Separation Process Engineering
Includes Mass Transfer Analysis

Third Edition
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To Dot, Chuck, and Jennie
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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.
Many people were very helpful in the writing of the first edition. Dr. Marjan Bace and Prof. Joe Calo got me started writing. A. P. V. Inc., Glitsch Inc., and The Norton Co. kindly provided photographs. Chris Roesel and Barb Naugle-Hildebrand did the original artwork. The secretarial assistance of Carolyn Blue, Debra Bowman, Jan Gray, and Becky Weston was essential for completion of the first edition. My teaching assistants Magdiel Agosto, Chris Buehler, Margret Shay, Sung-Sup Suh, and Narasimhan Sundaram were very helpful in finding errors. Professors Ron Andres, James Caruthers, Karl T. Chuang, Alden Emery, and David P. Kessler, and Mr. Charles Gillard were very helpful in reviewing portions of the text. I also owe a debt to the professors who taught me this material: Lowell Koppel, who started my interest in separations as an undergraduate; William R. Schowalter, who broadened my horizons beyond equilibrium staged separations in graduate school; and C. Judson King, who kept my interests alive while I was a professor and administrator through his articles, book, and personal example.

The assistance of Lee Meadows, Jenni Layne, and Karen Heide in preparing the second edition is gratefully acknowledged. I thank the reviewers, John Heydweiller, Stewart Slater, and Joe Shaeiwitz, for their very helpful reviews. The encouragement and occasional prodding from my editor, Bernard Goodwin, was very helpful in getting me to prepare the long-overdue second edition and kept me from procrastinating on the third edition.

The assistance of Karen Heide in preparing the third edition is gratefully acknowledged. The hospitality of the Department of Chemical and Process Engineering at the University of Canterbury, Christchurch, New Zealand, which gave me time to complete Chapter 15 and an opportunity to teach from the ion exchange and extraction sections, is greatly appreciated. I thank the reviewers, Ken Morison, Leonard Pease, David Rockstraw, and Joe Shaeiwitz, for their very helpful reviews. I thank my editor, Bernard Goodwin, for his continued support and encouragement.

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Phillip C. Wankat is the Clifton L. Lovell Distinguished Professor of Chemical Engineering and the Director of Undergraduate Degree Programs in the Department of Engineering Education at Purdue University. He has been involved in research and teaching of separations for more than forty years and is very interested in improving teaching and learning in engineering. He is the author of two books on how to teach and three books on separation processes. He has received a number of national research awards as well as local and national teaching awards.
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Nomenclature

Chapters 1 through 18

\(a\) interfacial area per volume, \(\text{ft}^2/\text{ft}^3\) or \(\text{m}^2/\text{m}^3\)

\(a_j\) interfacial area for heat transfer on stage \(j\), \(\text{m}^2\)

\(a_{\text{flow}}, a_{\text{heat}}, a_{\text{mass}}\) eddy diffusion parameters, Eqs. (15-48)

\(a_p\) surface area/volume, \(\text{m}^2/\text{m}^3\)

\(a_{p1}, a_{p2}, a_{p3}, a_{T1}, a_{T2}, a_{F6}\) constants in Eq. (2-30) and Table 2-3

\(A\) area, \(\text{m}^2\)

\(A, B, C\) 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)

\(A_{\text{active}}\) active area of tray, \(\text{ft}^2\) or \(\text{m}^2\)

\(A_c\) cross-sectional area of column, \(\text{ft}^2\) or \(\text{m}^2\)

\(A_d\) downcomer area, \(\text{ft}^2\) or \(\text{m}^2\)

\(A_{du}\) flow area under downcomer apron, Eq. (10-28), \(\text{ft}^2\)

\(A_f\) area for flow, \(\text{m}^2\)

\(A_{\text{hole}}\) area of holes in column, \(\text{ft}^2\)

\(A_I\) interfacial area between two phases, \(\text{ft}^2\) or \(\text{m}^2\)

\(A_{\text{mixer}}\) cross-sectional area of mixer, \(\text{m}^2\)

\(A_{\text{net}}\) net area, Eq. (10-13), \(\text{ft}^2\) or \(\text{m}^2\)

\(A_{\text{total}}\) total area in horizontal drum, \(\text{ft}^2\) or \(\text{m}^2\)

