

RECENT ADVANCES IN MEMBRANE SCIENCE AND TECHNOLOGY IN SEAWATER DESALINATION – WITH TECHNOLOGY DEVELOPMENT IN THE MIDDLE EAST AND SINGAPORE

Takeshi Matsuura and Dipak Rana

Industrial Membrane Research Laboratory, Department of Chemical and Biological Engineering, University of Ottawa, 161 Louis Pasteur, Ottawa, Ont. K1N 6N5, Canada

Mohamed Rasool Qtaishat

Chemical Engineering Department, University of Jordan, Amman 11942, Jordan

Gurdev Singh

Centre of Innovation, Environmental & Water Technology, Ngee Ann Polytechnic, 535 Clementi Road, 599489 Singapore

Keywords: Seawater desalination, membrane science and technology, reverse osmosis, membrane transport theory, asymmetric membrane, thin-film-composite membrane, surface modification, antifouling, membrane distillation, forward osmosis, desalination in the Middle East, desalination in Singapore.

Contents

1. Introduction
2. Membrane processes for desalination: overview
 - 2.1. Reverse Osmosis History
 - 2.2. Asymmetric Structure of the Membrane
 - 2.3. Phase Inversion Technique-Preparation of Integrally Skinned Asymmetric Membranes
 - 2.4. Interfacial *in-situ* Polymerization-Preparation of Thin Film Composite Membranes
 - 2.5. Membrane Performance Enhancement by Surface Modification
 - 2.6. RO Membrane Transport
 - 2.7. Reverse Osmosis Module
 - 2.8. Improvement of Membrane Performance; Boron Removal, Chlorine Tolerance, and Antibiofouling Membrane
 - 2.9. New Membrane Processes for Seawater Desalination and Water Treatment (Membrane Distillation and Forward Osmosis)
 - 2.10. Carbon Nanotube Membrane
3. Case study I: Membrane desalination in the Middle East
 - 3.1. Membrane Desalination in the Arab World
 - 3.2. Membrane Desalination Status in Saudi Arabia
 - 3.3. Membrane Desalination Status in Bahrain
 - 3.4. Membrane Desalination Status in Kuwait
 - 3.5. Membrane Desalination Status in the United Arab Emirates
 - 3.6. Membrane Desalination Status in Oman
 - 3.7. Membrane Desalination Status in the Gulf Cooperation Council Countries
 - 3.8. Membrane Desalination Status in Jordan and Palestine
 - 3.9. Membrane Desalination Status in Israel

3.10. Membrane Desalination Status in Egypt

4. Case study II: Membrane desalination in Singapore

4.1. National Water Taps Policies

4.2. First Desalination Plant in Singapore

4.3. Technologies to Further Reduce Energy Consumption of Desalination

4.4. Reducing Energy Consumption of Desalination to 0.75 kWh/m³

5. Conclusions and future outlooks

Glossary

Bibliography

Biographical Sketches

Summary

The development of seawater desalination membranes is continuously progressing and has demonstrated highly remarkable achievement in performance. Indeed, there appears to be no limit to the performance of these membranes in sight. The first historic discovery of Loeb-Sourirajan asymmetric reverse osmosis (RO) membrane enabled seawater desalination on an industrial scale. Later, the membrane performance was improved by the development of thin-film-composite (TFC) membranes by Cadotte. The fluxes of currently available commercial membranes are an order of magnitude higher than the RO membranes of 1960s with salt rejection as high as 99.8 %. Further attempts are being made to increase the flux and to improve membrane stability by incorporating nanoparticles and by modifying the membrane surface. Moreover, fabrication of membranes that can reject boron, arsenics, and organic compounds of low molecular weights to higher degrees than currently available membranes is required to produce less hazardous drinking water. Membranes that can withstand ultra-high pressure for seawater desalination and membranes that are operable at ultra-low pressures for brackish water desalination were achieved for drinking water production. Typically, membrane distillation, forward osmosis, and carbon nanotube membranes are considered potentially applicable for seawater desalination. The current status and future direction of membrane desalination in the Middle East and Singapore have been discussed as case studies.

