

Tesi doctoral presentada per En/Na

Marc PERA TITUS

amb el títol

**"Preparation, characterization and modeling of
zeolite NaA membranes for the pervaporation
dehydration of alcohol mixtures"**

per a l'obtenció del títol de Doctor/a en

QUÍMICA

Barcelona, 29 de maig del 2006

Facultat de Química
Departament d'Enginyeria Química



- Abeles, B.; Chen, L.F.; Johnson, J.W.; Drane, J.M. Capillary condensation and surface flow in microporous Vycor glass. *Israel J. Chem.* **19** (1991) 99-106.
- Aimar, P.; Meireles, M.; Sanchez, V. A contribution to the translation of retention curves into PSD for sieving membranes. *J. Membr. Sci.* **54** (1990) 321-338.
- Alfaro, S.; Arruebo, M.; Coronas, J.; Menendez, M.; Santamaria, J. Preparation of MFI type tubular membranes by steam-assisted crystallization. *Micropor. Mesopor. Mater.* **50** (2001) 195-200.
- Altman, M.; Hasson, D.; Semiat, R. Review of dynamic membranes. *Reviews in Chemical Engineering* **15** (1999) 1-40.
- Aoki, K.; Kusakabe, K.; Morooka, S. Gas permeation properties of A-type zeolite membrane formed on porous substrate by hydrothermal synthesis. *J. Membr. Sci.* **141** (1998) 197-205.
- Arruebo, M.; Coronas, J.; Menendez, M.; Santamaria, J. Separation of hydrocarbons from natural gas using silicalite membranes. *Sep. Purif. Tech.* **25** (2001) 275-286.
- Assabumrungrat, S.; Kiatkittipong, W.; Praserthdam, P.; Goto, S. Simulation of pervaporation membrane reactors for liquid phase synthesis of ethyl *tert*-butyl ether from *tert*-butyl alcohol and ethanol. *Catal. Today* **79-80** (2003) 249-257.
- Bai, C.; Jia, M.-D. Falconer, J.L.; Noble, R.D. Permeation and separation properties of silicate composite membranes. *J. Membr. Sci.* **105** (1995) 79-87.
- Baltus, R.E. The use of moment theory to interpret diffusion and sieving measurements in terms of the pore size distribution in heterogeneous membranes. *J. Membr. Sci.* **130** (1997a) 157-172.
- Baltus, R.E. Characterization of the pore area distribution in porous membranes using transport measurements. *J. Membr. Sci.* **123** (1997b) 165-184.
- Bakker, W. J. W.; Van den Broeke, L. J. P.; Kapteijn, F.; Moulijn, J. A. Temperature Dependence of One-Component Permeation through a Silicalite-1 Membrane. *AICHE J.* **43(9)**, 2203-2214 (1997).
- Bakker, W.J.W.; Kapteijn, F.; Poppe, J.; Moulijn, J.A. Permeation characteristics of a metal-supported silicate-1 zeolite membrane. *J. Membr. Sci.* **117** (1996) 57-78.
- Balkus Jr, K. J.; Scott, A. S. Zeolite coatings on three dimensional objects via laser ablation. *Chem. Mater.* **11** (1999) 189-191.
- Balkus Jr, K. J.; Munoz, T.; Gimon-Kinsel, M. E. Preparation of zeolite UTD-1 films by pulsed laser ablation evidence for oriented crystal growth. *Chem. Mater.* **10** (1998) 464-468.
- Barrer, R.M. Hydrothermal Chemistry of Zeolites, Academic Press, London-New York, UK-USA (1982).
- Bausach, M.; Pera-Titus, M.; Fite, C.; Cunill, F.; Izquierdo, J-F.; Tejero, J.; Iborra, M. Kinetic modeling of the reaction between hydrated lime and SO₂ at low temperature in the presence of water vapor. *AICHE J.* **51** (2005) 1455-1466.
- Bausach, M.; Krammer, G.; Cunill, F. Reaction of Ca(OH)₂ with HCl in the presence of water vapour at low temperature. *Thermochimica Acta* **421** (2004) 217-223.
- Bernal, M.P.; Coronas, J.; Menendez, M.; Santamaria, J. Coupling of reaction and separation at a microscopic level: esterification process in a H-ZSM-5 membrane reactor. *Chem. Eng. Sci.* **57** (2002) 1557-1562.
- Bernal, M.P.; Piera, E.; Coronas, J.; Menendez, M.; Santamaria, J. Mordenite and ZSM-5 hydrophilic tubular membranes for the separation of gas phase-mixtures. *Catal. Today* **56** (2000) 221-227.

- Bond, G. C. *Heterogeneous Catalysis: Principles and Applications*. Oxford Science Publications (1987).
- Boudreau, L. C.; Kuck, J. A.; Tsapatsis, M. Deposition of oriented zeolite A films in situ and secondary growth. *J. Membr. Sci.* **152** (1999) 41-59.
- Boudreau, L. C.; Tsapatsis, M. A highly oriented thin film of zeolite A. *Chem. Mater.* **98** (1997) 1705-1711.
- Boulicaut, L.; Brandani, S.; Ruthven, D.M. Liquid phase sorption and diffusion of branched and cyclic hydrocarbons in silicalite. *Micropor. Mesopor. Mater.* **25** (1998) 81-93.
- Bourgeois, A.; Bruneau, A.B.; Fisson, S.; Demarets, B.; Gross, D.; Cagnol, F.; Sanchez, C.; Rivory, J. Determination of pore size distribution in thin organized mesoporous silica films by spectroscopic ellipsometry in the visible and infrared range. *Thin Solid Films* **447** (2004) 46-50.
- Bowen, T.C.; Wyss, J.C.; Noble, R.D.; Falconer, J.L. Inhibition during multicomponent diffusion through ZSM-5 zeolite. *Ind. Eng. Chem. Res.* **43** (2004a) 2598-2601.
- Bowen, T.C.; Wyss, J.C.; Noble, R.D.; Falconer, J.L. Measurements of diffusion through a zeolite membrane by isotopic-transient pervaporation. *Micropor. Mesopor. Mater.* **71** (2004b) 199-210.
- Bowen, T.C.; Noble, R.D.; Falconer, J.L. Fundamentals and applications of pervaporation through zeolite membranes. *J. Membr. Sci.* **245** (2004c) 1-33.
- Bowen, T.C.; Li, S.; Noble, R.D.; Falconer, J.L. Driving force for pervaporation through zeolite membrane. *J. Membr. Sci.* **225** (2003) 165-176.
- Bowen, T.C.; Falconer, J.L.; Noble, R.D.; Skouidas, A.I.; Sholl, D.S. A comparison of atomistic simulations and experimental measurements of light gas permeation through zeolite membranes. *J. Membr. Sci.* **41** (2002) 1641-1650.
- Bowen, W.R.; Doneva, T.A. Atomic force microscopy studies of NF membranes: surface morphology, PSD and adhesion. *Desalination* **129** (2000) 163-172.
- Bowen, W.R.; Hilal, N.; Lovitt, R.W.; Sharif, A.O.; Williams, P.M. Atomic force microscope studies of membranes: force measurement and imaging in electrolyte solutions. *J. Membr. Sci.* **126** (1997) 77-89.
- Braunbarth, C.M.; Boudreau, L.C.; Tsapatsis, M. Synthesis of ETS-4/TiO₂ composite membranes and their pervaporation performance. *J. Membr. Sci.* **174** (2000) 31-42.
- Breck, D. W. *Zeolite Molecular Sieves*. Robert E. Krieger Publishing Company, USA (1984).
- Brinker, J. C.; Scherer, G. W. *Sol-Gel Science: the Physics and Chemistry of Sol-Gel Processing*. Academic Press Inc., San Diego, USA (1990).
- Bronic, J.; Sobunic, B.; Skreblin, M. Investigation of the influence of seeding on the crystallization of zeolite A in the membrane-type reactor. *Microp. Mesop. Mater.* **28** (1999) 73-82.
- Burggraaf, A.J. Single gas permeation of thin zeolite (MFI) membranes: theory and analysis of experimental observations. *J. Membr. Sci.* **155** (1999) 45-65.
- Bussai, C.; Vasenkov, S.; Liu, H.; Bohlmann, W.; Fritzsche, S.; Hannongbua, S.; Haberlandt, R.; Kärger, J. On the diffusion of water in silicalite-1: MD simulations using *ab initio* fitted potential and PFG NMR measurements. *Appl. Catal. A: General* **232** (2002a) 59-66.
- Bussai, C.; Hannongbua, S.; Fritzsche, S.; Haberlandt, R. Ab initio potential energy surface and molecular dynamics simulation for the determination of the diffusion coefficient of water in silicalite-1. *Chem. Phys. Lett.* **354** (2002b) 310-315.