\(A_{\text{vap}}\) Area for Vapor flow in horizontal drum, \(\text{ft}^2\) or \(\text{m}^2\)

\(b\) empirical constant, Eq. (13-63b)

\(b_{\text{flow}}, b_{\text{heat}}, b_{\text{mass}}\) eddy diffusion parameters, Eqs. (15-48)

\(B\) bottoms flow rate, \(\text{kmol/h} \) or \(\text{lbmol/h}\)

\(C\) number of components

\(C_{\text{BM}}\) bare module cost, Chapter 11

\(C_C\) concentration of solute in continuous phase, \(\text{kmol/m}^3\) continuous phase

\(C_{C\text{C}}\) concentration of solute in continuous phase in equilibrium with \(C_D\), \(\text{kmol/m}^3\)

\(C_D\) concentration of solute in dispersed phase, \(\text{kmol/m}^3\) dispersed phase

\(C_{\text{IL}}\) vapor load coefficient, Eq. (15-38)

\(C_A, C_B, C_m\) molar concentrations, of A, B, and mixture, \(\text{mol/m}^3\)

\(C_o\) orifice coefficient, Eq. (10-25)
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
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<tr>
<td>$C_p$</td>
<td>heat capacity, Btu/lb°F or Btu/lbmol°F or cal/g°C or cal/mol°C, etc.</td>
</tr>
<tr>
<td>$C_p$</td>
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<td>$D$</td>
<td>diffusivity, Fickian m$^2$/s or ft$^2$/h</td>
</tr>
<tr>
<td>$D, D_{Dia}$</td>
<td>distillate flow rate, kmol/h or kg/h</td>
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<tr>
<td>$D_{col}$</td>
<td>diameter of column, ft or m</td>
</tr>
<tr>
<td>$d_{d, hydraulic}$</td>
<td>column diameter, see Table 16-1, ft</td>
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<tr>
<td>$d_i$</td>
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<td>$d_p, d_d$</td>
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<tr>
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<tr>
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<td>mass extract, kg</td>
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<tr>
<td>$f$</td>
<td>friction factor</td>
</tr>
<tr>
<td>$f_{AB}$</td>
<td>friction coefficient between molecules A and B</td>
</tr>
<tr>
<td>$f = V/F$</td>
<td>fraction vaporized</td>
</tr>
<tr>
<td>$f$</td>
<td>fractional approach to flooding</td>
</tr>
<tr>
<td>$f$</td>
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<tr>
<td>$F$</td>
<td>charge to still pot (Chapter 9), moles or kg</td>
</tr>
<tr>
<td>$F$</td>
<td>mass of feed in batch extraction, kg</td>
</tr>
<tr>
<td>$F_D$</td>
<td>feed flow rate, kmol/h or lbmol/h or kg/h etc.</td>
</tr>
</tbody>
</table>
\[
\frac{W_L}{W_V} \sqrt{\frac{\rho_L}{\rho_V}} = \frac{L'}{G'} \sqrt{\frac{\rho_L}{\rho_V}}, \text{ flow parameter}
\]

**Nomenclature**

- **Fm**: Material factor for cost, Table 11-2
- **Fp**: Pressure factor for cost, Eqs. (11-5) and (11-6)
- **Fq**: Quantity factor for cost, Eq. (11-7)
- **Fs, Fsolv**: Flow rate solvent (Chapter 13), kg/h
- **Fsolid**: Solids flow rate in leaching, kg insoluble solid/h
- **Fweir**: 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/s², 9.81 m/s²
- **gC**: Conversion factor in English units, 32.2 ft • lbm/(lbf • s²)
- **G**: Flow rate carrier gas, kmol/h or kg/h
- **G'**: Gas flux, lb/s ft²
- **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)
- **h**: Pure component enthalpy
- **hf**: Enthalpy of liquid leaving feed stage
- **hF**: Feed enthalpy (liquid, vapor or two-phase)
- **heat transfer**: Heat transfer coefficient
- **hL**: Clear liquid height on stage, m or cm
- **h**: Hole diameter, inches
- **hp**: Packing height, ft or m
- **h**: Height of flash drum, ft or m
- **h**: 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.
- **HVij**: Partial molar enthalpy of component i in vapor on stage j, J/kmol
- **HT**: Height of tank, m
- **Hi,OD**: Overall height of a transfer unit for mass transfer driving force in concentration units, Eq. (16-83a analog), m
- **HG**: Height of gas phase transfer unit, ft or m
- **HL**: Height of liquid phase transfer unit, ft or m
- **HOG**: Height of overall gas phase transfer unit, ft or m
- **HOL**: Height of overall liquid phase transfer unit, ft or m
- **HETP**: Height equivalent to a theoretical plate, ft or m
- **HT**: Height of a transfer unit, ft or m
- **jD, jH**: j-functions, Eqs. (15-50)
- **JA**: Flux with respect to molar average velocity of fluid
- **k1, k2**: Empirical constants, Eq. (13-63b)
- **kB**: Boltzmann’s constant, J/k
\( k_{\text{conduction}} \) thermal conductivity, J/(ms K)

