
Separation Process Engineering

Includes Mass Transfer Analysis

Third Edition



Phillip C. Wankat

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Third Edition

PHILLIP C. WANKAT



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To Dot, Chuck, and Jennie

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Preface

In the twenty-first century, separations remain as important, if not more important, than in the previous century. The development of new industries such as biotechnology and nanotechnology, the increased importance of removing traces of compounds, and the probable need to recover and sequester carbon dioxide have brought new separations to the fore. Chemical engineers must understand and design new separation processes such as membrane separations, adsorption, and chromatography in addition to the standard equilibrium-staged separations including distillation, absorption, and extraction. Since membrane separations, adsorption, chromatography, and ion exchange were included, I changed the title of the second edition from *Equilibrium Staged Separations* to *Separation Process Engineering* to reflect this broader coverage. The new title has been retained for the third edition with the addition of a subtitle, *Includes Mass Transfer Analysis*, which reflects the addition of Chapter 15.

The second edition was unavoidably longer than the first, and the third edition is longer than the second. The first major addition to the third edition is the extensive Chapter 15, which includes mass transfer and diffusion. Both the Fickian and Maxwell-Stefan approaches to diffusion are covered in detail with examples and homework assignments. The old Chapter 15, which applied mass transfer techniques to equilibrium-staged separations, is now Chapter 16 with the removal of Section 15.1, which is now incorporated in the new Chapter 15.

The second major change is a much more extensive analysis of liquid-liquid extraction. Chapters 13 and 14 in the second edition both covered extraction, washing, and leaching. In the third edition, the material is reorganized so that Chapter 13 covers only extraction and Chapter 14 covers washing and leaching. In addition to the McCabe-Thiele, triangle, and computer-simulation analyses of extraction, Chapter 13 now includes a section on the detailed design of mixer-settlers and a shorter section on the design of Karr columns. Mass transfer analysis of liquid-liquid extraction systems has been added to Chapter 16.

All of the chapters have many new homework questions and problems. More than 300 new questions and problems are included. Since all of the problems were created and solved as I continued to teach this material at Purdue University, a Solutions Manual is available to professors who adopt this textbook for their course. A number of spreadsheet problems have been added, and the answers are provided in the Solutions Manual.

Since process simulators are used extensively in commercial practice, I have continued to include process simulation examples and homework problems throughout the text. I now teach the required three-credit, junior-level separations course at Purdue as two lectures and a two-hour computer lab every week. The computer lab includes a lab test to assess the ability of the students to use the simulator. Although I use Aspen Plus as the simulator, any

process simulator can be used. Chapters 2, 6, 8, 10, 12, 13, and 16 include appendices that present instructions for operation of Aspen Plus. The appendices to Chapters 2, 4, 5, 15, and 17 have Excel spreadsheets, some of which use Visual Basic programs. I chose to use spreadsheets instead of a higher-level mathematical program because spreadsheets are universally available. The appendix to Chapter 18 includes brief instructions for operation of the commercial Aspen Chromatography simulator—more detailed instruction sheets are available from the author: wankat@purdue.edu.

The material in the third edition has been extensively tested in the required junior-level course on separations at Purdue University. Although I teach the material at the junior level, Chapters 1 to 14 could be taught to sophomores, and all of the material is suitable for seniors. The book is too long to cover in one semester, but almost complete coverage is probably feasible in two quarters. If mass transfer is included, this text could easily be used for a two-semester sequence. Many schools, including Purdue, allocate a single three-credit semester course for separations. Because there is too much material, topics must be selected in this case. Several course outlines are included in the Solutions Manual. Instructors may register at www.pearsonhighered.com for access to this book's Solutions Manual and PowerPoint slides of figures in the book.

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Nomenclature

Chapters 1 through 18

a	interfacial area per volume, ft^2/ft^3 or m^2/m^3
a_j^I	interfacial area for heat transfer on stage j , m^2
$a_{\text{flow}}, a_{\text{heat}}, a_{\text{mass}}$	eddy diffusion parameters, Eqs. (15-48)
a_p	surface area/volume, m^2/m^3
$a_{p1}, a_{p2}, a_{p3}, a_{T1}, a_{T2}, a_{T6}$	constants in Eq. (2-30) and Table 2-3
A	area, m^2
A, B, C	constants in Antoine Eq. (2-34)
A, B, C, D, E	constants in Eq. (2-60)
A, B, C, D	constants in matrix form of mass balances, Eqs. (6-13) and (12-58)
A_E, B_E, C_E, D_E	constants in matrix form of energy balances, Eq. (6-34)
A_{active}	active area of tray, ft^2 or m^2
A_c	cross-sectional area of column, ft^2 or m^2
A_d	downcomer area, ft^2 or m^2
A_{du}	flow area under downcomer apron, Eq. (10-28), ft^2
A_f	area for flow, m^2
A_{hole}	area of holes in column, ft^2
A_I	interfacial area between two phases, ft^2 or m^2
A_{mixer}	cross-sectional area of mixer, m^2
A_{net}	net area, Eq. (10-13), ft^2 or m^2
A_{total}	total area in horizontal drum, ft^2 or m^2
A_{vap}	Area for Vapor flow in horizontal drum, ft^2 or m^2
b	empirical constant, Eq. (13-63b)
b	equilibrium constant for linear equilibrium, $y = mx + b$
$b_{\text{flow}}, b_{\text{heat}}, b_{\text{mass}}$	eddy diffusion parameters, Eqs. (15-48)
B	bottoms flow rate, kmol/h or lbmol/h
C	number of components
C_{BM}	bare module cost, Chapter 11
C_C	concentration of solute in continuous phase, kmol/m^3 continuous phase
C_C^*	concentration of solute in continuous phase in equilibrium with C_D , kmol/m^3
C_D	concentration of solute in dispersed phase, kmol/m^3 dispersed phase
C_{FL}	vapor load coefficient, Eq. (15-38)
C_A, C_B, C_m	molar concentrations, of A, B, and mixture, mol/m^3
C_o	orifice coefficient, Eq. (10-25)

C_p	heat capacity, Btu/lb°F or Btu/lbmol°F or cal/g°C or cal/mol°C, etc.
C_p	base purchase cost, Chapter 11
$C_{p,size}$	packing size factor, Table 10-5
C_{pw}	water heat capacity
C_s	capacity factor at flood, Eq. (10-48)
C_{sb}	capacity factor, Eq. (10-8)
d	dampening factor, Eq. (2-57)
D	diffusivity, Fickian m ² /s or ft ² /h
D	distillate flow rate, kmol/h or kg/h
D, Dia	diameter of column, ft or m
D'_{col}	column diameter, see Table 16-1, ft
$d_{hydraulic}$	hydraulic diameter of drop, Eq. (13-62), m
d_i	impeller diameter, m
d_p, d_d	drop diameter, m
d_p^o	characteristic drop diameter, Eq. (16-97b), m
d_{tube}	tube diameter, m
$d_{settler}, D_s$	diameter of horizontal settler, m
D_{large}, D_{pilot}	diameters of Karr columns for scale-up, Eq. (13-66), m
D^o	infinite dilution Fickian diffusivity, m ² /s
\mathfrak{D}	Maxwell-Stefan diffusivity, m ² /s
D_{eddy}	eddy diffusivity, Eq. (16-111a, b), m/s
D_{total}	total amount of distillate (Chapter 9), moles or kg
e	absolute entrainment, mol/h
e	plate fractional free area in Karr column
erf	error function, Eq. (18-70)
E	extract flow rate (Chapters 13 and 14), kg/h
\hat{E}	mass extract, kg
E_j^V	energy transfer rate on stage j from bulk liquid to bulk vapor, J/s
E_k	value of energy function for trial k , Eq. (2-51)
E_{ML}, E_{MV}	Murphree liquid and vapor efficiencies, Eqs. (4-58) and (4-59)
E_0	activation energy, Kcal/mol
E_o	Overall efficiency, Eq. (4-56)
E_{pt}	point efficiency, Eq. (10-5) or (15-76a)
\hat{E}_t	holdup extract phase in tank plus settler, kg
f	friction factor
f_{AB}	friction coefficient between molecules A and B
$f = V/F$	fraction vaporized
f	fractional approach to flooding
f	frequency of reciprocation of Karr column, strokes/s
$f(x)$	equilibrium function, Chapter 9
$f_k(V/F)$	Rachford-Rice function for trial K , Eq. (2-43)
F	packing factor, Tables 10-3 and 10-4
F	degrees of freedom, Eq. (2-4)
F	charge to still pot (Chapter 9), moles or kg
F	mass of feed in batch extraction, kg
F	feed flow rate, kmol/h or lbmol/h or kg/h etc.
F_D	diluent flow rate (Chapter 13), kg/h

