MASS TRANSFER OPERATION–MEMBRANE SEPARATIONS

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

Keywords: Membrane technology, chemical and process engineering, process design, integrated systems, sustainable growth, process intensification, nanotechnologies, tailored materials, advanced molecular separations and chemical conversions.

Contents

Summary

Because of its intrinsic properties that well fit the requirements of process intensification strategy, membrane technology has well established applications in most of the industrial processes ranging from water desalination, wastewater treatments, agro-food, chemical and petrol chemical industry, etc. In particular, integrated membrane systems are today recognized as an interesting tool for a better rationalization of numerous industrial cycles. However, a good understanding of the materials properties and transport mechanisms, as well as the development of innovative materials with improved properties, is a key issue for the further applications of this

technology. Appropriate module design, hydrodynamic studies, and, in general, engineering analysis are also relevant aspects for their large-scale applications.

In this work, an overview on the fundamentals and applications, including basic process design, modules configuration, and choice of materials, of some specific membrane processes (reverse osmosis, nanofiltration, ultrafiltration, microfiltration, electrodialysis, gas separation, pervaporation and vapor permeation, membrane contactors and catalytic membrane reactors), also integrated, is presented.

1. Introduction

A membrane is thin interphase that restricts the passage of different components in a specific mode and over a wide range of particle sizes and molecular weights, from ions to macromolecules.

Synthetic membranes may be manufactured as solid or liquid phase, using organic or inorganic materials; they may be homogeneous or heterogeneous, symmetrical or asymmetrical, porous or dense, electrically neutral or charged; they may exhibit isotropic or anisotropic properties.

The efficiency of a membrane basically is determined by two parameters: permeability (the rate at which a given component is transported through the membrane) and selectivity (the ability to separate in specific way a given component from others).

The transport of different species through a membrane is a non-equilibrium process, and the separation of the different components is due to differences in their transport rate.

In a membrane separation process, the transport rate of a component can be activated by various driving forces such as gradients in concentration, pressure, temperature or electrical potential.

In many membrane operations more than one driving force is involved (e.g. pressure and concentration in gas separation, concentration and electrical potential in electrodialysis, etc.), but all these parameters can be included in one thermodynamic function, the electrochemical potential η (which includes the chemical potential). For a single component i transported, the flux J_i can be described by a semi-empirical equation [1]:

$$J_i = -L \cdot \frac{d\eta_i}{dx} \tag{1}$$

where $\frac{d\eta_i}{dx}$ is the gradient in electrochemical potential of the component i and L is a phenomenological coefficient.

In multi-component systems, driving forces and fluxes are interdependent, giving rise to complex interactions; not far from equilibrium, linear equations derived from irreversible thermodynamics suggest that,

$$J_i = -L_{ij} \cdot \frac{d\eta_i}{dx} \qquad (2)$$

where L_{ij} is a proportionality coefficients.

Membrane can have two different configurations: flat sheet or tubular (Figure 1).

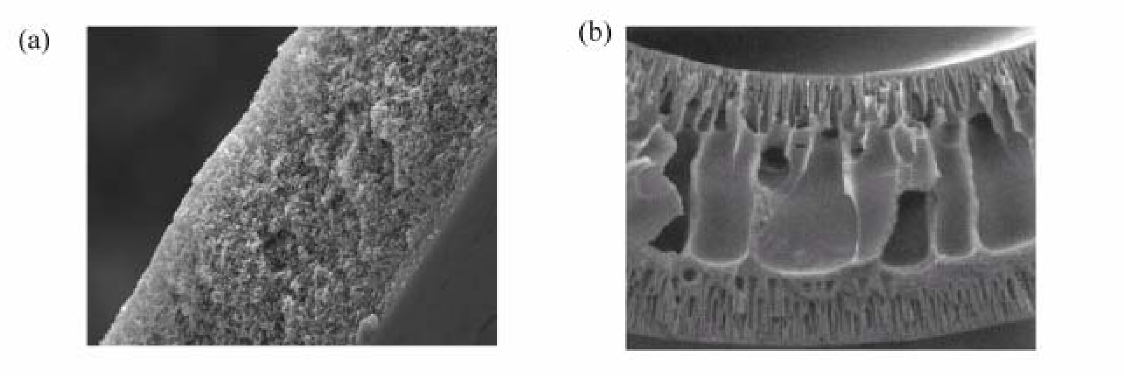

Figure 1: Scanning electron microscopy (SEM) images of the cross section of a flat sheet [2] (a) and of a hollow fiber [3] (b) membrane prepared from a modified polyetheretherketone known as PEEK-WC.

Tubular membranes can be distinguished in: hollow fibers (fiber diameter below 0.5 mm), capillary (fiber diameter comprised between 0.5 and 10 mm) and tubular (fiber diameter > 10mm).

For applications on large scale, membranes are efficiently packed in small and compact units or modules. Different typologies of module design are today available: flat membranes climbed on plate-and-frame (Figure 2) and spiral-wound modules (Figure 3); hollow fibers, capillary and tubular membranes assembled in modules having tubular geometry (Figure 4).

Properties of the different module configuration	**Plate and frame**	**Spiral wound**	**Tubular**	**Capillary**	**Hollow fiber**
Representative packing density (m^2/m^3)	100-400	300-1000	< 300	600-1200	Up to 30000
Capital cost	high	med-high	High	Low	low
Fouling tendency	low to moderate	med-high	Low	High	very high
Ease of cleaning	good	poor to good	good to excellent	Poor	poor
Operating cost	high	moderate	High	Low	low

Table 1: Properties of different module configurations

Plate-and-frame modules make use of flat-sheet membranes (in sandwich configuration) separated by support plates. These modules have low packing densities and are correspondingly expensive; they are for examples used to produce potable water in small-scale applications (Table 1).

Spiral-wound modules allow the efficient packaging of flat-sheet membrane in a convenient cylindrical form. They consist in an arrangement of two rectangular membranes placed back to back and sealed on three sides. They are rolled around a collector tube connected to the fourth side which remains open. The solution to be treated is brought to one end of this cylinder and the product circulates between both membranes to the collector tube. A spiral-wound module is contained in a pressure vessel assembly, consisting of a cylindrical housing for the modules, a plumbing to connect the modules together in series and a plumbing to connect the feed inlet, product and concentrate outlet. These modules have a good density, but cleaning is difficult. Modules composed by tubular membranes generally contain up to 30 tubes, normally supported within stainless steel vessels; with this module design, the feed and permeate channels can be easily cleaned. The major advantage of the tubular configuration is that the tube diameter is large enough to promote turbulent flow under most conditions without an excessive pressure drop. On the other hand, the low module packing density represents a serious disadvantage.

Capillary and hollow fiber modules have the highest membrane surface area per element; however, due to the high density packaging, these modules appear to be very sensitive to the feed stream quality in terms of fouling potential.