\( \bar{k}_x, \bar{k}_y \) 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\cdot m^3) or kmol/(s\cdot 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, \( D/\Delta z \), m/s

\( K_d \) \( y/x \), distribution coefficient for dilute extraction

\( K, K_i \) \( y/x \), equilibrium vapor-liquid ratio

\( K_{\text{drum}} \) parameter to calculate \( u_{\text{perm}} \) for flash drums, Eq. (2-64)

\( K_x, K_y \) overall mass transfer coefficient in liquid or vapor, lbmol/ft^2 h, or kmol/hm^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\cdot m^3) or kmol/(s\cdot m^3)

\( l_w \) weir length, ft

\( L \) length, m

\( L \) 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 \( HETP_{\text{practical}}/HETP_{\text{packing}} \) 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)
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>( n_{OG} )</td>
<td>number of overall gas phase transfer units</td>
</tr>
<tr>
<td>( n_{OL} )</td>
<td>number of overall liquid phase transfer units</td>
</tr>
<tr>
<td>( n_{org} )</td>
<td>moles organic in vapor in steam distillation</td>
</tr>
<tr>
<td>( n_{w} )</td>
<td>moles water in vapor in steam distillation</td>
</tr>
<tr>
<td>( N )</td>
<td>impeller revolutions per second</td>
</tr>
<tr>
<td>( N )</td>
<td>number of stages</td>
</tr>
<tr>
<td>( N_{A} )</td>
<td>flux of A, lbmol/(h)(ft^2) or kmol/(h)(m^2)</td>
</tr>
<tr>
<td>( N_{feed} )</td>
<td>feed stage</td>
</tr>
<tr>
<td>( N_{j} )</td>
<td>transfer to liquid from vapor on stage j, mol component i/s</td>
</tr>
<tr>
<td>( N_{fj} )</td>
<td>transfer to vapor from liquid on stage j, mol component i/s</td>
</tr>
<tr>
<td>( N_{min} )</td>
<td>number of stages at total reflux</td>
</tr>
<tr>
<td>( N_{feed,min} )</td>
<td>estimated feed stage location at total reflux</td>
</tr>
<tr>
<td>( N_{Po} )</td>
<td>power number, Eq. (13-52)</td>
</tr>
<tr>
<td>( N_{IOD} )</td>
<td>number of overall extraction transfer units for mass transfer driving force</td>
</tr>
<tr>
<td>( Nu )</td>
<td>Nusselt number, Eq. (15-33g)</td>
</tr>
<tr>
<td>( NTU )</td>
<td>number of transfer units</td>
</tr>
<tr>
<td>( O )</td>
<td>total overflow rate in washing, kg/h</td>
</tr>
<tr>
<td>( p )</td>
<td>pitch of sieve plate holes, m</td>
</tr>
<tr>
<td>( p, p_{tot} )</td>
<td>pressure, atm, kPa, psi, bar etc.</td>
</tr>
<tr>
<td>( P )</td>
<td>partial pressure</td>
</tr>
<tr>
<td>( P )</td>
<td>Number of phases</td>
</tr>
<tr>
<td>( P_e )</td>
<td>power, W</td>
</tr>
<tr>
<td>( Pe )</td>
<td>dimensionless Peclet number in terms of molecular diffusivity, Eq. (15-33c)</td>
</tr>
<tr>
<td>( Pe )</td>
<td>dimensionless Peclet number in terms of eddy diffusivity, Eq. (16-111a)</td>
</tr>
<tr>
<td>( Per_{f} )</td>
<td>flow perimeter, Figure 13-33B, m</td>
</tr>
<tr>
<td>( Pr )</td>
<td>dimensionless Prandt number, Eq. (15-33f)</td>
</tr>
<tr>
<td>( q )</td>
<td>( \frac{L_{f}}{F} = (L - L)/F ), feed quality</td>
</tr>
<tr>
<td>( q )</td>
<td>volumetric flow rate/plate width, m^2/s</td>
</tr>
<tr>
<td>( Q )</td>
<td>amount of energy transferred, Btu/h, kcal/h, etc.</td>
</tr>
<tr>
<td>( Q_{c} )</td>
<td>condenser heat load</td>
</tr>
<tr>
<td>( Q_{c}, Q_{C} )</td>
<td>volumetric flow rate continuous phase, m^3/s</td>
</tr>
<tr>
<td>( Q_{D}, Q_{D} )</td>
<td>volumetric flow rate dispersed phase, m^3/s</td>
</tr>
<tr>
<td>( Q_{flash} )</td>
<td>heat loss from flash drum</td>
</tr>
<tr>
<td>( Q_{L} )</td>
<td>volumetric flow rate of liquid, m^3/s</td>
</tr>
<tr>
<td>( Q_{R} )</td>
<td>reboiler heat load</td>
</tr>
<tr>
<td>( Q_{z} )</td>
<td>heat flux in z direction, J/s</td>
</tr>
<tr>
<td>( r )</td>
<td>radius of column, ft or m</td>
</tr>
<tr>
<td>( R )</td>
<td>gas constant, 1.9859 cal/(mol⋅K) or 8.314 m^3Pa/(mol⋅K)</td>
</tr>
<tr>
<td>( R )</td>
<td>raffinate flow rate (Chapter. 13), kg/h</td>
</tr>
<tr>
<td>( R_{A} )</td>
<td>solute radius, m</td>
</tr>
<tr>
<td>( \hat{R} )</td>
<td>mass raffinate, kg</td>
</tr>
<tr>
<td>( \hat{R}_{t} )</td>
<td>Holdup raffinate phase in tank plus settler, kg</td>
</tr>
<tr>
<td>( Re )</td>
<td>dimensionless Reynolds number, Eq. (15-33b)</td>
</tr>
<tr>
<td>( Re_{settler} )</td>
<td>Reynold's number for settler, Eq. (13-60a)</td>
</tr>
<tr>
<td>( S )</td>
<td>solvent flow rate kmol/h or lbmol/h</td>
</tr>
<tr>
<td>( S )</td>
<td>tray spacing, inches, Eq. (10-47)</td>
</tr>
</tbody>
</table>
Nomenclature

