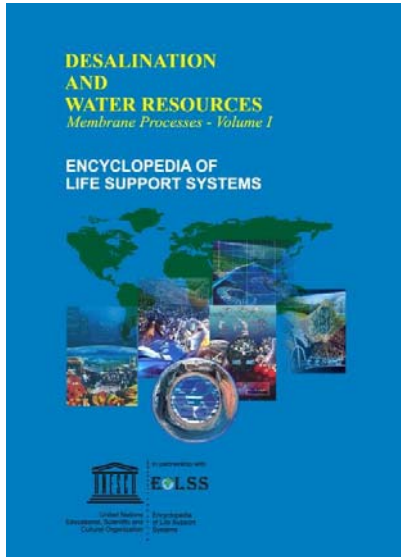


CONTENTS

DESALINATION AND WATER RESOURCES MEMBRANE PROCESSES



Membrane Processes - Volume 1

No. of Pages: 404

ISBN: 978-1-84826-427-4 (eBook)

ISBN: 978-1-84826-877-7 (Print Volume)

Membrane Processes - Volume 2

No. of Pages: 388

ISBN: 978-1-84826-428-1 (eBook)

ISBN: 978-1-84826-878-4 (Print Volume)

Membrane Processes - Volume 3

No. of Pages: 420

ISBN: 978-1-84826-417-5 (eBook)

ISBN: 978-1-84826-867-8 (Print Volume)

For more information of e-book and Print Volume(s) order, please [click here](#)

Or contact : eolssunesco@gmail.com

DESALINATION AND WATER RESOURCES (DESWARE)

International Editorial Board

Editor-in-Chief: Al-Gobaisi, D. M.K.

Members

Al Awadhi, A. Ali	Hammond, R. P.	Morris, R.
Al Radif, Adil	Hanbury, W. T.	Nada, N.
Al-Mutaz, I. S.	Harris, A.	Ohya, H.
Al-Sofi M.	Harrison, D.	Peluffo, P.
Andriane, J.	Hassan, A. M.	Rao, G. P.
Awerbuch, L.	Hodgekiess, T.	Rautenbach, R.
Balaban, M.	Husain, A.	Reddy, K. V.
Beraud-Sudreau, D.	Ismat, K.	Saal, D.
Birkett, James D.	Karabelas, A.J.	Sadhukhan, H.K.
Blanco, J.	Kesou, A.	Sage, A.P.
Bodendieck, F.	Krause, H. P.	Sarkodie-Gyan,
Borsani , R.	Kubota, S.	Thompson
Bushnak, A. A.	Kumar, A.	Sommariva, C.
Capilla, A. V.	Kurdali, A.	Strathmann, H.
Catanzaro, E.	Laborie, J.	Temperley, T.
Damak, S.	Leitner, G. F.	Tleimat B.
Darwish, M. Ali	Lennox, F. H.	Todd, B.
Delyannis, E.u E.	Lior, N.	Tony F.
Dempsey J.	Ludwig, H.	Tusel, G.
El-Din, S.	Lukin, G.	Belessiotis, V.
El-Mahgary, Y.	Magara, Y.	Veza, J. M.
El-Nashar, A. M.	Makkawi B.	Vigneswaran, S.
El-Sayed, Y. M.	Malato, S.	Wade, N. M.
Finan, M. A.	Mandil , M.A.	Wang, S.
Furukawa, D.	Marquardt, W.	Wangnick, K.
Genthner, K.	McArthur,N.	Woldai A.
Germana, A.	Meller, F. H.	Watson, I. C.
Ghiazza, E.	Mewes, V.	Wessling, M.
Glade, H.	Michels, T.	Winters, H.
Goto, T.	Miyatake, O.	
Grabow, W. O.K.	Morin, O. J.	

CONTENTS

VOLUME I

History And Current Status Of Membrane Desalination Processes

1

Ali M. El-Nashar, *Consultant, ICWES, Abu Dhabi, UAE*

1. Introduction
2. RO Process Fundamentals
 - 2.1 Osmosis and Reverse Osmosis
 - 2.2 Fundamentals of Pressure-Driven Membrane Processes
3. Feedwater Contaminants
4. General Characteristics of Membranes
5. RO Process Terminology
6. History of Membrane Technology
 - 6.1 Early History
 - 6.2 Recent History
7. Effect of Operating Variables on Membrane Parameters
 - 7.1 Water Recovery
 - 7.2 Permeate Flux
 - 7.3 Feed Water Temperature
 - 7.4 Feed Water Salinity and Quality
8. Feed Water Pretreatment & Permeate Post-Treatment
 - 8.1 Feedwater Pretreatment
 - 8.1.1 Seawater Intake Systems
 - 8.1.1.1 Surface Intake Systems
 - 8.1.1.2 Beach Wells System
 - 8.1.2 Coagulant/Flocculant Addition, Disinfection, Media Filtration, and Cartridge Filtration
 - 8.1.3 Membrane Pretreatment
 - 8.1.4 Comparison Between Conventional and Membrane Pretreatment
 - 8.2 Permeate Post-Treatment
9. Membrane Module Configurations
10. Membrane Fouling & Membrane Cleaning
 - 10.1 Membrane Fouling
 - 10.2 Biological Fouling
 - 10.3 Scaling
 - 10.4 Metal Oxide Fouling
 - 10.5 Membrane Cleaning
 - 10.5.1 Cleaning Equipment
 - 10.5.2 Cleaning Chemicals
11. Energy Requirements of Membrane Technology
 - 11.1 Minimum Energy Requirement for Separation
 - 11.2 Energy Recovery Systems
 - 11.2.1 Work and Pressure Exchangers
 - 11.2.2 Pelton Impulse Turbine (PIT)
 - 11.2.3 Hydraulic Turbocharger (HTC)
 - 11.2.4 Pressure Exchanger (PX)
 - 11.3 Actual Energy Requirement of RO Plants
12. Economics of RO Plants
13. Operational Performance and Design Features of Large Seawater RO Plants
 - 13.1 The Addur Seawater RO Plant
 - 13.2 Fujairah Seawater RO Plant
 - 13.3 Singapore Seawater RO Plant
 - 13.4 Barcelona Seawater RO Plant
 - 13.5 Curacao SWRO Desalination Plant
 - 13.6 Perth Seawater Desalination Plant (Australia)

14. CO₂ Emissions for Typical RO Plants
15. Recent Development in Membrane Technology
16. Boron, Arsenic and Organic Compound Removal
 - 16.1 Boron Removal
 - 16.1.1 Arsenic and Organic Compound Removal
 - 16.2 Research to Improve Membrane Fouling Resistance, Flux, and Selectivity
 - 16.3 Membrane Modification to Improve Fouling Resistance
 - 16.4 Carbon Nanotube(CNT)
 - 16.5 Thin Film Nanocomposite Membranes (TFNC)
 - 16.6 Biomimetic Membranes for Desalination
17. Conclusions