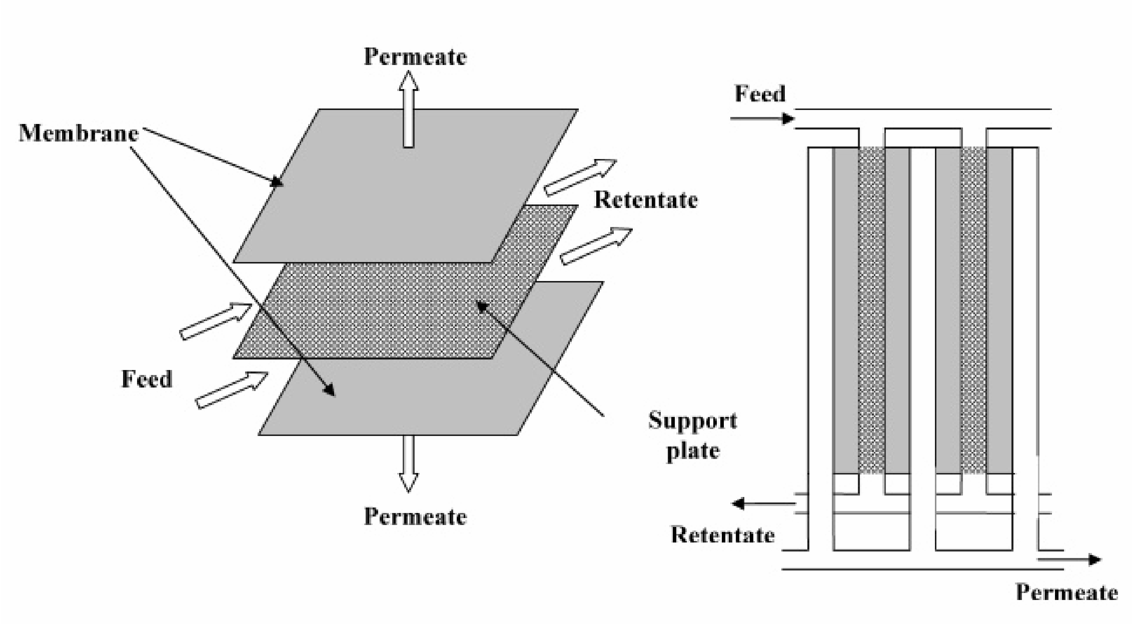

Figure 2: Scheme of a plate and frame membrane module

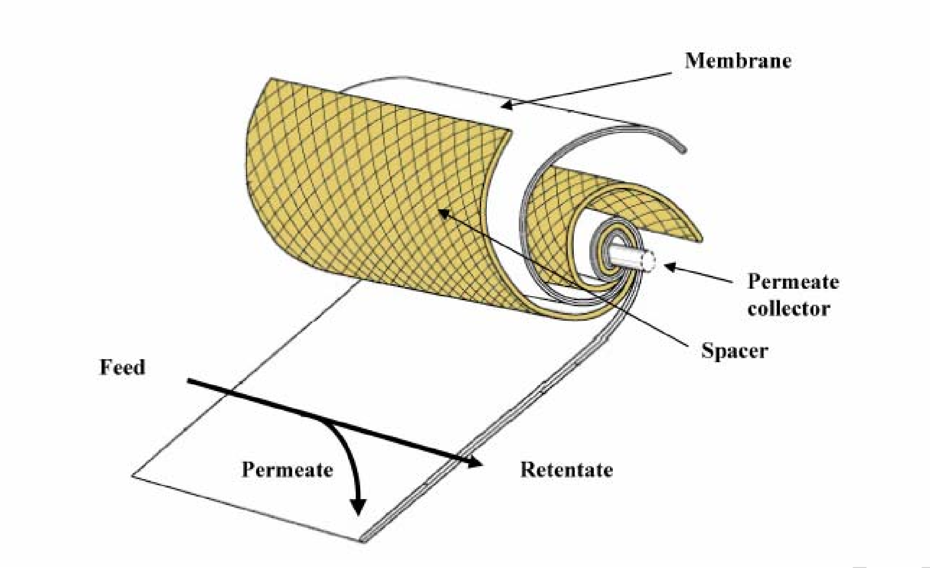

Figure 3: Scheme of a spiral wound module

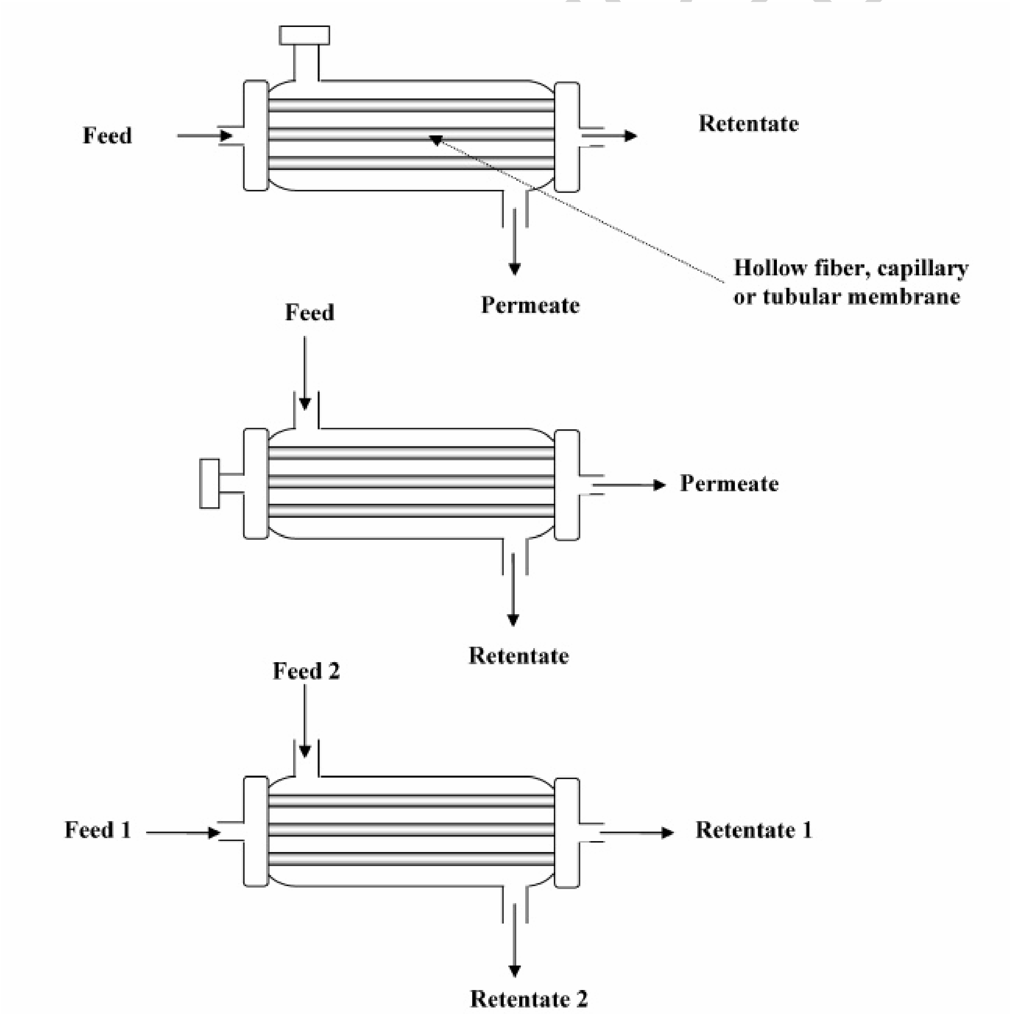

Figure 4: Scheme of tubular modules with different operative design

In a membrane separation process two main operative design are possible: cross-flow and dead-end

A schematic representation of a cross-flow and a dead-end membrane separation stage is reported in figure 5.