S moles second solvent in constant-level batch distillation
Ṡ mass of solvent, kg
S solvent flow rate, kg/h
ŠcL Schmidt number for liquid = \( \frac{\mu}{(\rho D)} \)
Šcv Schmidt number for vapor = \( \frac{\mu}{(\rho D)} \)
\( \text{Sh}_c, \text{Sh}_v, \text{Sh}_y \) dimensionless Sherwood numbers, Eq. (15-33a)
\( \text{St}_c, \text{St}_v, \text{St}_y \) dimensionless Stanton numbers, Eq. (15-33d)
t time, s, min, or h
tbatch period for batch distillation, Eq. (9-28)
tdown down time in batch distillation
t(\( t_{95} - t_0 \)) 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
\( t_{\text{L, residence}} \) liquid residence time, Eq. (16-111c), s
\( t_{\text{res, dispersed}} \) residence time of dispersed phase in settler, s
\( t_{\text{operating}} \) operating time in batch distillation
\( t_{\text{res, down}} \) residence time in downcomer, Eq. (10-30), s, or on plate, Eq. (16-35e)
ttray tray thickness, inches
T temperature, \( °C, °F, K, \) or \( °R \)
T\( _j^L, T_j^V \) liquid and vapor temperatures on stage \( j \) at the interface, K
Tref reference temperature
u vapor velocity, cm/s or ft/s
uflood flooding velocity, Eq. (10-8)
up operating velocity, Eq. (10-11)
uperm permissible vapor velocity, Eq. (2-64)
uthindered hindered settling velocity, Eq. (13-58)
\( u_i, u_{\text{Stokes}} \) Stokes’ law terminal velocity, Eq. (13-57), m/s
U superficial vapor velocity in active area of tray, m/s
Ua superficial vapor velocity, ft/s
v characteristic velocity of Karr column, Eq. (13-68), m/s
\( v_{\text{c, flood}}, v_{\text{d, flood}} \) continuous and dispersed phase flooding velocities, m/s
vo vapor velocity through holes, Eq. (10-29), ft/s
vo, bal velocity where valve is balanced, Eq. (10-36)
VA, VB component transfer velocities, Eqs. (15-15e, f)
vr reference or basis velocity, Eqs. (15-15c, d)
vref reference velocity
vy vertical velocity
V vapor flow rate, kmol/h or lbmol/h
Vj molar volume Eq. (13-1)
VA molar volume solute at normal boiling point, m\(^3\)/kmol
V\( _{\text{liq, tank}} \) volume of liquid in tank, m\(^3\)
Vmax maximum vapor flow rate
Vmixer volume of liquid in mixing tank, m\(^3\)
Vsettler volume settler, m\(^3\)
Vtank volume tank, m\(^3\)
Vsurge surge volume in flash drum, Eq. (2-68), ft\(^3\)
VP vapor pressure, same units as p
w plate width, m
WL liquid flow rate, kg/h or lb/h
Nomenclature

