

Contents

Preface *XI*

1	The Basics	<i>1</i>
1.1	General Introduction and Historical Perspective	<i>1</i>
1.2	The Basics of Membrane Separation	<i>4</i>
1.3	Membrane Separation Processes	<i>8</i>
1.4	The Morphology of Membranes	<i>11</i>
1.5	Membrane Modules	<i>15</i>
1.6	Fouling and Cleaning	<i>18</i>
1.6.1	Fouling	<i>18</i>
1.6.2	Cleaning	<i>20</i>
1.7	Ceramic versus Polymer Membranes	<i>22</i>
1.8	Raw Materials for Ceramic Membranes	<i>25</i>
1.8.1	Alumina	<i>26</i>
1.8.2	Silica	<i>27</i>
1.8.3	Titania	<i>28</i>
1.8.4	Zirconia	<i>29</i>
1.8.5	Zeolites	<i>30</i>
1.9	Preparation of Ceramic Membranes	<i>32</i>
1.9.1	Support Your Local Membrane	<i>32</i>
1.9.1.1	Forming the Initial Slurry	<i>34</i>
1.9.1.2	Mixing and Pugging	<i>39</i>
1.9.1.3	Shaping the Slurry	<i>41</i>
1.9.2	Drying and Thermolysis	<i>42</i>
1.9.3	Sintering	<i>45</i>
1.9.3.1	Sintering Variables	<i>50</i>
1.9.4	Finishing	<i>53</i>
1.10	Intermediate and Top Layers	<i>54</i>
1.10.1	Preparing the Intermediate Layers	<i>56</i>
1.10.2	Fundamentals of Chemical Vapour Deposition	<i>58</i>
1.10.3	Sol-Gel Coating	<i>66</i>
1.10.4	Zeolite Coating	<i>69</i>

- 1.11 Industrial Applications of Ceramic Membranes 73
- 1.12 Further Reading 74
- References 79

- 2 Fundamentals of Membrane Separation 91**
- 2.1 A Short Introduction to Mass Transfer Phenomena 91
- 2.2 Fick's Law 96
- 2.3 The Mass Diffusivity D_{AB} 99
- 2.3.1 Diffusion in Gases 99
- 2.3.2 Diffusion in Liquids 103
- 2.3.3 Diffusion in Solids 105
- 2.4 Integral and Differential Expressions of Mass Balance Equation 107
- 2.5 Convective Mass Transfer 111
- 2.5.1 Momentum and Mass Diffusivity Profiles 113
- 2.6 Fluxes of Liquids through Porous Membranes 115
- 2.6.1 The Flux of Pure Solutes 115
- 2.6.2 The Flux of Mixtures 117
- 2.6.2.1 The Concentration Polarization Model 118
- 2.6.2.2 The Resistance-in-Series Model 122
- 2.6.2.3 The Pore Blocking Model 123
- 2.7 Fluxes of Gases through Porous Membranes 124
- 2.7.1 Knudsen Diffusion 125
- 2.7.2 Surface Diffusion 128
- 2.7.3 Capillary Condensation 131
- 2.7.4 Molecular Sieving 133
- 2.7.5 Transport of Gases through Ceramic Membranes with Several Simultaneous Processes 134
- 2.7.5.1 The Parallel Transport Model 134
- 2.7.5.2 The Resistance-in-Series Model 138
- 2.8 Fluxes through Non-porous Membranes 138
- References 143

- 3 Characterization of Ceramic Membranes 149**
- 3.1 Introduction 149
- 3.2 Pore Size and Pore Size Distribution 150
- 3.2.1 Permeability 153
- 3.2.2 The Gas-Liquid Displacement Bubble Point Technique 156
- 3.2.3 Liquid-Liquid Displacement 158
- 3.2.4 Mercury Porosimetry 159
- 3.2.5 Gas Adsorption-Desorption 160
- 3.2.6 Gas-Liquid Permporometry 161
- 3.2.7 Solid-Liquid Thermoporometry 162
- 3.2.8 Nuclear Magnetic Resonance 164
- 3.2.9 Solute Rejection Tests 165
- 3.2.9.1 Solid Solutes 168