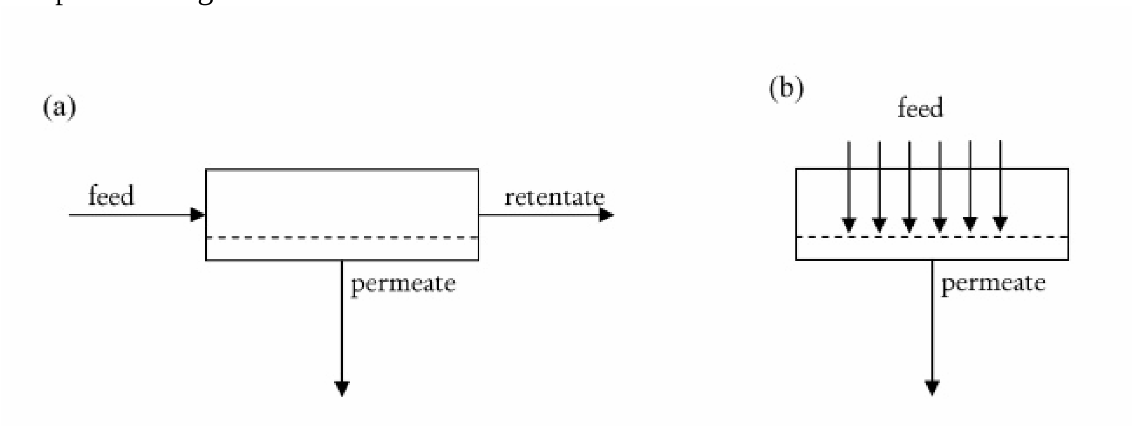

Figure 5: Schematic drawing of a membrane separation stage: cross-flow (a) and dead-end (b)

In the cross-flow mode, the feed stream flows parallel to the membrane and is separated into two streams: the retentate (or concentrate) and the permeate.

In the dead-end the feed is forced perpendicularly the membrane leading to a concentrate phase (retentate) and a permeate. This operative modality is characterized by a higher tendency to fouling phenomena than cross-flow mode, and so cross-flow operation is generally preferred for industrial applications [4, 5].

If the product stream coming from a single-stage design does not meet the requested level of purity, the retentate and/or permeate stream has to be treated in a multi-stage membrane process or cascade operation (Figures 6 and 7).

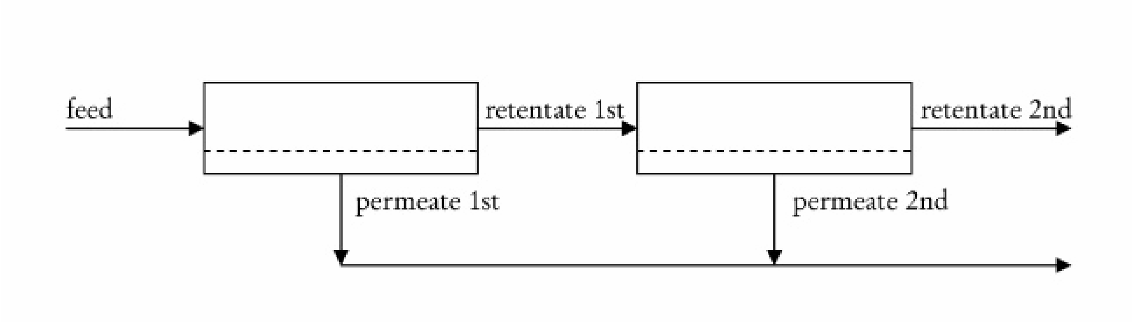

Figure 6: Two stage membrane separation system

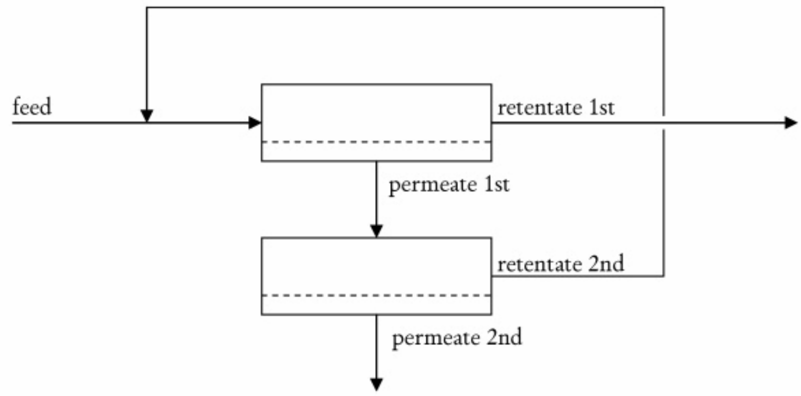

Figure 7: Two pass membrane separation system

2. An overview on the most industrialized membrane separation processes and emerging applications

Membrane operations, with their intrinsic characteristics of efficiency and operational simplicity, high selectivity and permeability for the transport of specific components, compatibility between different membrane operations in integrated systems, low energetic requirement, good stability under operative conditions, advanced control, easy scale-up and elevated flexibility, are today used in a large number of industrial applications.

The total annual market for membranes and membrane equipments is forecast to grow from $ 6.3 billion worldwide in 2004 to over $ 8.4 billion in 2007 [6]. The membrane industry is therefore an important economic factor; however, it is significant to realize that this market is extremely heterogeneous with a multitude of segments. Presently, water and wastewater treatment is the most relevant membrane application followed by food and beverage processing and drug and medical application. Catalytic membrane reactors, enantiospecific membrane separation processes and fuel cells can be considered emerging applications.

The vast majority of membrane materials are nowadays polymeric, although the demand for non polymeric materials for special applications, including ceramic, metal and composite types, registers a rapid growth. Typical examples are zeolite membranes applied to promote the molecular separation and the catalytic act [7,8] ceramic membranes for high temperature applications [9], and perovskite type membranes for oxygen separation and catalytic reactors for syngas production and the partial oxidation of hydrocarbons [10, 11, 12, 13].

The growing interest towards membrane science and technology is evident. At the 9th World Filtration Congress held in New Orleans (23-24 April, 2004 - Louisiana, USA) most of the scientific communications were held concerning applications of membrane systems in various production sectors. A confirmation of the industrial interest and strategic role for membrane operations, has been the presence of almost 200 exhibitors connected with the membrane world at the 9th edition of ACHEMA (19-24 May, 2003 - Frankfurt am Main, Germany), the world's largest exhibition for chemical engineering, environmental technology and biotechnology. A further evidence of the increasing interest on membrane systems is the presence of numerous research projects in this field, approved, in progress or carried out in the latest years, with the financial support from the European Union. In particular, a Network of Excellence: "Expanding membrane macroscale applications by exploring nanoscale material properties (NanoMemPro)", has been recently approved in the 6th Framework Programme (2002-2006) of the EU, and is now in progress. Significant transformations in the European membrane industry are also confirming the maturity of the membrane operation in various industrial areas. Danish Separation Systems (DSS) acquisition by Alfa Laval (2002), Nadir and Microdyn merging in the Advanced Separation Technologies Group Membranes (2003), Osmonics and Ionics (2005) acquisition by General Electrics (GE) are some consolidations which are taking place in industry.