Membrane Science And Technology For Wastewater Reclamation

70

A.F. Ismail and E. Yuliwati, *Advanced Membrane Technology Research Centre (AMTEC), Universiti Teknologi Malaysia (UTM), 81310, Johor Bahru, Malaysia*

1. Introduction
2. Wastewater reclamation: An overview
 - 2.1. The Fundamentals of Wastewater Reclamation
 - 2.1.1. Evolution of Wastewater Reclamation
 - 2.1.2. Current Status
 - 2.1.3. Wastewater Reclamation and Its Future
 - 2.1.4. Wastewater Regulations
 - 2.1.5. Health and Environmental Concerns in Wastewater Management
 - 2.2. Wastewater Characteristics
 - 2.3. Wastewater Reclamation Process
 - 2.3.1. Primary Treatment
 - 2.3.2. Secondary Treatment
 - 2.3.3. Tertiary or Advanced Treatment
3. Fundamental of Membrane Technology in Wastewater Reclamation
 - 3.1. Membrane Definition and Process Terminology
 - 3.2. Membrane process classification
 - 3.3. Membrane Configurations
 - 3.3.1. Module Configuration and Pressure Development
 - 3.4. Membrane Operation
 - 3.4.1. Microfiltration and Ultrafiltration
 - 3.4.2. Nanofiltration
 - 3.4.3. Reverse Osmosis
 - 3.5. Membrane Fouling
 - 3.5.1. Type of Fouling
 - 3.5.2. Effect of Cross-Flow Velocity
 - 3.5.3. Effect of Membrane Surface Treatment
 - 3.5.4. Membrane Fouling Control
4. Membrane life
5. Membranes market size
 - 5.1. Investment Cost Analysis
6. Membrane Bioreactor (MBR)
 - 6.1. MBR Configurations and Commercial Technologies
 - 6.2. MBR Characteristics
 - 6.2.1. Physical Parameters
 - 6.2.2. Chemical Parameters
 - 6.3. Fouling Control in MBR
 - 6.4. MBR Design and Operation
 - 6.4.1. MBR System Operational Parameters
 - 6.4.2. Design Calculation
 - 6.5. Case Studies
 - 6.5.1. Solbegra Plant

- 6.5.2. Eden Project, St Austeel, Cornwall, UK
- 7. Reverse Osmosis (RO)
 - 7.1. Types of Membrane used in RO
 - 7.2. Application of Reverse Osmosis
 - 7.3. Design and Operational Considerations for RO Systems
 - 7.4. Process Operating Parameters
 - 7.5. Pilot-Scale Studies for RO
- 8. Conclusions

Membrane Characterization

131

Khulbe KC, Feng CY and Matsuura T, *Industrial Membrane Research Laboratory, Chemical and Biological Engineering Department, University of Ottawa, Ottawa, K1N 6N5, Canada*

- 1. Introduction
- 2. Pore Size Distribution Measurement
 - 2.1. Bubble Gas Transport Method
 - 2.2. Mercury Intrusion Porosimetry
 - 2.3. Adsorption-Desorption Method (Barett-Joyner-Halenda (BJH) Method) [7]
 - 2.4. Gas Liquid Equilibrium Method (Permporometry)
 - 2.4.1. Liquid Displacement Permporometry (LDP) [11]
 - 2.4.2. Diffusional Permporometry (DP) [17]
 - 2.5. Liquid Solid Equilibrium Method (Thermoporometry)
 - 2.6. Gas Permeability Method
 - 2.7. Mass Transportation
- 3. Membrane morphology
 - 3.1. Microscopic Method
 - 3.1.1. Scanning Electron Microscopy (SEM) and Transmission Electron Microscopy (TEM)
 - 3.1.2. Atomic Force Microscopy
 - 3.2. Spectroscopic Method
 - 3.2.1. Infrared (IR) and Fourier Transform Infrared (FTIR) Spectroscopy
 - 3.2.2. Raman Spectroscopy (RS)
 - 3.2.3. Electron Spin Resonance (ESR)
 - 3.2.4. Nuclear Magnetic Resonance (NMR)
 - 3.2.5. Wide Angle X-ray Scattering (WAXS)
 - 3.2.6. X-ray Photoelectron Spectroscopy (XPS)
 - 3.2.7. Small Angle Neutron Scattering (SANS)
 - 3.2.8. Positronium Annihilation Lifetime Spectroscopy (PALS)
 - 3.2.9. Ultrasonic Spectroscopy
- 4. Other Characterization Methods
 - 4.1. Contact Angle
 - 4.2. Surface Charge (Zeta Potential)
 - 4.3. Differential Scanning Calorimetry (DSC) and Thermogravimetry (TGA)
- 5. Mechanical properties
 - 5.1. Tensile Strength
 - 5.2. Young's Modulus of Elasticity
- 6. Conclusion

Principles And Practices Of Reverse Osmosis

173

O.J. Morin, *Black and Veatch, Florida, USA*

- 1. Introduction
 - 1.1. General
 - 1.2. Purpose
 - 1.3. Reference Design
- 2. Theory
 - 2.1. Reverse Osmosis

- 3. Basic Water Chemistry
 - 3.1. Introduction
 - 3.1.1. Common Chemistry Terms
 - 3.1.2. Example 3.1: Hydrogen and Hydroxide Ion Concentration
 - 3.2. Water Analysis
 - 3.2.1. Equivalent Weight Method
 - 3.2.2. Calcium Carbonate Equivalents
 - 3.2.3. Example 3.2: Equivalents per Million and Calcium Carbonate Equivalents
 - 3.3. Test Methods
 - 3.3.1. Titration
 - 3.3.2. Colorimetric
 - 3.3.3. Hardness Test
 - 3.3.4. Silt Density Index
 - 3.3.5. Turbidity
 - 3.3.6. Alkalinity Titration
 - 3.3.7. Chloride Test
- 4. Process Considerations
 - 4.1. Introduction
 - 4.1.1. Treatment Terms and Expressions
 - 4.2. Process Characteristics
 - 4.2.1. Removal Characteristics
 - 4.2.2. Process Configuration
 - 4.2.3. Membrane Configurations
 - 4.2.4. Membrane Arrangements
 - 4.2.5. Energy Requirements
- 5. Pretreatment
 - 5.1. Fouling
 - 5.1.1. Metals
 - 5.1.2. Particles and Colloids
 - 5.1.3. Biological Material
 - 5.1.4. Scale Formation
 - 5.1.5. Summary
- 6. Process Design
 - 6.1. Design Procedure
 - 6.2. Water Analysis
 - 6.3. Blending
 - 6.4. Recovery
 - 6.5. Number of Stages
 - 6.6. Flux Rate
 - 6.7. Operating Pressure
- 7. Posttreatment
 - 7.1. Introduction
 - 7.2. Finished Water Quality Goals
 - 7.3. Degassification
 - 7.4. Blending
 - 7.5. Chemical Treatment
 - 7.6. Disinfection
- 8. Brine Disposal
 - 8.1. Introduction
 - 8.2. Brine Classification
 - 8.3. Sewer Systems
 - 8.4. Deep Well Injection
 - 8.5. Surface Water Disposal
 - 8.6. Solar Evaporation Ponds
 - 8.7. Zero (Liquid) Discharge
- 9. Auxiliary Equipment
 - 9.1. Pumps
 - 9.1.1. HP Pump Design