1. Introduction

It is reported that 96.5% of the earth's water is located in seas and oceans, 1.7% in the ice caps, 0.8% is considered to be fresh water with the rest being brackish water. Since water shortage has been a problem for many communities and humans have been searching for the solution for a long time, desalination, turning salty water into fresh water, is not necessarily a new concept. Today the shortage of drinking water is a serious world-wide concern due to population growth and the increased demand for drinking water that exceeds readily available water resources. Over 1 billion people are without clean drinking water and approximately 2.3 billion people (41% of the world population) are living in water scarce regions (Greenlee et al, 2009). As a result, people have started to search for solutions with water reuse and seawater desalination as the keys for the sustainable growth of human activities. Water reuse is basically for the production of water for uses such as irrigation, power plant cooling water, industrial process water and ground water recharge. It has also been accepted as a method for the

production of drinking water in Singapore (Newater). Alternatively, desalination has become a primary source of the drinking water production. Current desalination technology consists of two methods. One is a thermal desalination method that has been developed over the past 60 years, while the other is membrane processes that have been developed over the past 40 years.

Desalination is a general term for methods to remove salt from salty water to produce fresh water. Notably, the definition of fresh water depends on the country. For example, the US Environmental Protection Agency (EPA) has non-enforceable standards of 250 mg/L chloride and 500 mg/L total dissolved salts (TDS) for fresh water (EPA, 2002). The World Health Organization (WHO) and the Gulf Drinking Water standards recommended a drinking water standard of 1000 mg/L TDS (Fritzmann et al, 2007). In comparison to the government standards, most desalination facilities are designed to achieve a TDS of 500 mg/L or less (Greenlee et al, 2009).

When the desalinated water is used for other purposes, e.g. crop irrigation, the TDS concentration may be higher. The feed water salinity for desalination facilities ranges from 1000 mg/L to 60,000 mg/L. Most of the seawater resources contain 30,000 to 45,000 mg/L TDS, while the brackish water within a range of 1,000 to 10,000 mg/L is treated by Reverse Osmosis (RO) (Greenlee et al, 2009). As mentioned above, desalination processes fall into the following two categories, i.e. thermal processes and membrane processes.

The thermal process has been used for many years since the prehistoric era but the operation of the large scale distillation plant for drinking water production began in 1950s (Greenlee et al, 2009). In the beginning a process called multi-effect distillation (MED) was used but later a process called multi-stage flash (MSF) distillation was developed. The Middle East as a whole holds about 50% of the world desalination capacity and primarily uses MSF technology. However, facilities based on the membrane process have rapidly been installed since the 1960s and now surpass the thermal process in new plant installations. Outside of the Middle East, new RO plant installations have been continuing steadily. In 2001, 51% of the new installations were based on RO process, while in 2003, RO process accounted for 75% of the new production capacity.

RO, nanofiltration (NF) and electro-dialysis (ED) are the typical membrane processes available for desalination. RO and NF are called pressure-driven membrane processes since the transmembrane pressure difference is the driving force for the mass transport, while for ED the electrical potential difference is the driving force for the mass (ions) transport. ED is an older membrane desalination process than RO and NF. NF is a relatively new membrane separation process developed in 1980s. While NF can not desalinate seawater to produce drinking water in one step, it can be used successfully to treat the mildly brackish water (Greenlee et al, 2009). It is hence desirable to use NF in combination with RO for seawater desalination. The most important feature of NF is its capacity to remove divalent ions such as calcium and magnesium that contribute to hardness of water. However, RO membrane can remove monovalent ions such as sodium and chloride and hence has become the mainstream of membrane desalination technology. Salt rejection as high as 99.7 and 99.8%, can be achieved by RO

(Hydranautics, 2007; Greenlee et al, 2009; Reverberi and Gorenflo, 2007). RO membrane technology is also applicable for both seawater and brackish water desalination.

As mentioned earlier, the first countries that used the desalination process on a large scale for drinking water production were in the Middle East. Seawater desalination plants began to be developed in the 1950s, and the first industrial desalination plant was opened in Kuwait in 1960s. The first successful RO plant used brackish water as feed in the late 1960s (Amjad, 1993). In the following decades, membrane permeability was much improved and RO membranes were then applied for seawater desalination (Van der Bruggen and Vandecasteele, 2002). From the early 1960s to the end of the 1990s, the membrane productivity (flux) and salt rejection have much improved as shown in Figure 1. Table 1 also shows similar advancement made for the Dow RO membranes.

