Membrane Operations

Edited by
Enrico Drioli and Lidietta Giorno

Related Titles

Seidel-Morgenstern, A. (ed.)

Membrane Reactors

Case Studies to Improve Selectivity and Yields

2009
ISBN: 978-3-527-32039-4

Koltuniewicz, A., Drioli, E.

Membranes in Clean Technologies

Theory and Practice

2008
ISBN: 978-3-527-32007-3

Peinemann, K.-V., Pereira Nunes, S. (eds.)

Membrane Technology

Volume 1: Membranes for Life Sciences

2007
ISBN: 978-3-527-31480-5

Peinemann, K.-V., Pereira Nunes, S. (eds.)

Membrane Technology

Volume 2: Membranes for Energy Conversion

2007
ISBN: 978-3-527-31481-2

Li, K.

Ceramic Membranes for Separation and Reaction

2007
ISBN: 978-0-470-01440-0

Pereira Nunes, S., Peinemann, K.-V. (eds.)

Membrane Technology

in the Chemical Industry

2006
ISBN: 978-3-527-31316-7

Sammells, A. F., Mundschau, M. V. (eds.)

Nonporous Inorganic Membranes

for Chemical Processing

2006
ISBN: 978-3-527-31342-6

Freeman, B., Yampolskii, Y., Pinnau, I. (eds.)

Materials Science of Membranes for Gas and Vapor Separation

2006
ISBN: 978-0-470-85345-0

Ohlrogge, K., Ebert, K. (eds.)

Membranen

Grundlagen, Verfahren und industrielle Anwendungen

2006
ISBN: 978-3-527-30979-5

Membrane Operations

Innovative Separations and Transformations

Edited by
Enrico Drioli and Lidietta Giorno

WILEY-VCH Verlag GmbH & Co. KGaA

The Editors

Prof. Enrico Drioli
University of Calabria
Institute on Membrane Technology
Via P. Bucci 17 /C
87030 Rende (CS)
Italy

Prof. Lidietta Giorno
University of Calabria
Institute on Membrane Technology
Via P. Bucci 17 /C
87030 Rende (CS)
Italy

All books published by Wiley-VCH are carefully produced. Nevertheless, authors, editors, and publisher do not warrant the information contained in these books, including this book, to be free of errors. Readers are advised to keep in mind that statements, data, illustrations, procedural details or other items may inadvertently be inaccurate.

Library of Congress Card No.: applied for

British Library Cataloguing-in-Publication Data
A catalogue record for this book is available from the British Library.

Bibliographic information published by the Deutsche Nationalbibliothek
The Deutsche Nationalbibliothek lists this publication in the Deutsche Nationalbibliografie; detailed bibliographic data are available on the Internet at http://dnb.d-nb.de.

© 2009 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim

All rights reserved (including those of translation into other languages). No part of this book may be reproduced in any form – by photoprinting, microfilm, or any other means – nor transmitted or translated into a machine language without written permission from the publishers. Registered names, trademarks, etc. used in this book, even when not specifically marked as such, are not to be considered unprotected by law.

Composition Thomson Digital, Noida, India
Printing Betz-Druck GmbH, Darmstadt
Bookbinding Litges & Dopf GmbH, Heppenheim
Cover Design Formgeber, Eppelheim

Printed in the Federal Republic of Germany
Printed on acid-free paper

ISBN: 978-3-527-32038-7

Contents

Membrane Operations. Innovative Separations and Transformations. Edited by Enrico Drioli and Lidietta Giorno
Copyright © 2009 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim
ISBN: 978-3-527-32038-7

List of Contributors

Richard W. Baker
Membrane Technology and
Research, Inc.
1360 Willow Road
Menlo Park, CA 94025
USA

Giuseppe Barbieri
University of Calabria
Institute on Membrane Technology
(ITM-CNR)
Via P. Bucci, 17/C
87030 Rende (CS)
Italy

Loredana De Bartolo
University of Calabria
Institute on Membrane Technology
(ITM-CNR)
Via P. Bucci, 17/C
87030 Rende (CS)
Italy

Rune Bredesen
SINTEF Materials and Chemistry
P.O. Box 124
Blindern
0314 Oslo
Norway