-
-
-

Bibliography

1. Kedem O., Katchalsky A. (1961). A physical interpretation of the phenomenological coefficients of membrane permeability. *The Journal of General Physiology* **45**, 143–179. [In this paper, the phenomenological permeability coefficients are analysed in terms of friction and distribution coefficients amenable to physical interpretation, for both non-electrolytic and electrolytic permeants].

2. Fontananova E., Basile A., Cassano A., Drioli E. (2003). Preparation of polymeric membranes entrapping β-cyclodextrin and their molecular recognition of naringin. *Journal of Inclusion Phenomena and Macrocyclic Chemistry* **47**, 33-37. [An analysis of the recognition properties of the β-cyclodextrin derivative immobilized in amorphous polyetheretherketone (PEEK-WC) membranes towards naringin].

3. Tasselli F., Jansen J.C., Sidari F., Drioli E. (2005). Morphology and transport property control of modified poly(ether ether ketone) (PEEKWC) hollow fiber membranes prepared from PEEKWC/PVP blends: influence of the relative humidity in the air gap. *Journal of Membrane Science* **255**, 13–22. [A study on the effect of poly(vinyl pyrrolidone) (PVP) and of the humidity in the air gap on the porosity, morphology, transport and mechanical properties of hollow fiber PEEK-WC membranes, prepared via the dry-wet spinning process].

4. Vrijenhoek E. M., Hong S., Elimelech M. (2001). Influence of membrane surface properties on initial rate of colloidal fouling of reverse osmosis and nanofiltration membranes. *Journal of Membrane Science* **188**, 115–128. [The paper attempts to identify the most influential membrane properties (surface morphology, chemical properties, zeta potential etc.) governing colloidal fouling rate of NF and RO membranes during laboratory-scale cross flow experiments].

5. Mueller J., Davis R. H. (1996). Protein fouling of surface-modified polymeric microfiltration membranes. *Journal of Membrane Science 116*, 47-60. [The effects of varying morphology and surface chemistry on protein fouling of microfiltration membranes is here investigated].

6. http://www.mcilvainecompany.com/webtofc.html [Some forecasts on the market for membranes and membrane equipments are reported]

7. Gobina E. (1998). Zeolitic systems for gas separation and integrated membrane reactors. *Membrane Technology* **94**, 7-12. [A summary of the state-of-art on zeolite membranes for gas separation and

catalysis with applications in integrated membrane systems].

8. Ackley M. W., Rege S. U., Safena H. (2003). Application of natural zeolites in the purification and separation of gases. *Microporous and Mesoporous Materials* **61**, 25–42. [Patents and other literature are surveyed to identify the bulk separation and purification processes for which natural zeolites (including clinoptilolite, chabazite, mordenite, erionite, ferrierite, phillipsite etc.) have potential interest].

9. Drioli E., Criscuoli A. (2000). Microporous inorganic and polymeric membranes as catalytic reactors and membrane contactors in: Recent Advances in *Gas Separation by Microporous Ceramic Membranes* pp. 497-510, ed. N.K. Kanellopoulos. Amsterdam: Elsevier Science B.V. [A survey of microporous membranes for application in membrane contactors and catalytic membrane reactors].

10. Jin W., Li S., Huang P., Xu N., Shi J. (2001). Preparation of an asymmetric perovskite-type membrane and its oxygen permeability. *Journal of Membrane Science* **185**, 237–243. [This work describes the preparation procedure of a crack-free asymmetric membrane of perovskite-type oxide obtained by coating a slurry containing $La_{0.6}Sr_{0.4}Co_{0.2}Fe_{0.8}O_{3-\delta}$ powders directly on the surface of a green support of the same composition, followed by sintering].

11. Diethelm S., Van Herle J. (2004). Oxygen transport through dense $La_{0.6}Sr_{0.4}Fe_{0.8}Co_{0.2}O_{3-\delta}$ perovskite-type permeation membranes. *Journal of the European Ceramic Society* **24**, 1319–1323. [In this paper, the parameters (chemical diffusion and the surface exchange) governing the overall oxygen flux through a perovskite-type permeation membrane are investigated].

12. Islam M. S. (2002). Computer modeling of defects and transport in perovskite oxides. *Solid State Ionics* **154/155**, 75– 85. [Computer simulations are performed at atomic scale on vacancy ordering in order to predict transport properties of perovskite oxides].

13. Zenga Y., Lina Y.S., Swartzb S.L. (1998). Perovskite-type ceramic membrane: synthesis, oxygen permeation and membrane reactor performance for oxidative coupling of methane. *Journal of Membrane Science* **150**, 87-98. [In this study, several different synthesis methods are compared for the preparation of $La_{0.8}Sr_{0.2}Co_{0.6}Fe_{0.4}O_{3-\delta}$ (LSCF) powders. The coprecipitation method is found most suitable for preparation of the LSCF powder in terms of processibility into dense ceramic membranes].

14. Bhattacharya S., Hwang S.T. (1997). Concentration polarization, separation factor, and Peclet number in membrane processes. *Journal of Membrane Science* **132**, 73-90. [Authors propose a generalized equation relating the modified Peclet number to the concentration polarization that is shown applicable to the majority of membrane separation processes like gas separations, reverse osmosis, ultrafiltration, pervaporation, and dissolved gas permeation in liquid].

15. Mulder M.. (1996). *Basic principles of membrane technology*, pp. 584 Dordrecht: Kluwer Academic Publishers. [A comprehensive textbook on fundamentals of membrane science and technology].

16. Chakravorty B., Layson A. (1997). Ideal feed pretreatment for reverse osmosis by continuous microfiltration. *Desalination* **110**, 143-150. [A study on the performance of continuous microfiltration technology as feed pretreatment process capable of ensuring high degree of reliability for the Reverse Osmosis system].

17. Dudley L.Y., Darton E.G. (1997) Pretreatment procedures to control biogrowth and scale formation in membrane systems. *Desalination* **110**, 11-20. [This paper examines the importance of monitoring pretreatment plant used to control microbiological and general fouling and inhibiting the formation of inorganic scales].

18. Bae T.-H., Tak T.-M. (2005.). Interpretation of fouling characteristics of ultrafiltration membranes during the filtration of membrane bioreactor mixed liquor. *Journal of Membrane Science* **264**, 151–160. [A study on the preparation of ultrafiltration (UF) membranes with various pore sizes by the phase inversion technique method, and their fouling characteristics with membrane bioreactor (MBR) mixed liquor].

19. Gilron J., Belfer S., Vaisanen P., Nystrom M. (2001). Effects of surface modification on antifouling and performance properties of reverse osmosis membranes. *Desalination* **140**, 167-179. [Selected RO membranes, spanning ultra-low pressure to seawater membranes, were modified by *in-situ* graft polymerization using redox generation of monomer radicals].

20. Wavhal D.S., Fisher E.R. (2002). Hydrophilic modification of polyethersulfone membranes by low

temperature plasma-induced graft polymerization. *Journal of Membrane Science* **209**, 255–269. [A complete and permanent hydrophilic modification of polyethersulfone (PES) membranes is achieved by argon plasma treatment followed by polyacrylic acid (PAA) grafting in vapor phase.