F_{lv}, FP	$\frac{W_L}{W_V} \sqrt{\frac{\rho_L}{\rho_V}} = \frac{L'}{G'} \sqrt{\frac{\rho_L}{\rho_V}}$, flow parameter
F_m	material factor for cost, Table 11-2
F_p	pressure factor for cost, Eqs. (11-5) and (11-6)
F_q	quantity factor for cost, Eq. (11-7)
F_s, F_{solv}	flow rate solvent (Chapter 13), kg/h
F_{solid}	solids flow rate in leaching, kg insoluble solid/h
F_{weir}	weir modification factor, Eq. (10-26) and Figure 10-22
gap	gap from downcomer apron to tray, Eq. (10-28), ft
g	acceleration due to gravity, 32.2 ft/s ² , 9.81 m/s ²
g_c	conversion factor in English units, 32.2 ft·lbm/(lbf·s ²)
G	flow rate carrier gas, kmol/h or kg/h
G'	gas flux, lb/s ft ²
h	pressure drop in head of clear liquid, inches liquid
h	height of liquid on stage (Chapter 16), ft
h	height, m or ft
h	height of liquid in mixer, m
h	liquid enthalpy, kcal/kg, Btu/lbmol, etc.
h	step size in Euler's method = Δt , Eq. (8-29)
\bar{h}	pure component enthalpy
h_f	enthalpy of liquid leaving feed stage
h_F	feed enthalpy (liquid, vapor or two-phase)
$h_{heat transfer}$	heat transfer coefficient
h_L	clear liquid height on stage, m or cm
h_o	hole diameter, inches
h_p	packing height, ft or m
h_{total}	height of flash drum, ft or m
h_w	height of weir, m or cm
H	Henry's law constant, Eqs. (8-9), (8-10), and (12-1)
H	molar holdup of liquid on tray, Eqs. (8-27) and (8-28)
H	stage height in Karr column, m
H	vapor enthalpy, kcal/kg, Btu/lbmol, etc.
$\bar{H}_{i,j}^V$	partial molar enthalpy of component i in vapor on stage j, J/kmol
\bar{H}_t	height of tank, m
$H_{t,OD}$	overall height of a transfer unit for mass transfer driving force in concentration units, Eq. (16-83a analog), m
H_G	height of gas phase transfer unit, ft or m
H_L	height of liquid phase transfer unit, ft or m
H_{OG}	height of overall gas phase transfer unit, ft or m
H_{OL}	height of overall liquid phase transfer unit, ft or m
HETP	height equivalent to a theoretical plate, ft or m
HTU	height of a transfer unit, ft or m
j_D, j_H	j-functions, Eqs. (15-50)
J_A	flux with respect to molar average velocity of fluid
k_1, k_2	empirical constants, Eq. (13-63b)
k_B	Boltzmann's constant, J/k

$\frac{k_{\text{conduction}}}{k_x, k_y}$	thermal conductivity, J/(ms K) individual mass transfer coefficients in liquid and vapor phases, see Table 15-4
k_c	mass transfer coefficient with concentration driving force, m/s, Eq. (15-25b)
k'_y	mass transfer coefficient in concentrated solutions, Eq. (15-32f)
k_x, k_y	individual mass transfer coefficient in molar units
$k_{x,c}, k_{x,D}$	individual mass transfer coefficients in continuous and dispersed phases, kg/(s·m ³) or kmol/(s·m ³)
k_{LD}, k_{LC}	individual mass transfer coefficients in continuous and dispersed phases with driving force in concentration units, m/s
k_L, k_V	individual liquid and vapor mass transfer coefficients in distillation, Eq. (16-108), m/s
k	mass transfer coefficient in Maxwell-Stefan analysis, $\bar{D}/\Delta z$, m/s
K_d	y/x, distribution coefficient for dilute extraction
K, K_i	y_i/x_i , equilibrium vapor-liquid ratio
K_{drum}	parameter to calculate u_{perm} for flash drums, Eq. (2-64)
K_x, K_y	overall mass transfer coefficient in liquid or vapor, lbmol/ft ² h, or kmol/h·m ²
K_{LD}	overall mass transfer coefficient in extraction based on dispersed phase in concentration units, Eq. (16-80b analog), m/s
K_{O-ED}	overall mass transfer coefficient in extraction based on dispersed phase, Eq. (16-80a), kg/(s·m ³) or kmol/(s·m ³)
l_w	weir length, ft
L	length, m
\bar{L}	liquid flow rate, kmol/h or lbmol/h
\bar{L}	mass liquid flow rate, lb/h (Chapter 15)
L'	liquid flux, lb/(s)(ft ²)
L_g	liquid flow rate in gal/min, Chapter 10
m	linear equilibrium constant, $y = mx + b$
m	local slope of equilibrium curve, Eq. (15-30b)
M	ratio $\text{HETP}_{\text{practical}}/\text{HETP}_{\text{packing}}$ Eq. (10-46)
m_{CD}	slope of equilibrium curve of continuous versus dispersed phase mass or mole fractions, Eq. (16-80c)
$m_{CD, \text{conc_units}}$	slope of equilibrium curve of continuous versus dispersed phase in concentration units, Eq. (16-80c analog)
M	flow rate of mixed stream (Chapter 13), kg/h
M	multiplier times $(L/D)_{\text{min}}$ (Chapter 7)
MW	molecular weight
\bar{MW}	average molecular weight
n	moles
n	number of drops
n_1, n_2	empirical constants, Eq. (13-65)
n_G	number of gas phase transfer units
n_L	number of liquid phase transfer units
n_{O-ED}, n_{O-EC}	number of overall extraction transfer units in dispersed and continuous phases, Eq. (16-81)

n_{OG}	number of overall gas phase transfer units
n_{OL}	number of overall liquid phase transfer units
n_{org}	moles organic in vapor in steam distillation
n_w	moles water in vapor in steam distillation
N	impeller revolutions per second
N	number of stages
N_A	flux of A, lbmol/(h)(ft ²) or kmol/(h)(m ²)
N_f, N_{feed}	feed stage
$N_{f,j}^L$	transfer to liquid from vapor on stage j, mol component i/s
$N_{f,j}^V$	transfer to vapor from liquid on stage j, mol component i/s
N_{min}	number of stages at total reflux
$N_{feed,min}$	estimated feed stage location at total reflux
N_{Po}	power number, Eq. (13-52)
N_{IOD}	number of overall extraction transfer units for mass transfer driving force in concentration units, Eq. (16-81a analog)
Nu	Nusselt number, Eq. (15-33g)
NTU	number of transfer units
O	total overflow rate in washing, kg/h
p	pitch of sieve plate holes, m
p, p_{tot}	pressure, atm, kPa, psi, bar etc.
\bar{p}, p_B	partial pressure
P	Number of phases
P	power, W
Pe	dimensionless Peclet number in terms of molecular diffusivity, Eq. (15-33c)
Pe	dimensionless Peclet number in terms of eddy diffusivity, Eq. (16-111a)
Per_f	flow perimeter, Figure 13-33B, m
Pr	dimensionless Prandtl number, Eq. (15-33f)
q	$L_F/F = (L - L)/F$, feed quality
q	volumetric flow rate/plate width, m ² /s
Q	amount of energy transferred, Btu/h, kcal/h, etc.
Q_c	condenser heat load
Q_c, Q_C	volumetric flow rate continuous phase, m ³ /s
Q_d, Q_D	volumetric flow rate dispersed phase, m ³ /s
Q_{flash}	heat loss from flash drum
Q_L	volumetric flow rate of liquid, m ³ /s
Q_R	reboiler heat load
Q_z	heat flux in z direction, J/s
r	radius of column, ft or m
R	gas constant, 1.9859 cal/(mol·K) or 8.314 m ³ Pa/(mol·K)
R	raffinate flow rate (Chapter. 13), kg/h
R_A	solute radius, m
\hat{R}	mass raffinate, kg
\hat{R}_t	Holdup raffinate phase in tank plus settler, kg
Re	dimensionless Reynolds number, Eq. (15-33b)
Re_{settle}	Reynold's number for settler, Eq. (13-60a)
S	solvent flow rate kmol/h or lbmol/h
S	tray spacing, inches, Eq. (10-47)