- 9.2. Energy Recovery Equipment
- 9.3. Interstage Pumping
- 9.4. Piping and Valves
- 9.5. Controls
 - 9.5.1. Feed Water Control
 - 9.5.2. Permeate Production
 - 9.5.3. Brine Flow Control
 - 9.5.4. Chemical Feed
- 10. Operation and Maintenance
 - 10.1. Introduction
 - 10.2. Data Collection and Reporting
 - 10.2.1. Water Production
 - 10.2.2. Product Water Quality
 - 10.2.3. Membrane Profile
 - 10.2.4. Total Finished Water Quality
 - 10.2.5. System Performance
 - 10.2.6. Specific Energy Consumption
 - 10.2.7. Consumable Usage
 - 10.2.8. Operating Costs
 - 10.3. Data Normalization and Evaluation
 - 10.4. Membrane Cleaning
 - 10.5. Trouble Shooting
 - 10.5.1. Introduction
 - 10.5.2. Membrane Probing
 - 10.5.3. Scavenger Membrane
 - 10.6. Startup Procedure
 - 10.7. Shutdown Procedure
 - 10.8. Preventive Maintenance
 - 10.8.1. Pumps
 - 10.8.2. Instrumentation and Controls
- 11. Costs
 - 11.1. Introduction
 - 11.2. Process Considerations
 - 11.2.1. Recovery
 - 11.2.2. Concentrate Disposal
 - 11.2.3. Blending
 - 11.2.4. Electrical Consumption
 - 11.2.5. Pre-treatment
 - 11.2.6. Post-treatment
 - 11.3. Capital Cost
 - 11.3.1. Capital Cost Basis
 - 11.4. Operating Costs
 - 11.4.1. Operating Cost Basis

Reverse Osmosis: Introduction

269

S. Loeb, *Chemical Engineering Department, Ben-Gurion University, Beer Sheva, Israel*

- 1. Introduction
- 2. Historical Development
 - 2.1. Pioneering Work of Reid
 - 2.2. Anisotropic Membranes – Asymmetric Type
 - 2.3. Anisotropic Membranes – Composite Type (Cadotte and Petersen 1981)
 - 2.4. Module Geometries for Sheet Membranes (Dresner and Johnson 1980)
 - 2.5. Hollow Fibers and Hollow Fiber Modules
- 3. Principle of Reverse Osmosis
- 4. Technical and Economical Relevance of Reverse Osmosis

Hollow-Fiber Membranes

284

I. Moch Jr., *I. Moch and Associates Inc., Wilmington, Delaware, USA*

1. Introduction
2. Properties
 - 2.1. Basic Morphology
 - 2.2. Mechanical Considerations and Fiber Dimensions
3. Processing
 - 3.1. Spinning of Hollow-Fibers
 - 3.2. Spinnerets
 - 3.3. Melt Spinning
 - 3.4. Solution (Wet) Spinning
 - 3.5. Wet-and Dry-Jet Wet Spinning
 - 3.6. Macrovoids
 - 3.7. Fiber Treatment. Fiber Treatment In-Line
 - 3.8. Post-Treatment of the Hollow-Fibers
 - 3.9. Fiber Modification
 - 3.10. Composite Hollow-Fiber Membrane
 - 3.11. Interpenetrated Wall Matrix
 - 3.12. Fiber Handling and Unit Assembly
 - 3.13. Materials
 - 3.14. Cellulose
 - 3.15. Cellulose Ester
 - 3.16. Polysulfone
 - 3.17. Poly(Methyl Methacrylate) (PMMA)
 - 3.18. Polyamide
 - 3.19. Other Nitrogen Containing Polymers
 - 3.20 Glass and Inorganic Hollow-Fiber Membranes
 - 3.21. Others
4. Sorbent Fibers
 - 4.1. Filled Fibers
 - 4.2. Hollow-Fiber with Sorbent Walls
 - 4.3. Growth Prospects

Preparation And Characterization Of Ion-Exchange Membranes

318

T. Sata, *Yamaguchi University, Faculty of Engineering, Ohoshima Ohara 89-57, Tokuyama City, Yamaguchi Prefecture, 745 0803, Japan*

1. Introduction
2. Classification of Ion-exchange Membranes
3. Preparation of Ion-exchange Membranes
 - 3.1. General Preparation Methods
 - 3.1.1. Heterogeneous Membranes
 - 3.1.2. Membranes Prepared from Condensation of Monomeric Compounds
 - 3.1.3. Membranes Prepared by Polymerization of Vinyl Monomers
 - 3.1.4. Preparation of Membranes from Conventional Polymers
 - 3.1.5. Extrusion of Thermoplastic Polymers having Precursor Groups of Ion-exchange Groups into a Polymer Film and Conversion of the Groups into Ion-exchange Groups
 - 3.1.6. Preparation of Ion-exchange Membranes by Plasma Polymerization
 - 3.2. Preparation of Cation Exchange Membranes
 - 3.3. Preparation of Anion Exchange Membranes
 - 3.4. Ion-exchange Membranes having Special Functions
 - 3.4.1. Cation Exchange Membranes having Permselectivity for Monovalent Cations
 - 3.4.2. Anion Exchange Membranes having Permselectivity for a Specific Anion
 - 3.4.3. Anion Exchange Membranes with High Acid Retention
 - 3.4.4. Anti-fouling Ion-exchange Membranes
 - 3.4.5. Ion-exchange Membranes for Diffusion Dialysis