- Calvo, J.I.; Bottino, A.; Capannelli, G.; Hernandez, A. Comparison of liquid-liquid displacement porosimetry and scanning electron microscopy image analysis to characterize UF track-etched membranes. *J. Membr. Sci.* **239** (2004) 189-197.
- Calvo, J.I.; Pradanos, P.; Hernandez, A.; Bowen, W.R.; Hilal, N.; Lovitt, R.W.; Williams, P.M. Bulk and surface characterization of composite UF membranes. Atomic force microscopy, gas adsorption-desorption and liquid displacement techniques. *J. Membr. Sci.* **128** (1997) 7-21.
- Caro, J.; Noack, M.; Kolsch, P.; Schafer, R. Zeolite membranes – State of their development and perspectives. *Micropor. Mesopor. Mater.* **38** (2000) 3-24.
- Casado, L.; Mallada, R.; Tellez, C.; Coronas, J.; Menendez, M.; Santamaria, J. Preparation, characterization and pervaporation performance of mordenite membranes. *J. Membr. Sci.* **216** (2003) 135-147.
- Chau, J.L.H.; Tellez, C.; Yeung, K. L.; Ho, K. The role of surface chemistry un zeolite membrane formation *J. Membr. Sci.* **164** (2000) 257-275.
- Chen, X.; Yang, W.; Liu, J.; Lin, L. Characterization of the formation of NaA zeolite membrane under microwave radiation. *J. Mater. Sci.* **39** (2004) 671-673.
- Chen, C. C.; Chiang, B. H. Formation and characteristics of zirconium ultrafiltration dynamic membranes of various pore sizes. *J. Membr. Sci.* **143** (1998) 65-73.
- Chen, Y.D.; Yang, R.T. Concentration dependence of surface diffusion and zeolitic structures. *AIChE J.* **37** (1991) 1579-1582.
- Choudhary, V.R.; Nayak, V.S.; Mamman; A.S. Diffusion of straight and branched-chain liquid compounds in H-ZSM-5 zeolite. *Ind. Eng. Chem. Res.* **31** (1992) 624-628.
- Clark, T.E.; Deckman, H.W.; Cox, D.M.; Chance, R.R. In situ determination of the adsorption characteristics of a zeolite membrane. *J. Membr. Sci.* **230** (2004) 91-98.
- Cooper, A.R.; van Derveer, D.S. Characterization of UF membranes by polymer transport measurements. *Sep. Sci. Technol.* **14** (1979) 551-556.
- Coronas, J.; Santamaria, J. State-of-the-art in zeolite membrane reactors. *Topics in Catalysis* **29** (2004a) 29-44.
- Coronas, J.; Santamaria, J. The use of zeolite films in small-scale and micro-scale applications. *Chem. Eng. Sci.* **59** (2004b) 4879-4885.
- Coronas, J.; Santamaria, J. Separations using zeolite membranes. *Sep. Purif. Methods* **28** (1999) 127-177.
- Coronas, J.; Noble, R.D.; Falconer, J.L. Separations of C₄ and C₆ isomers in ZSM-5 tubular membranes. *Ind. Eng. Chem. Res.* **37** (1998) 166-176.
- Coronas, J.; Falconer, J. L.; Noble, R. D. Characterization and permeation properties of ZSM-5 tubular membranes. *AIChE J.* **43** (1997) 1797-1812.
- Costa, E.; Sotelo, J.L.; Calleja, G.; Marron, C. Adsorption of binary and ternary hydrocarbon-gas mixtures on activated carbon: experimental determination and theoretical prediction of the ternary equilibrium data. *AIChE J.* **27** (1981) 5-12.
- Crank, J. The Mathematics of Diffusion. Oxford Science Publications, Oxford, UK (2004).
- Cruz, A.J.; Pires, J.; Carvalho, A.P.; de Carvalho, M.B. Adsorption of acetic acid by activated carbons, zeolites, and other adsorbent materials related with the preventive conservation of lead objects in museum showcases. *J. Chem. Eng. Data* **49** (2004) 725-731.

- Cunill, F.; Tejero, J.; Fite, C.; Iborra, M.; Izquierdo, J-F. Conversión, selectivity and kinetics of the dehydration of 1-pentanol to di-n-pentyl ether catalyzed by a microporous ion-exchange resin.
- Debye, P.; Cleland, R.L. Flow of liquid hydrocarbons in porous Vycor. *J. Appl. Phys.* **30** (1959) 843-849.
- de la Iglesia, O.; Mallada, R.; Coronas, J.; Menendez, M.; Santamaria, J. Mordenite membranes for ethanol-acetic acid esterification. *Proceedings of the 7th International Conference on Catalysis in Membrane Reactors (ICCMR-7)*, Cetraro, Italy (2005), 354-356.
- de Vos, R. M.; Verweij, H. High-selectivity, high flux silica membranes for gas separation. *Science* **279** (1998) 1710-1711.
- Doelle, H.J.; Heering, J.; Riekert, L. Sorption and catalytic reaction in pentasil zeolites. Influence of preparation and crystal size on equilibrium and kinetics. *J. Catal.* **71** (1981) 27-40.
- Dong, J.; Dou, T.; Zhao, X.; Gao, L. Synthesis of membranes of zeolites ZSM-5 and ZSM-35 by the Vapor Phase Method. *J. Am. Soc. Chem. Commun.* (1992) 1056-1058.
- Doraiswamy, L.K.; Sharma, M.M. Heterogeneous reactions: analysis, examples and reactor design. Volume 1: gas-solid and solid-solid reactions. John Wiley & Sons, New York, USA, 1984.
- Dunne, J.A.; Rao, M.; Sircar, S.; Gorte, R.J.; Myers, A.L. Calorimetric heats of adsorption and adsorption isotherms. 2. O₂, N₂, Ar, CO₂, CH₄, C₂H₆, and SF₆ on NaX. *Langmuir* **12** (1996) 5896-5904.
- Espinosa, R. L.; Du Toit, E.; Santamaria, J.; Menendez, M.; Coronas, J.; Irusta, S. Use of membranes in Fischer-Tropsch reactors. *Stud. Surf. Sci. Catal.* **130A** (2000) 389-394.
- Esquena, J.; Solans, C.; Llorens, J. Nitrogen sorption studies of silica particles obtained in emulsion and microemulsion media. *J. Colloid Interface Sci.* **225** (2000) 291-298.
- Feng, X.; Huang, Y. M. Liquid separation by membrane pervaporation: a review. *Ind. Eng. Chem. Res.* **36** (1997) 1048-1066.
- Fleming, H.L. Consider membrane pervaporation. *Chem. Eng. Progr.* **88** (1992) 46-52.
- Furukawa, S.-I.; Goda, K.; Zhang, Y.; Nitta, T. Molecular simulation study on adsorption and diffusion behavior of ethanol/water molecules in NaA zeolite crystal. *J. Chem. Eng. Jpn* **37** (2004) 67-74.
- Gallego-Lizon, T.; Edwards, E.; Lobiundo, G.; Freitas dos Santos, L. Dehydration of water/t-butanol mixtures by pervaporation: comparative study of commercially available polymeric, microporous silica and zeolite membranes. *J. Membr. Sci.* **197** (2002) 309-319.
- Gao, Z.; Yue, Y.; Li, W. Application of zeolite-filled pervaporation membrane. *Zeolites* **16** (1996) 70-74.
- Gardner, T.Q.; Falconer, J.L.; Noble, R.D. Characterization of ZSM-5 and ZSM-11 zeolite membranes by transient permeation of butanes. *AICHE J.* **50** (2004) 2816-1834.
- Gardner, T.Q.; Flores, A.I.; Noble, R.D.; Falconer, J.L. Transient measurements of adsorption and diffusion in H-ZSM-5 membranes. *AICHE J.* **48** (2002) 1155-1167.
- Giavazzi, F.; Terna, D.; Patrini, D.; Ancillotti, F.; Pecci, G.C.; Trere, R.; Benelli, M. Oxygenated diesel fuels 2: practical aspects of their use. *9th Int. Symp. Alcohol Fuels* (1991) 327-335.
- Giaya, A.; Thompson, R.W. Single-component gas phase adsorption and desorption studies using a tapered element oscillating microbalance. *Micropor. Mexopor. Mater.* **55** (2002) 265-274.
- Gijsbertsen-Abrahamse, A.J.; Boom, R.M.; van der Padt, A. Why liquid displacement methods are sometimes wrong in estimating the pore-size distribution? *AICHE J.* **50** (2004) 1364-1371.