S	moles second solvent in constant-level batch distillation
\hat{S}	mass of solvent, kg
S	solvent flow rate, kg/h
Sc_L	Schmidt number for liquid = $\mu/(\rho D)$
Sc_v	Schmidt number for vapor = $\mu/(\rho D)$
Sh_x, Sh_y, Sh_z	dimensionless Sherwood numbers, Eq. (15-33a)
St_x, St_y, St_z	dimensionless Stanton numbers, Eq. (15-33d)
t	time, s, min, or h
t_{batch}	period for batch distillation, Eq. (9-28)
t_{down}	down time in batch distillation
$(t_{f,95} - t_0)$	residence time in extractor for 95% extraction, Eq. (16-105), s
t_L, t_V	average residence time per pass for liquid and vapor, s
$\bar{t}_{L,\text{residence}}$	liquid residence time, Eq. (16-111c), s
$t_{\text{residence,dispersed}}$	residence time of dispersed phase in settler, s
$t_{\text{operating}}$	operating time in batch distillation
t_{res}	residence time in downcomer, Eq. (10-30), s, or on plate, Eq. (16-35e)
t_{tray}	tray thickness, inches
T	temperature, °C, °F, K, or °R
$T_j^{\text{IL}}, T_j^{\text{IV}}$	liquid and vapor temperatures on stage j at the interface, K
T_{ref}	reference temperature
u	vapor velocity, cm/s or ft/s
u_{flood}	flooding velocity, Eq. (10-8)
u_{op}	operating velocity, Eq. (10-11)
u_{perm}	permissible vapor velocity, Eq. (2-64)
$u_{t,\text{hindered}}$	hindered settling velocity, Eq. (13-58)
$u_t, u_{t,\text{Stokes}}$	Stokes' law terminal velocity, Eq. (13-57), m/s
U	underflow liquid rate, (Chapter 14), kg/h
U_a	superficial vapor velocity in active area of tray, m/s
v	superficial vapor velocity, ft/s
$v_{\text{characteristic}}$	characteristic velocity of Karr column, Eq. (13-68), m/s
$v_{c,\text{flood}}, v_{d,\text{flood}}$	continuous and dispersed phase flooding velocities, m/s
v_o	vapor velocity through holes, Eq. (10-29), ft/s
$v_{o,\text{bal}}$	velocity where valve is balanced, Eq. (10-36)
V_A, V_B	component transfer velocities, Eqs. (15-15e, f)
v_{ref}	reference or basis velocity, Eqs. (15-15c, d)
v_y	vertical velocity
V	vapor flow rate, kmol/h or lbmol/h
V_i	molal volume Eq. (13-1)
V_A	molar volume solute at normal boiling point, m ³ /kmol
$V_{\text{liq,tank}}$	volume of liquid in tank, m ³
V_{max}	maximum vapor flow rate
V_{mixer}	volume of liquid in mixing tank, m ³
V_{settler}	volume settler, m ³
V_{tank}	volume tank, m ³
V_{surge}	surge volume in flash drum, Eq. (2-68), ft ³
VP	vapor pressure, same units as p
w	plate width, m
W_L	liquid flow rate, kg/h or lb/h

W_L	liquid mass flux, lb/s ft ² or lb/h ft ² , (Chapter 16)
W_V	vapor flow rate, kg/h or lb/h
x	weight or mole fraction in liquid
x	$[L/D - (L/D)_{\min}]/(L/D + 1)$ in Eqs. (7-42)
x^*	equilibrium mole fraction in liquid
$x_{A,\text{ref}}, x_{B,\text{ref}}$	fractions to calculate velocity of center of total flux, Eq. (15-17)
$x_{i,k}, x_{i,k+1}$	trials for integration, Eq. (8-29)
x_I	interfacial mole fraction in liquid
x^*_{out}	liquid mole fraction in equilibrium with inlet gas, Eq. (16-35b)
X	weight or mole ratio in liquid
y	weight or mole fraction in vapor
y_{vol}	volume fraction in vapor
y^*	equilibrium mole fraction in vapor
y^*_{out}	vapor mole fraction in equilibrium with inlet liquid in countercurrent system, Eq. (16-35a) or in equilibrium with outlet liquid in cocurrent contactor, Eq. (16-71)
y_{lm}	log mean difference, Eq. (15-32d)
y_I	interfacial mole fraction in vapor
\bar{y}	mass fraction in vapor
Y	weight or mole ratio in vapor
z	weight or mole fraction in feed
z	axial distance in bed (Chapters 15 and 16)
z_1	distance from downcomer exit to weir, m

Greek

α_{AB}	K_A/K_B , relative volatility
α_{thermal}	thermal diffusivity, m ² /s
β	$A_{\text{hole}}/A_{\text{active}}$
γ	activity coefficient
δ	thickness of mass transfer film or thickness of falling film, m
δ_p	characteristic dimension of packing, inch, Eq. (10-38)
δ_i	solubility parameter, Eq. (13-1)
Δ	change in variable or difference operator
ΔE_v	latent energy of vaporization, Eq. (13-1)
ΔH	steady state height of dispersion band in settler, m
$\Delta\rho$	$ \rho_C - \rho_D $
ε	limit for convergence
$\varepsilon_A, \varepsilon_B, \varepsilon_{AB}$	Lennard-Jones interaction energies, Table 15-2 and Eq. (15-22c)
η	fraction of column available for vapor flow
η	parameter, Eq. (15-42b)
θ	angle of downcomer, Figure 10-20B
λ	latent heat of vaporization, kcal/kg, Btu/lb, Btu/lbmol, etc.
μ	viscosity, cp or Pa·s = kg/(m s)
μ_w	viscosity of water, cp
ρ_L	liquid density, g/cm ³ or lb/ft ³ or kg/m ³
ρ_V	vapor density
σ, γ	surface tension, dynes/cm or interfacial tension

ζ	dimensionless distance, Eq. (15-14a)
χ	term defined in Eq. (13-49)
φ_c, φ_d	volumetric fraction of continuous and dispersed phases
$\varphi_{d,feed}$	volumetric fraction of dispersed phase in feed
ϕ	liquid phase packing parameter, Eq. (16-38)
ϕ_B	solvent interaction parameter, Eq. (15-23b)
ϕ_{dc}	relative froth density in downcomer, Eq. (10-29)
φ_e	effective relative froth density, Eq. (16-109d)
ψ	ρ_{water}/ρ_L , Chapter 10
ψ	$e/(e + L)$, fractional entrainment, Chapter 10
ψ	packing parameter for gas phase, Eq. (16-37)
Ω_D	collision integral, Table 15-2
μ_C, μ_D	viscosity of continuous and dispersed phases, Pa·s
μ_H, μ_L	viscosity of heavy and light phases, Pa·s
μ_m	mixture viscosity, Eq. (13-55), Pa·s
ρ_C, ρ_D	densities of continuous and dispersed phases, g/m ³
ρ_m	mixture density, Eq. (13-53), g/m ³
ρ_m	molar density, mol/m ³
ω	revolutions per second

Chapter 17

a, a_j	term in quadratic equations for well-mixed membrane systems, Eqs. (17-10b), (17-74a), and (17-74a)
\hat{a}	constant in expression to calculate osmotic pressure, kPa/mole fraction, Eq. (17-15a)
a'	constant in expression to calculate osmotic pressure, kPa/weight fraction, Eq. (17-15b)
a_i	activities, Eq. (17-51)
A	membrane area available for mass transfer, cm ² or m ²
b, b_j	term in quadratic equations for well-mixed membrane systems, Eqs. (17-10c), (17-74b), and (17-74b)
c, c_j	term in quadratic equations for well-mixed membrane systems, Eqs. (17-10d), (17-74c) and (17-74c)
c	concentration, g solute/L solution
c_{out}	outlet concentration of solute, g/L
c_p	permeate concentration of solute, g/L
c_w	concentration of solute at wall, g/L
c'	water concentration in permeate in Figure 17-17
$C_{PL,p}$	liquid heat capacity of permeate, kJ/(kg °C)
$C_{PV,p}$	vapor heat capacity of permeate, kJ/(kg °C)
d_t	diameter of tube, cm
d_{tank}	tank diameter, cm
D	diffusivity in solution, cm ² /s
D_m	diffusivity in the membrane, cm ² /s
F_p	volumetric flow rate of permeate, cm ³ /s
F_{out}	volumetric flow rate of exiting retentate, cm ³ /s
F_{solv}	volumetric flow rate of solvent in RO, cm ³ /s

