DIFFUSION

MASS TRANSFER IN FLUID SYSTEMS

THIRD EDITION

Diffusion: Mass Transfer in Fluid Systems brings unsurpassed, engaging clarity to a complex topic. Diffusion is a key part of the undergraduate chemical engineering curriculum and at the core of understanding chemical purification and reaction engineering. This spontaneous mixing process is central to our daily lives, important in phenomena as diverse as the dispersal of pollutants to digestion in the small intestine. For students, this new edition goes to the basics of mass transfer and diffusion, illustrating the theory with worked examples and stimulating discussion questions. For professional scientists and engineers, it explores emerging topics and explains where new challenges are expected. Retaining its trademark enthusiastic style, the book's broad coverage now extends to biology and medicine.

This accessible introduction to diffusion and separation processes gives chemical and biochemical engineering students what they need to understand these important concepts.

New to this Edition

- **Diffusion:** Enhanced treatment of topics such as Brownian motion, composite materials, and barrier membranes.
- **Mass transfer:** Fundamentals supplemented by material on when theories work and why they fail.
- **Absorption:** Extensions include sections on blood oxygenators, artificial kidneys, and respiratory systems.
- **Distillation:** Split into two focused chapters on staged distillation and on differential distillation with structured packing.
- **Advanced Topics:** Including electrolyte transport, spinodal decomposition, and diffusion through cavities.
- **New Problems:** Topics are broad, supported by password-protected solutions found at www.cambridge.org/cussler.

Professor Cussler teaches chemical engineering at the University of Minnesota. His research, which centers on membrane separations, has led to over 200 papers and 4 books. A member of the National Academy of Engineering, he has received the Colburn and Lewis awards from the American Institute of Chemical Engineers, the Separations Science Award from the American Chemical Society, the Merryfield Design Award from the American Society for Engineering Education, and honorary doctorates from the Universities of Lund and Nancy.

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For Jason, Liz, Sarah, and Varick
who wonder what I do all day

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List of Symbols

a	surface area per volume
a	major axis of ellipsoid (Section 5.2)
a, a_i	constant
A	area
A	absorption factor (Chapters 13 and 14)
b	constant
b	minor axis of ellipsoid (Section 5.2)
B	bottoms (Chapters 10, 12 and 13)
B, b	boundary positions (Section 7.3)
c	total molar concentration
c_1	concentration of species 1, in either moles per volume or mass per volume
c_{CMC}	critical micelle concentration (Section 6.2)
c_{T}	total concentration (Chapter 6)
$\overline{c}_1$	concentration of species 1 averaged over time (Sections 4.3 and 17.4)
c_1'	concentration fluctuation of species 1 (Sections 4.3, 17.3, and 17.4)
$\underline{c}$	vector of concentrations (Section 7.3)
c_{1i}	concentration of species 1 at an interface *i*
C	capacity factor (Section 13.1)
$\tilde{C}_p$, $\hat{C}_p$	molar and specific heat capacities respectively, at constant pressure
$\tilde{C}_v$, $\hat{C}_v$	molar and specific heat capacities respectively at constant volume
d	diameter or other characteristic length
D	binary diffusion coefficient
D	distillate (Chapters 12 and 13)
D_{eff}	effective diffusion coefficient, for example, in a porous solid
D_i	binary diffusion coefficient of species *i*
D_0	binary diffusion coefficient corrected for activity effects
D_{ij}	multicomponent diffusion coefficient (Chapter 7)
D_{Kn}	Knudsen diffusion coefficient of a gas in a small pore
D_{m}	micelle diffusion coefficient (Section 6.2)
D^*	intradiffusion coefficient (Section 7.5)
E	dispersion coefficient
E	extraction factor (Chapter 14)
$E(t)$	residence-time distribution (Section 9.2)
f	friction coefficient for a diffusing solute (Section 5.2)
f	friction factor for fluid flow (Chapter 21)
F	packing factor (Section 10.2)
F	feed (Chapters 12 and 13)
F	Faraday's constant (Section 6.1)
$F(D)$	solution to a binary diffusion problem (Section 7.3)
$\mathbf{g}$	acceleration due to gravity