- 3.2.9.2 Ions and Dissolved Organics 169
- 3.2.9.3 Spiking Tests 169
- 3.3 Visualization of Membrane Surfaces 171
 - 3.3.1 Optical Microscopy 172
 - 3.3.2 Confocal Scanning Laser Microscopy 173
 - 3.3.3 Scanning Electron Microscopy 174
 - 3.3.4 Transmission Electron Microscopy 176
 - 3.3.5 Atomic Force Microscopy 178
- 3.4 Chemical Methods for Membrane Characterization 181
 - 3.4.1 Backscattered Radiation 182
 - 3.4.2 Vibrational Spectroscopy 185
- 3.5 Physical Parameters of Ceramic Membranes 189
 - 3.5.1 Membrane Porosity and Pore Tortuosity 190
 - 3.5.2 Mechanical Strength Tests 192
 - 3.5.3 Hydrophobicity of Ceramic Membranes 196
 - 3.5.4 Charge of Ceramic Membranes 197
- 3.6 Conclusions 201
 - References 206

- 4 Applications 217**
 - 4.1 Classical Applications of Ceramic Membranes 217
 - 4.2 Gas Separation with Ceramic Membranes 221
 - 4.2.1 Sustainable Reduction of CO₂ Emissions with Ceramic Membranes 225
 - 4.2.1.1 CO₂ Capture from Flue Gases 226
 - 4.2.2 Hydrogen Purification 232
 - 4.2.3 Fuel Cell Applications: The Real Hydrogen Economy 239
 - 4.2.3.1 Dense Ceramic Membranes for Fuel Cell Applications 244
 - 4.2.3.2 Oxygen Separation by Dense Mixed Ionic–Electronic Conducting Membranes 249
 - 4.3 Ceramic Membrane Reactors 250
 - 4.3.1 Membrane Reactor Types and Their Applications 250
 - 4.3.2 The Inert Membrane Reactor 250
 - 4.3.3 The Catalytic Membrane Reactor 254
 - 4.3.4 Composite Infiltrated Ceramic Membranes 259
 - 4.3.5 Membrane Reactors Using Dense Ceramic Membranes 264
 - 4.4 Liquid Separation and Purification 265
 - 4.4.1 Water Treatment 266
 - 4.4.2 Surface Water Treatment with Ceramic Membranes 268
 - 4.4.3 Low-Cost Ceramic Filters 271
 - 4.4.4 Treating Additional Pollutants 274
 - 4.4.5 Membrane Distillation 275
 - 4.4.6 Pervaporation 280
 - 4.5 Cleaning of Wastewater with Ceramic Membranes 286
 - 4.5.1 Membrane Bioreactors 286

4.5.2	Oil–Water Separation	291
4.5.2.1	Applications in Oil Recovery	291
4.5.2.2	Applications in Bilge Water Treatment	295
4.6	Ceramic Membranes in Food Applications	297
4.6.1	The Dairy Industry	298
4.6.1.1	Cheese Production	300
4.6.1.2	Whey Separation	303
4.6.1.3	Brine Disinfection	304
4.6.1.4	Pathogen Removal	304
4.6.2	Mineral Water and Juice	307
4.6.2.1	Orange Juice	308
4.6.2.2	Apple Juice	310
4.6.3	Fermented Food Industry	314
4.6.3.1	Beer and Ceramic Membranes	315
4.6.3.2	Winemaking and Ceramic Membranes	321
	References	330
5	Economics	355
5.1	Introduction	355
5.2	A Layman Scientist’s Guide to Project Appraisal: SWOT, PEST and LCA	357
5.2.1	SWOT Analysis	358
5.2.1.1	Identifying, Matching and Converting	359
5.2.2	PEST Analysis	359
5.2.3	Life Cycle Assessment	360
5.3	Economic Considerations in the Manufacturing and Application of Ceramic Membranes	362
5.3.1	Case Study 1: Atech Innovations GmbH (Germany)	362
5.3.2	Case Study 2: LiqTech A/S (Denmark)	365
5.3.3	Case Study 3: Metawater Co. (Japan)	368
5.3.4	Case Study 4: Pretreatment of Petrochemical Wastewater in Mahshahr, Iran	370
5.3.5	Case Study 5: Techno-Economic Analysis of CO ₂ Capture from Flue Gases (France)	373
5.4	Discussion	376
5.4.1	Market Size and the Adversity to Change	378
5.4.2	Specific Product Demands Dictated by Application	379
5.4.3	Detailed Technical Know-How	380
5.5	Outlook	381
5.5.1	Persistent Market Entry Barriers	381
5.5.2	Global Changes and New Opportunities	381
	References	385
	Index	389