- 3.4.6. Cation Exchange Membranes for Chlor-alkali Production
- 3.4.7. Bipolar Ion-exchange Membranes
- 3.4.8. Mosaic Ion-exchange Membranes
- 4. Characterization of Ion-exchange Membranes
 - 4.1. Measurement of Electrical Resistance
 - 4.2. Measurement of Transport Number
 - 4.3. Determination of Ion-exchange Capacity and Water Content
 - 4.4. Diffusion Coefficient of Electrolytes through Membranes
 - 4.5. Water Transport
 - 4.6. Chemical Stability
- 5. Properties of Commercial Ion-exchange Membranes

Index **367**

About DESWARE **375**

VOLUME II

Preparation And Characterization Of Micro- And Ultrafiltration Membranes **1**
 G.H. Koops, *Department of Chemical Technology, University of Twente, The Netherlands*

- 1. Preparation of Micro- and Ultrafiltration Membranes
 - 1.1. Classification of Micro- and Ultrafiltration Membranes
 - 1.1.1. Materials
 - 1.1.2. Hydrophilicity and Hydrophobicity
 - 1.1.3. Geometries
 - 1.1.4. Structures
 - 1.1.5. Surface Charge
 - 1.2. Preparation of Filtration Membranes
 - 1.2.1. Inorganic Membranes
 - 1.2.1.1. Ceramic Membranes
 - 1.2.1.2. The Substrate
 - 1.2.1.3. Micro- and Ultrafiltration Coating Layers
 - 1.2.1.4. The Sol-gel Process
 - 1.2.1.5. Template Leaching
 - 1.2.1.6. Etching Techniques
 - 1.2.2. Polymeric Membranes
 - 1.2.2.1. Sintering
 - 1.2.2.2. Controlled Stretching
 - 1.2.2.3. Track Etching
 - 1.2.2.4. Phase Inversion
 - 1.2.2.5. Precipitation by Controlled Evaporation
 - 1.2.2.6. Precipitation by Vapor Penetration
 - 1.2.2.7. Precipitation by Immersion
 - 1.2.2.8. Precipitation by a Dual-bath Immersion System
 - 1.2.2.9. Thermally Induced Phase Separation (TIPS)
 - 1.2.2.10. Polymerization Induced Phase Separation
 - 1.2.2.11. Composite Membranes
 - 1.2.2.12. Dynamically Formed Membranes
 - 1.2.2.13. S-layer Ultrafiltration Membranes
- 2. Characterization of Micro- and Ultrafiltration Membranes
 - 2.1. Pure Water Flux
 - 2.2. Microscopy Techniques
 - 2.3. Sieving
 - 2.4. Retention and Molecular Weight Cut-off

- 2.5. Bacterial Challenge Test
- 2.6. Latex Sphere Retention Test
- 2.7. Bubble Point Method
- 2.8. Diffusion Test
- 2.9. Pore Size and Pore Size Distribution
 - 2.9.1. Mercury Porosimetry
 - 2.9.2. Gas-Liquid Displacement
 - 2.9.3. Liquid-Liquid Displacement
 - 2.9.4. Thermoporometry
 - 2.9.5. Gas Adsorption/Desorption
 - 2.9.6. Permporometry
- 2.10. Surface Analysis
 - 2.10.1. Surface Charge
 - 2.10.2. Surface Composition
- 2.11. Mechanical, Thermal and Chemical Stability
 - 2.11.1. Mechanical Stability
 - 2.11.2. Chemical and Temperature Stability

Membrane Distillation

62

Enrico Drioli and Alessandra Criscuoli, *Research Institute on Membranes and Chemical Reactors, Consiglio Nazionale delle Ricerche, c/o Dept. of Chemical and Mat. Eng., University of Calabria, Via P. Bucci, 87030 Rende (CS), Italy*

Louis Peña Molero, *On leave from Universidad Complutense de Madrid, Facultad de Ciencias Físicas, Departamento de Física Aplicada I, 28040 Madrid, Spain*

- 1. Introduction
 - 1.1. Principle of Membrane Distillation
 - 1.2. Future Development
- 2. Fundamentals of Membrane Distillation
 - 2.1. Process Description and Terminology
 - 2.2. Transport Phenomena in Membrane Distillation
 - 2.2.1. Membrane Transport Models
 - 2.2.2. Heat Transfer
 - 2.2.3. Mass Transfer Mechanisms
 - 2.2.3.1. Non volatile solutes
 - 2.2.3.2. Volatile solutes
 - 2.3. Membrane Distillation System Configuration
 - 2.3.1. Direct Contact Membrane Distillation (DCMD)
 - 2.3.2. Gas-gap Membrane Distillation (GGMD)
 - 2.3.3. Vacuum Membrane Distillation (VMD)
 - 2.3.4. Sweeping-gas Membrane Distillation (SGMD)
 - 2.3.5. Osmotic Membrane Distillation (OMD)
- 3. Membranes for Membrane Distillation
 - 3.1. Preparation of MD Membranes
 - 3.1.1. Commercial Membranes
 - 3.1.1.1. Membrane Materials
 - 3.1.2. Membrane Distillation Membranes in Development
- 4. Process and Equipment in Membrane Distillation
 - 4.1. MD modules
 - 4.1.1. Flat Membranes
 - 4.1.1.1. Plate-and-frame Modules
 - 4.1.1.2. Spiral-wound Modules
 - 4.1.2. Tubular Membranes
 - 4.1.2.1. Tubular Membranes Modules
 - 4.1.2.2. Capillary Membrane Modules
 - 4.1.2.3. Hollow Fiber Modules
 - 4.1.3. Comparison between the Different Module Configurations

- 4.2. System design
 - 4.2.1. Basic Plant Construction
 - 4.2.2. Energy Requirements in Membrane Distillation
 - 4.2.3. Pre-treatment
 - 4.2.4. Fouling and Wetting Processes
- 5. Membrane Distillation Applications
 - 5.1. Water Desalination
 - 5.2. Treatment of Waste-water
 - 5.3. Concentration of Fruit Juice
 - 5.4. Concentration of Chemical and Biological Solutions
- 6. Integrated Membrane Distillation Systems
 - 6.1. Case Studies

Desalination By Membrane Distillation

116

Mohamed Khayet, *Department of Applied Physics I, Faculty of Physics, University Complutense of Madrid, Avda. Complutense s/n, 28040, Madrid, Spain*