G	molar flux of gas
G''	mass flux of gas (Sections 10.2 and 13.1)
G'	molar flux of gas in stripping section (Chapters 12 and 13)
h	reduced plate height (Section 15.5)
h, h_i	heat transfer coefficients (Chapters 20 and 21)
H	partition coefficient
$\tilde{H}$, $\hat{H}$	molar and specific enthalpies (Chapters 20–21 and Chapter 7, respectively)
$\bar{H}_i$	partial specific enthalpy (Chapter 7)
HTU	height of transfer unit
$\mathbf{i}$	current density (Section 6.1)
j_v	volume flux across a membrane (Section 18.3)
$\boldsymbol{j}_{\mathrm{T}}$	total electrolyte flux (Section 6.1)
$\boldsymbol{j}_i$	diffusion flux of solute i relative to the volume average velocity
$\mathbf{j}_i^m$	diffusion flux of solute i relative to the mass average velocity
j_i^*	diffusion flux relative to the molar average velocity
$\mathbf{j}_1^{(2)}$	diffusion flux of solute (1) relative to velocity of solvent (2)
$\mathbf{j}_i^a$	diffusion flux of solute i relative to reference velocity a
$\boldsymbol{J}_{\mathrm{s}}$	entropy flux (Section 7.2)
$\boldsymbol{J}_{\mathrm{T}}$	total solute flux in different chemical forms (Section 6.2)
k	mass transfer coefficient based on a concentration driving force
k_p	mass transfer coefficient based on a partial pressure driving force (Table 8.2-2)
k_x, k_y	mass transfer coefficients based on mole fraction driving forces in liquid and gas, respectively (Table 8.2-2)
k_{B}	Boltzmann's constant
k_T	thermal conductivity (Chapters 20–21)
k^0	mass transfer coefficient at low transfer rate (Section 9.5)
k^0	mass transfer coefficient without chemical reaction (Chapter 17)
k'	capacity factor (Sections 4.4 and 15.1)
K	equilibrium constant for chemical reaction
K_{G}, K_{L}	overall mass transfer coefficients based on concentration driving force in gas or liquid, respectively
K_p	overall mass transfer coefficient based on partial pressure difference in gas
K_x, K_y	overall mass transfer coefficient based on mole fraction driving force in liquid or gas, respectively
Kn	Knudsen number (Section 6.4)
l	length, e.g., of a membrane
L	length, e.g., of a pipe
L	molar flux of liquid
L''	mass flux of liquid (Sections 10.2 and 13.1)
L'	molar flux of liquid in stripping section (Sections 12.3 and 13.3)
L_{ij}	Onsager phenomenological coefficient (Section 7.2)
L_p	solvent permeability (Section 18.3)
m	partition coefficient relating mole fractions in gas and liquid
M	mass
M	total solute (Sections 4.2 and 5.5)
$\tilde{M}_i$	molecular weight of species i

n	micelle aggregation number or hydration number (Section 6.2)
$\boldsymbol{n}_i$	flux of species i relative to fixed coordinates
N	number of ideal stages
$\tilde{N}$	Avogadro's number
N_i	flux of species i at an interface
N_i	number of moles of species i
NTU	number of transfer units
p	pressure
P	power
P	membrane permeability (Chapter 18)
P_{ij}	weighting factor (Section 7.3)
q	scattering vector (Section 5.6)
q	feed quality (Sections 12.3 and 13.3)
q	solute concentration per volume adsorbent (Chapter 15)
$\boldsymbol{q}$	energy flux (Chapters 7, 20, and 21)
r	radius
r, r_i	rate of chemical reaction
R	gas constant
R_D	reflux ratio (Chapters 12 and 13)
R_0	characteristic radius
s	distance from pipe wall (Section 9.4)
$\hat{S}$	specific entropy (Chapter 7)
$\bar{S}_i$	partial specific entropy of species i
t	time
$\mathbf{t}$	modal matrix (Section 7.3)
t_i	transference number of ion i (Section 6.1)
$t_{1/2}$	reaction half-life
T	temperature
u_i	ionic mobility (Section 6.1)
U	overall heat transfer coefficient
$\hat{U}$	specific internal energy
v_r, v_θ	velocities in the r and θ directions
v_x, v_y	velocities in the x and y directions
$\boldsymbol{v}$	mass average velocity
$\boldsymbol{v}^a$	velocity relative to reference frame a
$\boldsymbol{v}^{\mathrm{o}}$	volume average velocity
$\boldsymbol{v}'$	velocity fluctuation (Sections 4.3 and 17.4)
$\boldsymbol{v}^*$	molar average velocity
$\boldsymbol{v}_i$	velocity of species i
V	volume
$\bar{V}_i$	partial molar or specific volume of species i
V_{ij}	fraction of molecular volume (Section 5.1)
W	width
W	work (Section 20.2)
W_s	shaft work (Section 20.2)
x	mole fraction in liquid of more volatile species (Chapters 12 and 13)

