transfer operations

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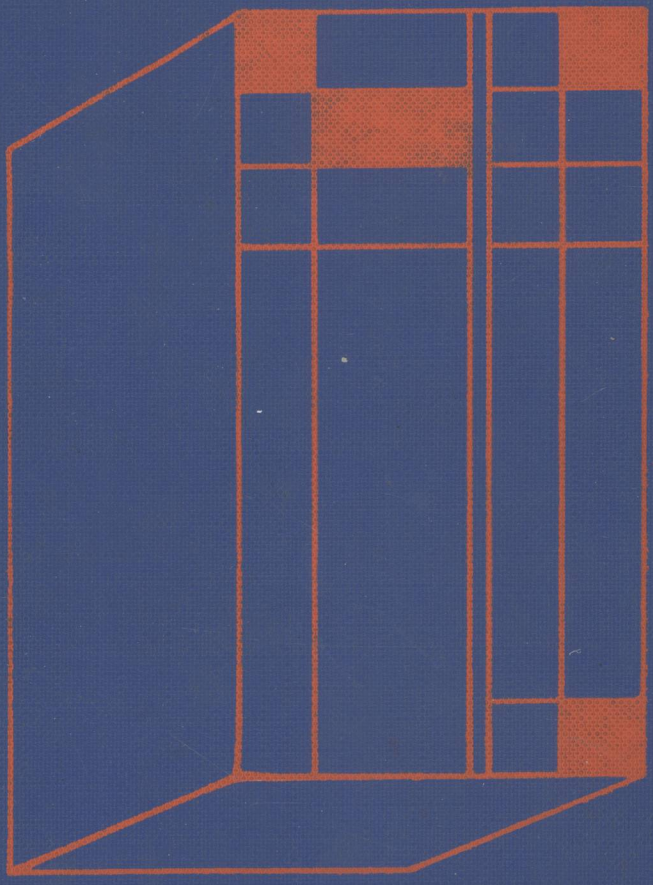

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to
Rosemary
and
Carolyn

preface

This book is intended as a textbook, not a reference book or handbook. Our objective is to present momentum, heat, and mass transfer from a macroscopic point of view. Specifically, we present material (1) to provide the student with a basic knowledge of the mechanisms by which momentum, heat, and mass are transferred and (2) to introduce the student to the design equations for momentum, heat, and mass and to the use of these equations. The course for which this textbook is used in the School of Chemical Engineering at Purdue University is the first of a three-course transport sequence. The second course in the sequence is one in transport phenomena—a microscopic point of view—and the third a laboratory where both transfer coefficients and transport coefficients are determined. We believe this sequence—presenting the macroscopic approach before the microscopic—to be the soundest from a pedagogical point of view. To use with understanding the transport approach, with its more sophisticated mathematics, requires the physical insight and the motivation of recognized applications which this text provides.

Although the course taught from this book is in a sequence in the School of Chemical Engineering, it does stand alone in that the techniques presented are immediately applicable. The course is required for juniors in chemical engineering, industrial engineering, and materials science and metallurgical engineering. Only the chemical engineers take the three-course sequence. Students from other departments, such as agricultural, nuclear, and mechanical engineering, and food science and home economics students who have sufficient background and who wish a course in momentum, heat, and mass transfer with practical application, also take this course.

The text is built around a large number of examples which are worked in detail. Many of the examples are, of course, idealized because their purpose is to illustrate elementary principles, but we have kept them as realistic as possible. The text is arranged in a matrix fashion as shown in Table 1.2-1 on page 5. Within reason, either the columns or rows of this matrix stand alone. In other words, one could go through the introductory material of column 1 as one "subject," the momentum transfer of column 2 as one "subject," etc., or one could look at mechanism in row 1 as one "subject," the design equation in row 2 as one "subject," etc.

At Purdue the course is taught by successive columns (which is the sequence for chapter numbers). Each column represents approximately one-fourth of a four-semester-credit course. The chapters on applications (Chap. 4, 7, 10, and 13) are not taught in their entirety since they do not contain principles; rather, they are assigned as reading and specific parts may be employed as illustrations by the instructor. These four chapters are designed to show how overall balances are used, how transfer coefficients are measured, how the design equations are used in a real system, and how these calculations are integrated into a real system. (The industrial and material science and metallurgical engineers at Purdue have the option of ending the course for three semester credits by omitting the fourth part on mass transfer.)