- 1. Introduction
- 2. Membrane Distillation (MD)
- 3. MD configurations
 - 3.1. Direct Contact Membrane Distillation (DCMD)
 - 3.2. Air Gap Membrane Distillation (AGMD)
 - 3.3. Sweeping Gas Membrane Distillation (SGMD)
 - 3.4. Vacuum Membrane Distillation (VMD)
- 4. Membranes and modules used in MD
- 5. Application of MD technology in desalination
 - 5.1. Effects of Membrane Characteristics
 - 5.1.1. Effects of Membrane Porosity and Thermal Conductivity
 - 5.1.2. Effects of Membrane Thickness and Pore Tortuosity
 - 5.1.3. Effects of Membrane Pore Size and its Distribution
 - 5.2. Effects of MD Process Conditions
 - 5.2.1. Effects of Feed Temperature
 - 5.2.2. Effects of Salt Concentration of the Feed Aqueous Solution
 - 5.2.3. Effects of Feed Flow Rate
 - 5.2.4. Effects of Permeate Conditions
 - 5.2.4.1. Permeate Temperature in DCMD, SGMD and AGMD
 - 5.2.4.2. Permeate Flow Rate in DCMD and SGMD
 - 5.2.4.3. Air Gap Width in AGMD
 - 5.2.4.4. Permeate Pressure in VMD
 - 5.3. Efficiency, Energy Analysis, Costs and MD Integrated Systems
- 6. Conclusions

Pervaporation

175

R.W. Baker, *Membrane Technology and Research, Inc. Menlo Park, CA, USA*
 J.G. Wijmans, *Membrane Technology and Research, Inc. Menlo Park, CA, USA*

- 1. Introduction
- 2. Fundamentals of Pervaporation
- 3. Membranes and Modules
- 4. Process and Equipment Design
 - 4.1. Concentration Polarization
 - 4.1.1. Measurement of the Peclet Number
 - 4.1.2. Effect of Membrane Type and Membrane Thickness
 - 4.1.3. Effect of Permeate Pressure
 - 4.2. Process Design

5. Applications of Pervaporation
 - 5.1. Wastewater Treatment
 - 5.2. Treatment of Fine Chemicals/Pharmaceuticals Process Streams
 - 5.3. Food Industry Applications
6. Conclusions and Future Directions

Dialysis And Diffusion Dialysis**211**T.A. Davis, *Independent Consultant, 5 Davis Farm Road, Annandale, NJ 08801, USA*

1. Introduction
2. The Principles of the Process and Fundamentals
 - 2.1. Mathematical Analysis
 - 2.2. Complicating Factors in Process Modeling
3. Technical and Economic Relevance
4. Membranes
5. Process and Equipment Design
 - 5.1. Dialyzer Design
 - 5.2. Process Design
6. Process Costs, Operational Problems, and Limitations of the Process
 - 6.1. Process Costs
 - 6.2. Operational Problems
 - 6.3. Process Limitations
7. Applications
8. Supplier Industry
9. Conclusions, Research Needs, and Future Outlook

Donnan Dialysis**230**T.A. Davis, *Independent Consultant, 5 Davis Farm Road, Annandale, NJ 08801 USA*

1. Introduction
2. Principles and Fundamentals
3. Technical and Economic Relevance
4. Membrane and System Development
5. Process and Equipment Design
6. Process Costs, Operational Problems, and Limitations of the Process
7. Applications
8. Supplier Industry
9. Conclusions, Research Needs, and Future Outlook

Modeling And Calculation Of Pressure-Driven Membrane Processes**242**Sergei P. Agashichev, *D. Mendelejev University of Chemical Technology, Moscow-125047, Russia. International Centre for Water and Energy Systems, Abu Dhabi, UAE*

1. Introduction
2. General Framework and Formulation of the Problem
 - 2.1. Premises and Assumptions Underlying Transport Submodels for Liquid Phases
 - 2.2. Ancillary Submodels for Shear Rate, Shear Stress, Apparent Viscosity, Velocity and Concentration Profiles
 - 2.2.1. Dimensionless Coordinates
 - 2.2.2. Balance Equation
 - 2.2.3. Shear Rate Field
 - 2.2.4. Apparent Viscosity Field
 - 2.2.5. Velocity Field
 - 2.2.6. Concentration Field
3. Concentration Polarization

- 3.1. Modeling Concentration Polarization in Channels of Plate-and-Frame Configuration
 - 3.1.1. Premises and Input Mathematical Formulations
 - 3.1.2. Modeling Tangential Distribution of CP Degree
 - 3.1.3. Implication and Analysis of the Model
- 3.2. Modeling and Calculation of Concentration Polarization in Tubular Channels
 - 3.2.1. Premises and Input Mathematical Formulation
 - 3.2.2. Modeling Tangential Distribution of CP Degree
 - 3.2.3. Implication and Analysis of Submodel
 - 3.2.3.1. Analysis of Influence of Rheological Parameters of Fluid
 - 3.2.3.2. Analysis of Influence of Membrane Solute Rejection
 - 3.2.3.3. Analysis of Influence of Transmembrane Flux
- 3.3. Modeling Concentration Polarization Phenomena for Shell-side Flow
 - 3.3.1. Premises and Input Mathematical Formulations
 - 3.3.2. Modeling Tangential Distribution of CP Degree
 - 3.3.3. Implication and Analysis of Submodel
- 4. Accumulation of Gel or Porous Precipitate on Membrane Surface
 - 4.1. Mass Balance
 - 4.2. Non-Newtonian Behavior and Tangential Flow of Gel
 - 4.2.1. Shear Rate Field
 - 4.2.2. Apparent Viscosity
 - 4.2.3. Gel Velocity Field
 - 4.2.4. Shear Stress Field
 - 4.3. Flow Through Porous Precipitate
 - 4.3.1. Compressibility of Cake
- 5. Transport Through Porous Membranes Matrix
 - 5.1. Simplifying Assumptions and Underlying Premises
 - 5.1.1. Membrane Matrix
 - 5.1.2. Flow
 - 5.1.3. Suspended Phase
 - 5.2. Modeling Transmembrane Flow of Solvent
 - 5.2.1. Flow Through Individual Membrane Pore with Arbitrary Radius
 - 5.2.2. Flow Through all Spectrum of Pores
 - 5.2.3. Implication and Analysis of Submodel
 - 5.3. Modeling Membrane Resistance
 - 5.3.1. Specific Energy Losses Due to Friction in Individual Membrane Pore
 - 5.3.2. Overall Viscous Losses
 - 5.3.3. Implication and Analysis of Submodel
 - 5.4. Modeling Transmembrane Transport of Suspended Phase
 - 5.4.1. Underlying Premises and Modeling
 - 5.4.2. Implication and Analysis of Submodel
- 6. Modeling Driving Force
 - 6.1. Simplifying Assumptions and Underlying Premises
 - 6.2. Modeling
 - 6.3. Implication and Analysis of Submodel
- 7. Appendix
 - 7.1. Appendix-3.1.A
 - 7.2. Appendix-3.1-B
 - 7.3. Appendix-3.2.A
 - 7.4. Appendix-3.2.B
 - 7.5. Appendix-3.2.C
 - 7.6. Appendix-3.3.A
 - 7.7. Appendix-3.3.B
 - 7.8. Appendix-4.2.A
 - 7.9. Appendix-5.3A
 - 7.10. Appendix-6.A
 - 7.11. Appendix-6.B
 - 7.12. Appendix-6.C
 - 7.13. Appendix-6.D