21. Pavlova S. (2005). Study on the cleaning of new ultrafiltration spiral-wound modules to prevent membrane fouling (including biological fouling). *Desalination* **172**, 267-270. [This study compares chemical cleaning procedures of new ultrafiltration spiral-wound membrane modules based on sodium metabisulfite and formaldehyde].

22. Songa W., Ravindran V., Koel B.E., Pirbazari M. (2004). Nanofiltration of natural organic matter with H_2O_2/UV pretreatment: fouling mitigation and membrane surface characterization. *Journal of Membrane Science* **241**, 143–160. [This paper investigates the application of H_2O_2/UV oxidation for source water pretreatment, and membrane cleaning to improve the performance of nanofiltration processes].

23. Drioli E., Romano M. (2001). Progress and new perspectives on integrated membrane operations for sustainable industrial growth. *Industrial Engineering Chemical Research* **40**, 1277-1300. [Authors present a summary review of the extent to which membrane processes have been integrated into industrial practice. Some of the most interesting results already achieved in membrane engineering are discussed, and predictions about future developments and the possible impact of new membrane science and technology on sustainable industrial growth are analyzed].

24. Muthukumarana S., Kentish S.E., Ashokkumarb M., Stevens G.W. (2005) Mechanisms for the ultrasonic enhancement of dairy whey ultrafiltration. *Journal of Membrane Science* **258**, 106–114. [Low frequency ultrasound are here used to facilitate cross-flow ultrafiltration of dairy whey solutions].

25. Krstic D.M., Tekic M.N., Caric M.D., Milanovic S.D. (2004). Static turbulence promoter in cross-flow microfiltration of skim milk. *Desalination* **163**, 297-309. [This study investigates the influence of static turbulence promoter on permeate flux during skim milk microfiltration and the potential application of this arrangement for an industrial development].

26. Noordman T.R., de Jonge A., Wesselingh J.A., Bel W., Dekker M., Ter Voorde E., Grijpma S.D. (2004). Application of fluidised particles as turbulence promoters in ultrafiltration Improvement of flux and rejection. *Journal of Membrane Science* **208**, 157–169 [It is shown that fluidised particles permit to obtain an high degree of turbulence in order to limit fouling of ultrafiltration membranes during processing of protein solutions].

27. Mameri N., Oussedik S., Yeddou R., Piron D.L., Belhocine D., Lounici H., Grib H. (1999). Enhancement of ultrafiltration flux by coupling static turbulence promoter and electric field. *Separation and Purification Technology* **17**, 203–211. [This work aims to determine the effect of the static metal deployed sheet on the performance of the ultrafiltration process; reversible polarisation layer and fouling is controlled by appropriate electric field strength].

28. Scott K., Mahmood A.J., Jachuck R.J., Hu B. (2000). Intensified membrane filtration with corrugated membranes. *Journal of Membrane Science* **173**, 1–16. [The experimental activity carried out on corrugated membranes shows that increases in crossflow velocity and decreases in flow channel height result in an improved permeate flux caused by increased shear effects on the membrane surface].

29. Broussous L., Schmitz P., Boisson H., Prouzet E., Larbot A. (2000) Hydrodynamic aspects of filtration antifouling by helically corrugated membranes. *Chemical Engineering Science* **55**, 5049-5057. [New ceramic tubular membrane geometry with a helical relief stamp at the membrane surface have been developed in order to maintain a high level of turbulence close to the surface during filtration].

30. Finnigan S.M., Howell J.A. (1989). The effects of pulsatile flow on ultrafiltration fluxes in a baffled tubular membrane system. *Chemical Engineering Research and Design* **67**, 278-280. [The filtration performance of a UF tubular membrane was improved by a factor of about 3 by the incorporation of periodically spaced baffles of a doughnut shape within the tubes].

31. Goma H., Al Taweel A.M. (2004). Dynamic analysis of mass transfer at vertically oscillating surfaces. *Chemical Engineering Journal* **102**, 71–82. [The dynamical behaviour of mass transfer at vertically oscillating surfaces is investigated both experimentally and analytically].

32. Cui Z.F., Chang S., Fane A.G. (2003). The use of gas bubbling to enhance membrane processes, *Journal of Membrane Science* **221**, 1-35. [This paper reviews the state-of-the-art of the use of gas bubbles

and slugs in microfiltration and ultrafiltration with flow inside tubes and fibres, across flat sheets and outside fibres].

33. Bixler H.J., RappeG.C. (1970) Increasing the mass transport rate across ultrafiltration membranes, US Patent 3 541 006 [In this patent gas bubbles are used to reduce fouling in ultrafiltration membranes].

34. Jamal K., Khan M.A., Kamil M. (2004). Mathematical modeling of reverse osmosis systems *Desalination* **160** 29-42. [A model based on non-linear differential equation combining material balances on the feed tank, membrane module and product tank with membrane mass transfer is proposed in order to simulate small-scale reverse osmosis systems].

35. Jonsson G. (1980). Overview of Theories for Water and Solute Transport in UF/RO Membranes. *Desalination* **35**, 21 -38. [The applicability of various models for the transport of water and solute in UF/RO membranes is outlined in this paper].

36. Soltanieh M., Gill W. (1981). Review of Reverse Osmosis Membranes and Transport Models. *Chemical Engineering Communications* **12**, 279-363. [This paper describes the structure and properties of membranes and membrane transport theory, the mechanism of salt rejection. Solubility, diffusivity, and permeability of membranes to solutes and solvents are also reviewed critically and compared with each other].

37. Mazid M. (1984). Mechanisms of Transport Through Reverse Osmosis Membranes. *Separation Science and Technology* **19**, 357 – 372. [In this paper, the two main Reverse Osmosis membrane transport mechanisms - i.e. solution-diffusion model and sorption-capillary flow mechanism - are reviewed].

38. Pusch W. (1986). Measurement Techniques of Transport Through Membranes. *Desalination* **59**, 105-198. [Membrane model-independent and dependent relationships for transport of matter across synthetic membranes are compiled].

39. Dickson J. (1988). Fundamental Aspects of Reverse Osmosis, in *Reverse Osmosis Technology, (ed.* B. Parekh), pp. 1-51. New York: Marcel Dekker Inc. [A comprehensive understanding of the basic concepts of Reverse Osmosis technology].

40. Rautenbach R., Albrecht R. (1989). Membrane Processes, 459, pp. New York: John Wiley & Sons. [A widespread book on membranes and membrane processes].

41. *IDA news*, July/August 2002, Vol. 11, Issue 78 [This present a comparison between the desalting capacity based on reverse osmosis plants and thermal plants].

42. Van der Bruggen B., Vandercasteele C. (2003). Removal of pollutants from surface water and ground water by nanofiltration: overview of possible applications in the drinking water industry. *Environmental Pollution 22*, 435-445 [This paper investigates the potentialities of nanofiltration in water treatment].

43. Bowen W.R., Welfoot J.S. (2002). Predictive modeling of nanofiltration: membrane specification and process optimization. *Desalination* **147**, 197-203 [The paper reviews the mathematical models concerning the description of rejection and flux at nanofiltration pores, the inclusion in calculations of pore size distributions with pore size dependent physical properties, the linearization of these models to facilitate rapid calculations, and the use of such calculations to specify membranes for technically demanding separations].