We have taken the position in writing this book that it is *part* of the instructional material available to the student—the instructor teaching the course is the other part. The procedures presented are common ones which provide the base for various, but limited, solution procedures on which the instructor may choose to build further, or not as he sees fit. We have accepted equipment as a basic but secondary part of transfer operations; we concentrate on the principles and we use practical examples and system applications. The equipment is included as a matter of fact. A particular instructor may wish to emphasize or deemphasize this point depending on his own approach to the topics.

We owe an original debt to Professors Jack Myers and Alexander Sesonske in whose association both the authors were introduced to this general area of undergraduate teaching. We also have been helped in construction of examples and review of the notes by Professors Ron Barile, Neal Houze, and Theo Theofanous of the School of Chemical Engineering at Purdue, by Larry Hochreiter, a graduate student in Nuclear Engineering, and by Dr. Tom Sifferman, a former graduate student in Mechanical Engineering. We wish to thank Susie O'Dore and Linda Rhodes for their patient efforts in typing and retyping the manuscript. In addition, the Chemical Engineering Department of the University of California, Berkeley, deserves our thanks for permitting one of the authors to teach a course from the notes as a visiting professor at a critical time in the text development. The Pan American Petroleum Corporation was most cooperative. It provided the flow sheet for the Natural Gasoline Plant and reviewed the application examples in Chaps. 7, 10, and 13. A last but most significant debt goes to Snooker Table Number 4 in the Purdue Billiard Room—where the emotions and frustrations associated with writing the text found release.

R. A. GREENKORN
D. P. KESSLER

list of symbols

A = area, L^2

a = interfacial area per unit volume of bed, L^{-1}

C = discharge coefficient, dimensionless

$\hat{C}_p$ = heat capacity at constant pressure, per unit mass, $L^2/t^2\,T$

$\hat{C}_v$ = heat capacity at constant volume, per unit mass, $L^2/t^2\,T$

C_p = pitot tube coefficient, dimensionless

c = total molar concentration, moles/L^3

C_V = venturi coefficient, dimensionless

c_i = molar concentration of species i, moles/L^3

D = characteristic length in dimensional analysis or diameter of sphere or cylinder, L

D_p = particle diameter, L

$\mathscr{D}_{AB}$ = binary diffusivity for system A-B, L^2/t

$\mathscr{D}_{ij}$ = binary diffusivity for system i-j, L^2/t

E = $U + K + \phi$ = total fluid energy, ML^2/t^2

e = 2.71828...

e = emissivity, dimensionless

e = total energy flux relative to stationary coordinates, M/t^3

F = force of a fluid on an adjacent solid, ML/t^2

F_{12} = direct view factor, dimensionless

$\bar{F}_{12}$ = indirect view factor, dimensionless

$\mathscr{F}_{12}$ = combined emissivity and view factor, dimensionless

f = friction factor or drag coefficient, dimensionless

G = molar velocity, moles/tL^2

G = $H - TS$ = Gibbs free energy, or "free enthalpy," ML^2/t^2

g = gravitational acceleration, L/t^2

g_c = force-mass conversion factor

H = $U + pV$ = enthalpy, ML^2/t^2

h = heat transfer coefficient, $M/t^3\,T$

h = Planck's constant, ML^2/t

h = elevation, L

i = $\sqrt{-1}$

J_i = molar flux of i relative to mass average velocity, moles/tL^2

J_i^* = molar flux of species i relative to the molar average velocity, moles/tL^2

j_i = mass flux of i relative to mass average velocity, M/tL^2

j_i^* = mass flux of species i relative to the molar average velocity, M/tL^2

j_D = Chilton-Colburn j factor for mass transfer, dimensionless

j_H = Chilton-Colburn j factor for heat transfer, dimensionless

K = kinetic energy, ML^2/t^2

k = roughness, L

k = shape factor, dimensionless

k = thermal conductivity, ML/t^3T

k_n = homogeneous chemical reaction rate constant, moles$^{1-n}/L^{3-3n}t$

k_x = mass transfer coefficient in a binary system, moles/tL^2

k_{xi} = mass transfer coefficient of species i in a multicomponent mixture, moles/tL^2