Index	353
About DESWARE	359

VOLUME III

Survey Of Theoretical Approaches To Modeling Pressure-Driven Membrane Processes (Submodels For Transport In Phases) 1

Sergei P. Agashichev, *International Center for Water and Energy Systems, Abu Dhabi, UAE;*
D. Mendelejev University of Chemical Technology, Moscow, 125047, Russia

1. Introduction
2. Modeling Hydrodynamic Field
 - 2.1. Hydrodynamic Field in Symmetric Semipermeable Channel Having Rectangular Cross Section
 - 2.2. Hydrodynamic Field in Cylindrical Channel
 - 2.2.1. Solution for Cylindrical Channel Under Small Transmembrane Reynolds Numbers (Re_z)
 - 2.2.2. Solution for Cylinder Channel Under Large Transmembrane Reynolds Numbers (Re_z)
 - 2.3. Asymmetric Flow Field in Plate-and-frame Type Channel
 - 2.4. Shell Side Flow
 - 2.5. Submodels for Transverse Velocity
3. Modeling Concentration Field
 - 3.1. Modeling Concentration Field for Unstirred Batch Cell Systems
 - 3.2. Modeling Concentration Field for Membrane Systems of Cross-flow Type
 - 3.2.1. Solution for Convective Diffusion Equation Having Two Convective and One Diffusion Terms (Solution proposed by P. Brian)
 - 3.2.2. Solution for Convective Diffusion Equation Having Two Convective and One Diffusion Terms (Solution proposed by T. Sherwood, P. Brian R. Fisher and L. Dresner)
 - 3.2.2.1. Infinite Series Solution to Equation of Convection Diffusion
 - 3.2.2.2. Approximate Analytical Solution
 - 3.2.3. Numerical Solution for Steady State Two-dimensional Convective Diffusion Equation Having Two Convective and One Diffusion Terms (Solution proposed by Lee and Clark)
 - 3.2.4. Approach Based on One-dimensional Film Theory Model
 - 3.2.4.1. Membrane with Ideal Rejection ($R = 1$)
 - 3.2.4.2. Non-ideal Membrane ($R < 1$)
 - 3.3. Modeling Concentration Field Under Condition of Shear-induced Diffusion
 - 3.3.1. Similarity Solution for Steady State Convective Diffusion Equation Assuming Concentration Dependent Shear Viscosity and Shear Induced Diffusivity (Solution is proposed by Davis and Sherwood)
 - 3.4. Calculation of Mass Transfer Coefficients
 - 3.4.1. Mass Transfer Coefficient in Laminar Flow
 - 3.4.2. Mass Transfer Coefficients Turbulent Flow
 - 3.4.2.1. Influence of Free Convection
4. Modeling Cake or Gel Layer Growth and Accumulation
 - 4.1. Statement of the Problem: Main Factors and Variables
 - 4.2. Gel-polarization Models and Their Modifications
 - 4.3. Approaches Based on the Standard Filtration Theory
 - 4.4. Approach Based on Consideration of Lateral Migration Phenomena
 - 4.5. Approach Based on Analysis of Particle Trajectory
 - 4.6. Approach Based on Analysis of the Forces Acting on a Particle
 - 4.7. Modeling Blocking Phenomena
 - 4.8. Modeling Cake Compressibility

Reverse Osmosis Process And System Design 78

Y. Taniguchi, *Water Reuse Promotion Center, Japan*
H. Ohya, *Department of Chemical Engineering, Yokohama National University, Japan*

1. General Considerations
 - 1.1. Applied Pressure
 - 1.2. Concentration Factor
 - 1.3. Recovery Ratio
 - 1.4. Feed Temperature
 - 1.5. Removal of Suspended Matter
 - 1.6. pH Range
 - 1.7. Disinfectant Dosing Rate
 - 1.8. Feed Flow Rate and Brine Flow Rate
2. Basic Reverse Osmosis Plant Construction
 - 2.1. Feedwater Supply Facility
 - 2.2. Pre-treatment Facility
 - 2.3. Reverse Osmosis Facility
 - 2.4. Post Treatment Facility
 - 2.5. Water Supply and Distribution Facility
3. Basic Principles Involved in Reverse Osmosis Process
 - 3.1. Applied Pressure and Membrane Performance
 - 3.2. Arrangement of Reverse Osmosis Modules
4. Feed Water Pre- and Productwater Post-treatment Procedures
 - 4.1. Feedwater Pre-treatment
 - 4.1.1. The Sterilization
 - 4.1.2. Coagulation, Sedimentation and Filtration
 - 4.1.3. Chemical Injection Facilities
 - 4.2. Productwater Post-treatment
5. Operational Problems of Reverse Osmosis System
 - 5.1. General Review
 - 5.2. Examples of Operational Problems
 - 5.2.1. Chemical Attack
 - 5.2.2. Physical Attack
6. Instrumentation and Automation
 - 6.1. Introduction
 - 6.2. Basic Control Concepts
 - 6.3. Control Panel and the Operator

Practical Aspects Of Large-Scale Reverse Osmosis Applications

100

M. Kishi, *Mechano Chemical Research Institute, Japan*

Ichiro Kawada, *Nitto Denko Corporation Japan*

Keuuchi Ohta, *Water Reuse Promotion Center, Japan*

Mituhaur Furuichi, *Kurita Water Industry, Japan*

Makio Tamura, *Central Research Laboratories, Organo Corporation, Japan*

Yoshinari Fussaoka, *Toray Industries, Inc., Japan*

Yoshiaki Nakanishi, *Daicel Chemical Industry Ltd, Japan*

1. Seawater Desalination
 - 1.1. Outline of Seawater Desalination Plant
 - 1.2. Process and Equipment Design
 - 1.2.1. Seawater Intake Facilities
 - 1.2.2. Pre-treatment Equipment
 - 1.2.3. Chemical Dosing Facilities
 - 1.2.4. Check-Filters
 - 1.2.5. High Pressure Pump and Recovery Turbines
 - 1.2.6. Design of an RO Module
 - 1.2.7. Post Treatment
 - 1.2.8. Examples of Actual Product Water Post Treatment for an RO Plant
 - 1.3. Product Water Cost
 - 1.3.1. Construction Cost and Depreciation Rate

