HANDBOOK OF SEPARATION TECHNIQUES FOR CHEMICAL ENGINEERS

Philip A. Schweitzer, Editor in Chief

Handbook of Separation Techniques for Chemical Engineers

PHILIP A. SCHWEITZER *Editor-in-chief*
Contract Manager, Chem-Pro Equipment Corp.

A James Peter Book
James Peter Associates, Inc.

McGRAW-HILL BOOK COMPANY
New York St. Louis San Francisco Auckland Bogotá
Düsseldorf Johannesburg London Madrid
Mexico Montreal New Delhi Panama
Paris São Paulo Singapore
Sydney Tokyo Toronto

Library of Congress Cataloging in Publication Data

Main entry under title:

Handbook of separation techniques for chemical engineers.

"A James Peter book."
Includes index.
1. Separation (Technology)—Handbooks, manuals, etc. I. Schweitzer, Philip A.
TP156.S45H35 660.2'842 79-4096
ISBN 0-07-055790-X

1234567890 KPKP 7865432109

The editors for this book were Harold B. Crawford and Joseph Williams, the designer was Naomi Auerbach, and the production supervisor was Sally Fliess. It was set in Caledonia by University Graphics, Inc.

Printed and bound by The Kingsport Press.

Handbook of Separation Techniques for Chemical Engineers

OTHER McGRAW-HILL HANDBOOKS OF INTEREST

Contributors

Charles M. Ambler *Registered Professional Engineer*

Robert E. Anderson *Senior Research Scientist, Functional Polymers Division, Diamond Shamrock Corporation* (SEC. 1.12)

Frank F. Aplan *Mineral Processing Section, Department of Mineral Engineering, The Pennsylvania State University* (SEC. 5.2)

Allan W. Ashbrook *Manager, Research and Development Division, Eldorado Nuclear, Ltd.*

R. C. Bennett *Manager, Swanson Division of Whiting Corporation* (SEC. 2.3)

David M. Boyd, Jr. *Manager, Instrument Design & Service Department, UOP Process Division, UOP Inc.* (SEC. 1.5)

Clifford W. Cain, Jr. *Senior Research Engineer, Filtration and Minerals Research, Johns-Manville* (SECS. 4.1 AND 4.2)

H. T. Chen *Professor of Chemical Engineering, New Jersey Institute of Technology* (SEC. 1.15)

Eng J. Chou *Sr. Development Engineer, Research and Development, Research Cottrel Inc.*

Roger W. Day *Marketing Director, Solids Control Operations, Geosource, Inc.* (SEC. 4.9)

John W. Drew *Director of Engineering, Chem-Pro Equipment Corp.* (SEC. 1.6)

John S. Eckert *Consulting Engineer* (SEC. 1.7)

R. W. Ellerbe *Project Manager, The Rust Engineering Company* (SECS. 1.3 AND 1.4)

Robert C. Emmett, Jr. *Program Manager, Industrial Processing Technology, Eimco-BSP Division of Envirotech Corporation* (SEC. 4.4)

Charles N. Grichar *Supervisor of Application Engineering, Solids Control Operations, Geosource, Inc.* (SEC. 4.9)

William B. Hooper *Engineering Fellow, Process Design, Corporate Engineering Department, Monsanto Company* (SEC. 1.11)

T. I. Horzella *Enviro Energy Corporation* (SEC. 6.2)

Roy A. Hutchins *Technical Services Superintendent, Agricultural Chemicals Division, Texas Gulf, Inc.* (SEC. 1.14)

Louis J. Jacobs, Jr. *Engineering Specialist, Corporate Engineering Department, Monsanto Company* (SEC. 1.11)

E. G. Kominek *Technical Director, Industrial Water and Waste Operations, Eimco-PMD Division, Envirotech Corporation* (SEC. 4.8)

J. Louis Kovach *President, Nuclear Consulting Services* (SEC. 3.1)

L. D. Lash *Systems Project Manager, Eimco-PMD Division, Envirotech Corporation* (SEC. 4.8)

Teh Cheng Lo *Technical Fellow, Development Department, Hoffmann-La Roche, Inc.* (SEC. 1.10)

Joseph H. Maas *Independent Chemical Engineer and Consultant* (SECS. 1.1 AND 6.1)

John E. McCormick *Associate Professor of Chemical Engineering, New Jersey Institute of Technology* (SEC. 1.2)

Nicholas Nickolaus *Vice-President Marketing, Pall Corporation* (SEC. 4.6)

