

**Separations
in Chemical Engineering**

EQUILIBRIUM STAGED SEPARATIONS

Phillip C. Wankat



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To Dot and Charles

PREFACE

Separations have always been very important in chemical engineering. This importance has recently escalated with the imminent emergence of new industries in biotechnology and high-performance materials. Separations will continue to remain important in bulk chemical manufacturing, petroleum processing, and the other standard areas of chemical engineering interest.

The development of new industries requiring the expertise of chemical engineers leads to problems and opportunities for chemical engineering education. Chemical engineering students need to be prepared for both the "known future" and the "unknown future." The known future includes the use of standard chemical engineering separation methods such as distillation and absorption which will remain important for many years. The unknown future involves the use of many relatively new separation methods such as adsorption, chromatography, electrophoresis, membrane separations, and zone melting. Up to now, these methods have not been included in the education of most undergraduate and graduate students.

In writing this book I have tried to satisfy the need of students to learn about the standard separation methods. *Equilibrium-Staged Separations*, covers the classical separations such as distillation, absorption and extraction. The equilibrium staged analysis procedure is developed in a rigorous way. Problem solving is emphasized throughout the text. There are detailed examples in each chapter and many homework problems which are solved in the solution manual.

Starting with flash distillation, the text leads the student into binary multistage distillation and then into multicomponent distillation. Both rigorous and short-cut methods for multicomponent distillation are explored. Azeotropic and extractive distillation are introduced, and binary batch distillation is discussed in detail. Then the design of staged and packed columns is discussed in depth. The section on distil-

lation is finished with a chapter on economics and methods of coupling columns.

The principles developed for distillation are then used to study absorption, stripping, immiscible extraction, and washing. Since the basic tools are the same as for distillation, these subjects are covered in less depth. Partially miscible extraction and leaching are analyzed using triangular diagrams. The last chapter discusses mass transfer analyses.

This book has been extensively tested in a junior class at Purdue University. This class is taken before the students have had mass transfer. This book could also be used for sophmores or seniors. The order of prerequisite material is illustrated in Figure 1-2; this should help in arranging courses.

A second book, *Mass Transfer Limited Separations*, will include separation processes which require a mass transfer analysis for complete understanding. This includes most of the newer separation methods such as crystallization, adsorption, chromatography, and membrane separations. The style is similiar to the style of this book and problem solving is emphasized throughout. However, a higher level of mathematical analysis is required, and the second book is aimed for seniors and graduate students.

Many people have helped me with the writing of this book. Professor Joe Calo got me started writing the book, and Dr. Marjan Bace strongly supported this effort. My students have been most helpful in helping me develop clear methods to explain the separation methods. My teaching assistants over the last several years: Magdiel Agosto, Chris Buehler, Margret Shay, Sung-Sup Suh, and Narasimhan Sundaram, have been very helpful in solving problems and finding errors. Professor Ron Andres used the book in class. His comments were very helpful and have been incorporated into the text. Professors Karl T. Chuang and David P. Kessler, and Mr. Charles F. Gillard were very helpful in reviewing Chapter 12. Professors Alden Emery and James Caruthers were helpful in reviewing Chapter 19. A.P.V. Inc., Glitsch Inc., and The Norton Co. were very kind in providing photographs.

Because of the length of this book many secretaries have been involved in the typing and production. Most of the work was done by Carolyn Blue, Debra Bowman, Jan Gray, and Becky Weston. I am grateful for their efforts. The copy editors and proof readers at Elsevier were very helpful in polishing the manuscript. The assistance of Philip Schafer is greatly appreciated.

A much more indirect but perhaps more important type of help came

from the professors who helped me learn about the topics in this book. Professors Lowell B. Koppel and William R. Schowalter taught me my undergraduate and graduate courses in separations. They awakened my interest in separations. Dean C. Judson King through his book, his articles, and his personal example has helped keep that interest alive. My interest in problem solving has been sparked by Professors Richard Noble and Donald Woods.

Finally, my wife Dot has supported me when I thought I would never finish, and my son Charles has provided light to my life.

NOMENCLATURE

a	interfacial area per volume, ft^2/ft^3 or m^2/m^3
$a_{p_1}, a_{p_2}, a_{p_3}, a_{T_1}, a_{T_2}, a_{T_6}$	constants in Eq. (2-12) and Table 2-4
A, B, C	constants in Antoine Eq. (2-18)
A, B, C, D, E	constants in Eq. (3-51)
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. (12-28), ft^2
A_{hole}	area of holes in column, ft^2
A_I	interfacial area between two phases, ft^2 or m^2
A_{net}	net area, Eq. (12-13), ft^2 or m^2
b	equilibrium constant for linear equilibrium, $y = mx + b$
B	bottoms flow rate, kg mole/hr or lb mole/hr
C	number of components
C_{FL}	vapor load coefficient, Eq. (19-38)
C_p	heat capacity, $\text{Btu/lb}^\circ\text{F}$ or $\text{Btu/lbmole}^\circ\text{F}$ or $\text{cal/g}^\circ\text{C}$ or $\text{cal/g mole}^\circ\text{C}$, etc.
C_{pH}	humid heat capacity, Eq. (19-89a)
C_{pW}	water heat capacity
C_{py}	vapor phase mass heat capacity
C_o	orifice coefficient, Eq. (12-25)

