Principles of Chemical Separations with Environmental Applications

Chemical separations are of central importance in many areas of environmental science, whether it is the clean-up of polluted water or soil, the treatment of discharge streams from chemical processes, or modification of a specific process to decrease its environmental impact. This book is an introduction to chemical separations, focusing on their use in environmental applications.

The authors first discuss the general aspects of separations technology as a unit operation. They also describe how property differences are used to generate separations, the use of separating agents, and the selection criteria for particular separation techniques. The general approach for each technology is to present the chemical and/or physical basis for the process, and explain how to evaluate it for design and analysis.

The book contains many worked examples and homework problems. It is an ideal textbook for undergraduate and graduate students taking courses on environmental separations or environmental engineering.

RICHARD NOBLE received his Ph.D. from the University of California, Davis. He is a professor of Chemical Engineering and Co-Director of the Membrane Applied Science and Technology Center at the University of Colorado, Boulder.

PATRICIA TERRY received her Ph.D. from the University of Colorado, Boulder, and is an associate professor in the Department of Natural and Applied Sciences at the University of Wisconsin, Green Bay. She has also held positions at Dow Chemicals and Shell Research and Development.

CAMBRIDGE SERIES IN CHEMICAL ENGINEERING

Books in the series

E. L. Cussler, *Diffusion: Mass Transfer in Fluid Systems, second edition*
Liang-Shih Fan and Chao Zhu, *Principles of Gas–Solid Flows*
Hasan Orbey and Stanley I. Sandler, *Modeling Vapor–Liquid Equilibria: Cubic Equations of State and Their Mixing Rules*
T. Michael Duncan and Jeffrey A. Reimer, *Chemical Engineering Design and Analysis: An Introduction*
John C. Slattery, *Advanced Transport Phenomena*
A. Verma, M. Morbidelli and H. Wu, *Parametric Sensitivity in Chemical Systems*
Pao C. Chau, *Process Control: A First Course with MATLAB*
E. L. Cussler and G. D. Moggridge, *Chemical Product Design*
Richard D. Noble and Patricia A. Terry, *Principles of Chemical Separations with Environmental Applications*

Principles of Chemical Separations with Environmental Applications

Richard D. Noble
University of Colorado, Boulder

and

Patricia A. Terry
University of Wisconsin, Green Bay

CAMBRIDGE UNIVERSITY PRESS

PUBLISHED BY THE PRESS SYNDICATE OF THE UNIVERSITY OF CAMBRIDGE
The Pitt Building, Trumpington Street, Cambridge, United Kingdom

CAMBRIDGE UNIVERSITY PRESS
The Edinburgh Building, Cambridge, CB2 2RU, UK
40 West 20th Street, New York, NY 10011-4211, USA
477 Williamstown Road, Port Melbourne, VIC 3207, Australia
Ruiz de Alarcón 13, 28014 Madrid, Spain
Dock House, The Waterfront, Cape Town 8001, South Africa

http://www.cambridge.org

First published 2004

Printed in the United Kingdom at the University Press, Cambridge

Typefaces Times 10/14 pt and Gill Sans *System* LaTeX 2$_\varepsilon$ [TB]

A catalogue record for this book is available from the British Library

Library of Congress Cataloguing in Publication data

Noble, R. D. (Richard D.), 1946–
Principles of chemical separations with environmental applications / Richard D. Noble and Patricia A. Terry.
p. cm. – (Cambridge series in chemical engineering)
Includes bibliographical references and index.
ISBN 0 521 81152 X – ISBN 0 521 01014 4 (pbk.)
1. Separation (Technology) 2. Environmental chemistry. 3. Environmental management.
I. Terry, Patricia A. (Patricia Ann), 1965– II. Title. III. Series.
TP156.S45N63 2003
660′.2842–dc21 2003053072

ISBN 0 521 81152 X hardback
ISBN 0 521 01014 4 paperback

Contents

Preface

Separation – the process of separating one or more constituents out from a mixture – is a critical component of almost every facet of chemicals in our environment, whether it is remediation of existing polluted water or soil, treatment of effluents from existing chemical processes to minimize discharges to the environment, or modifications to chemical processes to reduce or eliminate the environmental impact (chemically benign processing). Having said this, there is no text today for this subject which describes conventional processing approaches (extraction, ion exchange, etc.) as well as newer techniques (membranes) to attack the serious environmental problems that cannot be adequately treated with conventional approaches. Existing texts for this subject primarily focus on wastewater treatment using technology that will not be suitable in the larger context of environmental separations. Interestingly, most chemical engineering texts on separations technology are primarily based on whether the separation is equilibrium or rate based. Thus, it is difficult to find one source for separations technology in general.

This text is meant as an introduction to chemical separations in general and various specific separations technologies. In Chapter 1 we give a generalized definition of separation processes and their environmental applications. Following this, the approach to the organization of this text is to first discuss, in Chapter 2, the generic aspects of separations technology as unit operations. This chapter will include a discussion of the use of property differences to generate the separation, the use of a separating agent to facilitate the separation, as well as some discussion on the criteria for selection of a particular separation process. This last point is usually discussed at the end of a text on separations, but we felt that it was better to give students this "food for thought" prior to any description of specific technologies.

Mass transfer fundamentals, including equilibrium- and rate-based mechanisms, are introduced in Chapter 3, before any description of specific technologies. Many readers will be chemists, civil engineers and others with little or no previous experience in the design or analysis of these processes. It is important that everyone be "brought up to

speed" prior to any discussion of a specific process. If this is not done, each technology appears to have its own set of rules and design algorithms. This "unique" set for each process diminishes the ability of the reader to use generic principles to compare alternatives and evaluate new approaches as they become available. Once this major division of the approaches has been covered, later chapters describe the specific technologies.

The section in Chapter 3 on equilibrium stage separations will include both graphical and analytical techniques. The graphical techniques are useful to visualize the process for the student and the analytical methods reinforce the principles. Rate-based separations will focus on diffusional processes and convective/dispersive effects which can be described by mass transfer coefficients (k). Initial discussion will focus on which approach to use based on what information is available and what one wants to determine. For analyses using mass transfer coefficients, both the use of correlations to estimate a value for k and the determination of an overall mass transfer coefficient (K) will be covered.

In discussing individual separations technologies in Chapters 4 through 9 we consider separations using physical property differences as well as chemical interactions. Distillation, extraction, absorption, adsorption, ion exchange, and membranes are covered. Our approach to each technology is not to provide an exhaustive description. Rather, we want to explain the physical and/or chemical basis for the process and how to evaluate it for design or analysis. Books that describe a given technology in detail will be given as references. Membrane separations represent a new and emerging technology which has been used commercially for filtration and gas separation. It is a topic that is rarely discussed in any text on separations, so we plan to insure that it receives adequate coverage.

Special thanks go to the students that assisted us including Kendra Axness, Katie Benko, Liz Galli, Jill Gruber, Blue Parish, Laura Weber, and Tony Worsham. We also want to thank others in the chemical separations community that helped to encourage us along the way including Ed Cussler, Phil Wankat, Jud King, Ed Lightfoot, Norman Li and Bill Koros. I (RDN) would like to thank Ben McCoy who taught my first separations class and started me, perhaps inadvertently, on this career path.

We are deeply indebted to Ellen Romig. Without her help in the typing and editing, it is highly doubtful that this book would have seen the light of day.