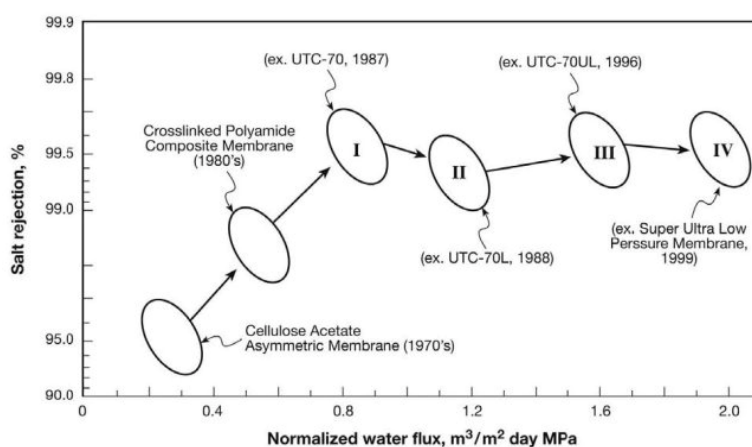


Figure 1. Progress in membrane performance during the past forty years. Reverse osmosis conditions: feed NaCl concentration, 1500-3000 ppm; operating pressure, 0.5-3.0 MPa; temperature, 25°C; pH, 6.5. I, II, III and IV are fully aromatic polyamide TFC membranes (adapted from Kurihara and Fusaoka, 1999)

Year	Production capacity (gpd)	Salt rejection (%)
Brackish water		
1990	8,000	98
1998	10,000	99.2
2007	11,000	99.8
Seawater		
1990	4,000	99.4
1998	5,500	99.5
2007	7,500-8,000	99.8

Table 1. Advances in Dow RO membrane

From 1996 to 2007 the rejection of typical seawater desalination membrane increased from 99.6 to 99.8% and the flux increases from 43 to 69 L/m² day bar (Mickols et al, 2005). As of 2009, over 15,000 desalination plants were in operation world-wide, and approximately 50% of those are RO plants. A new recent trend is to construct large

seawater desalination plants with a production capacity of 100,000 m³/day or more (Greenlee et al, 2009).

Saudi Arabia is currently the world leader in desalination with approximately 26% of global production capacity, followed by the United States (17%). In Saudi Arabia most of the desalination plants are based on the thermal process (newly constructed plants are different) and the source water is seawater. In contrast, in the United States 69% of the desalination plants are based on RO and only 7% is seawater desalination plants. While only 20% of the total number of the desalination plants world-wide use thermal process, 50% of the total production capacity is based on the thermal processes. Israel has opened the world's largest seawater RO desalination plant with a production capacity of 330,000 m³/day, or 100 million m³/year. The United Arab Emirates (UAE) opened its Fujairah desalination plant in 2005 with a combined MSF and RO production capacity of 454,000 m³/day.

2. Membrane Processes for Desalination: Overview

2.1. Reverse Osmosis History

As mentioned, RO is currently dominant in membrane separation processes for desalination. Interestingly, the early development of RO membrane for seawater desalination began with the following fundamental equation called the Gibbs Adsorption Isotherm (Sourirajan, 1970).

$$\Gamma = -\frac{1}{RT} \frac{\partial \sigma}{\partial \ln a}, \quad (1)$$

where Γ is the surface excess, R is universal gas constant, T is absolute temperature, σ is surface tension and a is activity.

The equation predicts the presence of a very thin pure water layer at the surface of saline water. Table 2 summarizes the thickness of such pure water layers calculated on the basis of Eq. (1). As the table shows the thickness ranges from 2.6 to 5.6 nm, depending on the concentration of sodium chloride.

NaCl concentration in molality (mol kg ⁻¹)	Pure water layer thickness (nm)
0	0.56
0.747	0.38
1.603	0.34
2.435	0.24

Table 2. The thickness of pure water layer at the air/sodium chloride solution interface

It was Yuster's group at University of California at Los Angeles (UCLA) who attempted to skim the pure surface water layer mechanically (Yuster et al, 1958). However, the attempt failed. Applying the concept underlying the Gibbs Adsorption Isotherm, Sourirajan further attempted to collect the pure water layer by applying pressure on the saline water that was brought to contact with one side of a membrane.

Sourirajan's attempt was soon found to be successful and desalinated water was produced as permeate from the membrane. After initial attempts using cellulose and silicone coated cellulose membranes, a commercial cellulose acetate (CA) membrane was used, which resulted in a high salt rejection. Even though the latter rejection was considered high enough for drinking water production, the flux of water was extremely low with few drops of permeate collected in a day and the membrane was thought to be practically useless. It should be noted that Reid and Breton obtained, quite independently, similar experimental results of seawater desalination by using a CA membrane at the University of Florida (Reid and Breton, 1959). It took another 4 years for Loeb and Sourirajan to develop CA membranes with fluxes of practical usefulness, which opened up the avenue to the novel membrane desalination process, called Reverse Osmosis (RO).