- Gonthier, S.; Thompson, R.W. Effects of Seeding on Zeolite Crystallization, and the Growth Behavior of Seeds. *Stud. Surf. Sci. Catal.* **85** (1994) 43-73.
- Gora, L.; Streletzky, K.; Thompson, R.W.; Phillipes, G.D.J. Study of the Effects on Initial-bred Nuclei on Zeolite NaA Crystallization by Quasi-elastic Light Scattering Spectroscopy and Electron Microscopy. *Zeolites* **19** (1997) 98-106.
- Gouzinis, A.; Tsapatsis, M. On the preferred orientation and microstructural manipulation of molecular sieve films prepared by secondary growth. *Chem. Mater.* **10** (1998) 2497-2504.
- Gu, X.; Dong, J.; Nenoff, T.M. Synthesis of defect-free FAU-type zeolite membranes and separation for dry and moist CO₂/N₂ mixtures. *Ind. Eng. Chem. Res.* **44** (2005) 937-944.
- Han, Y.; Ma, H.; Qiu, S.; Xiao, F. Preparation of zeolite A membranes by microwave heating. *Microp. Mesop. Mater.* **30** (1999) 321-326.
- Hanebuth, M.; Dittmeyer, R.; Mabande, G.T.P.; Schwieger, W. On the combination of different transport mechanisms for the simulation of steady-state mass transfer through composite systems using H₂/SF₆ permeation through stainless steel supported silicalite-1 membranes as a model system. *Catal. Today.* **104** (2005) 352-359.
- Hansen, E.W.; Schmidt, R.; Stöcker, M. Pore size characterization of porous silica by ¹H NMR using water, benzene and cyclohexane as probe molecules. *J. Phys. Chem.* **100** (1996) 11396-11401.
- Hernandez, A.; Calvo, J.I.; Pradanos, P.; Tejerina, F. Pore size distributions of track-etched membranes: comparison of surface and bulk porosities. *Colloid Surface A* **138** (1998) 391-401.
- Himmelblau, D. Process Analysis by Statistical Methods. Wiley & Sons, Inc., USA, 1970.
- Holmes, S.M.; Schmitt, M.; Markert, R.J.; Plaisted, J.O.; Forrest, P.N.; Sharratt, P.N.; Garforth, A.A.; Cundy, C.S.; Dwyer, J. Zeolite A membranes for use in alcohol/water separations. Part I. Experimental investigation. *Chem. Eng. Res. Design* **78** (2000) 1084-1088.
- Hsieh, H. P. Inorganic Membranes for Separation and Reaction. Elsevier, Amsterdam, The Netherlands (1996).
- Huang, A.; Lin, Y.S.; Yang, W. Synthesis and properties of A-type zeolite membranes by secondary growth method with vacuum seeding. *J. Membr. Sci.* **245** (2004) 41-51.
- Huang, H. P.; Xu, N.; Shi, J.; Lin, Y.S. Characterization of asymmetric ceramic membranes by modified permoporometry. *J. Membr. Sci.* **116** (1996) 301-305.
- Huang, P. Pervaporation Membrane Separation Processes, Elsevier, Amsterdam, The Netherlands (1991).
- Huang, C. P.; Rhoads, E. A. Adsorption of zinc onto hydrous aluminosilicates. *J. Colloid Interf. Sci.* **131** (1989) 289-306.
- Ishikiriyama, K.; Todoki, M.; Kobayashi, T.; Tanzawa, H. Pore Size Distribution Measurements of Poly(methacrylate) Hydrogel Membranes for Artificial Kidneys Using Differential Scanning Calorimetry. *J. Colloid Interface. Sci.* **173** (1995) 419.
- Itoh, N.; Xu, W.C. Selective hydrogenation of phenol to cyclohexanone using palladium-based membranes as catalyst. *Appl. Catal. A: General* **107** (1993) 83-100.
- Iza, M.; Woerly, S.; Danumah, C.; Kaliaguine, S.; Bousmina, M. Determination of pore size distribution for mesoporous materials and polymeric gels by means of DSC measurements: thermoporometry. *Polymer* **41** (2000) 5885-5893.

- Jafar, J.J.; Budd, P.M. Separation of alcohol/water mixtures by pervaporation through zeolite A membranes. *Micropor. Mater.* **12** (1997) 305-311.
- Jakobs, E.; Koros, W.J. Ceramic membrane characterization via the bubble point technique. *J. Membr. Sci.* **124** (1997) 149-159.
- Jansen, J.C.; Kashchuev, D.; Erdemensatalar, A.E. Preparation of coatings of molecular-sieve crystals for catalysis and separation. *Stud. Surf. Sci. Catal.* **85** (1994) 215-250.
- Jaroniec, M.; Kruk, M.; Olivier, J. M. Fractal analysis of composite adsorption isotherms obtained by using density functional theory data for argon in slitlike pores. *Langmuir* **13** (1997) 1031-1034.
- Jaroniec, M. Evaluation of the fractal dimension from a single adsorption isotherm. *Langmuir* **11** (1995) 2316-2317.
- Jayaraman, V.; Lin, Y. S. Synthesis and hydrogen permeation of ultrathin palladium sylver. *J. Membr. Sci.* **104** (1995) 251-262.
- Jobic, H.; Paoli, H.; Methivier, A.; Ehlers, G.; Karger, J.; Krause, C. Diffusion of n-hexane in 5A zeolite studied by the neutron spin-echo and pulsed-field gradient NMR techniques. *Micropor. Mesopor. Mater.* **59** (2003) 113-121.
- Jobic, H.; Methivier, A.; Ehlers, G. Different diffusivities in BaX zeolite measured by the neutron spin echo technique. *Micropor. Mesopor. Mater.* **56** (2002) 27-32.
- Jobic, H.; Fitch, A.N.; Combet, J. Diffusion of benzene in NaX and NaY zeolites studied by quasi-electric neutron scattering. *J. Phys. Chem. B* **104** (2000) 8491-8497.
- Jobic, H.; Kärger, J.; Bee, M. Simultaneous measurement of self- and transport diffusivities in zeolites. *Phys. Rev. Lett.* **82** (1999) 4260-4263.
- Jonquieres, A.; Clement, R.; Lochon, P.; Neel, J. ; Dresch, M.; Chretien, B. Industrial-state-of-the-art of pervaporation and vapour permeation in the Western Countries. *J. Membr. Sci.* **206** (2002) 87-117.
- Kapteijn, F.; Moulijn, J.A.; Krishna, R. The generalized Maxwell-Stefan model for diffusion in zeolites: sorbate molecules with different saturation loadings. *Chem. Eng. Sci.* **55** (2000) 2923-2930.
- Kapteijn, F.; Bakker, W. J. W.; Van der Graaf, J.; Zheng, G.; Poppe, J.; Moulijn, J. A. Permeation and separation behavior of a silicalite-1 membrane. *Catal. Today* **25** (1995) 213-218.
- Karlsson, H.O.E.; Trägårdh, G. Pervaporation of dilute organic-water: a literature review on modeling studies and applications to aroma compound recovery. *J. Membr. Sci.* **76** (1993) 121-146.
- Kazemimoghadam, M.; Pak, A.; Mohammadi, T. Dehydration of water/1,1-dimethylhydrazine mixtures by zeolite membranes. *Micropor. Mesopor. Mater.* **70** (2004) 127-134.
- Kemp, D.; Paul, D.R. Gas Sorption in Polymer Membranes Containing Adsorption Filters. *J. Polym. Sci.* **12** (1974) 485-500.
- Khayet, M.; Khulbe, K.C.; Matsuura, T. Characterization of membranes for membrane distillation by atomic force microscopy and estimation of their water vapor transfer coefficients in vacuum membrane distillation process. *J. Membr. Sci.* **238** (2004) 199-211.
- Khulbe, K.C.; Matsuura, T. Characterization of synthetic membranes by Raman spectroscopy, electron spin resonance, and atomic force microscopy: a review. *Polymer* **41** (2000) 1917-1935.
- Kita, H.; Fuchida, K.; Horita, T.; Asamura, H.; Okamoto, K.-I. Preparation of faujasite membranes and their permeation properties. *Sep. Purif. Tech.* **25** (2001) 261-268.