\hat{F}	molar flow rate, mol/s, mol/min, etc.
F'	mass flow rate, g/s, g/min, kg/min, etc.
h	$\frac{1}{2}$ distance between parallel plates, cm
h_{in}	enthalpy of inlet liquid stream in pervaporation, kJ/kg
h_{out}	enthalpy of outlet liquid retentate stream in pervaporation, kJ/kg
H_A	solubility parameter, cc(STP)/[cm ³ (cm Hg)]
H_p	enthalpy of vapor permeate stream in pervaporation, kJ/kg
k	mass transfer coefficient, typically cm/s, Eq. (17-33)
K'_{solv}	permeability of the solvent through membrane, L/(atm m ² day) or similar units
j	counter for stage location in staged models in Figure 17-19
J	volumetric flux, cm ³ /(s cm ²) or m ³ /(m ² day), Eq. (17-1b)
J'	mass flux, g/(s cm ²) or g/(m ² day), Eq. (17-1c)
\hat{J}	mole flux, mol/(s cm ²) or kmol/(day m ²), Eq. (17-1d)
K'_A	solute permeability, g/(m s wt frac)
$K_{m,i}$	rate transfer term for multicomponent gas permeation, dimensionless, Eq. (17-11d)
L	tube length, cm
M	concentration polarization modulus in wt fraction units, dimensionless, Eq. (17-17)
M_c	concentration polarization modulus in concentration units, dimensionless, Eq. (17-48)
MW	molecular weight, g/mol or kg/kmol
N	number of well-mixed stages in models in Figure 17-19
p	pressure, Pa, kPa, atm, mm Hg, etc.
p_A	partial pressure of species A, Pa, atm, mm Hg, etc.
p_p	total pressure on the permeate (low pressure) side, Pa, kPa, atm, mm Hg, etc.
p_r	total pressure on the retentate (high pressure) side, Pa, kPa, atm, mm Hg, etc.
P_A	permeability of species A in the membrane, cc(STP) cm/[cm ² s cm Hg]
R	rejection coefficient in wt frac units, dimensionless, Eq. (17-24a)
R^o	inherent rejection coefficient ($M = 1$), dimensionless
R_c	rejection coefficient in conc. units, dimensionless, Eq. (17-48)
R	tube radius, cm
Re	Reynolds number, dimensionless, Eq. (17-35b)
Sc	Schmidt number, dimensionless, Eq. (17-35c)
Sh	Sherwood number, dimensionless, Eq. (17-35a)
t_{ms}	thickness of membrane skin doing separation, μ m, mm, cm, or m
T	temperature, °C
T_{ref}	reference temperature, °C
u_b	bulk velocity in tube, cm/s
$v_{solvent}$	partial molar volume of the solvent, cm ³ /gmole
x	wt frac of retentate in pervaporation. In binary system refers to more permeable species.
x_g	wt frac at which solute gels in UF
x_p	wt frac solute in liquid permeate in RO and UF
x_r	wt frac solute in retentate in RO and UF
y	wt frac of permeate in pervaporation. In binary system refers to more permeable species.

y_p	mole fraction solute in gas permeate for gas permeation
y_r	mole fraction solute in gas retentate for gas permeation
$y_{r,w}$	mole fraction solute in gas retentate at membrane wall
$y_{t,A}$	mole fraction solute A in gas that transfers through the membrane

Greek letters

α	selectivity, dimensionless, Gas Permeation: Eq. (17-4b), RO: Eq. (17-20), pervaporation: Eq. (17-53a)
Δx	difference in wt frac of solute across the membrane
$\Delta \pi$	difference in the osmotic pressure across the membrane, Pa, atm, mm Hg, etc.
π	osmotic pressure, Pa, kPa, atm, mm Hg, etc.
θ	cut = \hat{F}_p / \hat{F}_{in} , with flows in molar units, dimensionless
θ'	cut = F'_p / F'_{in} in flows in mass units, dimensionless
μ	viscosity, centipoise or g/(cm s)
$\nu = \mu/\rho$	kinematic viscosity, cm ² /s
ρ_{solv}	mass solvent density, kg/m ³
$\hat{\rho}_{solv}$	molar solvent density, kmol/m ³
λ_p	mass latent heat of vaporization of the permeate in pervaporation determined at the reference temperature, kJ/kg
ω	stirrer speed in radians/s

Chapter 18

a	constant in Langmuir isotherm, same units as q/c , Eq. (18-6c)
a	argument for error function, dimensionless, Eq. (18-70), Table 18-7
a_p	surface area of the particles per volume, m ⁻¹
A_c	cross sectional area of column, m ²
A_w	wall surface area per volume of column for heat transfer, m ⁻¹
b	constant in Langmuir isotherm, (concentration) ⁻¹ , Eq. (18-6c)
c_A	concentration of species A, kg/m ³ , kmol/m ³ , g/L, etc.
c_i	concentration of species i, kg/m ³ , kmol/m ³ , g/L, etc., or
c_i	concentration of ion i in solution, typically equivalents/m ³
c_i^*	concentration of species i that would be in equilibrium with \bar{q}_i , same units as c_i
\bar{c}_i	average concentration of solute in pore, same units as c_i
c_{pore}	fluid concentration at surface of adsorbent pores, same units as c_i
$c_{i,surface}$	fluid concentration at surface of particles, $\epsilon_p = 0$, same units as c_i
c_{Ri}	concentration of ion i on the resin, typically equivalents/m ³
c_{RT}	total concentration of ions on the resin, typically equivalents/m ³
c_T	total concentration of ions in solution, typically equivalents/m ³
C_i	constant relating solute velocity to interstitial velocity, dimensionless, Eq. (18-15e)
$C_{p,f}$	heat capacity of the fluid, cal/(g °C), cal/(mol °C), J/(g K), etc.
$C_{p,p}$	heat capacity of particle including pore fluid, same units $C_{p,f}$
$C_{p,s}$	heat capacity of the solid, same units as $C_{p,f}$
$C_{p,w}$	heat capacity of the wall, same units as $C_{p,f}$
d_p	particle diameter, cm or m
D	desorbent rate in SMB, same units as F

D/F	desorbent to feed ratio in SMB, dimensionless
D_{col}	column diameter, m or cm
D	diffusivity including both molecular and Knudsen diffusivities, m^2/s or cm^2/s
$D_{\text{effective}}$	effective diffusivity, m^2/s or cm^2/s , Eq. (18-4)
D_K	Knudsen diffusivity, m^2/s or cm^2/s , Eq. (18-51)
$D_{\text{molecular}}$	molecular diffusivity in free solution, m^2/s or cm^2/s
D_s	surface diffusivity, m^2/s or cm^2/s , Eq. (18-53)
erf	error function, Eq. (18-70) and Table 18-7
E_D	axial dispersion coefficient due to both eddy and molecular effects, m^2/s or cm^2/s
E_{DT}	thermal axial dispersion coefficient, m^2/s or cm^2/s
E_{eff}	effective axial dispersion coefficient, same units E_D , Eq. (18-68)
F	volumetric feed rate, e.g., m^3/h , cm^3/min , liter/h
h_p	particle heat transfer coefficient, $\text{J}/(\text{K s m}^2)$ or similar units
h_w	wall heat transfer coefficient, $\text{J}/(\text{K s m}^2)$ or similar units
HETP	height of equilibrium plate, cm/plate, Eq. (18-78b)
k_f	film mass transfer coefficient, m/s or cm/s
$k_{m,c}$	lumped parameter mass transfer coefficient with concentration driving force, m/s or cm/s , Eqs. (18-56a) and (18-57a)
$k_{m,q}$	lumped parameter mass transfer coefficient with amount adsorbed driving force, m/s or cm/s , Eqs. (18-56b) and (18-57b)
K_{AB}	mass action equilibrium constant for monovalent-monovalent ion exchange, dimensionless, Eq. (18-40a)
$K_{A,c}$	adsorption equilibrium constant in terms of concentration, units are $(\text{concentration})^{-1}$
$K'_{i,c}$	linearized adsorption equilibrium constant in terms of concentration, units are units of q/c , Eq. (18-6b)
K_{Ao}	pre-exponential factor in Arrhenius Eq. (18-7a), same units as K_A
$K_{A,p}$	adsorption equilibrium constant in terms of partial pressure, units are $(\text{pressure})^{-1}$
$K'_{A,p}$	linearized adsorption equilibrium constant in terms of partial pressure, units are units of q_A/p_A , Eq. (18-5b)
K_d	size exclusion parameter, dimensionless
K_{DB}	mass action equilibrium constant for divalent-monovalent ion exchange, same units as c_T/c_{RT} , Eq. (18-41)
K_{DE}	Donnan exclusion factor, dimensionless, following Eq. (18-44)
L	length of packing in column, m or cm
L_{MTZ}	length of mass transfer zone, Figure 18-23, m or cm
M	molecular weight of solute, g/mol or kg/kmol
M_i	multipliers in Eqs. (18-29), dimensionless
N	equivalent number of plates in chromatography, Eq. (18-78)
N_{Pe}	Peclet number, dimensionless, Eq. (18-62)
p_A	partial pressure of species A, mm Hg, kPa, or other pressure units
p_h	high pressure, mm Hg, kPa, or other pressure units
p_L	low pressure, mm Hg, kPa, or other pressure units
Pe_L	Peclet number based on length, dimensionless, Eq. (18-78a)
q_A	amount of species A adsorbed, kg/kg adsorbent, mol/kg adsorbent, or kg/L adsorbent
$q_{A,\text{max}}$	maximum amount of species A that can adsorb, kg/kg adsorbent, mol/kg adsorbent, or kg/L