L = length of tube or other characteristic length, L

L = molar velocity, moles/tL^2

M = molar mean molecular weight, M/mole

M_A = molecular weight of A, M/mole

$\mathscr{M}$ = moles of material

$\mathscr{M}_i$ = moles of component i

m = mass of a molecule, M

m = mass of flow system, M

m_i = mass of component i in flow system, M

$\tilde{N}$ = Avogadro's number, (g mole)$^{-1}$

N = rate of rotation of a shaft, t^{-1}

N_i = molar flux with respect to stationary coordinates, moles/L^2t

n_i = mass flux with respect to stationary coordinates, M/L^2t

$\mathbf{n}$ = molecular concentration or number density, L^{-3}

$\mathbf{n}$ = outward normal

P = momentum, ML/t

$\mathscr{P}$ = $p + \rho gh$ (for constant ρ and g), M/LT^2

p = fluid pressure, M/Lt^2
p' = vapor pressure, M/Lt^2
$\bar{p}$ = partial pressure, M/Lt^2
Q' = amount of heat transfer, ML^2/t^3
Q = volumetric flow rate, L^3/t
Q = rate of energy flow across a surface, ML^2/t^3
Q_{12} = radiant energy flow from surface 1 to surface 2, ML^2/t^3
Q_{12} = net radiant energy interchange between surface 1 and surface 2, ML^2/t^3
q = energy flux relative to mass average velocity, M/t^3
R = gas constant, ML^2/t^2T mole
R = radius of sphere or cylinder, L
R_h = hydraulic radius, L
R_A = molar rate of production of species A, moles/tL^3
r = radial distance in both cylindrical and spherical coordinates, L
r_A = mass rate of production of species A, M/tL^3
S = cross-sectional area, L^2
$\mathbf{S}$ = vector giving cross-sectional area and its orientation, L^2
s = $R - r$ = distance into fluid from solid boundary in cylindrical coordinates, L
T = absolute temperature, T
t = time, t
U = internal energy, ML^2/t^2
U = overall heat transfer coefficient, M/t^3T
V = characteristic speed in dimensional analysis, L/t
V = volume, L^3
v = mass average velocity, L/t
v_i = velocity of species i, L/t
v_∞ = approach velocity, L/t
v^* = molar average velocity, L/t
W = rate of doing work on surroundings, ML^2/t^3
W' = amount of work done
$\mathscr{W}$ = molar flow rate, moles/t
$\mathscr{W}_A$ = molar flow of species A through a surface, moles/t
$\mathbf{w}$ = vector giving mass flow rate and its direction, M/t
w = mass flow rate, M/t

w_A = mass flow of species A through a surface, M/t
x = rectangular coordinate, L
x_i = mole fraction of species i, dimensionless
y = rectangular coordinate, L
y_i = mole fraction of species i, dimensionless
z = rectangular coordinate, L
α = $k/\rho\hat{C}_p$ = thermal diffusivity, angle, absorptivity
β = thermal coefficient of volumetric expansion, T^{-1}
γ = $\hat{C}_p/\hat{C}_v$, reflectivity, dimensionless
Δa = $a_2 - a_1$, in which 1 and 2 refer to two control surfaces
δ = film thickness, L
ϵ = fractional void space, emissivity, dimensionless
η = non-Newtonian viscosity, M/Lt
θ = angle in cylindrical or spherical coordinates, radians
λ = wavelength of electromagnetic radiation, L
μ = viscosity, M/Lt
μ_p = parameter in Bingham model, M/Lt
ν = frequency of electromagnetic radiation, t^{-1}
ν = μ/ρ = kinematic viscosity, L^2/t
π = 3.14159...
ρ = nm = fluid density, M/L^3
ρ_i = mass concentration of species i, M/L^3
σ = Stefan-Boltzmann constant, M/t^3T^4
τ = transmissivity, dimensionless
τ_0 = parameter in Bingham model, M/t^2L
τ_0 = magnitude of shear stress at fluid-solid interface, M/t^2L
Φ = potential energy, ML^2/t^2
ϕ = angle in spherical coordinates, radians
ψ = stream function; dimensions depend on coordinate system
Ω = potential function
ω_i = mass fraction of i, dimensionless

Overlines

$\sim$ = per mole
$\wedge$ = per unit mass
— = partial molal
— = time smoothed

Brackets

$<a>$	= weighted value of a over a flow cross section

Superscripts

$*$	= reduced with respect to some characteristic dimension
$'$	= deviation from time-smoothed value
t	= turbulent
l	= laminar

Subscripts

A, B	= species in binary systems
av	= arithmetic mean driving force or associated transfer coefficient
b	= bulk or "mixing-cup" value for enclosed stream
G	= gas
L	= liquid
i, j, k	= species in multicomponent systems
lm	= logarithmic mean driving force or associated transfer coefficient
loc	= local transfer coefficient
m	= mean transfer coefficient for a submerged object
tot	= total quantity in a macroscopic system
0	= quantity evaluated at a surface
1,2	= quantity evaluated at cross sections "1" and "2"

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