- Kita, H.; Asamura, H.; Tanaka, K.; Okamoto, K.-I. Preparation and pervaporation properties of X- and Y-type zeolite membranes. *ACS Symp. Ser.* **744** (2000) 330-341.
- Kita, H.; Inoue, T.; Asamura, H.; Tanaka, K.; Okamoto, K. NaY zeolite membrane for the pervaporation separation of methanol-methyl *tert*-butyl ether mixtures. *Chem. Commun.* (1997) 45-46.
- Knierim, K.D.; Mason, E.A. Heterogeneous sieving membranes: rigorous bounds on pore-size distributions and sieving curves. *J. Membr. Sci.* **42** (1989) 87-107.
- Knierim, K.D.; Waldman, M.; Mason, E.A. Bounds on solute flux and pore-size distributions for non-sieving membranes. *J. Membr. Sci.* **17** (1984) 173-203.
- Kölsch, P.; Venzke, D.; Noack, M.; Toussaint, P.; Caro, J. Zeolite-in-Metal Membranes: Preparation and Testing. *J. Chem. Soc. Chem. Commun.* (1994) 2491-2492.
- Kondo, M.; Komori, M.; Kita, H.; Okamoto, K. Tubular-type pervaporation module with zeolite NaA membrane. *J. Membr. Sci.* **133** (1997) 133-141.
- Krishna, R. Diffusion of binary mixtures across zeolite membranes: entropy effects on permeation selectivity. *Int. Comm. Heat Mass Transfer* **38** (2001) 337-346.
- Krishna, R. Diffusion of binary mixtures in zeolites: molecular dynamics simulations versus Maxwell-Stefan theory. *Chem. Phys. Lett.* **326** (2000) 477-484.
- Krishna, R.; Wesseling, J. A. The Maxwell-Stefan approach to mass transfer. *Chem. Eng. Sci.* **52** (1997) 861-911.
- Krishna, R.; van den Broeke, J.L.P. The Maxwell-Stefan description of mass transport across zeolites membranes. *Chem. Eng. J.* **57** (1995) 155-162.
- Krishna, R. Problems and pitfalls in the use of the Fick formulation for intraparticle diffusion. *Chem. Eng. Sci.* **48** (1993) 845-861.
- Krishna, R. Multicomponent surface diffusion of adsorbed species. A description based on the generalized Maxwell-Stefan diffusion equations. *Chem. Eng. Sci.* **45** (1990) 1779-1791.
- Kumakiri, I. Preparation and Permeation Mechanism of Zeolite Membranes. Ph.D. Thesis, University of Tokyo, Japan (2000).
- Kumakiri, I.; Yamaguchi, T.; Nakao, S.-I. Preparation of zeolite A and faujasite membranes from a clear solution. *Ind. Eng. Chem. Res.* **38** (1999) 4682-4688.
- Kusakabe, K.; Kuroda, T.; Uchino, K.; Hasegawa, Y.; Morooka, S. Gas permeation properties of ion-exchanged faujasite-type zeolite membranes. *AIChE J.* **45** (1999) 1220-1226.
- Kusakabe, K.; Kuroda, T.; Morooka, S. Separation of carbon dioxide from nitrogen using ion-exchanged faujasite-type zeolite membranes formed on porous support tubes. *J. Membr. Sci.* **148** (1998) 13-23.
- Kusakabe, K.; Kuroda, T.; Murata, A.; Morooka, S. Formation of a Y-type zeolite membrane on a porous α -alumina tube for gas separation. *Ind. Eng. Chem. Res.* **36** (1997) 649-655.
- Labanda, J.; Llorens, J. Rheological model to predict the thixotropic behaviour of colloidal dispersions. *Colloid Surface A* **249** (2004) 123-126.
- Lai, R.; Gavalas, G.R. Surface seeding in ZSM-5 membrane preparation. *Ind. Eng. Chem. Res.* **37** (1998) 4275-4283.
- Lee, S.; Park, G.; Amy, G.; Hong, S-K.; Moon, S-H.; Lee, D-H.; Cho, J. Determination of membrane pore size distribution using the fractional rejection of nonionic and charged macromolecules. *J. Membr. Sci.* **201** (2002) 191-201.

- Lee, H.; Dutta, P. K. Synthesis of free-standing chabazite films. *Microp. Mesop. Mater.* **38** (2000) 151-159.
- Lee, Y.; Jeong, J.; Youn, I.J.; Lee, W.H. Modified liquid displacement method for determination of pore size distribution in porous membranes. *J. Membr. Sci.* **130** (1997a) 149-156.
- Lee, C.-C.; Gorte, R.J.; Farneth, W.E. Calorimetric study of alcohol and nitrile adsorption complexes in H-ZSM-5. *J. Phys. Chem. B* **101** (1997b) 3811-3817.
- Levenspiel, O. Chemical reaction engineering, 3rd edition, Wiley, cop., New York, 1999.
- Levine, I.N. Physical Chemistry. Mc Graw-Hill, Boston, USA, 5th edition, 2002.
- Leypoldt, J. Determining PSDs of UF membranes by solute sieving - Mathematical limitations. *J. Membr. Sci.* **31** (1987) 289-305.
- Li, S.; Tuan, V.A.; Falconer, J.L.; Noble, R.D. X-type zeolite membranes: preparation, characterization and pervaporation performance. *J. Membr. Sci.* **53** (2005) 59-70.
- Li, G.; Kikuchi, E.; Matsukata, M. Separation of water-acetic acid mixtures by pervaporation using a thin mordenite membrane. *Sep. Purif. Tech.* **32** (2003) 199-206.
- Li, S.; Tuan, V. A.; Noble, R. D.; Falconer, J. L. Separation of 1,3-propanediol from aqueous solutions using pervaporation through an X-type zeolite membrane. *Ind. Eng. Chem. Res.* **40** (2001a) 1952-1959.
- Li, S.; Tuan, V. A.; Noble, R. D.; Falconer, J. L. Pervaporation of Water/THF Mixtures Using Zeolite Membranes. *Ind. Eng. Chem. Res.* **40** (2001b) 4577-4585.
- Li, S.; Tuan, V.A.; Noble, R.D.; Falconer, J.L. A Ge-substituted ZSM-5 zeolite membrane for the separation of acetic acid from water. *Ind. Eng. Chem. Res.* **40** (2001c) 6165-6171.
- Lin, X.; Kita, H.; Okamoto, K.-I. Silicate membrane preparation, characterization and separation performance. *Ind. Eng. Chem. Res.* **40** (2001) 4069-4078.
- Lin, X.; Kikuchi, E.; Matsukata, M. Preparation of mordenite membranes on α -alumina tubular supports for pervaporation of water-isopropyl alcohol mixtures. *Chem. Commun.* (2000) 957-958.
- Lin, Y.S.; Ma, Y.H. Liquid diffusion and adsorption of aqueous ethanol, propanols, and butanols in silicalite by HPLC. *ACS Symp. Ser.* **368** (1988) 454-456.
- Lipnizki, F.; Field, R. W. Integration of vacuum and sweep gas pervaporation to recover organic compounds from wastewater. *Sep. Purif. Tech.* **22-23** (2001) 347-360.
- Llorens, J. Characterization of microporous materials for gas adsorption: application to the adsorption of hydrogen in active carbons. Internal UB report, Barcelona, 2005.
- Lopez, F.; Bernal, M.P.; Mallada, R.; Coronas, J.; Santamaria, J. Preparation of silicalite membranes on stainless steel grid supports. *Ind. Eng. Chem. Res.* **44** (2005) 7627-7632.
- Lovallo, M. C.; Tsapatsis, M. Preferentially oriented submicron silicalite membranes. *AIChE J.* **42** (1996) 3020-3029.
- Lovallo, M. C.; Okubo, T.; Tsapatsis, M. Preparation of an asymmetric zeolite film. *Chem. Mater.* **88** (1996) 1579-1585.
- Maginn, E.J.; Bell, A.T.; Theodorou, D.N. Transport diffusivity of methane in silicalite from equilibrium and non-equilibrium simulations. *J. Phys. Chem.* **97** (1993) 4173-4181.
- Mallada, R. Study of the selective oxidation of butane to maleic anhydride in membrane reactors. Ph.D. Thesis, University of Zaragoza, Spain (1999).