- 1.3.2. Electric Power Consumption Rate and Electricity Cost
- 1.3.3. Membrane Replacement Cost
- 1.3.4. Examples of Cost Calculation
- 1.4. Operational Problems and Other Technical Information
 - 1.4.1. Plant Operation
 - 1.4.2. Feed Seawater Quality Control for RO membrane
 - 1.4.3. Operational Problems
- 2. Brackish Water Desalination
 - 2.1. Principle of the Process
 - 2.1.1. An Outline of Brackish Water Desalination by RO
 - 2.1.2. Brackish Water Desalination by RO Process
 - 2.2. Process, Design of the Equipment and the Process Costs
 - 2.2.1. Pre-treatment Process
 - 2.2.2. RO Desalination Equipment
 - 2.2.2.1. RO Desalination Equipment
 - 2.2.2.2. Advancement of RO Membrane
 - 2.2.2.3. Design of RO System
 - 2.2.3. Cost
 - 2.2.3.1. Components of Annual Expenditure for Brackish water Desalination Plant
 - 2.2.3.2. Fluctuating Factors for the Unit Cost of Brackish Water Desalination Plant
 - 2.2.3.3. Cost Deduction Plan
 - 2.2.4. Example of Large-Scale Brackish Water Desalination Plant
 - 2.2.4.1. Yuma Desalting Plant of 274 000 m³ d⁻¹ in Arizona, USA
 - 2.2.4.2. Englewood RO Desalination Plant of 7600 m³ d⁻¹ in Florida, USA
 - 2.3. Operational Problems and Technical Limitation
 - 2.3.1. Resistance to Oxidizing Agents
 - 2.3.2. Degradation and Fouling for RO Membrane
 - 2.4. Feedwater Pre-treatment
 - 2.4.1. Pre-treatment and Investigation of Raw Water Quality by Water Resource
 - 2.4.2. Types and Features of Pre-treatment Systems
 - 2.4.2.1. Coagulation and Sedimentation
 - 2.4.2.2. Coagulation Filtration Process
 - 2.4.2.3. Water-softening
 - 2.4.2.4. Iron Removal and Demanganese
 - 2.4.2.5. Desilicate
 - 2.4.2.6. Activated Carbon Filtration
 - 2.4.2.7. Pre-treatment by Membrane
 - 2.4.3. Analysis and Evaluation
 - 2.4.3.1. Feedwater Analysis
 - 2.4.3.2. Trace Analysis for Suspended Solids
 - 2.5. Product Water Post-treatment
 - 2.5.1. Characteristic of Desalinated Water
 - 2.5.2. Post-treatment
- 3. Wastewater Treatment
 - 3.1. Process Principles
 - 3.1.1. Application of Reverse Osmosis Technology in Wastewater Treatment
 - 3.1.2. Various Wastewater Treatment Processes and Role of Reverse Osmosis
 - 3.1.3. Reverse Osmosis Membrane Modules
 - 3.2. Process and Equipment Design
 - 3.2.1. Design Considerations
 - 3.2.1.1. Selection of RO membrane
 - 3.2.1.2. Setting of Operating Conditions
 - 3.2.1.3. Number of RO Membrane Modules and Configuration
 - 3.2.1.4. Cleaning of RO Membrane Modules
 - 3.2.1.5. Pre-treatment
 - 3.2.2. Application Examples
 - 3.2.2.1. Reclamation Points for Treated Municipal Sewage
 - 3.3. Operational Problems and Technical Limitations

- 3.3.1. Fall in Permeate Quantity and Rise in Operating Pressure
- 3.3.2. Regeneration of Membrane Modules by Cleaning
- 3.3.3. Periodical Inspection and Maintenance
- 3.4. Feed Water Pre-treatment
- 3.5. Product Water Post-treatment
- 4. Other Applications of Reverse Osmosis
 - 4.1. Treatment of Surface Water by Reverse Osmosis
 - 4.2. Preparation of Ultra-pure Water
 - 4.3. Reverse Osmosis in the Chemical Industry
 - 4.3.1. Introduction
 - 4.3.2. RO Performance of PEC-1000 Membrane
 - 4.3.3. Concentration of ϵ -Caprolactam by PEC-1000 Membrane
 - 4.3.4. Basic Experiment with Actual Process Waste Stream
 - 4.3.5. Field Test
 - 4.3.6. Membrane Cleaning
 - 4.3.7. Estimation of Membrane Life
 - 4.3.8. Reverse Osmosis Plant
 - 4.3.9. Status of Reverse Osmosis Plant Operation
 - 4.4. Reverse Osmosis in the Food and Beverage Industry
 - 4.4.1. Application to Food and Beverage
 - 4.4.2. Tomato Juice Concentration by RO Membrane
 - 4.4.2.1. Process Flow
 - 4.4.2.2. Operating Condition of RO System
 - 4.4.3. Grape Juice Concentration for Wine by RO Membrane
 - 4.4.3.1. Process Flow

Health, Safety And Environmental Considerations

178

Y. Magara, *Urban Environment Engineering, School of Engineering, Hokkaido University, Japan*
 S. Iso, *Tokyo Kyuei Co. Ltd., Japan*

- 1. Health Hazards of Reverse Osmosis Water Desalination
 - 1.1. Quality of Production Water
 - 1.2. Health Hazards due to By-products of Operation
- 2. Reverse Osmosis Effect on the Environment
 - 2.1. Properties of Concentrated Seawater
 - 2.2. Effects of Highly-concentrated Salinity Water on Marine Organisms
 - 2.3. Brine Diffusion

Membrane Separation Technologies

189

Takeshi Matsuura, *Department of Chemical Engineering, University of Ottawa, Ottawa, Ont. Canada*

- 1. History
- 2. Definition and classification
- 3. Performance parameters
- 4. Membrane separation processes where the driving force is pressure
 - 4.1. Reverse osmosis
 - 4.1.1. Principle of reverse osmosis
 - 4.1.2. Membrane materials and membrane structure
 - 4.1.3. Transport
 - 4.1.4. Concentration polarization
 - 4.1.5. Membrane modules
 - 4.1.6. Applications
 - 4.2. Nanofiltration, ultrafiltration and microfiltration
 - 4.2.1. Description of the processes
 - 4.2.2. Membrane materials and membrane structure
 - 4.2.3. Gel model for ultrafiltration