Carla Campana
University of Calabria
Institute on Membrane Technology
(ITM-CNR)
Via P. Bucci, 17/C
87030 Rende (CS)
Italy

and

University of Calabria
Department of Chemical Engineering
and Materials
Via P. Bucci, cubo 45/A
87030 Rende (CS)
Italy

Angela Caruso
University of Calabria
Department of Chemical Engineering
and Materials
Via P. Bucci, cubo 45/A
87030 Rende (CS)
Italy

Membrane Operations. Innovative Separations and Transformations. Edited by Enrico Drioli and Lidietta Giorno
Copyright © 2009 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim
ISBN: 978-3-527-32038-7

Tzyy H. Chong
Nanyang Technological University
Singapore Membrane Technology Centre
School of Civil and Environmental Engineering
Singapore
639798

João G. Crespo
Universidade Nova de Lisboa
Faculdade de Ciências e Tecnologia
Requimte-CQFB
Departamento de Química
2829-516 Caparica
Portugal

Enrico Drioli
University of Calabria
Institute on Membrane Technology (ITM-CNR)
Via P. Bucci, 17/C
87030 Rende (CS)
Italy

and

University of Calabria
Department of Chemical Engineering and Materials
Via P. Bucci, cubo 44/A
87030 Rende (CS)
Italy

Alessandra Criscuoli
University of Calabria
Institute on Membrane Technology (ITM-CNR)
Via P. Bucci, 17/C
87030 Rende (CS)
Italy

Anthony G. Fane
University of New South Wales
UNESCO Centre for Membrane Science & Technology
School of Chemical Sciences and Engineering
Sydney, NSW 2052
Australia

and

Nanyang Technological University
Singapore Membrane Technology Centre
School of Civil and Environmental Engineering
Singapore
639798

Alberto Figoli
University of Calabria
Institute on Membrane Technology (ITM-CNR)
Via P. Bucci, 17/C
87030 Rende (CS)
Italy

Enrica Fontananova
University of Calabria
Institute on Membrane Technology (ITM-CNR)
Via P. Bucci, 17/C
87030 Rende (CS)
Italy

and

University of Calabria
Department of Chemical Engineering and Materials
Via P. Bucci, cubo 44/A
87030 Rende (CS)
Italy

Soccorso Gaeta
GVS S.P.A.
Via Roma 50
40069 Zola Predosa (Bo)
Italy

Lidietta Giorno
University of Calabria
Institute on Membrane Technology
(ITM-CNR)
Via P. Bucci, 17/C
87030 Rende (CS)
Italy

David Hasson
Technion – Israel Institute of
Technology
Stephen and Nancy Grand Water
Research Institute
Wolfson Chemical Engineering
Department
Rabin Desalination Laboratory
Technion City
Haifa, 32000
Israel

Tzyy Haur
Nanyang Technological University
Singapore Membrane Technology
Centre
School of Civil and Environmental
Engineering
Singapore
639798

Dieter Hofmann
GKSS Research Center
Center for Biomaterial Development
of the Institute of Polymer Research
Kantstr. 55
14513 Teltow
Germany

Shabbir Husain
Georgia Institute of Technology
School of Chemical & Biomolecular
Engineering
Atlanta, GA 30332-0100
USA

Michel Y. Jaffrin
UMR CNRS 6600
Technological University of Compiegne
60200 Compiegne
France

William J. Koros
Georgia Institute of Technology
School of Chemical & Biomolecular
Engineering
Atlanta, GA 30332-0100
USA

Adam Kratochvil
PRISM Membranes
Air Products and Chemicals, Inc.
St. Louis, Mo 63146
USA

Izumi Kumakiri
SINTEF Materials Technology
P.O. Box 124
Blindern
0314 Oslo
Norway

Pierre Le-Clech
University of New South Wales
UNESCO Centre for Membrane Science
& Technology
School of Chemical Sciences and
Engineering
Sydney, NSW 2052
Australia

Cécile Legallais
UMR CNRS 6600
Technological University of Compiegne
60200 Compiegne
France

TorOve Leiknes
NTNU - Norwegian University of
Science and Technology
Department of Hydraulic and
Environmental Engineering
S.P. Andersensvei 5
7491 Trondheim
Norway

Giorgio De Luca
University of Calabria
Institute on Membrane Technology
(ITM-CNR)
Via P. Bucci, 17/C
87030 Rende (CS)
Italy