44. http://www.smalltimes.com/document_display.cfm?section_id=46&document_id=3943 [About the world's first nanofiltration facility for drinking water (Generale des Eaux's), located in Auvers-sur-Oise, north of Paris, able to supply four million people].

45. Gekas V. (1986). Terminology for pressure driven membrane operations. Approved and issued June 1986 by The European Society of Membrane Science and Technology. [A report on the terminology for pressure driven membrane operations].

46. Munson-McGee S. H. (2002). An approximate analytical solution for the fluid dynamics of laminar flow in a porous tube. *Journal of Membrane Science* **197**, 223-230. [This study reports an approximate solution for the fluid dynamics of flow through a porous tube, such as encountered in the cross-flow filtration process].

47. Zaidi S.K., Kumar A. (2005). Experimental analysis of a gel layer in dead-end ultrafiltration of a

silica suspension, *Desalination* **172**, 107-117. [Unstirred dead-end ultrafiltration of a silica suspension is studied using a fully retentive membrane, and the effects of operating conditions such as applied pressure and bulk concentration on specific resistance, thickness, porosity and silica concentration of gel are reported].

48. Christy C., Vermant S. (2002). The state-of-the-art of filtration in recovery processes for biopharmaceutical production. *Desalination* **147**, 1-4. [This paper reviews the application of membranes from microporous, through ultrafiltration to nanofiltration/reverse osmosis types using actual examples of systems designed for cell harvesting, protein concentration, small molecule processing, virus removal and sterile filtration].

49. Bhanushali D., Kloos S., Kurth C., Bhattacharyya D. (2001). Performance of solvent-resistant membranes for non-aqueous systems: solvent permeation results and modeling. *Journal of Membrane Science* **189**, 1–21. [A study on the development and experimental verification of membrane materials and transport models to explain permeation properties of non-aqueous solvent systems].

50. Strathmann, H. (1986). Electrodialysis, in *Synthetic Membranes: Science, Engineering and Applications.* (eds. P.M. Bungay, H.K. Lonsdale, and M.N.D. de Pinho), Holland: Reidel Publishing Company, Dordrecht. [A chapter that extensively describes the basic principles and applications of electrodialysis].

51. Pourcelly G. (2002). Electrodialysis with Bipolar Membranes: Principles, Optimization, and Applications. *Russian Journal of Electrochemistry* **38**, 919–926 [This paper is an overview of the process of electrodialysis with bipolar membrane (EDBM) along with the different configurations].

52. Lee H.-J., Oh S.-J., Moon S.-H. (2003). Recovery of ammonium sulfate from fermentation waste by electrodialysis. *Water Research* **37**, 1091–1099. [In this work, electrodyalisis experiments of the lysine fermentation waste were performed to generate demineralized feed and ammonium sulphate].

53. Lee H.-J., Sarfert F., Strathmann H., Moon S.-H. (2002). Designing of an electrodialysis desalination plant. *Desalination* **142**, 267-286 [In this study the design and optimization of an electrodialysis plant to be used for brackish water desalination has been treated].

54. Al Madani H.M.N. (2003). Water desalination by solar powered electrodialysis process, *Renewable Energy* **28**, 1915–1924 [This paper describes a water desalination process carried out by using an electrodialysis process operated with photovoltaic cells].

55. Hàbovfi V., Melzoch K., Rychtera M., Sekavovà B. (2004). Electrodialysis as a useful technique for lactic acid separation from a model solution and a fermentation broth. *Desalination* **162**,361-372. [This presents a two-stage electrodialysis (ED) method used for lactic acid recovery].

56. Tongwen X. (2002). Electrodialysis processes with bipolar membranes (EDBM) in environmental protection—a review. *Resources, Conservation and Recycling* **37**, 1–22.[A review on the use of electrodialysis in environmental applications]

57. Tzanetakis N., Taama W.M., Scott K., Jachuck R.J.J., Slade R.S., Varcoe J. (2003). Comparative performance of ion exchange membranes for electrodialysis of nickel and cobalt. *Separation and Purification Technology* **30**, 113-127. [The extraction of nickel and cobalt from their sulfate solutions by electrodialysis in a modified three compartment cell is described].

58. Pandey P., Chauhan R.S. (2001). Membranes for gas separation. *Progress in Polymer Science* **26**, 853-893. [A review on the preparation of membranes for gas separation and transport mechanisms].

59. Schaetzel P., Bendjama Z., Vauclair C., Nguyen Q.T. (2001). Ideal and non-ideal diffusion through polymers: Application to pervaporation. *Journal of Membrane Science* **191**, 95-102. [A comparison between experimental diffusion data and theoretical models for ideal and non-ideal systems is reported].

60. Yantovski E., Gorski J., Smyth B., Elshof J. (2004). Zero-emission fuel-fired power plants with ion transport membrane. *Energy* **29**, 2077–2088. [This paper describes the zero emission, gas-fired power plant for electricity generation. Oxygen for combustion it is supplied by a ion transport membrane].

61. Wijmans J.G., Baker R.W. (1995). The solution-diffusion model: a review. *Journal of membrane science* **107**, 1-21. [A review on solution-diffusion transport mechanism in reverse osmosis, pervaporation, gas separation and dialysis].

62. Zhang S., Drioli E. (1995). Pervaporation membranes. *Separation science and technology* **30**, 1-31. [This presents a review and discussion of some works on developments in pervaporation processes].

63. Lipnizki F., Field R.W., Ten P.-K. (1999). Pervaporation-based hybrid process: a review of process design, applications and economics. *Journal of Membrane Science* **153**, 183-210. [This paper focuses on pervaporation-based hybrid processes, in particular pervaporation combined with distillation and with chemical reactors].

64. Jonquières A., Clément R., Lochon P., Néel J., Dresch M., Chrétien B. (2002) Industrial state-of-the-art of pervaporation and vapor permeation in the western countries. *Journal of Membrane Science* **206**, 87-117. [This work reviews the trends of industrial pervaporation and vapour permeation in Europe and the USA].

65. Simmons V., Kaschemekat J., Jacobs M.L., Dortmundt D.D. (1994). Membrane systems offer a new way to recover volatile organic air pollutants. *Chemical Engineering* September issue. [This presents some industrial applications of vapor permeation for VOCs recovery]

66. Baker R.W., Baker M. (1996). Improve monomer recovery from polyolefin resin degassing, *Hydrocarbon processing* March issue. [This presents membrane-based vapor separation processes for monomer recovery from polyolefin resins].

67. Criscuoli A., Curcio E., Drioli E. (2003). Polymeric membrane contactors. *Recent Research. Developments in Polymer Science* **7**, 1-21. [A review on recent developments in polymeric membrane contactors].

68. Jing-Liang J.-L., Chen B.H. (2005). Review of CO_2 absorption using chemical solvents in hollow fiber membrane contactors. *Separation and Purification Technology* **41**, 109-122. [A review on separation of CO_2 from a gas stream, using a hollow fiber membrane contactor]

69. Qi Z., Cussler E.L. (1985). Microporous hollow fibers for gas absorption. I. Mass transfer in the liquid. *Journal of Membrane Science* **23**, 321–333. [This paper compares gas absorption in microporous hollow fiber membrane modules with that possible in packed towers. A particular attention is devoted to the mass transfer in the liquid phase].

