is our belief that students should be comfortable with the physical mechanisms and conditions of heat transfer. What, for example, are the mechanisms associated with transfer by conduction, convection, and radiation? What is thermal energy storage? Thermal energy generation? A buoyancy force? A blackbody? When is heat transfer one dimensional or time invariant? Such concepts are introduced throughout the text, and comprehension is essential if the student is to be able to identify heat transfer modes and conditions pertaining to a physical system.

Implicit in the second objective is our belief that students should learn to deal rationally with problems involving thermal system design and performance. They should be able to discern relevant transport processes and simplifying assumptions, identify key dependent and independent variables, and choose or develop appropriate expressions for evaluating the dependent variables. In short, students must be able to effect the kind of engineering analysis that, although not always exact, often provides useful information concerning the behavior of a particular system or process.

Preparation of this edition has been strongly motivated by the foregoing objectives, as well as by the survey of opinion on the first edition. The responses to this survey have led us to make many small changes that have improved the book's overall quality. We have also made larger changes that have enhanced the role of exact solutions in the heat and boundary layer equations, improved the discussion of numerical solution methods, expanded the treatment of heat transfer with phase change (to include more recent results), and expanded the treatment of heat exchangers (to include compact geometries). *Perhaps the most significant change has been the preparation of two versions of the text, one with and a second without mass transfer.*

To enhance the student's appreciation of exact methods of heat transfer analysis, we have illustrated use of the separation of variables method for two-dimensional conduction in Chapter 4, presented (without derivation) series solutions for the three Heisler chart geometries in Chapter 5, and illustrated use of the similarity method of forced-convection boundary layer analysis in Chapter 7. In all three cases, our intent is to have students recognize the existence of such solutions, the form which they take, and their advantages and limitations. In the third case our aim is to have students appreciate the manner in which convection coefficients may be determined theoretically. However, it is not our objective to foster competence in the application of these methods. Although the equations of heat transfer provide fertile material for enhancing student skills in applied mathematics, we do not believe that significant effort should be devoted to this purpose in a first course in heat transfer.

We have improved our treatment of numerical methods in Chapters 4 and 5. We eliminated the relaxation method and placed more emphasis on other iterative methods. We have also increased our emphasis on implicit methods, while expanding our discussion of stability criteria associated with explicit methods. We have not, however, included any stock computer programs or subroutines that could be used to effect these solutions, since such software is accessible in most computer libraries and/or is easily written by the student.

Two versions of the book have been prepared. One version, *Fundamentals of Heat and Mass Transfer*, is the second edition of the previously entitled *Fundamentals of Heat Transfer*. Although it is concerned primarily with heat transfer, it includes mass transfer effects *to whatever extent they can be inferred by analogy to heat transfer*. The manner in which this is done varies with the mass transfer mode. Because engineering applications of mass transfer by diffusion are limited, all topics related to this mode are treated separately in a single chapter at the end of the text. Therefore, any instructor wishing to ignore the subject may readily do so. In contrast, because engineering applications of convection mass transfer are extensive and because the process can make a significant contribution to total energy exchange at a vapor–liquid interface, its treatment is integrated with that of convection heat transfer. This integration permits a *unified* treatment of heat, mass, and momentum transfer in the study of boundary layer behavior and provides excellent opportunities for developing important similarity concepts.

The second version of the book, *Introduction to Heat Transfer*, is intended for users who do not wish to consider mass transfer. It is simply the first version, without mass transfer.

Chapters 1 through 5 are equivalent in both versions. Chapter 1 develops the physical basis of heat transfer by conduction, convection, and radiation and emphasizes the important role played by the requirement of energy conservation. Through carefully selected examples and problems, the student is encouraged to develop the facility to identify the relevant heat transfer processes for a variety of practical situations. Chapter 2 provides a detailed introduction to the conduction process. The nature and origin of Fourier's law are discussed, and general forms of the conduction heat equation are developed. The physical significance of each of the terms in the equation is emphasized, along with the nature of the simplifications that often may be made. Chapters 3, 4, and 5 are structured along traditional lines, with methods of solution developed for one-dimensional, two-dimensional, and transient conduction problems.