Rosalinda Mazzei
University of Calabria
Institute on Membrane Technology
(ITM-CNR)
Via P. Bucci, 17/C
87030 Rende (CS)
Italy

and

University of Calabria
Department of Ecology
Via P. Bucci 6/B
87036 Rende (CS)
Italy

Raffaele Molinari
University of Calabria
Department of Chemical Engineering
and Materials
Via P. Bucci
87030 Rende (CS)
Italy

Sabrina Morelli
University of Calabria
Institute on Membrane Technology
(ITM-CNR)
Via P. Bucci, 17/C
87030 Rende (CS)
Italy

T.M. Murphy
The University of Texas at Austin
Department of Chemical Engineering
Austin, TX 78712
USA

Endre Nagy
University of Pannonia
Research Institute of Chemical and
Process Engineering
P.O. Box 158
8201, Veszprém
Hungary

Grant T. Offord
The University of Texas at Austin
Department of Chemical Engineering
Austin, TX 78712
USA

Leonardo Palmisano
University of Palermo
Department of Chemical Engineering
Processes and Materials
'Schiavello-Grillone' Photocatalysis
Group
viale delle Scienze
90128 Palermo
Italy

Don R. Paul
The University of Texas at Austin
Department of Chemical Engineering
Austin, TX 78712
USA

Thijs Peters
SINTEF Materials Technology
P.O. Box 124
Blindern
0314 Oslo
Norway

Emma Piacentini
University of Calabria
Institute on Membrane Technology
(ITM-CNR)
Via P. Bucci, 17/C
87030 Rende (CS)
Italy

Antonella Piscioneri
University of Calabria
Institute of Membrane Technology
National Research Council of Italy
ITM-CNR
Via P. Bucci, cubo 17/C
87030 Rende (CS)
Italy

and

University of Calabria
Department of Cell Biology
via P. Bucci
87030 Rende (CS)
Italy

Maria Rende
University of Calabria
Institute on Membrane Technology
(ITM-CNR)
Via P. Bucci, 17/C
87030 Rende (CS)
Italy

and

University of Calabria
Department of Chemical Engineering
and Materials
Via P. Bucci, cubo 45/A
87030 Rende (CS)
Italy

Simona Salerno
University of Calabria
Institute on Membrane Technology
(ITM-CNR)
Via P. Bucci, 17/C
87030 Rende (CS)
Italy

Štefan Schlosser
Slovak University of Technology
Institute of Chemical and
Environmental Engineering
Radlinského 9
812 37 Bratislava
Slovakia

Raphael Semiat
Technion – Israel Institute of
Technology
Wolfson Chemical Engineering
Department
Rabin Desalination Laboratory
Stephen and Nancy Grand Water
Research Institute
Technion City
Haifa, 32000
Israel

Francesco Scura
University of Calabria
Institute on Membrane Technology
(ITM-CNR)
Via P. Bucci, 17/C
87030 Rende (CS)
Italy

Shu Shu
Georgia Institute of Technology
School of Chemical & Biomolecular
Engineering
Atlanta, GA 30332-0100
USA

Heinrich Strathmann
University of Stuttgart
Institute of Chemical Technology
Böblingerstr. 72
70199 Stuttgart
Germany

Heru Susanto
Universität Duisburg-Essen
Lehrstuhl für Technische Chemie II
45117 Essen
Germany

Elena Tocci
University of Calabria
Institute on Membrane Technology
(ITM-CNR)
Via P. Bucci, 17/C
87030 Rende (CS)
Italy

Mathias Ulbricht
Universität Duisburg-Essen
Lehrstuhl für Technische Chemie II
45117 Essen
Germany

Bart Van der Bruggen
K.U. Leuven, Department of Chemical
Engineering
Section Applied Physical Chemistry and
Environmental Technology
W. de Croylaan 46
3001 Heverlee (Leuven)
Belgium

Introduction

Membrane processes are state of the art technologies in various industrial sectors, including gas separation, wastewater treatment, food processing and medical applications.

Modelling methodologies are contributing significantly to the knowledge-based development of membrane materials and engineering.