70. Qi Z., Cussler E.L. (1985). Microporous hollow fibers for gas absorption. II. Mass transfer across the membrane. *Journal of Membrane Science* **23**, 333–345. [This paper compares gas absorption in microporous hollow fiber membrane modules with that possible in packed towers. A particular attention is devoted to the mass transfer across the membrane].

71. Gabelman A., Hwang S.-T. (1999). Hollow fibre membrane contactors. *Journal of Membrane Science* **159**, 61–106. [A review on of hollow fiber membrane contactors, including operating principles, relevant mathematics, and applications].

72. Drioli E., Jiao B.L., Calabrò V. (1992). The preliminary study on the concentration of orange juice by membrane distillation. *Proceeding of International Society of Citriculture* **3**, 1140-1144. [This presents a review of the application of membrane distillation in orange juice concentration].

73. Schofield R.W., Fane A.G., Fell C.J.D. (1987). Heat and mass transfer in membrane distillation. *Journal of Membrane Science* **33**, 299-313. [In this paper equations for heat and mass transfer in membrane distillation have been developed and tested experimentally].

74. Pena L., Godino M.P., Mengual J.I. (1998). A Method to Evaluate the Net Membrane Distillation Coefficient. *Journal of Membrane Science* **143**, 219-233. [This presents a method to evaluate the net membrane distillation coefficient. This method emphasizes the influence of the unstirred boundary layers on the membrane distillation processes].

75. Martinez L., Vazquez-Gonzalez M.I. (2000). A method to evaluate coefficients affecting flux in membrane distillation. *Journal of Membrane Science* **173**, 225-235. [This presents a method to evaluate the membrane mass transfer coefficient, the membrane heat transfer coefficient and the boundary layer heat transfer coefficient in a membrane distillation system]

76. Ugrozov V. V., Elkina I. B. (2002). Mathematical modeling of influence of porous structure a membrane on its vapour-conductivity in the process of membrane distillation. *Desalination* **147**, 167-

171. [In this work the influence of membrane porous structure on vapor conductivity coefficient in membrane distillation process was studied theoretically using the pore network as a model of porous medium].

77. Curcio E., Di Profio G., Drioli E. (2002). Membrane crystallization of macromolecular solutions. *Desalination* **145**, 173-177. [In this work the membrane crystallization technique was employed to obtain protein crystals from supersaturated solutions].

78. Di Profio G., Curcio E., Drioli E. (2003). Membrane crystallization of lysozyme: kinetic aspects. *Journal of Crystal Growth* **257**, 359-369. [This presents a kinetic study on lysozime crystallization in a membrane crystallizer].

79. Curcio E., Di Profio G., Drioli E. (2003). Recovery of fumaric acid by membrane crystallization in the production of L-malic acid. *Separation and Purification Technology* **33**, 63-73. [A study on the realization of a separation unit based on a membrane crystallizer aiming to recover the unreacted fumaric acid leaving a biocatalytic membrane reactor for the production of L-malic acid].

80. Di Profio G., Perrone G., Curcio E., Cassetta A., Lamba D., Drioli E. (2005). Preparation of Enzyme Crystals with Tunable Morphology in Membrane Crystallizers. *Industrial and Engineering Chemistry Research* **44,** 10005-10012. [This describes the trypsins crystallization by using membrane crystallization techniques, both in static and dynamic configurations].

81. Lynch M.J., Griffin W.C. (1974). Food emulsions, in: *Emulsions and Emulsion Technology, Surfactant Science Series* vol. 6 (1), Chapter 5, 249-289. Marcel Dekker, New York. [This presents an overview on emulsion technology if food applications]

82. Walstra P., Smulders P.E.A. (1998). Emulsion formation, in *Modern Aspects of Emulsion Science*. B.P. Binks (Ed.), The Royal Society of Chemistry: Cambridge (UK). [This presents data about energy use in emulsion formation]

83. Nakashima T., Shimizu M., Kukizaki M. (1994). Mono-dispersed single and double emulsions and method of producing same. United States Patent n. 5,326,484. [A patent on the use of membrane emulsification technique to obtain emulsions characterized by uniform droplets and low energy consumption]

84. Giorno, L.; Li, N.; Drioli, E. (2003). Preparation of oil-in-water emulsions using polyamide 10 kDa hollow fiber membrane. *Journal of Membrane Science* **217**, 173–180. [In this paper asymmetric polyamide hollow fibre membranes have been used to prepare oil-in-water emulsions].

85. Suzuki K., Fujiki I., Hagura Y. (1998). Preparation of High Concentration O/W and W/O Emulsions by the Membrane Phase Inversion Emulsification Using PTFE Membranes. *Food Science and Technology Research* **5**, 234-238. [In this paper PTFE membranes have been used to prepare corn oil-in-water and water/corn oil emulsions].

86. Katoh R., Asano Y., Furuya A., Sotoyama K., Tomita M.(1996). Preparation of food emulsions using a membrane emulsification system. *Journal of Membrane Science*. **113**, 131-135. [A study on the effect of the flux in membrane emulsification process on the droplets diameter].

87. De Luca G., Sindona A., Giorno L., Drioli E. (2004). Quantitative analysis of coupling effects in cross-flow membrane emulsification. *Journal of Membrane Science* **229**, 199–209. [A theoretical and experimental study on effects concerning droplet growth and detachment from membrane pores during membrane emulsification process].

88. Schroder V., Schubert H. (1999). Production of emulsions using microporous, ceramic membranes. *Colloids and Surfaces A* **152**, 103-109. [This presents an experimental study on emulsification using ceramic membranes in terms of droplet size and disperse phase flux as a function of the main parameters of the process, for example. dynamic interfacial tension of the emulsifier, transmembrane pressure and wall shear stress].

89. Abrahamse A.J., Van der Padt A., Boom R.M. (2004). Status of cross-flow membrane emulsification and outlook for industrial applications. *Journal of Membrane Science* **230**, 149-159. [In this paper the effects of membrane parameters on the disperse phase flux in membrane emulsification experiments are estimated]

90. Vankelecom I. F. J., Jacobs P. A. (2000). Dense organic catalytic membranes for fine chemical

synthesis]. *Catalysis Today* **56**, 147-157. [This a work on the heterogenization of homogeneous and heterogeneous catalysts in dense PDMS membranes and their application in catalytic membrane reactors].

91. Bonchio M., Carraro M., Scorrano G., Fontananova E., Drioli E. (2003). Heterogeneous Photooxidation of Alchols in Water by Photocatalytic Membranes Incorporating Decatungstate. *Advanced Synthesis & Catalysis* **345,** 1119-1126. [A study on the heterogenization of decatungstate in dense and porous polymeric membranes, and their use in the photooxidation reactions].

92. Li N., Giorno L., Drioli E. (2003). Effect of Immobilization Site and Membrane Materials on Multiphasic Enantiocatalytic Enzyme Membrane Reactors. *Annals of New York Academy of Sciences* **984**, 436-452. [An experimental study on the optical resolution of racemic naproxen methyl ester with crude lipase immobilized in a multiphasic enantiocatalytic enzyme membrane reactor].

93. Brockmann M, Seyfried CF. (1997). Sludge activity under the conditions of crossflow microfiltration. *Water Science and Technology* **35**, 173-181. [A study on a pilot plant anaerobic pretreatment of potato starch wastewater].