C_{sb}	capacity factor, Eq. (12-8)
d	dampening factor, Eq. (3-45)
D	diffusivity, cm^2/s or ft^2/hr
D, Dia	diameter of column, ft or m
D'_{col}	column diameter, see Table 19-2, ft
D_{total}	total amount of distillate (Chapt. 11), moles or kg
D	distillate flow rate, kg mole/hr or lb mole/hr
e	absolute entrainment, moles/hr
E	extract flow rate (Chapters 16 and 18), kg/hr
E_k	value of energy function for trial k, Eq. (3-38)
E_{ML}, E_{MV}	Murphree liquid and vapor efficiencies
E_o	Overall efficiency
E_{pt}	point efficiency, Eq. (12-3) or (19-76a)
$f = V/F$	fraction vaporized
f	friction factor, Eq. (19-86a)
$f_k(V/F)$	Rachford-Rice function for trial k, Eq. (3-29)
F	packing factor, Figure 13-4 and Tables 13-1 and 13-2
F	degrees of freedom, Eq. (2-5)
F	charge to still pot (Chapt. 11), moles or kg
F	feed flow rate, kgmole/hr or lbmole/hr or kg/hr etc.
F_D	diluent flow rate (Chapt. 16), kg/hr
F_{lv}	$\frac{W_L}{W_V} \sqrt{\frac{\rho_V}{\rho_L}} = \frac{L'}{G'} \sqrt{\frac{\rho_V}{\rho_L}}$, flow parameter
F_s, F_{solv}	flow rate solvent (Chapts. 16 and 17), kg/hr
F_{solid}	solids flow rate in leaching, kg insoluble solid/hr
F_w	modification factor, Eq. (12-26) and Figure 12-20

gap	gap from downcomer apron to tray, Eq. (12-28), ft
g	32.2 ft/s^2
G	flow rate carrier gas, kgmole/hr or kg/hr
G'	gas flux, lb/s, ft ²
h	pressure drop in head of clear liquid, inches liquid
h	height of liquid on stage (Chapter 19), ft.
h	height, m or ft
h	liquid enthalpy, kcal/kg, Btu/lb mole, etc.
\tilde{h}	pure component enthalpy
h_o	hole diameter, inches
h_p	packing height, ft or m
h_y	vapor phase heat transfer coefficient, Btu/(hr)(ft ²)(° F)
H	Henry's law constant, Eqs. (10-12) and (15-1)
H	vapor enthalpy, kcal/kg, Btu/lbmole, etc.
H_G	height of gas phase transfer unit, ft or m
\bar{H}_G	height of a transfer unit, Eq. (19-85b)
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
H_{Ty}	gas phase height transfer unit for heat transfer, ft
H_y	enthalpy wet air, Eq. (19-89b), Btu/lb
HETP	height equivalent to a theoretical plate, ft or m
HTU	height of a transfer unit, ft or m
J_A	flux with respect to molar average velocity of fluid

k	thermal conductivity, Btu/(hr) (ft)(°F)
k_x, k_y	individual mass transfer coefficients in liquid and vapor phases, see Table 19-2
k'_y	mass transfer coefficient in concentrated solutions, Eq. (19-43)
\bar{k}_x, \bar{k}_y	individual mass transfer coefficient in weight units
K	parameter to calculate column diameter, Eqs. (12-7), (12-8)
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. (3-50)
K_x, K_y	overall mass transfer coefficient in liquid or vapor, lbmoles/ft ² hr
l_w	weir length, ft
L	liquid flow rate, kgmoles/hr or lbmoles/hr
\bar{L}	mass liquid flow rate, lb/hr (Chapt. 19)
L'	liquid flux, lb/(s) (ft ²)
Le	Lewis number = $k/\rho D_{AB} C_{py}$
L_g	liquid flow rate in gal/min, Chapt. 12
m	linear equilibrium constant, $y = mx + b$
m	local slope of equilibrium curve, Eq. (19-5b)
M	flow rate of mixed stream (Chapt. 18), kg/hr
MW	molecular weight
n	moles
n_G	number of gas phase transfer units
\bar{n}_G	number of transfer units calculated from mass fractions, Eq. (19-85c)
n_{Hy}	number of transfer units for humidification, Eq. (19-92b)
n_L	number of liquid phase transfer units