- Mandelbrot, B. Los objetos fractals. Tusquets Editores, Barcelona, 1988.
- Marchionna, M.; Patrini, R.; Giavazzi, F.; Pecci, G.C. Linear ethers as high-quality components for reformulated diesel fuels. *Symposium on the Removal of Aromatics, Sulfur and Olefins from Gasoline and Diesel*, 212th National Meeting, American Chemical Society: Washington DC (1996) 585-589.
- Masselin, I.; Durand-Bourlier, L.; Laine, J-M.; Sizaret, P-Y.; Chasseray, X.; Lemordant, D. Membrane characterization using microscopic image analysis. *J. Membr. Sci.* **186** (2001) 85-96.
- Masselin, I.; Chasseray, X.; Chevalier, M.-R.; Laine, J.-M.; Lemordant, D. Determination of the porosity to thickness ratio $A_k/\Delta x$ for UF and MF membranes by diffusion experiments. *J. Membr. Sci.* **172** (2000) 125-133.
- Masuda, T.; Fukada, K.; Fujikata, Y.; Ikeda, H.; Hashimoto, K. Measurement and prediction of the diffusivity of Y-type zeolite. *Chem. Eng. Sci.* **51** (1996) 1879-1888.
- Matsukata, M.; Ogura, M.; Osaki, T.; Raja, P.; Rao, H. P.; Nomura, M.; Kikuchi, E. Conversion of dry gel to microporous crystals in gas phase. *Top. Catal.* **9** (1999) 77-92.
- Matsukata, M.; Kikuchi, E. Zeolitic membranes: Synthesis, Properties, and Prospects. *Bull. Chem. Soc. Jpn.* **70** (1997) 2341-2356.
- Matsukata, M.; Nishiyama, N.; Ueyama, K. J. Zeolitic membrane synthesized on a porous alumina support. *Chem. Commun.* (1994) 339-340.
- McCool, B.; Xomeritakis, G.; Lin, Y. S. Composition control and hydrogen permeation characteristics. *J. Membr. Sci.* **161** (1999) 67-76.
- McGuire, K.S.; Lawson, K.W.; Lloyd, D.R. Pore size distribution from liquid permeation through microporous membranes. *J. Membr. Sci.* **99** (1995) 127-137.
- Meininghaus, C.K.W.; Prins, R. Sorption of volatile organic compounds on hydrophobic zeolites. *Micropor. Mesopor. Mater.* **35-36** (2000) 349-365.
- Michaels, A.S. Analysis and prediction of sieving curves for ultrafiltration membranes: A universal correlation? *Sep. Sci. Technol.* **15** (1980) 1305-1322.
- Micke, A.; Bulow, M.; Kocirik, M. A non-equilibrium surface-barrier for sorption kinetics of p-ethyltoluene on ZSM-5 molecular sieves. *J. Phys. Chem.* **98** (1994) 924-929.
- Mietton-Peuchot, M.; Condat, C.; Courtois, T. Use of gas-liquid porometry measurements for selection of MF membranes. *J. Membr. Sci.* **133** (1997) 73-82.
- Millot, B.; Methivier, A.; Jobic, H.; Moueddeb, H.; Dalmon, J.A. Permeation of linear and branched alkanes in ZSM-5 supported membranes. *Micropor. Mesopor. Mater.* **38** (2000) 85-95.
- Millot, B.; Methivier, A.; Jobic, H.; Clemençon, I.; Rebours, B. Adsorption of branched alkanes in silicalite-1: a temperature-programmed-equilibration study. *Langmuir* **15** (1999) 2534-2539.
- Morigami, Y.; Kondo, M. Abe, J. Kita, H. Okamoto, K. The first large-scale pervaporation plant using tubular-type module with zeolite NaA membrane. *Sep. Purif. Tech.* **25** (2001) 251-260.
- Morishige, K.; Shikimi, M. Adsorption hysteresis and pore critical temperature in a single cylindrical pore. *J. Chem. Phys.* **108** (1998) 7821-7824.
- Moron, F.; Pina, M.P.; Urriolabeitia, E.; Menendez, M.; Santamaria, J. Preparation and characterization of Pd-zeolite composite membranes for hydrogen separation. *Desalination* **147** (2002) 425-431.
- Mota, S.; Miachon, S.; Volta, J. C.; Dalmon, J. A. Membrane reactor for selective oxidation of butane to maleic anhydride. *Catal. Today* **67** (2001) 169-176.