WL liquid mass flux, lb/s ft² or lb/h ft², (Chapter 16)
WV 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
xA,ref, xB,ref fractions to calculate velocity of center of total flux, Eq. (15-17)
xI interfacial mole fraction in liquid
x* interfacial mole fraction in liquid
x*l 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
yvol volume fraction in vapor
y* equilibrium mole fraction in vapor
y*l 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)
ylm log mean difference, Eq. (15-32d)
yI interfacial mole fraction in vapor
y mass fraction in vapor
Y weight or mole ratio in vapor
z weight or mole fraction in feed
z distance from downcomer exit to weir, m

Greek

αAB KA/KB, relative volatility
αthermal thermal diffusity, m²/s
β A_hole/A_active
γ activity coefficient
δ thickness of mass transfer film or thickness of falling film, m
δ_λ characteristic dimension of packing, inch, Eq. (10-38)
δ_i solubility parameter, Eq. (13-1)
Δ change in variable or difference operator
ΔEv latent energy of vaporization, Eq. (13-1)
ΔH steady state height of dispersion band in settler, m
Δρ |ρ_C − ρ_D |
ε limit for convergence
εA,εB, εAB 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
ρL liquid density, g/cm³ or lb/ft³ or kg/m³
ρV vapor density
σ,γ surface tension, dynes/cm or interfacial tension
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
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<tr>
<td>$\zeta$</td>
<td>dimensionless distance, Eq. (15-14a)</td>
</tr>
<tr>
<td>$\chi$</td>
<td>term defined in Eq. (13-49)</td>
</tr>
<tr>
<td>$\Psi_c, \Psi_d$</td>
<td>volumetric fraction of continuous and dispersed phases</td>
</tr>
<tr>
<td>$\Psi_{d,\text{feed}}$</td>
<td>volumetric fraction of dispersed phase in feed</td>
</tr>
<tr>
<td>$\phi$</td>
<td>liquid phase packing parameter, Eq. (16-38)</td>
</tr>
<tr>
<td>$\phi_B$</td>
<td>solvent interaction parameter, Eq. (15-23b)</td>
</tr>
<tr>
<td>$\phi_{ac}$</td>
<td>relative froth density in downcomer, Eq. (10-29)</td>
</tr>
<tr>
<td>$\phi_e$</td>
<td>effective relative froth density, Eq. (16-109d)</td>
</tr>
<tr>
<td>$\psi$</td>
<td>$\rho_{\text{water}}/\rho_L$, Chapter 10</td>
</tr>
<tr>
<td>$\psi$</td>
<td>$c/(e + L)$, fractional entrainment, Chapter 10</td>
</tr>
<tr>
<td>$\psi$</td>
<td>packing parameter for gas phase, Eq. (16-37)</td>
</tr>
<tr>
<td>$\Omega_D$</td>
<td>collision integral, Table 15-2</td>
</tr>
<tr>
<td>$\mu_C, \mu_D$</td>
<td>viscosity of continuous and dispersed phases, Pa·s</td>
</tr>
<tr>
<td>$\mu_H, \mu_L$</td>
<td>viscosity of heavy and light phases, Pa·s</td>
</tr>
<tr>
<td>$\mu_m$</td>
<td>mixture viscosity, Eq. (13-55), Pa·s</td>
</tr>
<tr>
<td>$\rho_C, \rho_D$</td>
<td>densities of continuous and dispersed phases, g/m³</td>
</tr>
<tr>
<td>$\rho_m$</td>
<td>mixture density, Eq. (13-53), g/m³</td>
</tr>
<tr>
<td>$\rho_m$</td>
<td>molar density, mol/m³</td>
</tr>
<tr>
<td>$\omega$</td>
<td>revolutions per second</td>
</tr>
</tbody>
</table>