Paul G. Nygren *Senior Staff Engineer, Union Carbide Corporation* (SEC. 1.8)

Yoshiyuki Okamoto *Professor of Chemistry, Polytechnic Institute of New York* (SEC. 2.5)

Dr. M. C. Porter *Vice President of Research & Development, Nuclepore Corporation* (SEC. 2.1)

Rajaram K. Prabhudesai *Senior Process Engineer, Stauffer Chemical Company* (SEC. 5.1)

Gordon M. Ritcey *Head, Extractive Metallurgy Section, Mineral Sciences Laboratory, Canada Centre for Mineral and Energy Technology* (SEC. 2.2)

Lanny A. Robbins *Associate Scientist, Dow Chemical USA* (SEC. 1.9)

Edward C. Roche, Jr. *Professor of Chemical Engineering, New Jersey Institute of Technology* (SEC. 1.2)

G. G. Schneider *Enviro Energy Corporation* (SEC. 6.2)

Gyanendra Singh *Section Head, Food Products Research. The Procter & Gamble Company* (SEC. 2.4)

P. J. Striegl *Amex Corporation* (SEC. 6.2)

John R. Thygeson, Jr. *Associate Professor of Chemical Engineering, Drexel University* (SEC. 4.10)

Theodore H. Wentz *Sales Manager, Proctor and Schwartz Division, SCM Corp.* (SEC. 4.10)

Arthur C. Wrotnowski *Consultant* (SEC. 4.7)

F. A. Zenz *Vice-President, Engineering, The Ducon Company* (SEC. 3.2)

James F. Zievers *Vice-President, Industrial and Pump Mfg. Co.* (SEC. 4.3)

Preface

Many textbooks have been written on the subject of separation techniques. These books are usually devoted to the derivation of correlations, are highly theoretical, and provide relatively few concrete examples of the application of theory to practical everyday problems. Very seldom is more than one separation technique covered in a single volume, which makes it somewhat difficult to evaluate which technique is best suited for a particular application. This handbook, however, includes all the major separation techniques which are used industrially.

This handbook has been designed to provide the chemical engineer with sufficient information to evaluate which technique is best suited for his or her specific requirements and then, by means of illustrative problems, to show how the theory is applied. Since an understanding of the theory is necessary for proper application, the basic theory is presented and ample references are supplied for those interested in further theoretical study and in the derivation of the correlations used.

For the purpose of this book, *separation techniques* are defined as those operations which isolate specific ingredients of a mixture without a chemical reaction taking place. One deviation has been made from this principle by the inclusion of the section dealing with *ion exchange*. This was done because of the importance of ion exchange to the field of separation techniques.

The separation techniques covered are widely used in chemical manufacturing operations as well as in the design of pollution control equipment. The latter application usually involves the greatest degree of evaluation of one technique versus another.

This handbook should be helpful to chemical engineers, consultants, environmentalists, government officials, and others who are involved in the separation of mixtures of ingredients whether for manufacturing operations or for pollution control.

The editor-in-chief wishes to thank the many contributors who made their time available and were willing to share their expertise with other members of the engineering profession through the sections of the handbook which they contributed. Thank yous are also extended to the many organizations, companies, and individuals who graciously permitted use of their charts, data, photographs, and other pertinent information. An additional thank you is extended to the editor-in-chief's wife, for her understanding and many hours of typing throughout the course of the preparation of this handbook.

Philip A. Schweitzer

International System (SI) of Units and Conversion Factors

This coherent system of measurement, designated "SI" in all languages, has been accepted as the preferred system of units by 36 countries, including the United States.

Since most nations have or are in the process of converting from their individual national systems of measurement to SI units, it will only be a matter of time until the conversion is made in all nations. Many industries in the United States are already in the process of converting.

Throughout this handbook a dual system of measurement has been utilized—the English (U.S. Customary) and SI systems.

Tables giving SI base units and prefixes to be used in forming multiples and submultiples of SI units are given. And to assist the reader in making conversions, a table has been included which provides conversion factors for the more common English units to their equivalent SI units, and vice versa.