94. Shim J.K., Yoo Y.-K., Lee Y.M. (2002). Design and operation considerations for wastewater treatment using a flat submerged membrane bioreactor. *Process Biochemistry* **38**, 279-285 [This presents an investigation on combining a flat submerged membrane with a biological reactor for synthetic wastewater treatment].

95. Wenten I.G. (2002). Recent development in membrane science and its industrial applications. *Journal of Science Technology* **24**, 1009-1024. [A study on industrial applications of membrane processes]

96. Ebrahim S., Bou-Hamed S., Abdel-Jawad M., Burney N. (1997). Microfiltration system as a pretreatment for RO units: Technical and economic assessment. *Desalination* **109**, 165-175. [This paper presents the results of a research project on the use of microfiltrationunit as a pre-treatment technique for a sweater reverse osmosis system].

97. Bonnelye V., Sanz M.A., Durand J.-P., Plasse L., Gueguen F., Mazounie P. (2004). Reverse osmosis on open intake seawater: pre-treatment strategy. *Desalination* **167**, 191-200. [This paper is focussing on two case studies of seawater pre-treatment upstream reverse osmosis desalination. Depending on the water quality, the pre-treatment uses different technology strategies, conventional pre-treatment (coagulation and direct filtration on dual media filters) and innovative technologies (high rate dissolved air flotation, ultrafiltration and microfiltration)]

98. Drioli E., Criscuoli A., Curcio E. (2002). Integrated membrane operations for seawater desalination. *Desalination* **147**, 77-81. [This presents a study on the advantages of integrated membrane system for seawater desalination]

99. Drioli E., Curcio E., Criscuoli A., Di Profio G. (2004). Integrated membrane system for recovery of $CaCO_3$ NaCl and $MgSO_4 \cdot 7H_2O$ from nanofiltration retentate. *Journal. of Membrane Science* **239**, 27-38 [An experimental study on an integrated membrane system for recovery of dissolved salts present, at low concentration, in typical feed streams to desalination plants].

100. Jiao B., Cassano A., Drioli E. (2004). Recent advances on membrane processes for the concentration of fruit juices, Journal of Food Engineering, Journal of Food Engineering **63**, 303-324. [Advances and developments of the use of membrane processes (also integrated) for concentrating fruit juice are reviewed and discussed in this paper.

101. Rao M.A., Acree T.E., Cooley H.J., Ennis R.W. (1987). Clarification of apple juice by hollow fiber ultrafiltration: fluxes and the odor-active volatiles. Journal of Food Science **52**, 375-378 [A study on fresh apple juice clarification in a pilot scale ultrafiltration (UF) unit, with membranes made of polysulfone and polyamide and plate and frame and vacuum drum filters].

102. Cassano A., Molinari R., Romano M. E. Drioli (2001). Treatment of aqueous effluents of the leather industry by membrane processes. *Journal of Membrane Science* **181**, 111-126. [An overview on the potentiality of membrane processes in the treatment of aqueous solutions coming from the leather industry].

Biographical Sketches

Enrico Drioli

Professor of Chemistry and Electrochemistry at the School of Engineering of the University of Naples (since 1968) and Full Professor at the School of Engineering of the University of Calabria (since 1981).

- Dean of the School of Engineering of the University of Calabria (1982-1985).
- Director of the Institute on Membrane Technology of the National Research Council (former Research Institute on Membranes and Modelling of Chemical Reactors - IRMERC) (since 1993).
- President of the European Society of Membrane Science and Technology (1982 - 1998).
- Chairman of the Working Party on Membranes of the European Federation of Chemical Engineering (since 1985).
- Doctorate *Honoris Causa* in Chemistry and Chemical Technology from Russian Academy of Science (February 1992).
- Honorary Professor at the China Northwest University in Xi'an, Shaanxi, People's Republic of China (Sept. 1991).
- Honorary Founding President of the European Membrane Society (from 1999).
- Honorary Member of the A. V. Topchiev Institute of Petrochemical Synthesis at the Russian Academy of Sciences, Moscow (from 1999).
- Patron Member of the Indian Membrane Society.
- Member of the Advisor Board of the UNESCO Center on Membrane Science and Technology at the New South Wales University, Australia.
- Member of the European Communities Chemistry Council (E.C.C.C.).
- Member of Executive Council of the European Federation of Chem. Engineering (from 1996)
- Member of the Interim Board of Governors of the Middle East Desalination Research Center, Oman, Muscat (1994 - 1996); Member and Moderator of the Research Advisory Council of the Middle East Desalination Research Center , Oman, Muscat (from May 1997)
- Member of the NATO/CCMS Pilot Study on "Clean Products and Processes"
- International Scientific Counselor of the Membrane Industry Association of China
- Member of the Editorial Boards of the: Chemical Engineering and Processing Elsevier); Desalination – Elsevier; Journal of Membrane Science – Elsevier; Journal of Molecular Catalysis (1982–1992) – Elsevier; Chemical Engineering and Technology Journal - Wiley-VCH; Industrial & Engineering Chemistry Research (from Jan. 2002) – American Chemical Society; Journal of Clean Products and Processes - Springer-Verlag; Acqua-Aria – Arti poligrafiche europee; Chimica Oggi - TeknoScienze; La Chimica e L'Industria - Editrice di chimica; Orizzonti Tecnologici - CESVITEC; Water Treatment - China Ocean Press; Anales de Fisica - La Sociedad; Russian Journal of Physical Chemistry - MAIK Nauka, Interperiodica Publ.; Journal of Separation and Purification Technology - Childwall University Press; Membrane Science and Technology – Lanzhou (China)

Author of more than 440 scientific papers and 14 patents in the field of Membrane Science and Technology:

Efrem Curcio

He received his Degree and Ph.D in Chemical Engineering at the University of Calabria in 1999 and 2005, respectively.

He is Researcher at the Department of Chemical Engineering and Materials of the University of Calabria. Since 1999 he is in the research staff of the Institute on Membrane Technology (ITM-CNR) of the Italian Research National Council, where he developed his expertise on membrane science and technology.

His present research interests concern: development of membrane crystallization devices and advanced membrane contactors, design and optimisation of integrated membrane desalination systems, implementation of new brine disposal strategies, development of membrane bio-reactors for hepatocyte cells culture.

He is co-author of the book "Membrane Contactors: fundamentals, applications and potentialities" (Elsevier, 2005), author of about 30 publications in referred journals and several proceedings of international scientific conferences and workshops.

Dr. Curcio received the European Membrane Society Award for the best published paper in Membrane

Science and Engineering on 2004.

Enrica Fontananova
Graduated *cum laude* in Chemistry at the University of Calabria (Rende (CS), Italy) in 2001.
Contract Researcher at the Engineering Faculty of the University of Calabria and at the Institute on membrane Technology (ITM-CNR) (since 2001).
Research interests: membrane preparation and application in membrane reactor, membrane contactor, fuel cell and stereoselective recognition in membrane separation processes.
Tutor of Chemistry at the Engineering Faculty of the University of Calabria (since 2001).
Author of about 20 research papers in international journals and numerous presentations in international scientific meetings on membrane science and technology.
1st Prize for "New ideas for industrial applications" NanoMemPro Awards - Euromembrane 2006, Giardini Naxos (ME), Italy; 24-28 September 2006.