Chapters 6, 7, and 8 of *Fundamentals of Heat and Mass Transfer* provide an integrated treatment of heat and species transfer by forced convection. In Chapter 6 the concepts of the velocity, thermal, and concentration boundary layers are developed, and the related conservation equations are derived. The physical significance of the various terms in the equations and their relation to the wall shear stress and to convection heat and mass transfer are emphasized. Similarity parameters relevant to convection transfer are obtained by non-dimensionalizing the conservation equations, and the important role that they play in the generalization of heat and mass transfer results is developed. The dimensionless forms of the conservation equations are also used to infer important boundary layer analogies.

In many respects Chapter 6 is a cornerstone to the treatment of convection transfer. It sets forth important physical principles before providing the student with the tools to perform engineering calculations. In Chapters 7 and 8 these tools are presented for external and internal flows, respectively. Chapters 6, 7, and 8 of *Introduction to Heat Transfer* are organized in precisely the same manner, except that the mass transfer content has been deleted.

Chapters 9 (free convection), 10 (boiling and condensation), 11 (heat exchangers), 12 (surface radiation), and 13 (enclosure radiation exchange) are equivalent in both versions of the book. Mass transfer effects have been deleted from Chapter 14 (multimode heat transfer) in *Introduction to Heat Transfer*. In both versions, however, the material of Chapter 14 can contribute greatly to developing student confidence in using the tools of heat transfer analysis, and the instructor is urged to include it in the course requirements. Examples related to industrial and environmental applications illustrate the manner in which previously developed tools may be systematically integrated for effective problem solving. Emphasis is placed on engineering problems for which the student must establish objectives, make appropriate assumptions, and develop solutions that best respond to the objectives. Chapter 15 (mass diffusion) appears only in *Fundamentals of Heat and Mass Transfer*.

A significant number of respondents expressed concern about the coverage of surface radiation in Chapter 12 and noted that this material is difficult for students to assimilate. We are in sympathy with this concern and are cognizant of our own students' difficulties in grasping the subject. However, Chapter 12 was written with the conviction that nature is spectral and directional and that too many important engineering applications involve nondiffuse, nongray behavior. Hence, in an effort to systematically deal with directional and spectral effects, we have had to include details that require careful reading by even the best of students. We attempt to help our students by pointing out that their difficulties may be verbal, rather than physical or mathematical, in nature. We urge them to carefully consider each new term and to fully digest the contents of Table 12.3. Because we devote almost four weeks to radiation (Chapters 12 and

13), the conscientious student has time to achieve a good level of understanding and to develop confidence in using the material.

Although we have opted to retain our approach to radiation, we recognize that some instructors may be unable to commit sufficient time for satisfactory coverage of the material. In such cases we recommend that directional effects be de-emphasized. This may be done by having the students read Sections 12.2 and 12.7 for background and not holding them responsible for application of the contents. In other sections, expressions involving hemispherical (total and spectral) properties could be emphasized, and those involving directional properties could be treated lightly. Problems that deal exclusively with spectral, total, and hemispherical properties could be assigned. To paraphrase several of the respondents who treat the subject in this manner, "Although coverage is limited, students are at least aware of the importance of other effects and know where to go if they had to deal with them."

Other key features of the first edition have been retained and expanded. For example, we continue to stress the importance of conservation principles, particularly the first law of thermodynamics, in heat transfer analysis. General formulations of the energy conservation requirement are provided early in the text and are used as a basis for systematically treating all subsequent applications, whether to a differential or to a macroscopic control volume. The importance of the first law to heat transfer analysis is firmly established through numerous examples and problems.