- Muller, J.C.M.; Hakvoort, G.; Jansen, J.C. DSC and TG study of water adsorption and desorption on zeolite NaA. *J. Therm. Anal.* **53** (1998) 449-466.
- Myatt, G. J.; Budd, P. M.; Price, C.; Carr, S. W. Synthesis of a zeolite NaA membrane. *J. Mater. Chem.* **2** (1992) 1103-1104.
- Myers, A.L. Thermodynamics of mixed gas adsorption. *AICHE J.* **48** (2002) 145-160.
- Myers, A.L.; Prausnitz, J.M. Thermodynamics of mixed gas adsorption. *AICHE J.* **11** (1965) 121-130.
- Nakao, S.I. Review: determination of pore size and pore size distribution. 3. Filtration membranes. *J. Membr. Sci.* **96** (1994) 131-165.
- Navajas, A.; Mallada, R.; Tellez, C.; Coronas, J.; Menendez, M.; Santamaria, J. Preparation of mordenite membranes for pervaporation of water/ethanol mixtures. *Desalination* **148** (2002) 25-29.
- Nayak, V.S.; Moffat, J.B. Sorption and diffusion of alcohols in heteropoly oxometalates and ZSM-5 zeolite. *J. Phys. Chem.* **92** (1988) 7097-7102.
- Neimark, A. A new approach to the determination of the surface fractal dimension of porous solids. *Physica A* **191** (1992) 258-262.
- Nelson, P.H.; Tsapatsis, M.; Auerbach, S.M. Modeling permeation through anisotropic zeolite membranes with nanoscopic defects. *J. Membr. Sci.* **184** (2001) 245-255.
- Nicholson, D.; Petropoulos, J.H. Influence of Adsorption Forces on the Flow of Dilute Gases through Porous Media. *J. Colloid Interface Sci.* **45** (1973) 459-466.
- Nikolakis, V.; Xomeritakis, G.; Abibi, A.; Dickson, M.; Tsapatsis, M.; Vlachos, D.G. Growth of faujasite-type zeolite membrane and its application in the separation of saturated/unsaturated hydrocarbon mixtures. *J. Membr. Sci.* **184** (2001) 209-219.
- Nishiyama, N.; Park, D-H.; Egashira, Y.; Ueyama, K. Pore size distributions of silylated mesoporous silica MCM-48 membranes. *Sep. Purif. Tech.* **32** (2003) 127-132.
- Nishiyama, N.; Matsuguji, T.; Ueyama, K.; Matsukata, N. FER membrane synthesized by a Vapor-Phase Transport method: its structure and separation characteristics. *Micropor. Mater.* **12** (1997) 293-303.
- Nishiyama, N.; Ueyama, K.; Matsukata, N. Synthesis of defect-free zeolite-alumina composite membranes by a Vapor-Phase Transport method. *Micropor. Mater.* **7** (1996) 299-308.
- Nishiyama, N.; Ueyama, K.; Matsukata, M. A defect-free mordenite membrane synthesized by Vapor-Phase transport method. *J. Chem. Soc. Chem. Commun.* **19** (1995) 1967-1968.
- Noack, M.; Kölsch, P.; Caro, J.; Schneider, M.; Toussaint, P.; Sieber, I. MFI membranes of different Si/Al ratios for pervaporation and steam permeation. *Micropor. Mesopor. Mater.* **35-36** (2000) 253-265.
- Nomura, M.; Yamaguchi, T.; Nakao, S. Transport phenomena through intercrystalline and intracrystalline pathways of silicalite zeolite membranes. *J. Membr. Sci.* **187** (2001) 203-212.
- Nunes, S.P.; Peinemann, K.-V. Membrane Technology in the Chemical Industry, Wiley-VCH Verlag GmbH, D-69469, Weinheim, Germany (2001).
- Okamoto, K.; Kita, H.; Horii, K.; Tanaka, K. Zeolite NaA Membrane: Preparation, Single-Gas Permeation, and Pervaporation and Vapor Permeation of Water/Organic Liquid Mixtures *Ind. Eng. Chem. Res.* **40** (2001) 163-175.
- Ortiz, I.; Gorri, D.; Casado, C.; Urtiaga, A. Modeling of the pervaporative flux through hydrophilic membranes. *J. Chem. Technol. & Biotechnol.* **80** (2005) 397-405.

- Pakseresht, S.; Kazemeini, M.; Akbarnejad, M.M. Equilibrium isotherms for CO, CO₂, CH₄, and C₂H₄ on the 5A molecular sieve by a simple volumetric apparatus. *Sep. Purif. Tech.* **28** (2002) 53-60.
- Pantazidis, A.; Dalmon, J. A.; Mirodatos, C. Oxidative dehydrogenation of propane on catalytic membrane reactors. *Catal. Today* **25** (1995) 403-408.
- Paoli, H.; Methivier, A.; Jobic, H.; Krause, C.; Pfeifer, H.; Stallmach, F.; Kärger, J. Comparative QENS and PFG NMR diffusion studies of water in zeolite NaCaA. *Micropor. Mesopor. Mater.* **55** (2002) 147-158.
- Pappenheimer, J.R.; Renkin, E.M.; Borrero, L.M. Filtration, diffusion and molecular sieving through peripheral capillary membranes. A contribution to the pore theory of capillary permeability. *Am. J. Physiology* **167** (1951) 13-46.
- Paschek, D.; Krishna, R. Inter-relation between self- and jump-diffusivities in zeolites. *Chem. Phys. Lett.* **333** (2001) 278-284.
- Pera-Titus, M.; Mallada, R.; Llorens, J.; Cunill, F.; Santamaria, J. Preparation of inner-side tubular zeolite NaA membranes in a semi-continuous synthesis system. *J. Membr. Sci.* (2006a) (In Press).
- Pera-Titus, M.; Bausach, M.; Llorens, J.; Cunill, F. Dehydration of alcohol/water mixtures by pervaporation with zeolite NaA membranes: application to zeolite membrane reactors. (2006b) *Manuscript in Preparation*.
- Pera-Titus, M.; Llorens, J.; Tejero, J.; Cunill, F. Description of the pervaporation dehydration performance of A-type zeolite membranes: a modeling approach based on the generalized Maxwell-Stefan diffusional theory. *Catal. Today* (2006c) (In Press).
- Pera-Titus, M.; Bausach, M.; Llorens, J.; Cunill, F. Determination of pore size distributions in ultrafiltration, nanofiltration and microfiltration ceramic membranes: a novel method based on moment theory. (2006d). *Manuscript in Preparation*.
- Pera-Titus, M.; Bausach, M.; Llorens, J.; Cunill, F. Characterization of large non-zeolite defects in zeolite NaA membranes. (2006e). *Manuscript in Preparation*.
- Pera-Titus, M.; Llorens, J.; Cunill, F.; Mallada, R.; Santamaria, J. Preparation of zeolite NaA membranes on the inner side of tubular supports by means of a controlled seeding technique. *Catal. Today* **104** (2005) 281-287.
- Pera-Titus, M. Càlcul i disseny d'una planta per a obtenir di-n-pentileter. Master Chemical Engineering Thesis, University of Barcelona, Barcelona, 2001.
- Pecci, G.C.; Clerici, M.G.; Giavazzi, F.; Ancillotti, F.; Marchionna, M.; Patrini, R. Oxygenated fuel diesels. Part 1- Structure and properties correlation. *9th Int. Symposium Alcohol Fuels* (1991) 321-335.
- Philibert, J. Atom movements. Diffusion and mass transport in solids, Les Éditions de Physique, 1991.
- Piera, E.; Salomon, M.A. Coronas, J.; Menendez, M.; Santamaria, J. Synthesis, characterization and separation properties of a composite mordenite/ZSM-5/chabazite hydrophilic membrane. *J. Membr. Sci.* **149** (1998) 99-114.
- Piera, E.; Giroir-Fendler, A.; Mouddeb, H.; Dalmon, J.-A.; Coronas, J.; Menendez, M.; Santamaria, J. Separation of alcohols and alcohol/O₂ mixtures using zeolite MFI membranes. *J. Membr. Sci.* **142** (1997) 97-109.
- Pina, M.P.; Arruebo, M.; Felipe, M.; Fleta, F.; Bernal, M.P.; Coronas, J.; Menendez, M.; Santamaria, J. A semi-continuous method for the synthesis of NaA zeolite membranes on tubular supports, *J. Membr. Sci.* **244** (2004) 141-150.