q_F	amount adsorbed in equilibrium with feed concentration, same units as q_A
q_i	average amount of species i adsorbed, kg/kg adsorbent, mol/kg adsorbent, or kg/L
q_i^*	amount adsorbed that would be in equilibrium with fluid of concentration c_i , same units as q_A
Q	volumetric flow rate, m^3/s , L/min, etc.
r_p	pore radius, m or cm
R	resolution, dimensionless, Eq. (18-82)
R	gas constant (e.g., $R = 8.314 \frac{m^3 Pa}{mol K}$)
Re	Reynolds number, dimensionless, Eq. (18-60)
Sc	Schmidt number, dimensionless, Eq. (18-60)
Sh	Sherwood number, dimensionless, Eq. (18-60)
t	time, s, min, or h
t_{br}	breakthrough time, s, min, or h
t_{center}	time center of pattern exits column, s, min, or h, Eq. (18-85b)
$t_{elution}$	elution time, s, min, or h
t_F, t_{feed}	feed time, s, min, or h
t_{MTZ}	time of mass transfer zone, Figure 18-23, s, min, or h
t_R	retention time, s, min, or h
t_{sw}	switching time in SMB, s, min, or h
T	temperature, °C or K
T_{amb}	ambient temperature, °C or K
T_s	solid temperature, °C or K
$u_{ion,i}$	velocity of ion i , m/s or cm/s
u_s	average solute velocity, m/s or cm/s
\bar{u}_s	average of solute velocities for A and B, cm/s, Eq. (18-83)
$u_{s,ion,i}$	diffuse wave velocity of ion i , m/s or cm/s
u_{sh}	shock wave velocity, m/s or cm/s
$u_{sh,ion,i}$	shock wave velocity of ion i , m/s or cm/s
u_{th}	thermal wave velocity, m/s or cm/s
u_{total_ion}	velocity of total ion wave, m/s or cm/s
$v_{A,product}$	interstitial velocity of A Product if it was in the column, m/s or cm/s = $(A \text{ Product})/(\epsilon_e A_c)$
$v_{B,product}$	interstitial velocity of B Product if it was in the column, m/s or cm/s = $(B \text{ Product})/(\epsilon_e A_c)$
v_D	interstitial velocity of desorbent if it was in the column, m/s or cm/s = $D/(\epsilon_e A_c)$
v_{Feed}	interstitial velocity of feed if it was in the column, m/s or cm/s = $F/(\epsilon_e A_c)$
v_{inter}	interstitial velocity, m/s or cm/s, Eq. (18-2b)
v_{super}	superficial velocity, m/s or cm/s, Eq. (18-2a)
$V_{available}$	volume available to molecule, m^3 , Eq. (18-1c)
V_{column}	column volume, m^3
V_{feed}	volume feed gas, m^3
V_{fluid}	volume available to fluid, m^3 , Eq. (18-1a)
V_{purge}	volume purge gas, m^3
w_A, w_B	width of chromatographic peak, s, min or hours
W	weight of the column per length, kg/m

x	deviation from the location of the peak maximum, dimensionless Eq. (18-79)
x_l	deviation from peak maximum in length units, Eq. (18-80b)
x_t	deviation from peak maximum in time units, Eq. (18-80a)
x	weight or mole fraction solute in liquid, kg solute/kg liquid or kmol solute/kmol liquid, dimensionless
x_i	$= c_i/c_T$ equivalent fraction of ion in solution, dimensionless
$X_{\text{breakthrough}}(z,t)$	general solution for column breakthrough for linear isotherms, same units as c , Eq. (18-72)
y	weight or mole fraction solute in gas, kg solute/kg gas, or kmol solute/kmol gas, dimensionless
y_i	$= c_{Ri}/c_{RT}$ equivalent fraction of ion on resin, dimensionless
z	axial distance in column, m or cm. (Measured from closed end for PSA pressure change calculations)

Greek letters

β_{strong}	ratio velocities of strong and weak solutes, Eq. (18-27), dimensionless
Δc	change in solute concentration, same units as c
ΔH_{ads}	heat of adsorption, J/kg, cal/gmole, etc.
Δp_A	change in partial pressure, kPa, atm, etc.
Δq	change in amount adsorbed, kmol/kg adsorbent, kg/kg adsorbent, kmol/m ³ , or kg/m ³
Δt	change in time, s, min, or h
ΔT_f	change in fluid temperature, °C or K
Δz	increment of column length, m
γ	volumetric purge to feed ratio in PSA, dimensionless, Eq. (18-26)
ε_e	external porosity, dimensionless
ε_p	internal or pore porosity, dimensionless
ε_T	total porosity, dimensionless, Eq. (18-1b)
ρ_b	bulk density of adsorbent, kg/m ³ , Eq. (18-3b)
ρ_f	fluid density, kg/m ³
$\bar{\rho}_f$	molar density of fluid, kmol/m ³
ρ_p	particle density, kg/m ³ , Eq. (18-3a)
ρ_s	structural density of solid, kg/m ³
σ	standard deviation of Gaussian chromatographic peak, Eq. (18-79)
σ_l	standard deviation in length units, m or cm, Eq. (18-80b)
σ_t	standard deviation in time units, min or s, Eq. (18-80a)
τ	tortuosity, dimensionless, Eq. (18-4)
ζ	Greek letter zeta used as dummy variable in Eq. (18-70)

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Introduction to Separation Process Engineering

1.1 IMPORTANCE OF SEPARATIONS

Why does chemical engineering require the study of separation techniques? Because separations are crucial in chemical engineering. A typical chemical plant is a chemical reactor surrounded by separators, as diagramed in the schematic flow sheet of Figure 1-1. Raw materials are prepurified in separation devices and fed to the chemical reactor; unreacted feed is separated from the reaction products and recycled back to the reactor. Products must be further separated and purified before they can be sold. This type of arrangement is very common. Examples for a variety of traditional processes are illustrated by Biegler et al. (1997), Chenier (2002), Couper et al. (2005), Matar and Hatch (2001), Shreve and Austin (1984), Speight (2002), and Turton et al. (2003), whereas recent processes often are shown in *Chemical Engineering* magazine. Chemical plants commonly have from 40% to 70% of both capital and operating costs in separations (Humphrey and Keller, 1997).

Since separations are ubiquitous in chemical plants and petroleum refineries, chemical engineers must be familiar with a variety of separation methods. We will first focus on some of the most common chemical engineering separation methods: flash distillation, continuous column distillation, batch distillation, absorption, stripping, and extraction. These separations all contact two phases and can be designed and analyzed as equilibrium stage processes. Several other separation methods that can also be considered equilibrium stage processes will be briefly discussed. Chapters 17 and 18 explore two important separations—membrane separators and adsorption processes—that do not operate as equilibrium stage systems.

The *equilibrium stage* concept is applicable when the process can be constructed as a series of discrete stages in which the two phases are contacted and then separated. The two separated phases are assumed to be in equilibrium with each other. For example, in distillation, a vapor and a liquid are commonly contacted on a metal plate with holes in it. Because of the intimate contact between the two phases, solute can transfer from one phase to another. Above the plate the vapor disengages from the liquid. Both liquid and vapor can be sent to additional stages for further separation. Assuming that the stages are equilibrium stages, the engineer can calculate concentrations and temperatures without detailed knowledge of

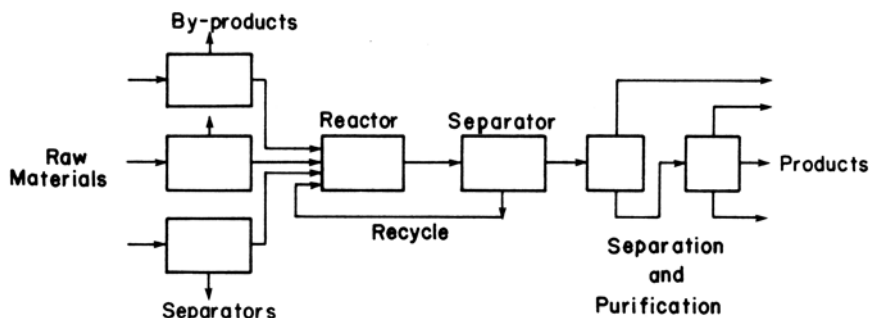


FIGURE 1-1. Typical chemical plant layout

flow patterns and heat and mass transfer rates. Although this example shows the applicability of the equilibrium stage method for equipment built with a series of discrete stages, we will see that the staged design method can also be used for packed columns where there are no discrete stages. This method is a major simplification in the design and analysis of chemical engineering separations that is used in Chapters 2 to 14.