- 4.2.4. Brownian diffusion, lateral migration and shear induced diffusion in microfiltration
- 4.2.5. Applications
- 5. Membrane separation processes where the driving force is partial pressure
 - 5.1. Membrane gas separation
 - 5.1.1. Description of the process
 - 5.1.2. Transport model
 - 5.1.3. Applications
 - 5.2. Pervaporation
 - 5.2.1. Description of the process
 - 5.2.2. Transport
 - 5.2.3. Applications
 - 5.3. Recovery of vapor from air
- 6. Membrane process where the driving force is difference in electrical potential
 - 6.1. Electrodialysis
 - 6.2. Bipolar membrane
- 7. Other membrane processes
 - 7.1. Membrane distillation
 - 7.2. Membrane extraction
 - 7.3. Membrane reactor
 - 7.4. Hybrid processes

Concentration Of Liquid Foods**226**Hernandez, Ernesto, *OmegaPure Technology and Innovation Center, Houston, Texas, USA*

- 1. Introduction
- 2. Physical Properties of Liquid Foods
- 3. Concentration by Evaporation
 - 3.1. Evaporator Types and Applications
 - 3.2. Design of Evaporators
 - 3.2.1. Multiple-Effect Evaporators
 - 3.3. Fouling
 - 3.4. Food Applications
- 4. Concentration with Membranes
 - 4.1. Concentration by Reverse Osmosis
 - 4.2. Design Considerations
 - 4.3. Construction Materials
 - 4.4. Membrane Configurations
 - 4.5. Concentration by Direct Osmosis
 - 4.6. Concentration by Membrane Distillation
 - 4.7. Concentration by Osmotic Distillation
- 5. Combined Technologies in the Concentration of Liquid Foods
- 6. Freeze Concentration

Mass Transfer Operation–Membrane Separations**250**

Enrico Drioli, Efram Curcio and Enrica Fontananova, *Institute on Membrane Technology, ITM-CNR, c/o University of Calabria, Rende (CS), Italy*
Department of Chemical Engineering and Materials, University of Calabria, Rende (CS), Italy

- 1. Introduction
- 2. An overview on the most industrialized membrane separation processes and emerging applications
 - 2.1. Pressure driven membrane processes
 - 2.1.1. Reverse osmosis
 - 2.1.2. Nanofiltration
 - 2.1.3. Ultrafiltration
 - 2.1.4. Microfiltration
 - 2.2. Electrodialysis

- 2.3. Gas separation
- 2.4. Pervaporation and vapor permeation
- 2.5. Membrane contactors
 - 2.5.1. Membrane distillation
 - 2.5.2. Membrane crystallization
 - 2.5.3. Membrane emulsification
- 2.6. Catalytic membranes reactors
3. Sustainable growth and integrated membrane operations
 - 3.1. Case study 1: Membrane technology in desalination
 - 3.2. Case study 2: Membrane technology in fruit juices industry
 - 3.3. Case study 3: Membrane technology for wastewaters treatment in the leather industry
4. Conclusions

Mass Transfer Operations: Hybrid Membrane Processes

307

E. Drioli, E. Curcio and E. Fontananova, *National Research Council of Italy, Institute on Membrane Technology (ITALY)*
Department of Chemical Engineering and Materials, University of Calabria (ITALY)

1. Introduction
2. Hybrid Membrane Desalination Systems
 - 2.1. MSF/RO Systems
 - 2.2. NF/MSF Systems
 - 2.3. MF and UF as Pretreatment Processes
3. Integrated membrane systems in agrofood industry
4. Hybrid membrane operations for wastewater treatment
5. Integrated membrane operations in Gas Separation
6. Integration of molecular separation and chemical/energy conversion
 - 6.1. Catalytic Membrane Reactors
 - 6.2. Fuel Cells
7. Conclusions

Recent Advances In Membrane Science And Technology In Seawater Desalination – With Technology Development In The Middle East And Singapore

330

Takeshi Matsuura and Dipak Rana, *Industrial Membrane Research Laboratory, Department of Chemical and Biological Engineering, University of Ottawa, 161 Louis Pasteur, Ottawa, Ont. K1N 6N5, Canada*
 Mohamed Rasool Qtaishat, *Chemical Engineering Department, University of Jordan, Amman 11942, Jordan*
 Gurdev Singh, *Centre of Innovation, Environmental & Water Technology, Ngee Ann Polytechnic, 535 Clementi Road, 599489 Singapore*

1. Introduction
2. Membrane processes for desalination: overview
 - 2.1. Reverse osmosis history
 - 2.2. Asymmetric structure of the membrane
 - 2.3. Phase inversion technique-preparation of integrally skinned asymmetric membranes
 - 2.4. Interfacial *in-situ* polymerization-preparation of thin film composite membranes
 - 2.5. Membrane performance enhancement by surface modification
 - 2.6. RO membrane transport
 - 2.7. Reverse osmosis module
 - 2.8. Improvement of membrane performance; boron removal, chlorine tolerance, and antibiofouling membrane
 - 2.9. New membrane processes for seawater desalination and water treatment (membrane distillation and forward osmosis)
 - 2.10. Carbon nanotube membrane
3. Case study I: Membrane desalination in the Middle East
 - 3.1. Membrane desalination in the Arab world

- 3.2. Membrane desalination status in Saudi Arabia
- 3.3. Membrane desalination status in Bahrain
- 3.4. Membrane desalination status in Kuwait
- 3.5. Membrane desalination status in the United Arab Emirates
- 3.6. Membrane desalination status in Oman
- 3.7. Membrane desalination status in the Gulf Cooperation Council countries
- 3.8. Membrane desalination status in Jordan and Palestine
 - 3.8.1. Red to Dead conveyer project
- 3.9. Membrane desalination status in Israel
 - 3.9.1. Ashkelon the largest SWRO plant in the world (2005-2011)
 - 3.9.2. Ashkelon plant design and special features
 - 3.9.3. Future trends of membrane desalination in Israel
- 3.10. Membrane desalination status in Egypt
- 3.11. Membrane desalination status in Algeria
- 3.12. Membrane desalination status in Tunisia
- 3.13. Membrane desalination status in Iran
- 4. Case study II: Membrane desalination in Singapore
 - 4.1. National water taps policies
 - 4.1.1. 1st National tap: Catchment area
 - 4.1.2. 2nd National tap: Imported water
 - 4.1.3. 3rd National tap: NEWater
 - 4.1.4. 4th National tap: Desalination in Singapore
 - 4.2. First desalination plant in Singapore
 - 4.3. Technologies to further reduce energy consumption of desalination
 - 4.4. Reducing energy consumption of desalination to 0.75 kWh/m³
- 5. Conclusions and future outlooks

Index **383**

About DESWARE **391**