According to Sourirajan, the mechanism of desalination by RO membrane is as follows: When salty water; e.g, sodium chloride solution, is in contact with the surface of a membrane, an interfacial pure water layer is formed at the solution/membrane interface. Assuming analogy between sodium chloride solution-air interface and sodium chloride solution-membrane interface, the interfacial pure water layer, t , is as thick as a fraction of nanometer. In the presence of a pore, the diameter of which is smaller than or equal to $2t$, the pure water layer will flow through the pore under the pressure applied on the sodium chloride solution and appear on the other side of the membrane as permeate (see Figure 2a). If the pore size is larger than $2t$, the sodium chloride solution will flow in the central region of the pore, contaminating the permeate (Figure 2b).

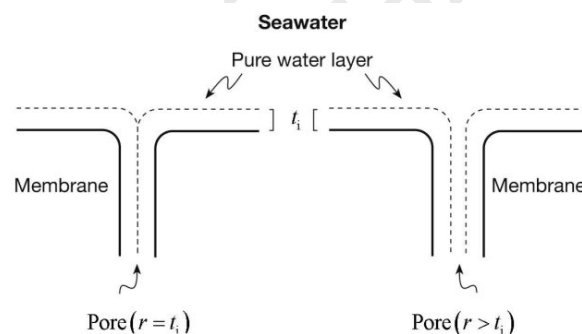


Figure 2. Preferential sorption capillary flow mechanism of RO

Thus, there are twin requirements for the success of RO membrane development. One is the presence of the interfacial pure water layer and the other is the formation of pores, the sizes of which are as small as a fraction of nanometer. The pore sizes of RO membranes were evaluated theoretically by several researchers. For example, Schultz and Assumma concluded that the size of the pore should be 1.85 nm, based on the SEM images of polymer nodules at the surface of a CA RO membrane (Schultz and Assumma, 1970). Glückauf calculated the salt (sodium chloride) rejection as a function of the pore size based on the Onsager-Samalas equation for the dielectric force (Glückauf, 1965).

Positronium Annihilation Lifetime Spectroscopy (PALS) has become a popular tool recently to characterize the subnanopores. For example, Boussu et al characterized (in-

depth) six commercial NF membranes. By using depth-selective PALS measurements, it was revealed that the skin layer had two different pore sizes: a pore size of 1.25-155 Å as well as a pore size of 3.20-3.90 Å (both depending on the membrane type) (Boussu et al, 2007). Thus, the presence of sub-nanometer pores predicted in the 1960s can now be measured by a sophisticated instrumental technique.

2.2. Asymmetric Structure of the Membrane

Most of membranes that are used in industrial separation processes have an asymmetric structure and so are called asymmetric membranes. Figure 3 shows schematically a typical cross-sectional view of an asymmetric membrane (Matsuura, 1994). As shown in the figure, an asymmetric membrane consists of two layers; i.e. one very thin dense layer at the top of the membrane and a porous sublayer underneath the top dense layer (also called top skin layer). While the top dense layer governs the permeation properties of the membrane, the porous sub-layer only provides the membrane with mechanical strength. When the material of the top skin layer and the porous sublayer are the same, the membrane is called integrally skinned asymmetric membrane. This type of membrane is made by the dry-wet phase inversion technique. When the polymer for the top skin layer is different from the polymer for the porous sub-layer, the membrane is called composite membrane. The advantage of the composite membrane over the integrally skinned asymmetric membrane is that the material for the top skin layer and for the porous sublayer can be chosen separately to optimize the overall performance. This type of membrane is made by coating a thin layer on top of the surface of a porous substrate. Various coating techniques are available but the interfacial in-situ polymerization method has been proven to be commercially most successful.

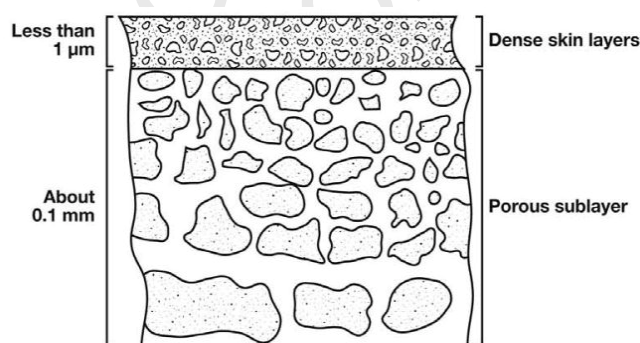


Figure 3. Asymmetric structure of the membrane

2.3. Phase Inversion Technique-Preparation of Integrally Skinned Asymmetric Membranes

Phase inversion is a process in which a polymer is transformed from a liquid to a solid state. There are a number of methods to achieve phase inversion. Among others, the dry-wet phase inversion technique and the temperature induced phase separation (TIPS) are most commonly used in the industrial membrane manufacturing. The dry-wet phase inversion technique was applied by Loeb and Sourirajan in their development of the first CA membrane for seawater desalination (Loeb and Sourirajan, 1961, 1963, 1964). Therefore, this method is often called the Loeb-Sourirajan method. In the Loeb-