**Chapter 17**

- $a, a_j$ | term in quadratic equations for well-mixed membrane systems, Eqs. (17-10b), (17-74a), and (17-74a) |
- $a$ | 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, cm² or m² |
- $b, b_j$ | 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, cm²/s |
- $D_m$ | diffusivity in the membrane, cm²/s |
- $F_p$ | volumetric flow rate of permeate, cm³/s |
- $F_{out}$ | volumetric flow rate of exiting retentate, cm³/s |
- $F_{solv}$ | volumetric flow rate of solvent in RO, cm³/s |
\( \hat{F} \) molar flow rate, mol/s, mol/min, etc.

\( F' \) mass flow rate, g/s, g/min, kg/min, etc.

\( h \) 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)/[cm³ (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 m² day) or similar units

\( j \) counter for stage location in staged models in Figure 17-19

\( J \) volumetric flux, cm³/(s cm²) or m³/(m² day), Eq. (17-1b)

\( J' \) mass flux, g/(s cm²) or g/(m² day), Eq. (17-1c)

\( \dot{J} \) mole flux, mol/(s cm²) or kmol/(day m²), 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/[cm² 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, μm, 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, cm³/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.
Greek letters

\( \alpha \) selectivity, dimensionless, Gas Permeation: Eq. (17-4b), RO: Eq. (17-20), pervaporation: Eq. (17-53a)

\( \Delta x \) difference in wt frac of solute across the membrane

\( \Delta \pi \) difference in the osmotic pressure across the membrane, Pa, atm, mm Hg, etc.

\( \pi \) osmotic pressure, Pa, kPa, atm, mm Hg, etc.

\( \theta \) cut = \( \frac{F_p}{F_{in}} \), with flows in molar units, dimensionless

\( \theta' \) cut = \( \frac{F'_{p}}{F'_{in}} \) in flows in mass units, dimensionless

\( \mu \) viscosity, centipoise or g/(cm s)

\( \nu = \frac{\mu}{\rho} \) kinematic viscosity, cm²/s

\( \rho_{solv} \) mass solvent density, kg/m³

\( \rho_{solv} \) molar solvent density, kmol/m³

\( \lambda_p \) mass latent heat of vaporization of the permeate in pervaporation determined at the reference temperature, kJ/kg

\( \omega \) 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 the column, m²

\( A_w \) 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/m³, kmol/m³, g/L, etc.

\( c_i \) concentration of species i, kg/m³, kmol/m³, g/L, etc., or

\( c_i \) concentration of ion i in solution, typically equivalents/m³

\( c_i' \) concentration of species i that would be in equilibrium with \( q_i \), same units as \( c_i \)

\( c_i \) average concentration of solute in pore, same units as \( c_i \)

\( c_{i,pore} \) fluid concentration at surface of adsorbent pores, same units as \( c_i \)

\( c_{i,surface} \) fluid concentration at surface of particles, \( \varepsilon_p = 0 \), same units as \( c_i \)

\( c_{Ri} \) concentration of ion i on the resin, typically equivalents/m³

\( c_{RT} \) total concentration of ions on the resin, typically equivalents/m³

\( c_T \) total concentration of ions in solution, typically equivalents/m³

\( C_i \) constant relating solute velocity to interstitial velocity, dimensionless, Eq. (18-15e)

\( C_{Pf} \) heat capacity of the fluid, cal/(g °C), cal/(mol °C), J/(g K), etc.