A second useful concept is that of a *unit operation*. The idea here is that although the specific design may vary depending on what chemicals are being separated, the basic design principles for a given separation method are always the same. For example, the basic principles of distillation are always the same whether we are separating ethanol from water, separating several hydrocarbons, or separating liquid metals. Consequently, distillation is often called a unit operation, as are absorption, extraction, etc.

A more general idea is that design methods for related unit operations are similar. Since distillation and absorption are both liquid-vapor contacting systems, the design is much the same for both. This similarity is useful because it allows us to apply a very few design tools to a variety of separation methods. We will use *stage-by-stage* methods where calculation is completed for one stage and then the results are used for calculation of the next stage to develop basic understanding. Matrix solution of the mass and energy balances will be used for detailed computer simulations.

1.2 CONCEPT OF EQUILIBRIUM

The separation processes we are studying in Chapters 1 to 14 are based on the equilibrium stage concept, which states that streams leaving a stage are in equilibrium. What do we mean by equilibrium?

Consider a vapor and a liquid that are in contact with each other as shown in Figure 1-2. Liquid molecules are continually vaporizing, while vapor molecules are continually condensing. If two chemical species are present, they will, in general, condense and vaporize at different rates. When not at equilibrium, the liquid and the vapor can be at different pressures and temperatures and be present in different mole fractions. At equilibrium the temperatures, pressures, and fractions of the two phases cease to change. Although molecules continue to evaporate and condense, the rate at which each species condenses is equal to the rate at which

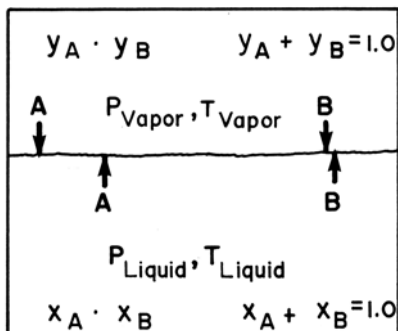


FIGURE 1-2. Vapor-liquid contacting system

it evaporates. Although on a molecular scale nothing has stopped, on the macroscopic scale, where we usually observe processes, there are no further changes in temperature, pressure, or composition.

Equilibrium conditions can be conveniently subdivided into thermal, mechanical, and chemical potential equilibrium. In thermal equilibrium, heat transfer stops and the temperatures of the two phases are equal.

$$T_{\text{liquid}} = T_{\text{vapor}} \quad (\text{at equilibrium}) \quad (1-1)$$

In mechanical equilibrium, the forces between vapor and liquid balance. In the staged separation processes we will study, this usually implies that the pressures are equal. Thus for the cases in this book,

$$P_{\text{liquid}} = P_{\text{vapor}} \quad (\text{at equilibrium}) \quad (1-2)$$

If the interface between liquid and vapor is curved, equal forces do not imply equal pressures. In this case the Laplace equation can be derived (e.g., see Levich, 1962).

In phase equilibrium, the rate at which each species is vaporizing is just equal to the rate at which it is condensing. Thus there is no change in composition (mole fraction in Figure 1-2). However, in general, the compositions of liquid and vapor are *not* equal. If the compositions were equal, no separation could be achieved in any equilibrium process. If temperature and pressure are constant, equal rates of vaporization and condensation require a minimum in the free energy of the system. The resulting condition for phase equilibrium is

$$(\text{chemical potential } i)_{\text{liquid}} = (\text{chemical potential } i)_{\text{vapor}} \quad (1-3)$$

The development of Eq. (1-3), including the necessary definitions and concepts, is the subject of a large portion of many books on thermodynamics (e.g., Balzhiser et al., 1972; Denbigh, 1981; Elliott and Lira, 1999; Sandler, 2006; Smith et al., 2005; Walas, 1985) but is beyond the scope of this book. However, Eq. (1-3) does require that there be some relationship between liquid and vapor compositions. In real systems this relationship may be very

complex and experimental data may be required. We will assume that the equilibrium data or appropriate correlations are known (see Chapter 2), and we will confine our discussion to the use of the equilibrium data in the design of separation equipment.

1.3 MASS TRANSFER

In the vapor-liquid contacting system shown in Figure 1-2 the vapor and liquid will not be initially at equilibrium. By transferring mass from one phase to the other we can approach equilibrium. The basic mass transfer equation in words is

$$\text{Mass transfer rate} = (\text{area}) \times (\text{mass transfer coefficient}) \times (\text{driving force}) \quad (1-4)$$

In this equation the mass transfer rate will typically have units such as kmol/h or lbmol/h. The area is the area across which mass transfer occurs in m² or ft². The driving force is the concentration difference that drives the mass transfer. This driving force can be represented as a difference in mole fractions, a difference in partial pressures, a difference in concentrations in kmol/L, and so forth. The value and units of the mass transfer coefficient depend upon which driving forces are selected. The details are discussed in Chapter 15.

For equilibrium staged separations we would ideally calculate the mass transfer rate based on the transfer within each phase (vapor and liquid in Figure 1-2) using a driving force that is the concentration difference between the bulk fluid and the concentration at the interface. Since this is difficult, we often make a number of simplifying assumptions (see Section 15.4 for details) and use a driving force that is the difference between the actual concentration and the concentration we would have if equilibrium were achieved. For example, for the system shown in Figure 1-2 with concentrations measured in mole fractions, we could use the following rate expressions.

$$\text{Rate / volume} = K_y a (y_A^* - y_A) \quad (1-5a)$$

$$\text{Rate / volume} = K_x a (x_A - x_A^*) \quad (1-5b)$$

In these equations K_y and K_x are overall gas and liquid mass transfer coefficients, y_A^* is the mole fraction in the gas in equilibrium with the actual bulk liquid of mole fraction x_A , x_A^* is the mole fraction in the liquid in equilibrium with the actual bulk gas of mole fraction y_A , and the term “a” is the interfacial area per unit volume (m²/m³ or ft²/ft³).

By definition, at equilibrium we have $y_A^* = y_A$ and $x_A^* = x_A$. Note that as $y_A \rightarrow y_A^*$ and $x_A \rightarrow x_A^*$ the driving forces in Eqs. (1-5) approach zero and mass transfer rates decrease. In order to be reasonably close to equilibrium, the simplified model represented by Eqs. (1-5) shows that we need high values of K_y and K_x and/or “a.” Generally speaking, the mass transfer coefficients will be higher if diffusivities are higher (details are in Chapter 15), which occurs with fluids of low viscosity. Since increases in temperature decrease viscosity, increasing temperature is favorable as long as it does not significantly decrease the differences in equilibrium concentrations and the materials are thermally stable. Mass transfer rates will also be increased if there is more interfacial area/volume between the gas and liquid (higher “a”). This can be achieved by having significant interfacial turbulence or by using a packing material with a large surface area (see Chapter 10).

Although some knowledge of what affects mass transfer is useful, we don't need to know the details as long as we are willing to assume we have equilibrium stages. Thus, we will delay discussing the details until we need them (Chapters 15 through 18).

1.4 PROBLEM-SOLVING METHODS

To help develop your problem-solving abilities, an explicit strategy, which is a modification of the strategy developed at McMaster University (Woods et al., 1975), is used throughout this book. The seven stages of this strategy are:

0. I want to, and I can
1. Define the problem
2. Explore or think about it
3. Plan
4. Do it
5. Check
6. Generalize

Step 0 is a motivation and confidence step. It is a reminder that you got this far in chemical engineering because you can solve problems. The more different problems you solve, the better a problem solver you will become. Remind yourself that you *want* to learn how to solve chemical engineering problems, and you *can* do it.

In step 1 you want to *define* the problem. Make sure that you clearly understand all the words. Draw the system and label its parts. List all the known variables and constraints. Describe what you are asked to do. If you cannot define the problem clearly, you will probably be unable to solve it.

In step 2 you *explore* and *think about* the problem. What are you *really* being asked to do? What basic principles should be applied? Can you find a simple limiting solution that gives you bounds to the actual solution? Is the problem over- or underspecified? Let your mind play with the problem and chew on it, and then go back to step 1 to make sure that you are still looking at the problem in the same way. If not, revise the problem statement and continue. Experienced problem solvers always include an *explore* step even if they don't explicitly state it.