We have also expanded our emphasis on the aspect of heat transfer that seems to hold the greatest appeal to students, namely, the large number of applications. Many of these applications deal with familiar topics such as energy conversion and conservation, space heating and cooling, propulsion, material and chemical processing, and thermal protection. To whatever extent possible, the relationship of heat transfer to the *behavior* of related *thermal systems* is stressed. Reference to applications is interwoven with text and example material, and many assigned problems are couched in terms of actual thermal systems. Such problems reinforce the relationship of the course to the *design process* by having the student make decisions concerning the configuration and/or operation of the system.

A goal of all engineering courses is to condition the student to perform engineering analyses that provide useful information concerning system design or performance. We have attempted to foster this goal by advocating a systematic approach to problem solving. The approach involves delineating all relevant processes on a schematic diagram of the physical system, making appropriate assumptions, identifying relevant variables, and introducing appropriate rate and conservation equations to predict thermal system behavior. We feel that students adopting this methodology are better able to apply heat transfer to industrial problems.

This text has evolved from many years of teaching heat transfer and from experiences gained through use of the first edition. In its preparation we have tried to remain conscious of student needs and difficulties, to be true to our objectives, and to incorporate many of the constructive suggestions made by our colleagues. We thank all those who participated in the survey and/or took the time to personally communicate their views. We would be remiss if we did not offer special thanks to Professor J. T. Pearson, who has been a constant source of suggestions and encouragement.

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SYMBOLS

A	area, 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	area of prime (unfinned) surface, m^2
A_s	surface area, m^2
a	acceleration, m/s^2
Bi	Biot number
Bo	Bond number
C	heat capacity rate, W/K
C_D	drag coefficient
C_f	friction coefficient
C_t	thermal capacitance, J/kg
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_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, $kg/s \cdot m^2$

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	convection heat transfer coefficient, $W/m^2 \cdot K$; Planck's constant
h_{fg}	latent heat of vaporization, J/kg
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_H	Colburn j factor for heat transfer
k	thermal conductivity, $W/m \cdot K$; Boltzmann's constant
L	characteristic length, m
M	mass, kg; number of heat transfer lanes in a flux plot; reciprocal of the Fourier number for finite-difference solutions
$\mathcal{M}$	molecular weight, kg/kmol
m	mass, kg
$\dot{m}$	mass flow rate, kg/s
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
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	heat 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
$R_{t,c}$	thermal contact resistance, K/W
R_e	electric resistance, Ω
R_f	fouling factor, $m^2 \cdot K/W$
$R_{m,n}$	residual for the m,n nodal point
R_t	thermal resistance, K/W
r_o	cylinder or sphere radius, m
r, ϕ, z	cylindrical coordinates
r, θ, ϕ	spherical coordinates
S	shape factor for two-dimensional conduction, m
S_c	solar constant
S_D, S_L, S_T	diagonal, longitudinal, and transverse pitch of a tube bank, m

St	Stanton number
T	temperature, K
t	time, s
U	overall heat transfer coefficient, $W/m^2 \cdot K$
u, v, w	mass average fluid velocity components, m/s
V	volume, m^3; fluid velocity, m/s
v	specific volume, m^3/kg
$\dot{W}$	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
$x_{fd,h}$	hydrodynamic entry length, m
$x_{fd,t}$	thermal entry length, m

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_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^2/s
η	similarity variable
η_f	fin efficiency
η_o	fin temperature effectiveness
θ	zenith angle, rad; temperature difference, K
κ	absorption coefficient, m^{-1}
λ	wavelength, μm
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

Subscripts

abs	absorbed
adv	advection
am	arithmetic mean

b	base of an extended surface; blackbody
c	cross-sectional; cold fluid
cr	critical insulation thickness
cond	conduction
conv	convection
CF	counterflow
D	diameter; drag
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	inner surface of an annulus; initial condition; tube inlet condition; incident radiation
L	based on characteristic length
l	saturated liquid conditions
lm	log mean condition
M	momentum transfer condition
m	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
∞	freestream conditions

Superscripts

$'$	fluctuating quantity
$*$	dimensionless quantity

Overbar

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

CONTENTS