n_{OG}	number of overall gas phase transfer units
n_{OL}	number of overall liquid phase transfer units
n_{Ty}	number of transfer units for heat transfer, Eq. (19-83b)
N	number of stages
N_A	flux of A, lbmoles/(hr)(ft ²)
N_f, N_{feed}	feed stage
N_{min}	number of stages at total reflux
$N_{feed,min}$	estimated feed stage location at total reflux
N_T	energy flux, Eqs. (19-80), Btu/(hr)(ft ²)
\bar{N}_w	mass flux of water, lb/(hr)(ft ²)
NTU	number of transfer units
O	total overflow rate in washing, kg/hr
p	pressure, atm, kPa, psi etc.
\bar{p}, p_B	partial pressure
P	Number of phases
q	$L_F/F = (\bar{L} - L)/F$, feed quality
Q	amount of energy transferred, Btu/hr, kcal/hr etc
Q_c	condenser heat load
Q_{flash}	heat loss from flash drum
Q_R	reboiler heat load
r	radius of column, ft or m
R	gas constant
R	raffinate flow rate (Chapts. 16 and 18), kg/hr
S	solvent flow rate (Chapt 10) kgmoles/hr or lbmoles/hr
S	solvent flow rate (Chapt. 18), kg/hr
Sc_L	Schmidt number for liquid = $\mu/\rho D$
Sc_v	Schmidt number for vapor = $\mu/\rho D$
t	time, s, min, or hr

t_{batch}	period for batch distillation, Eq. (11-25)
t_{down}	down time in batch distillation
$t_{\text{operating}}$	operating time in batch distillation
t_{res}	residence time in downcomer, Eq. (12-30), s
t_{tray}	tray thickness, inches
T	temperature, °C, °F, K or °R
T_I	interfacial temperature
T_{ref}	reference temperature
T_w	water temperature
T_y	vapor phase temperature
u	vapor velocity, cm/s or ft/s
u_{flood}	flooding velocity, Eq. (12-7)
u_{op}	operating velocity, Eq. (12-11)
u_{perm}	permissible vapor velocity, Eq. (3-50)
U	underflow liquid rate, (Chapt. 17), kg/hr
v	vapor velocity, Eq. (19-86a)
v_o	vapor velocity through holes, Eq. (12-29), ft/s
$v_{o,\text{bal}}$	velocity where valve is balanced, Eq. (12-36)
V	vapor flow rate, kgmoles/hr or lbmoles/hr
V_{max}	maximum vapor flow rate
V_{surge}	surge volume in flash drum, Figure 3-4, ft ³
W	flow of phase co-current to L in 3 phase contactor (Chapt. 17)
W_L	liquid flow rate, kg/hr or lb/hr
W_L	liquid mass flux, lb/s ft ² or lb/hr ft ² , (Chapt. 19)
W_V	vapor flow rate, kg/hr or lb/hr
x	weight or mole fraction in liquid
x	$[L/D - (L/D)_{\text{min}}]/(L/D + 1)$ in Eqs. (9-42)
x^*	equilibrium mole fraction in liquid

x_I	interfacial mole fraction in liquid
x_{out}^*	liquid mole fraction in equilibrium with inlet gas, Eq. (19-35b)
x'	pseudo-equilibrium, Eq. (17-15)
X	weight or mole ratio in liquid
y	weight or mole fraction in vapor
y^*	equilibrium mole fraction in vapor
y_{out}^*	vapor mole fraction in equilibrium with inlet liquid in counter current system, Eq. (19-35a) or in equilibrium with outlet liquid in cocurrent contactor, Eq. (19-71)
y_I	interfacial mole fraction in vapor
\bar{y}	mass fraction in vapor
Y	weight or mole ratio in vapor
Y_w	humidity, Eq. (19-88)
z	weight or mole fraction in feed
z	axial distance in bed (Chapt. 19)
<i>Greek</i>	
α_{AB}	K_A/K_B , relative volatility
β	A_{hole}/A_{active}
γ	activity coefficient
Δ	change in variable
ϵ	limit for convergence
η	fraction of column available for vapor flow
θ	angle of downcomer, Figure 12-18B
λ	latent heat of vaporization, kcal/kg, Btu/lb, Btu/lbmole etc.
λ	mG/L in Eqs. (12-5) and (12-6)
λ_{ref}	latent heat of vaporization of water at 32 ° F
μ	viscosity, cp
μ_w	viscosity of water, cp

ρ_L	liquid density, g/cm ³ or lb/ft ³
ρ_V	vapor density
ρ_w	water density
σ	surface tension, dynes/cm
σ_w	surface tension of water, dynes/cm
ϕ	liquid phase packing parameter, Eq. (19-38)
ϕ_{dc}	relative froth density in downcomer, Eq. (12-29)
ψ	ρ_{water}/ρ_L , Chapter 13
ψ	$e/(e+L)$, fractional entrainment, Chapter 12
ψ	packing parameter for gas phase, Eq. (19-37)

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