Micro-ultrafiltration and reverse osmosis are mature technologies for separations based on molecular exclusion and solution-diffusion mechanisms, respectively. Cleaning and maintenance procedures able to control fouling to an acceptable extent have made these processes commercially suitable.

Some of the largest plants for seawater desalination, wastewater treatment and gas separation are already based on membrane engineering. For example, the Ashkelon Desalination Plant for seawater reverse osmosis (SWRO), in Israel, has been fully operational since December 2005 and produces more than 100 million m^3 of desalinated water per year. One of the largest submerged membrane bioreactor unit in the world was recently built in Porto Marghera (Italy) to treat tertiary water. The growth in membrane installations for water treatment in the past decade has resulted in a decreased cost of desalination facilities, with the consequence that the cost of the reclaimed water for membrane plants has also been reduced.

Membranes are growing significantly also in gas separation, for example, the current market size of carbon-dioxide separation from natural gas is more than 70 million Euro/year.

Medical applications are among the most important in the membrane market, with hemodialysis, blood oxygenators, plasma separation and fractionation being the traditional areas of applications, while artificial and bioartificial organs and regenerative medicine represent emerging areas in the field.

Nanofiltration has achieved a good stage of development, gaining attention in various applications for separations based on both molecular exclusion and charge interaction as well as on the solution-diffusion mechanism. In particular, nanofiltration is considered among the most suitable technologies for solvent separation. More recent processes such as membrane reactors, membrane contactors, and membranes in life science are also developing very rapidly. The optimal design of

Membrane Operations. Innovative Separations and Transformations. Edited by Enrico Drioli and Lidietta Giorno
Copyright © 2009 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim
ISBN: 978-3-527-32038-7

chemical transformation processes with control of reagent supply and/or product removal through catalytic membranes and membrane reactors is one of the most attractive solutions in process intensification. The catalytic action of biocatalysts is extremely efficient, selective and highly stereospecific when compared to conventional chemical catalysts. Membrane bioreactors are particularly attractive in terms of ecocompatibility, because they do not require additives, are able to operate at moderate temperature and pressure, reduce the formation of by-products, while permitting the production of high valuable coproducts. This may allow challenges in developing new production lines moving towards zero discharge to be faced. The development of catalytic membrane reactors for high-temperature applications became realistic more recently, with the development of high-temperature-resistant membranes.

The major market for membrane bioreactors is represented by wastewater treatment with the use of submerged modules configuration. These are considered among the best available technologies by the European Directives on Environment. Membrane bioreactors are also applied in food, red and white biotechnology. In these cases, the external loop configuration is used.

Membrane contactors, including membrane crystallizers and membrane emulsifiers, are among the most recent membrane operations with growing interest in various industrial sectors. For example, membrane emulsification has grown from the 1990s, when it was first developed in Japan, to nowadays with applications in food, chemical, pharmaceutical and cosmetic fields. In Europe, the research at the academic level has achieved a thorough knowledge both from experimental and theoretical points of view. This is fuelling the industrial interest towards the membrane emulsification technology, especially for those productions that involve labile bioactive molecules.

In general, nowadays the attention towards membrane science and technology is increasing significantly. Drivers of this interest include the need for technologies to enable sustainable production, directives and regulations about the use of ecofriendly technologies, consumer demand for high-quality and safe products, public concern about environment, and stakeholder confidence in and acceptance of advanced technologies.

Current initiatives recognize that a sustainable solution to the increasing demand of goods and energy is in the rational integration and implementation of new technologies able to achieve concrete benefits for manufacturing and processing, substantially increasing process precision, reducing equipment size, saving energy, reducing costs, and minimizing environmental impact.

Membranes and membrane processes are best suited in this context as their basic aspects well satisfy the requirements of process intensification for a sustainable industrial production. In fact, they are precise and flexible processing techniques, able to maximize phase contact, integrate conversion and separation processes, with improved efficiency and with significantly lower energy requirements compared to conventional techniques.

This multiauthor book highlights the current state and advances in membranes and membrane operations referring to three major roles of the membrane: mole-

cular separation, (bio)chemical transformation and phase contactors. Each topic includes fundamentals and applications of membranes and membrane operations.

The largest section is constituted by membranes in molecular separation, which is the most traditional application of membranes. Significant advances of membrane science and technologies are expected in transformation processes and membrane contactors for conventional and innovative applications.