SI Base Units

Quantity	Base unit	Symbol
Length	meter	m
Mass	kilogram	kg
Time	second	s
Electric current	ampere	A
Thermodynamic temp.	kelvin	K
Amount of substance	mole	mol
Luminous intensity	candela	cd

SI Prefixes

Multiple	SI prefix	Symbol
10^{18}	exa	E
10^{15}	peta	P
10^{12}	tera	T
10^{9}	giga	G
10^{6}	mega	M
10^{3}	kilo	k
10^{2}	hecto	h
10	deka	da
10^{-1}	deci	d
10^{-2}	centi	c
10^{-3}	milli	m
10^{-6}	micro	μ
10^{-9}	nano	n
10^{-12}	pico	p
10^{-15}	femto	f
10^{-18}	atto	a

System of Consistent Units

Measurement	English	Metric
Absolute temperature	°R or °F abs.	K or °C abs.
Area	square inch	square centimeter
	square foot	square meter
Capacity	quart	liter
	gallon	liter
Density	pound per cubic foot	gram per cubic centimeter
Force of gravity conversion factor	$32.17 \left(\frac{\text{lb mass}}{\text{lb force}}\right)\left(\frac{\text{ft}}{\text{s}^2}\right)$	$980.6 \left(\frac{\text{g mass}}{\text{g force}}\right)\left(\frac{\text{cm}}{\text{s}^2}\right)$
Gas constant	$1546 \frac{\text{ft-lb force}}{\text{lb}\cdot\text{mol}\cdot{}^\circ\text{F}}$	$84{,}400 \frac{\text{cm}\cdot\text{g force}}{\text{g}\cdot\text{mol}\cdot{}^\circ\text{C}}$
Gas flow rate	cubic foot per second	cubic centimeter per second
Length	inch	millimeter
	foot	centimeter
	foot	meter
Molecular weight	lb·mol	g·mol
Number of gas molecules in a mole	2.76×10^{26}/lb·mol	6.06×10^{23}/g·mol
Pressure	pound per square inch	kilogram per square centimeter
	pound per square foot	kilogram per square meter
Specific heat	Btu/(°F)(lb)	cal/(°C)(g)
Thermal conductivity	Btu/(s)(ft²)(°F/ft)	cal/(s)(cm²)(°C/cm)
Velocity	foot per second	centimeter per second
Viscosity	pound per foot-second	poise
		pascal-second
Volume	cubic inch	cubic centimeter
	cubic foot	cubic meter
	gallon	liter
Weight	ounce	gram
	pound	kilogram

Conversion Factors

To convert from:	to	Multiply by
atmosphere (atm)	millimeter of mercury (mmHg) at 32°F	760
atmosphere (atm)	dyne per square centimeter (dyn/cm^2)	1.1033×10^6
atmosphere (atm)	foot of water at 39.1°F (ftH_2O)	33.90
atmosphere (atm)	gram per square centimeter (g/cm^2)	1033.3
atmosphere (atm)	inch of mercury at 32°F (inHg)	29.921
atmosphere (atm)	pound per square foot (lb/ft^2)	2116.3
atmosphere (atm)	pound per square inch (lb/in^2)	14.696
Btu (British thermal unit)	foot-pound (ft·lb)	777.9
Btu	horsepower-hour (hp·h)	3.929×10^{-4}
Btu	joule (J)	1055.1
Btu	kilowatthour (kWh)	2.93×10^{-4}
Btu/ft^3	joule per cubic meter (J/m^3)	37,260
Btu/h	watt (W)	0.29307
Btu/min	horsepower (hp)	0.02357
Btu/lb	joule per kilogram (J/kg)	2326
Btu/(lb)(°F)	calorie per gram degree Celsius [cal/(g)(°C)]	1
Btu/(lb)(°F)	joule per kilogram kelvin [J/(kg)(K)]	4186.8
Btu/s	watts (W)	1054.4
Btu/(ft^2)(h)	joules per square meter per second [J/(m^2)(s), or W/m^2]	3.1546
Btu/(ft^2)(min)	kilowatt per square foot (kW/ft^2)	0.1758
Btu(60°F)/°F	calorie per degree Celsius (cal/°C)	543.6
calorie (gram)	Btu	3.968×10^{-3}
calorie (gram)	joule (J)	4.186
centigrade heat unit	Btu	1.8
centimeter (cm)	foot (ft)	0.03281
centimeter (cm)	inch (in)	0.3937
centimeter (cm)	meter (m)	0.01
centimeter (cm)	micron	10,000
cubic centimeter (cm^3)	cubic foot (ft^3)	3.532×10^{-5}
cubic centimeter (cm^3)	gallon (gal)	2.6417×10^{-4}
cubic foot (ft^3)	cubic centimeter (cm^3)	28,317
cubic foot (ft^3)	cubic meter (m^3)	0.028317
cubic foot (ft^3)	gallon (gal)	7.481
cubic foot (ft^3)	liter (L)	28.316
cubic foot per minute (ft^3/min)	cubic centimeters per second (cm^3/s)	472
cubic inch (in^3)	cubic meter (m^3)	1.6387×10^{-5}
degree Celsius (°C)	kelvin (K)	K = °C + 273
degree Celsius (°C)	degree Fahrenheit (°F)	°F = 9/5(°C) + 32
degree Fahrenheit (°F)	degree Celsius (°C)	°C = (°F − 32)/1.8
degree Fahrenheit (°F)	kelvin (K)	K = (°F + 459)/1.8
degree Rankine (°R)	kelvin (K)	K = °R/1.8
dyne per square centimeter (dyn/cm^2)	pascal (Pa)	0.1
foot (ft)	meter (m)	0.3048
foot per minute (ft/min)	centimeter per second (cm/s)	0.5080
foot per square second (ft/s^2)	meter per square second (m/s^2)	0.3048
gallon (U.S.) (gal)	cubic meter (m^3)	0.003785
gallon (gal)	liter (L)	3.785
gallon per minute (gal/min)	cubic foot per hour (ft^3/h)	8.021
gallon per minute (gal/min)	cubic meter per hour (m^3/h)	0.227
gallon per minute per square foot (gal/min·ft^2)	meter per hour (m/h)	2.44