In step 3 the problem solver *plans* how to subdivide the problem and decides what parts to attack first. The appropriate theory and principles must be selected and mathematical methods chosen. The problem solver assembles required resources such as data, paper, and calculator. While doing this, new subproblems may arise; you may find there are not enough data to solve the problem. Recycle through the problem-solving sequence to solve these subproblems.

Step 4, *do it*, is often the first step that inexperienced problem solvers try. In this step the mathematical manipulations are done, the numbers are plugged in, and an answer is generated. If your plan was incomplete, you may be unable to carry out this step. In that case, return to step 2 or step 3, the *explore* or *plan* steps, and recycle through the process.

In step 5, *check* your answer. Is it the right order of magnitude? For instance, commercial distillation columns are neither 12 centimeters nor 12 kilometers high. Does the answer seem reasonable? Have you avoided blunders such as plugging in the wrong number or incorrectly punching the calculator? Is there an alternative solution method that can serve as an independent check on the answer? If you find errors or inconsistencies, recycle to the appropriate step and solve the problem again.

The last step, *generalize*, is important but is usually neglected. In this step you try to learn as much as possible from the problem. What have you learned about the physical situation? Did including a particular phenomenon have an important effect, or could you have ignored it? Generalizing allows you to learn and become a better problem solver.

At first these steps will not “feel” right. You will want to get on with it and start calculating instead of carefully defining the problem and working your way through the procedure. Stick with a systematic approach. It works much better on difficult problems than a “start calculating, maybe something will work” method. The more you use this or any other strategy, the more familiar and less artificial it will become.

In this book, example problems are solved using this strategy. To avoid repeating myself, I will not list step 0, but it is always there. The other six steps will usually be explicitly listed and developed. On the simpler examples some of the steps may be very short, but they are always present.

I strongly encourage you to use this strategy and write down each step as you do homework problems. In the long run this method will improve your problem-solving ability.

A problem-solving strategy is useful, but what do you do when you get stuck? In this case *heuristics* or rules of thumb are useful. A heuristic is a method that is often helpful but is not guaranteed to help. A large number of problem-solving heuristics have been developed. I have listed ten (Wankat and Oreovicz, 1993) that are often helpful to students.

Problem-Solving Heuristics:

1. Try solving simplified, limiting cases.
2. Relate the problem to one you know how to solve. This heuristic encapsulates one of the major reasons for doing homework.
3. Generalize the problem.
4. Try putting in specific numbers. Heuristics 3 and 4 are the opposite of each other. Sometimes it is easier to see a solution path without all the details, and sometimes the details help.
5. Solve for ratios. Often problems can be solved for ratios, but there is not enough information to solve for individual values.
6. Do the solvable parts of the problem. This approach may provide information that allows you to solve previously unsolvable parts.
7. Look for information that you haven't used.
8. Try to guess and check. If you have a strong hunch, this may lead to an answer, but you *must* check your guess.
9. Take a break. Don't quit, but do something else for a while. Coming back to the problem may help you see a solution path.
10. Ask someone for a *little* help. Then complete the problem on your own.

Ten heuristics is probably too many to use on a regular basis. Select four or five that fit you, and make them a regular part of your problem-solving method. If you want to read more about problem solving and heuristics, I recommend *How to Model It: Problem Solving for the Computer Age* (Starfield et al., 1994) and *Strategies for Creative Problem Solving* (Fogler and LeBlanc, 1995).

1.5 PREREQUISITE MATERIAL

No engineering book exists in a vacuum, and some preparatory material is always required. The first prerequisite, which is often overlooked, is that you must be able to read well. If you don't read well, get help immediately.

A second set of prerequisites involves certain mathematical abilities. You need to be comfortable with algebra and the manipulation of equations, as these skills are used throughout the text. Another required mathematical skill is graphical analysis, since many of the design methods are graphical methods. You need to be competent and to feel comfortable plotting curves and straight lines and solving simultaneous algebraic equations graphically. Familiarity with exponential and logarithmic manipulations is required for Chapter 7. The only chapters requiring calculus are Section 8.5.2, and Chapters 9 and 15 through 18.

The third area of prerequisites concerns mass balances, energy balances, and phase equilibria. Although the basics of mass and energy balances can be learned in a very short time, facility with their use requires practice. Thus, this book will normally be preceded by a course on mass and energy balances. A knowledge of the basic ideas of phase equilibrium, including the concept of equilibrium, Gibbs' phase rule, distribution coefficients, familiarity with graphical representations of equilibrium data, and a working knowledge of vapor-liquid equilibrium (VLE) correlations will be helpful.

Units are a fourth critically important area. The United States' NASA program crashed a space craft into Mars because of failure to convert between the metric and English systems of units. Because conversion of units will remain necessary throughout your career, I have used data in the units in which they were originally presented. Thus, you must do conversions throughout the book. Although problem solutions and Appendix C show conversion factors, it is assumed that you are very familiar and proficient with unit conversions. This includes conversion from weight to mole fractions, and vice versa.

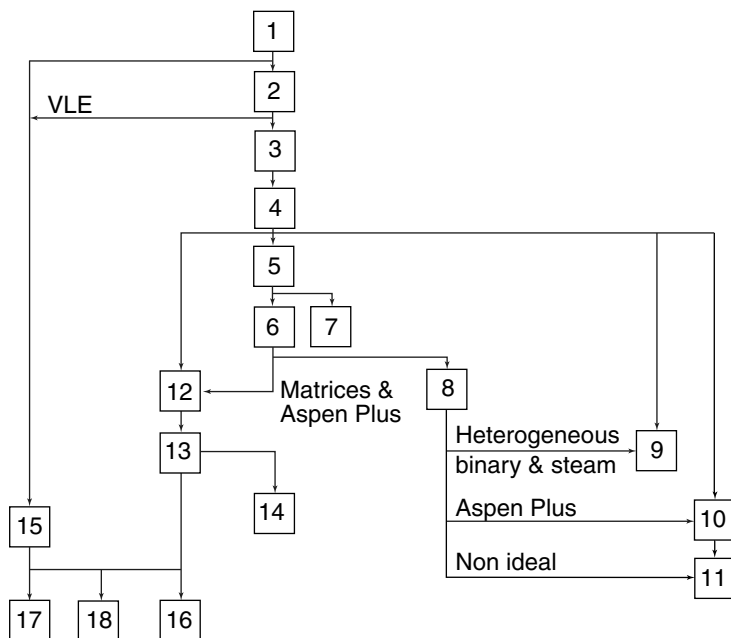
A fifth area of prerequisites is problem-solving skills. Because the chemical engineer must be a good problem solver, it is important to develop skills in this area. The ability to solve problems is a prerequisite for all chemical engineering courses.

In general, later chapters depend on the earlier chapters, as shown schematically in Figure 1-3. Chapters 11, 14, 16, and 17 are not required for the understanding of later chapters and can be skipped if time is short. Figure 1-3 should be useful in planning the order in which to cover topics and for adapting this book for special purposes.

1.6 OTHER RESOURCES ON SEPARATION PROCESS ENGINEERING

Since students have different learning styles, you need to customize the way you use this book to adapt to your learning style. Of course, you will have to take charge of your learning and do this for yourself. If you are interested in exploring your learning style, a good place to start is the Index of Learning Styles, which was developed by Richard M. Felder and Linda K. Silverman. This index is available free on the Internet at www4.ncsu.edu/unity/lockers/users/felder/public/ILSpa.html. Alternatively, you may search on the term "Felder" using a search engine such as Google.

Since students (and professors) have different learning styles, no single approach to teaching or writing a book can be best for all students. Thus, there will undoubtedly be parts of this book that do not make sense to you. Many students use other students, then the teaching



assistant, and finally the professor as resources. Fortunately, a number of good textbooks and Web pages exist that can be helpful because their presentations differ from those in this textbook. Table 1-1 presents a short annotated bibliography of some of the available handbook and textbook resources. A large number of useful Web sites are available but are not listed because URLs change rapidly. They can be accessed by searching on the term “separation processes” using any popular search engine.

Belter, P. A., E. L. Cussler, and W.-S. Hu, *Bioseparations. Downstream Processing for Biotechnology*, Wiley-Interscience, New York, 1988. Separations textbook with emphasis on bioseparations.

Cussler, E. L., *Diffusion: Mass Transfer in Fluid Systems*, 3rd ed., Cambridge University Press, Cambridge, UK, 2009. Textbook on basics of diffusion and mass transfer with applications to a variety of separation processes in addition to other applications.