x_B, x_D, x_F	mole fractions of more volatile species in bottoms, distillate and feed, respectively (Chapters 12 and 13)
x_i	mole fraction of species *i*, especially in a liquid or solid phase
$\mathbf{X}_i$	generalized force causing diffusion (Section 7.2)
y	mole fraction in vapor of more volatile species (Chapters 12 and 13)
y_i	mole fraction of species *i* in a gas
z	position
$\lvert z \rvert$	magnitude of charge (Section 6.1)
z_i	charge on species *i*
α	thermal diffusivity (Chapters 20 and 21)
α	thermal diffusion factor (Section 21.5)
α	flake aspect ratio (Sections 6.4 and 9.5)
α_{ij}	conversion factor (Section 7.1)
β	diaphragm cell calibration constant (Sections 2.2 and 5.5)
β	pervaporation selectivity (Section 18.4)
γ	interfacial influence (Section 6.3)
γ	surface tension (Section 6.4)
γ_i	activity coefficient of species *i*
δ	thickness of thin layer, especially a boundary layer
$\delta(z)$	Dirac function of *z*
δ_{ij}	Kronecker delta
ε	void fraction
ε	enhancement factor (Section 17.1)
ε_{ij}	interaction energy between colliding molecules (Sections 5.1 and 20.4)
ζ	combined variable
η	Murphree efficiency (Section 13.4)
η	effectiveness factor (Section 17.1)
θ	dimensionless concentration
θ	fraction of unused adsorption bed (Section 15.3)
θ	fraction of surface elements (Section 9.2)
κ_i, κ_{-i}	forward and reverse reaction rate constants respectively of reaction *i*
λ	length ratio (Section 6.4)
λ	heat of vaporization (Sections 12.3 and 13.3)
λ_i	equivalent ionic conductance of species *i* (Section 6.1)
Λ	equivalent conductance
μ	viscosity
μ_i	chemical potential of species *i*
μ_i	partial specific Gibbs free energy of species *i*, i.e., the chemical potential divided by the molecular weight (Section 7.2)
ν	kinematic viscosity
ν	stoichiometric coefficient (Sections 16.5 and 17.2)
ξ	dimensionless position
ξ	correlation length (Section 6.3)
$\prod$	osmotic pressure (Section 18.3)
ρ	total density, i.e., total mass concentration
ρ_i	mass concentration of species *i*
σ	rate of entropy production (Section 7.2)

σ	standard deviation (Sections 5.5 and 15.4)
σ, σ'	reflection coefficients (Section 18.3)
σ	Soret coefficient (Section 21)
$\boldsymbol{\sigma}$	diagonal matrix of eigenvalues (Chapter 7)
σ_i	eigenvalue (Section 7.3)
σ_{ij}	collision diameter
τ	characteristic time
τ	tortuosity (Section 6.4)
τ	residence time for surface element (Section 9.2)
τ	shear stress (Chapter 21)
τ_0	shear stress at wall (Section 9.4)
ϕ	Thiele modulus (Section 17.1)
ϕ_i	volume fraction of species *i*
ψ	electrostatic potential
$\boldsymbol{\psi}$	combined concentration (Section 7.3)
ω	jump frequency (Section 5.3)
ω	regular solution parameter (Section 6.3)
ω	coefficient of solute permeability (Section 18.3)
ω_i	mass fraction of species *i*
Ω	collision integral in Chapman–Enskog theory (Section 5.1)