\( C_{tp} \) heat capacity of particle including pore fluid, same units \( C_{Pf} \)

\( C_{ps} \) heat capacity of the solid, same units as \( C_{Pf} \)

\( C_{pw} \) heat capacity of the wall, same units as \( C_{Pf} \)

\( d_p \) particle diameter, cm or m

\( D \) desorbent rate in SMB, same units as \( F \)
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>D/F</td>
<td>desorbet to feed ratio in SMB, dimensionless</td>
</tr>
<tr>
<td>$D_{col}$</td>
<td>column diameter, m or cm</td>
</tr>
<tr>
<td>$D$</td>
<td>diffusivity including both molecular and Knudsen diffusivities, m$^2$/s or cm$^2$/s</td>
</tr>
<tr>
<td>$D_{effective}$</td>
<td>effective diffusivity, m$^2$/s or cm$^2$/s, Eq. (18-4)</td>
</tr>
<tr>
<td>$D_K$</td>
<td>Knudsen diffusivity, m$^2$/s or cm$^2$/s, Eq. (18-51)</td>
</tr>
<tr>
<td>$D_{molecular}$</td>
<td>molecular diffusivity in free solution, m$^2$/s or cm$^2$/s</td>
</tr>
<tr>
<td>$D_s$</td>
<td>surface diffusivity, m$^2$/s or cm$^2$/s, Eq. (18-53)</td>
</tr>
<tr>
<td>erf</td>
<td>error function, Eq. (18-70) and Table 18-7</td>
</tr>
<tr>
<td>$E_D$</td>
<td>axial dispersion coefficient due to both eddy and molecular effects, m$^2$/s or cm$^2$/s</td>
</tr>
<tr>
<td>$E_{DT}$</td>
<td>thermal axial dispersion coefficient, m$^2$/s or cm$^2$/s</td>
</tr>
<tr>
<td>$E_{eff}$</td>
<td>effective axial dispersion coefficient, same units $E_D$, Eq. (18-68)</td>
</tr>
<tr>
<td>F</td>
<td>volumetric feed rate, e.g., m$^3$/h, cm$^3$/min, liter/h</td>
</tr>
<tr>
<td>$h_p$</td>
<td>particle heat transfer coefficient, J/(K s m$^2$) or similar units</td>
</tr>
<tr>
<td>$h_w$</td>
<td>wall heat transfer coefficient, J/(K s m$^2$) or similar units</td>
</tr>
<tr>
<td>HETP</td>
<td>height of equilibrium plate, cm/plate, Eq. (18-78b)</td>
</tr>
<tr>
<td>$k_f$</td>
<td>film mass transfer coefficient, m/s or cm/s</td>
</tr>
<tr>
<td>$k_{m,c}$</td>
<td>lumped parameter mass transfer coefficient with concentration driving force, m/s or cm/s, Eqs. (18-56a) and (18-57a)</td>
</tr>
<tr>
<td>$k_{m,q}$</td>
<td>lumped parameter mass transfer coefficient with amount adsorbed driving force, m/s or cm/s, Eqs. (18-56b) and (18-57b)</td>
</tr>
<tr>
<td>$K_{AB}$</td>
<td>mass action equilibrium constant for monovalent-monovalent ion exchange, dimensionless, Eq. (18-40a)</td>
</tr>
<tr>
<td>$K_{A,c}$</td>
<td>adsorption equilibrium constant in terms of concentration, units are (concentration)$^{-1}$</td>
</tr>
<tr>
<td>$K'_{i,c}$</td>
<td>linearized adsorption equilibrium constant in terms of concentration, units are units of q/c, Eq. (18-6b)</td>
</tr>
<tr>
<td>$K_{Ao}$</td>
<td>pre-exponential factor in Arrhenius Eq. (18-7a), same units as $K_A$</td>
</tr>
<tr>
<td>$K_{A,p}$</td>
<td>adsorption equilibrium constant in terms of partial pressure, units are (pressure)$^{-1}$</td>
</tr>
<tr>
<td>$K'_{A,p}$</td>
<td>linearized adsorption equilibrium constant in terms of partial pressure, units are units of $q_A/p_A$, Eq. (18-5b)</td>
</tr>
<tr>
<td>$K_d$</td>
<td>size exclusion parameter, dimensionless</td>
</tr>
<tr>
<td>$K_{DB}$</td>
<td>mass action equilibrium constant for divalent-monovalent ion exchange, same units as $c_T/c_R$, Eq. (18-41)</td>
</tr>
<tr>
<td>$K_{DE}$</td>
<td>Donnan exclusion factor, dimensionless, following Eq. (18-44)</td>
</tr>
<tr>
<td>L</td>
<td>length of packing in column, m or cm</td>
</tr>
<tr>
<td>$L_{MTZ}$</td>
<td>length of mass transfer zone, Figure 18-23, m or cm</td>
</tr>
<tr>
<td>M</td>
<td>molecular weight of solute, g/mol or kg/kmol</td>
</tr>
<tr>
<td>$M_i$</td>
<td>multipliers in Eqs. (18-29), dimensionless</td>
</tr>
<tr>
<td>N</td>
<td>equivalent number of plates in chromatography, Eq. (18-78)</td>
</tr>
<tr>
<td>$N_{Pe}$</td>
<td>Peclet number, dimensionless, Eq. (18-62)</td>
</tr>
<tr>
<td>$p_A$</td>
<td>partial pressure of species A, mm Hg, kPa, or other pressure units</td>
</tr>
<tr>
<td>$p_h$</td>
<td>high pressure, mm Hg, kPa, or other pressure units</td>
</tr>
<tr>
<td>$p_L$</td>
<td>low pressure, mm Hg, kPa, or other pressure units</td>
</tr>
<tr>
<td>$P_{eL}$</td>
<td>Peclet number based on length, dimensionless, Eq. (18-78a)</td>
</tr>
<tr>
<td>$q_A$</td>
<td>amount of species A adsorbed, kg/kg adsorbent, mol/kg adsorbent, or kg/L</td>
</tr>
<tr>
<td>$q_{A,max}$</td>
<td>maximum amount of species A that can adsorb, kg/kg adsorbent, mol/kg adsorbent, or kg/L</td>
</tr>
</tbody>
</table>
\( q_H \) 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., \( R = 8.314 \frac{m^3 Pa}{mol K} \))
\( \text{Re} \) Reynolds number, dimensionless, Eq. (18-60)
\( \text{Sc} \) Schmidt number, dimensionless, Eq. (18-60)
\( \text{Sh} \) 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
\( t_{feed} \) 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
\( u_{i,ion} \) velocity of ion \( i \), m/s or cm/s
\( u_i \) average solute velocity, m/s or cm/s
\( \bar{u}_s \) average of solute velocities for A and B, cm/s, Eq. (18-83)
\( u_{k,ion,i} \) 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 = \( (A \text{ Product})/(\varepsilon_e A_c) \)
\( v_{B,product} \) interstitial velocity of B Product if it was in the column, m/s or cm/s = \( (B \text{ Product})/(\varepsilon_e A_c) \)
\( v_D \) interstitial velocity of desorbent if it was in the column, m/s or cm/s = \( D/(\varepsilon_e A_c) \)
\( v_{Feed} \) interstitial velocity of feed if it was in the column, m/s or cm/s = \( F/(\varepsilon_e A_c) \)
\( v_{inter} \) 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