- Pina, M.P. Catalytic combustion of volatile organic compounds. Ph.D. Thesis, University of Zaragoza, Spain (1998).
- Pradanos, P.; Rodriguez, M.L.; Calvo, J.I.; Hernandez, A.; Tejerina, F.; de Saja, J.A. Structural characterization of an UF membrane by gas adsorption-desorption and AFM measurements. *J. Membr. Sci.* **117** (1996) 291-302.
- Ramaswamy, S.; Greenberg, A.R.; Peterson, M.L. Non-invasive measurement of membrane morphology via UFDR: pore-size characterization. *J. Membr. Sci.* **239** (2004) 143-154.
- Ramsay, J. D. F.; Kallus, S. Zeolite Membranes. *Membrane Science and Technology Series* **6** (2000) 373-395.
- Rase, H.F. *Chemical reactor design for process plants*, Vol. I, John Wiley & Sons, Inc., USA, 1977.
- Reed, D.A.; Ehrlich, G. Surface diffusion, atomic jump and thermodynamics, *Surf. Sci.* **102** (1981) 588-609.
- Rege, S.U.; Yang, R.T. A novel FTIR method for studying mixed gas adsorption at low concentrations: H_2O and CO_2 on NaX zeolite and γ -alumina. *Chem. Eng. Sci.* **56** (2001) 3781-3796.
- Reid, R.C.; Prausnitz, J.M.; Poling, B.E. *The Properties of Gases and Liquids*. 4th edition. McGraw-Hill Book Company, New York, 1987.
- Richter, H.; Voigt, I.; Fischer, G.; Puhlfürß, P. Preparation of zeolite membranes on the inner surface of ceramic tubes and capillaries. *Sep. Purif. Tech.* **32** (2003) 133-138.
- Ruthven, D.M. *Principles of Adsorption and Adsorption Processes*. Wiley, New York, 1984.
- Sahouli, B.; Blacher, S.; Brouers, F. Fractal surface analysis by using nitrogen adsorption data: the case of the capillary condensation regime. *Langmuir* **12** (1996) 2872-2874.
- Saito, Y.; Hirai, K.; Emori, H.; Murata, S.; Uetani, Y.; Kii, K. Carrier Diffusivity in Porous Membranes. *J. Phys. Chem. B* **108** (2004) 1137-1142.
- Saksena, S.; Zydny, A.L. Pore size distribution effects on electrokinetic phenomena in semipermeable membranes. *J. Membr. Sci.* **105** (1995) 203-215.
- Sakuth, M.; Meyer, J.; Gmehling, J. Measurement and prediction of binary adsorption equilibria of vapors on dealuminated Y-zeolites (DAY). *Chem. Eng. Sci.* **37** (1998) 267-277.
- Salomon, M.A.; Coronas, J.; Menendez, M.; Santamaria, J. Synthesis of MTBE in zeolite membrane reactors. *Appl. Catal. A: General* **200** (2000) 201-210.
- Sanchez, J.; Gijiu, C.L.; Hynek, V.; Muntean, O.; Julbe, A. The application of transient-lag method for the diffusion coefficient estimation on zeolite composite membranes. *Sep. Purif. Tech.* **25** (2001) 467-474.
- Sano, T.; Ejiri, S.; Hasegawa, M.; Kawakami, Y.; Enomoto, N.; Tamai, Y. Separation of methanol/methyl-tert-butyl ether mixture by pervaporation using a silicalite membrane. *Chem. Lett.* **107** (1995) 193-196.
- Sano, T.; Hasegawa, M.; Kawakami, Y.; Kiyozumi, Y.; Yanagishita, H.; Kiamoto, D.; Mizukami, F. Potentials of silicalite membranes for the separation of alcohol/water mixtures. *Stud. Surf. Sci. Catal.* **84** (1994) 1175-1182.
- Schwartz, C.E.; Smith, J.M. Flow distribution in packed beds. *Ind. Eng. Chem. Res.* **45** (1953) 1209-1218.

- Scott, K. *Handbook of Industrial Membranes*. 1st edition. Elsevier Science Publishers LTD, Oxford, UK (1995).
- Shah, D.; Kissick, K.; Ghorpade, A.; Hannah, R.; Bhattacharyya, D. Pervaporation of alcohol-water and dimethylformamide-water mixtures using hydrophilic zeolite NaA membranes: mechanisms and experimental results. *J. Membr. Sci.* **179** (2000) 185-205.
- Shah, D.; Bhattacharyya, D.; Magnum, A.; Ghorpade, A. Pervaporation of pharmaceutical waste streams and synthetic mixtures using water selective membranes. *Environ. Progress* **18** (1999) 21-29.
- Shah, D.B.; Hayhurst, D.T.; Evanina, G.; Guo, C.J. Sorption and diffusion of benzene in HZSM-5 and silicalite crystals. *AIChE J.* **34** (1988) 1713-1717.
- Shao, P.; Huang, R.Y.M.; Feng, X; et al. Gas-liquid displacement method for estimating membrane pore-size distributions. *AIChE J.* **50** (2004) 557-565.
- Shapiro, A.A.; Stenby, E.H. Kelvin equation for a non-ideal multicomponent mixture. *Fluid Phase Equilibria* **134** (1997) 87-101.
- Shelekhin, A.B.; Dixon, A.G.; Ma, Y.H. Theory of Gas Diffusion and Permeation in Inorganic Molecular-Sieve Membranes. *AIChE J.* **41** (1995) 58-67.
- Shinde, M.H.; Kulkarni, S.S.; Musale, D.A.; Joshi, S.G. Improvement of the water purification capability of poly(acrylonitrile) ultrafiltration membranes. *J. Membr. Sci.* **162** (1999) 9-22.
- Singh, S.; Khulbe, K.C.; Matsuura, T.; Ramamurthy, P. Membrane characterization by solute transport and atomic force microscopy. *J. Membr. Sci.* **142** (1998) 111-127.
- Sircar, S. Role of adsorbent heterogeneity on mixed gas-adsorption. *Ind. Eng. Chem. Res.* **30** (1991) 1032-1039.
- Slangen, P.M.; Jabseb, J.C.; van Bekkum, H. Effect of aging on the microwave synthesis of zeolite NaA. *Micropor. Mater.* **9** (1997) 259-265.
- Song, L.J.; Sun, Z.L.; Rees, L.V.C. Experimental and molecular simulation studies of adsorption and diffusion of cyclic hydrocarbons in silicalite-1. *Micropor. Mesopor. Mater.* **55** (2002) 31-49.
- Stefanopoulos, K.L.; Romanos, G.E.; Mitropoulos, A.Ch. Kanellopoulos, N.K.; Heenan, R.K. Characterization of porous alumina membrane by adsorption in conjunction with SANS. *J. Membr. Sci.* **153** (1999) 1-7.
- Sun, M.S.; Shah, D.B.; Xu, H.H.; Talu, O. Adsorption equilibria of C₁ to C₄ alkanes, CO₂, and SF₆ on silicalite. *J. Phys. Chem. B* **102** (1998) 1466-1473.
- Sun, M.S.; Talu, O.; Shah, D.B. Diffusion measurements through embedded zeolite crystals. *AIChE J.* **42** (1996) 3001-3007.
- Suzuki, M. *Adsorption Engineering*. Kodansha, Elsevier, New York, 1990.
- Suzuki, H. Composite membrane having a surface layer of an ultrathin film of cage-shaped zeolite and processes of production thereof. *US Patent* 4,699,892 (1987).
- Tavolaro, A.; Julbe, A.; Guizard, C.; Basile, A.; Cot, L.; Drioli, E. Synthesis and characterization of a mordenite membrane on an α-alumina tubular support. *J. Mater. Chem.* **10** (2000) 1131-1137.
- Tavolaro, A.; Drioli, E. Zeolite membranes. *Adv. Mater.* **11** (1999) 975-996.
- Tellez, C. Oxidative dehydrogenation of butane in membrane reactors. Ph.D. Thesis, University of Zaragoza, Spain (1998).