Doherty, M. F., and M. F. Malone, *Conceptual Design of Distillation Systems*, McGraw-Hill, New York, 2001. Advanced distillation textbook that uses residue curve maps to analyze complex distillation processes.

Geankoplis, C. J., *Transport Processes and Separation Process Principles*, 4th ed., Prentice Hall PTR, Upper Saddle River, NJ, 2003. Unit operations textbook that has expanded coverage of separation processes and transport phenomena.

TABLE 1-1. *Annotated bibliography of resources on separation process engineering (continued)*

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- Harrison, R. G., P. Todd, S. R. Rudge, and D. P. Petrides, *Bioseparations Science and Engineering*, Oxford University Press, New York, 2003. Separations textbook with emphasis on bioseparations.
- Hines, A. L., and R. M. Maddox, *Mass Transfer: Fundamentals and Applications*, Prentice-Hall PTR, Upper Saddle River, NJ, 1985. Textbook on basics of diffusion and mass transfer with applications to separation processes.
- Humphrey, J. L., and G. E. Keller II, *Separation Process Technology*, McGraw-Hill, New York, 1997. Industrially oriented book that includes performance, selection and scaleup information.
- King, C. J., *Separation Processes*, 2nd ed., McGraw-Hill, New York, 1980. Textbook that seeks to integrate knowledge of separation processes and has extensive case studies.
- McCabe, W. L., J. C. Smith, and P. Harriott, *Unit Operations of Chemical Engineering*, 7th ed., McGraw-Hill, New York, 2004. Unit operations textbook that includes extensive coverage of separations and transport phenomena.
- Noble, R. D., and P. A. Terry, *Principles of Chemical Separations with Environmental Applications*, Cambridge University Press, Cambridge, UK, 2004. Basic separation principles with environmental examples and problems in a non-calculus based format.
- Perry, R. H., and D. W. Green (Eds.), *Perry's Chemical Engineers' Handbook*, 8th ed., McGraw-Hill, New York, 2008. General handbook that has extensive coverage on separations, but coverage often assumes reader has some prior knowledge of technique.
- Rousseau, R. W. (Ed.), *Handbook of Separation Process Technology*, Wiley-Interscience, New York, 1987. Handbook containing detailed information on a number of different separation methods.
- Schweitzer, P. A. (Ed.), *Handbook of Separation Techniques for Chemical Engineers*, 3rd ed., McGraw-Hill, New York, 1997. Handbook containing detailed information on many separations. Coverage often assumes reader has some prior knowledge of technique.
- Seader, J. D., E. J. Henley, and D. J. Roper, *Separation Process Principles*, 3rd ed., Wiley, New York, 2011. Textbook covering an introduction to mass transfer and a large variety of separation processes.
- Seidel, A. (Ed.), *Kirk-Othmer Encyclopedia of Chemical Technology*, 5th Ed., Wiley-Interscience, New York, 2004. Extensive encyclopedia with many entries by authorities on separation processes.
- Treybal, R. E., *Mass-Transfer Operations*, 3rd ed., McGraw-Hill, New York, 1980. Textbook on basics of diffusion and mass transfer with detailed applications to separation processes.
- Wankat, P. C., *Mass Transfer Limited Separations*, Springer, Berlin, 1990. Advanced textbook on crystallization, adsorption, chromatography, ion exchange, and membrane separations.
- <http://www.engineeringtoolbox.com/> and <http://www.cheric.org/research/kdb/> (click on box Korean Physical Properties Data Bank) are excellent sources for data needed for separation problems.
-

1.7 SUMMARY—OBJECTIVES

We have explored some of the reasons for studying separations and some of the methods we will use. At this point you should be able to satisfy the following objectives:

1. Explain how separations are used in a typical chemical plant
2. Define the concepts of equilibrium stages and unit operations
3. Explain what is meant by phase equilibrium
4. Explain the basic concepts of mass transfer
5. List the steps in the structured problem-solving approach and start to use this approach
6. Have some familiarity with the prerequisites

Note: In later chapters you may want to turn to the Summary—Objectives section first to help you see where you are going. Then when you've finished the chapter, the Summary—Objectives section can help you decide if you got there.

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- Matar, S., and L. F. Hatch, *Chemistry of Petrochemical Processes*, 2nd ed., Gulf Publishing Co., Houston, TX, 2001.
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- Shreve, R. N., and G. T. Hatch, *Chemical Process Industries*, 5th ed., McGraw-Hill, New York, 1984.
- Smith, J. M., H. C. Van Ness, and M. M. Abbott, *Introduction to Chemical Engineering Thermodynamics*, 7th ed., McGraw-Hill, New York, 2005.
- Speight, J. G., *Chemical and Process Design Handbook*, McGraw-Hill, New York, 2002.
- Starfield, A. M., K. A. Smith, and A. L. Bleloch, *How to Model It: Problem Solving for the Computer Age*, 2nd ed., McGraw-Hill, New York, 1994.
- Turton, R., R. C. Bailie, W. B. Whiting, and J. A. Shaeiwitz, *Analysis, Synthesis and Design of Chemical Processes*, 2nd ed., Prentice Hall, Upper Saddle River, NJ, 2003.
- Walas, S. M., *Phase Equilibria in Chemical Engineering*, Butterworth, Boston, 1985.
- Wankat, P. C., and F. S. Oreovicz, *Teaching Engineering*, McGraw-Hill, New York, 1993. Available free at https://engineering.purdue.edu/ChE/News_and_Events/teaching_engineering/index.html.

HOMEWORK

A. Discussion Problems

- A1. Return to your successful solution of a fairly difficult problem in one of your previous technical courses (preferably chemical engineering). Look at this solution but from the point of view of the *process* used to solve the problem instead of the technical details. Did you follow a structured method? Most people don't at first. Did you eventually do most of the steps listed? Usually, the *define*, *explore*, *plan*, and *do it* steps are done sometime during the solution. Rearrange your solution so that these steps are in order. Did you check your solution? If not, do that now. Finally, try *generalizing* your solution.
- A2. Without returning to the book, answer the following:
 - a. Define a unit operation. Give a few examples.
 - b. What is the equilibrium stage concept?
 - c. What are the steps in the systematic problem solving approach? Explain each step in your own words.
- A3. The equilibrium stage concept
 - a. is a hypothetical construct.
 - b. assumes that phases leaving the stage are in equilibrium.
 - c. is useful even when phases are not in equilibrium.
 - d. all of the above.
- A4. If you have studied heat transfer, relate Eq. (1-4) to the similar basic definition of heat transfer by conduction and convection.
- A5. Do you satisfy the prerequisites? If not, how can you remedy this situation?
- A6. Develop a key relations chart (one page or less) for this chapter. A key relations chart is a summary of everything you need to solve problems or answer questions from the chapter. In general, it will include equations, sketches, and key words. Organize it in your own way. The purpose of developing a key relations chart is to force your brain to actively organize the material. This will greatly aid you in remembering the material.

B. Generation of Alternatives

- B1. List as many products and how they are purified or separated as you can. Go to a large supermarket and look at some of the household products. How many of these could you separate? At the end of this course you will know how to purify most of the liquid products.
- B2. Some separation methods are common in homes in the United States. Most of these are concerned with water treatment. List the separations that you are familiar with and briefly describe how you think they work.
- B3. The body uses several membrane separation methods. List as many of these as you can and describe how you think they work.
- B4. Separation operations are very common in chemistry laboratories. List the separations that you employed in various chemistry labs.

C. Derivations

- C1. Write the mass and energy balances (in general form) for the separator shown in Figure 1-1. If you have difficulty with this, review a book on mass and energy balances.

D. Problems

- D1.** One of the prerequisites for study of separations is the ability to convert from weight to mole fractions and vice versa. As a refresher in this conversion, solve the following problem: We have a flow rate of 1500 kmol/h of a feed that is 40 mol% ethanol and 60 mol% water. What is the weight fraction of ethanol, and what is the total flow rate in pounds per hour?

E. Complex Problems

There are no complex problems for this chapter.

F. Problems Using Other Resources

- F1.** Look through several recent issues of *Chemical Engineering* magazine or similar technical magazines and find an article that contains a process flow chart. Read the article and write a short (less than one page) critique. Explicitly comment on whether the flow sheet for the process fits (at least approximately) the general flow sheet shown in Figure 1-1.
- F2.** Arrange a tour of the unit operations laboratory in your institution to observe the different types of separation equipment. Note that although this equipment is often much larger than the separation equipment that you used in chemistry laboratory, it is much smaller than industrial-scale equipment.

G. Simulator Problems

There are no simulator problems for this chapter.

H. Computer Spreadsheet Problems

There are no computer spreadsheet problems for this chapter.

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