\( \text{Nomenclature} \)
x  deviation from the location of the peak maximum, dimensionless Eq. (18-79)
x_t  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  \frac{c_i}{c_T} equivalent fraction of ion in solution, dimensionless
X_{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  = \frac{c_{R_i}}{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  \beta_{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
ρ_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_i  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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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
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 1-1. Typical chemical plant layout
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.

\[ T_{\text{liquid}} = T_{\text{vapor}} \quad \text{(at equilibrium)} \]  

(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,

\[ p_{\text{liquid}} = p_{\text{vapor}} \quad \text{(at equilibrium)} \]  

(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

\[ (\text{chemical potential } i)_{\text{liquid}} = (\text{chemical potential } i)_{\text{vapor}} \]  

(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

\[
\text{Mass transfer rate} = (\text{area}) \times (\text{mass transfer coefficient}) \times (\text{driving force})
\]  

(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.

\[
\text{Rate / volume} = K_y a (y_A^* - y_A)
\]  

(1-5a)

\[
\text{Rate / volume} = K_x a (x_A - x_A^*)
\]  

(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/ILSpage.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.

**Table 1-1. Annotated bibliography of resources on separation process engineering**


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


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.

REFERENCES

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. \textit{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. \textit{Complex Problems}
There are no complex problems for this chapter.

F. \textit{Problems Using Other Resources}

F1. Look through several recent issues of \textit{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. \textit{Simulator Problems}
There are no simulator problems for this chapter.

H. \textit{Computer Spreadsheet Problems}
There are no computer spreadsheet problems for this chapter.
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