Conversion Factors *(Continued)*

To convert from:	to	Multiply by
grain (gr)	gram (g)	0.06480
grain per cubic foot (gr/ft^3)	gram per cubic meter (g/m^3)	2.2884
grain per gallon (gr/gal)	parts per million (ppm)	17.118
gram (g)	kilogram (kg)	0.001
gram per cubic centimeter (g/cm^3)	pound per cubic foot (lb/ft^3)	62.43
gram per cubic centimeter (g/cm^3)	pound per gallon (lb/gal)	8.345
gram per liter (g/L)	pound per cubic foot (lb/ft^3)	0.0624
gram per square centimeter (g/cm^2)	pound per square foot (lb/ft^2)	2.0482
gram per square centimeter (g/cm^2)	pound per square inch (lb/in^2)	0.014223
inch (in)	meter (m)	0.0254
kilogram (kg)	pound (lb avoirdupois)	2.2046
kilogram per square centimeter (kg/cm^2)	pounds per square inch (lb/in^2)	14.223
liter (L)	cubic meter (m^3)	0.001
micron	micrometer (μm)	1
millimeter (mm)	meter (m)	0.001
millimeter mercury at 0°C (mmHg)	foot of water at 39.1°F (ftH$_2$O)	0.446
millimeter mercury at 0°C (mmHg)	pound per square inch (lb/in^2)	0.1934
pound (lb avoirdupois)	grain (gr)	7000
pound (lb avoirdupois)	kilogram (kg)	0.454
pound per cubic foot (lb/ft^3)	gram per cubic centimeter (g/cm^3)	0.016
pound per cubic foot (lb/ft^3)	kilogram per cubic meter (kg/m^3)	16.018
pound per cubic foot (lb/ft^3)	gram per liter (g/L)	16
pound per gallon (lb/gal)	gram per liter (g/L)	120
pound per square foot (lb/ft^2)	atmosphere (atm)	4.725×10^{-4}
pound per square foot (lb/ft^2)	kilogram per square meter (kg/m^2)	4.882
pound per square inch (lb/in^2)	atmosphere (atm)	0.068
pound per square inch (lb/in^2)	kilogram per square centimeter (kg/cm^2)	0.07
pound per square inch per foot	kilogram per square centimeter per meter	0.23
square centimeter (cm^2)	square foot (ft^2)	1.08×10^{-3}
square foot (ft^2)	square meter (m^2)	0.0929
square foot per hour (ft^2/h)	square meter per second	2.581×10^{-5}
square inch (in^2)	square centimeter (cm^2)	6.452
square inch (in^2)	square meter (m^2)	6.452×10^{-4}
tons (metric)	kilogram (kg)	1000
tons (metric)	pound (lb)	2204.6

Contents

PART THREE Gas (Vapor) Mixtures

PART FOUR Solid-Liquid Mixtures

PART FIVE Solid Mixtures

PART SIX Gas-Solid Mixtures

Index follows Section 6.2

Part 1

Liquid-Liquid Mixtures