- Terzyk, A.P.; Gauden, P.A. Fractal geometry concept in physical adsorption on solids. *The Arabian Journal for Science and Engineering* **28** (2003) 133-167.
- Tiscareño-Lechuga, C.; Menendez, M.; Santamaría, J. A novel device for preparing zeolite-A membranes under a centrifugal force field. *J. Membr. Sci.* **212** (2003) 135-146.
- Tsay, C.S.; Chiang, A.S.T. Supported zeolite membrane by Vapor-Phase Regrowth. *AICHE J.* **46** (2000) 616-625.
- Tsuru, T.; Takata, Y.; Kondo, H.; Hirano, F.; Yoshioka, T.; Asaeda, M. Characterization of sol-gel derived membranes and zeolite membranes by nanopermorometry. *Sep. Purif. Tech.* **32** (2003) 23-27.
- Tzevelekos, K.P.; Kikkides, E.S.; Stubos, A.K.; Kainourgiakis, M.E.; Kanellopoulos, N.K. On the possibility of characterizing mesoporous materials by permeability measurements of condensable vapors: theory and experiments. *Adv. Colloid Interface Sci.* **76/77** (1998) 373-388.
- Ullmann's Encyclopedia of Industrial Chemistry, 6th edition, Wiley-VCH Verlag GmbH, D-69451 Weinheim, Germany (1998).
- Urtiaga, A.; Gorri, E.D.; Casado, C.; Ortiz, I. Pervaporative dehydration of industrial solvents using a zeolite NaA commercial membrane. *Sep. Purif. Tech.* **32** (2003) 207-213.
- Valenzuela, D.P.; Myers, A.L. Adsorption Equilibrium Handbook. Prentice-Hall, Englewood Cliffs, NJ, 1989.
- Van den Berg, A.W.C.; Gora, L.; Jansen, J. C.; Maschmeyer, T. Improvement of zeolite NaA nucleation sites on (001) rutile by means of UV-radiation. *Micropor. Mesopor. Mater.* **66** (2003a) 303-309.
- Van den Berg, A.W.C.; Gora, L.; Jansen, J. C.; Makkee, M., Maschmeyer, T. Zeolite A membranes synthesized on a UV-irradiated TiO₂ coated metal support: the high pervaporation performance. *J. Membr. Sci.* **224** (2003b) 29-37.
- Van den Bleek, C.M.; Van der Wiele, K.; Van den Berg, P.J. Effect of dilution on the degree of conversion in fixed bed catalytic reactors. *Chem. Eng. Sci.* **24** (1969) 681-694.
- Van den Broeke, J.L.P. Simulation of diffusion in zeolitic structures. *AICHE J.* **41** (1995) 2399-2414.
- Van den Broeke; J.L.P.; Krishna, R. Experimental verification of the Maxwell-Stefan theory for micropore diffusion. *Chem. Eng. Sci.* **50** (1995) 2507-2522.
- Van den Graaf, J. M.; Kapteijn, F.; Moulijn, J. A. Modeling permeation of binary mixtures through zeolite membranes. *AICHE J.* **45** (1999) 497-511.
- Van den Graaf, J.; van den Broeke, L.J.P.; Kapteijn, F.; Moulijn, J.A. TEOM: a unique technique for measuring adsorption properties. Light alkanes in silicalite-1. *Ind. Eng. Chem. Res.* **37** (1998) 1934-1942.
- Van Heerden, J.; Botha, J.J.; Roets, N.J. Improvements of diesel performance with the addition of linear ethers to diesel fuels. *Proceedings of the 12th International Symposium on Alcohol Fuels*, Beijing, People's Republic of China, 1998, 188-199.
- Verkerk, A.W.; van Male, P.; Vorstman, M.A.G.; Keurentjes, J.T.F. Description of dehydration performance of amorphous silica pervaporation membranes. *J. Membr. Sci.* **193** (2001) 227-238.
- Vignes, A. Diffusion in binary solutions. *Ind. Eng. Chem. Fundam.* **5** (1966) 189-& 1966.
- Wang, F.; Li, S. Determination of the surface fractal dimension for porous media by capillary condensation. *Ind. Eng. Chem. Res.* **36** (1997) 1598-1602.

- Warzywoda, J.; Edelman, R.D.; Thompson, R.W. Crystallization of high-silica ZSM-5 in the presence of seeds. *Zeolites* **11** (1991) 318-324.
- Weast (Ed), R.C. Handbook of Chemistry and Physics, 52nd Edition, Ohio, USA, 1971-1972.
- Wijmans, J. G.; Baker, R. W. The solution-diffusion model: a review. *J. Membr. Sci.* **107** (1995) 1-21.
- Xiao, J.R.; Wei, J. Diffusion Mechanism of Hydrocarbons in Zeolites: I. Theory. *Chem. Eng. Sci.* **47** (1992) 1123-1141.
- Xomeritakis, G.; Tsapatsis, M. Permeation of aromatic isomer vapors through oriented MFI-type membranes made by secondary growth. *Chem. Mater.* **11** (1999) 875-879.
- Xomeritakis, G.; Gouzinis, A.; Nair, S.; Okubo, T.; He, M.; Overney, R.M.; Tsapatsis, M. Growth, microstructure, and permeation properties of supported zeolite (MFI) films and membranes prepared by secondary growth. *Chem. Eng. Sci.* **54** (1999) 3521-3531.
- Xu, X.; Bao, Y.; Song, C.; Yang, W.; Liu, J.; Lin, L. Synthesis, characterization and single gas permeation properties of NaA zeolite membranes. *J. Membr. Sci.* **249** (2005) 51-64.
- Xu, X.; Yang, W.; Liu, J.; Lin, L.; Stroh, N.; Brunner, H. Synthesis of NaA zeolite membrane on a ceramic hollow fiber. *J. Membr. Sci.* **229** (2004) 81-85.
- Xu, X.; Yang, W.; Liu, J.; Lin, L. Synthesis of NaA zeolite membrane by microwave heating. *Sep. Purif. Tech.* **25** (2001a) 241-249.
- Xu, X.; Yang, W.; Liu, J.; Lin, L. Synthesis of NaA zeolite membranes from clear solution. *Micropor. Mesopor. Mater.* **43** (2001b) 299-311.
- Xu, W.; Dong, J.; Li, J.; Li, W.; Wu, F. A novel method for the preparation of zeolite ZSM-5. *J. Am. Chem Soc. Chem. Comm.* (1990) 755-756.
- Yamazaki, S.; Tsutsumi, K. Synthesis of A-type zeolite membrane using a plate heater and its formation mechanism. *Micropor. Mesopor. Mater.* **37** (2000) 67-80.
- Yamazaki, S.; Tsutsumi, K. Adsorption characteristics of synthesized mordenite membranes. *Adsorption* **3** (1997) 165-171.
- Yang, R.T. Gas Separation by Adsorption Processes. Butterworths, London, 1987.
- Yopps, J. A.; Furstenau, D. W. The zero point of charge of α -alumina. *J. Colloid Sci.* **19** (1964) 61-71.
- Yoshioka, T.; Nakanishi, E.; Tsuru, T.; Asaeda, M. Experimental Studies of Gas Permeation through Microporous Silica Membranes. *AICHE J.* **47** (2001) 2052-2063.
- Youn, I.J.; Jeong, J.; Kim, T.; Lee, J-C. Light transmission study for determination of pore size distribution in microporous membranes. *J. Membr. Sci.* **145** (1998) 265-269.
- Zeman, L.; Denault, L. Characterization of microfiltration membranes by image analysis of electron micrographs. Part I. Method development. *J. Membr. Sci.* **71** (1992a) 221-231.
- Zeman, L. Characterization of microfiltration membranes by image analysis of electron micrographs. Part II. Functional and morphological parameters. *J. Membr. Sci.* **71** (1992b) 233-246.
- Zhao, C.; Zhou, X.; Yue, Y. Determination of pore size and pore size distribution on the surface of hollow-fiber filtration membranes: a review of methods. *Desalination* **129** (2000a) 107-123.
- Zhao, H.; Jin, T.; Kuraoka, K.; Yazawa, T. A novel method for the synthesis of ZSM-5 zeolite membranes on a porous alumina tube: the role of a dry-gel barrier in pores. *Chem. Commun.* (2000b) 1621-1622.

Zhu, W.; Gora, L.; Van den Berg, A.W.C.; Kapteijn, F.; Jansen, J.C.; Moulijn, J.A. Water vapour separation from permanent gases by a zeolite-4A membrane. *J. Membr. Sci.* **253** (2005) 57-66.

Zhu, W.; Kapteijn, F.; van der Linden, B.; Moulijn, J.A. Equilibrium adsorption of linear and branched C₆ alkanes on silicalite-1 studied by the tapered oscillating microbalance. *Phys. Chem. Chem. Phys.* **3** (2001) 1755-1761.

Zhu, W.; van den Graaf, J.; Van den Broeke, L.J.P.; Kapteijn, F.; Moulijn, J.A. TEOM: a unique technique for measuring adsorption properties. Light alkanes in silicalite-1. *Ind. Eng. Chem. Res.* **37** (1998) 1934-1942.

WEB SITES

Atlas of zeolites (<http://www.izastructure.org/databases/>) (revised 1st July 2006).

BAM, <http://www.bam.de> (revised 1st January 2006)

Wynn, N. Pervaporation Comes of Age (<http://www.cepmagazine.org/databases/>) (revised 1st January 2006).