Sourirajan method, a polymer solution is prepared by mixing polymer, solvent and sometimes even nonsolvent. The solution is then cast on a suitable surface by a doctor blade to a thickness of about 250 μm . After partial evaporation of the solvent, the cast film is immersed in a bath of nonsolvent medium, often called gelation medium. Due to a sequence of two desolvation steps, i.e. evaporation of solvent and solvent-nonsolvent exchange in the gelation bath, solidification of polymer film takes place. It is desirable to choose a solvent of strong dissolving power with high volatility. During the first step of desolvation by solvent evaporation, a thin skin layer of solid polymer is formed instantly at the top of the cast film due to the loss of solvent. In the solvent-nonsolvent exchange process that follows, nonsolvent diffuses into, while solvent diffuses out of the polymer solution film through the thin solid layer. The change in the composition of the polymer solution film during the solvent-nonsolvent exchange process, often called a composition path, is illustrated schematically in a triangular diagram that involves polymer-solvent-nonsolvent (Figure 4).

At a given moment, the content of the solvent in the solution film becomes so low that the solvent no longer is able to hold polymer in one phase. Phase separation takes place, forming droplets of one liquid phase dispersed in the other continuous liquid phase. The moment of phase separation, and the size and the number of the dispersed droplets depend on the nature of solvent and nonsolvent and the polymer solution composition. The control of the number and the size of the droplets will eventually control the structure of the porous substrate (Kesting, 1971).

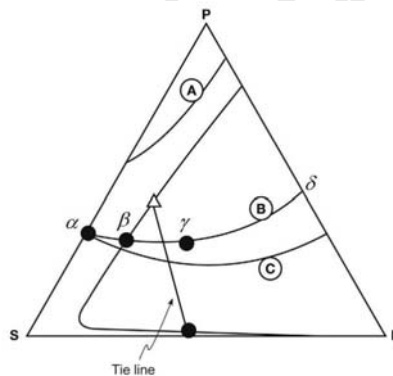


Figure 4. A typical composition path

The thin layer of solid polymer that forms during the first evaporation step becomes the top skin layer that will govern the selectivity and the flux of the membrane, while the porous structure that forms during the solvent-nonsolvent extraction step becomes the porous sublayer, providing the mechanical strength.

Hence, the membrane obtained by the dry-wet phase inversion process is an integrally skinned asymmetric membrane. The top skin layer can also be made porous by lowering the polymer concentration in the casting solution and the solvent evaporation period. The asymmetric membranes can also be made in tubular form using a casting bob assembly and hollow fibers can be spun using a hollow fiber spinneret (Sourirajan and Matsuura, 1985).

-
-
-

TO ACCESS ALL THE 54 PAGES OF THIS CHAPTER,
Visit: <http://www.desware.net/DESWARE-SampleAllChapter.aspx>

Bibliography

Abu Tarboush B.J, Rana D, Matsuura T, Arafat H.A, Narbaitz R.M. (2008). Preparation of thin-film-composite polyamide membranes for desalination using novel hydrophilic surface modifying macromolecules. *Journal of Membrane Science* 325, 166–175. [An original article describing the development of surface modifying macromolecules for seawater desalination]

Cath T.Y, Childress, A.E, Elimelech M. (2006). Forward osmosis: Principles, applications, and recent developments. *Journal of Membrane Science* 281, 70–87. [An excellent review article giving an overview of forward osmosis]

Curcio E, Drioli E. (2005). Membrane distillation and related operations - a review. *Separation and Purification Reviews* 34, 35–86. [A state-of-art review article on the membrane distillation and related processes for general readers]

El-Bourawi M.S, Ding Z, Ma R, Khayet M. (2006). A framework for better understanding membrane distillation separation process. *Journal of Membrane Science* 285, 4–29. [An excellent review article describing the basics of membrane distillation for general understanding]

Greenlee L.F, Lawler D.F, Freeman B.D, Marrot B, Moulin P. (2009). Reverse osmosis desalination: Water sources, technology, and today's challenges. *Water Research* 43, 2317–2348. [One of the best articles on reverse osmosis process for water treatment]

Hanma A, Pham V.A, Matsuura T, Santerre J.P. (1997). Development of membranes with low surface energy to reduce the fouling in ultrafiltration applications. *Journal of Membrane Science* 131, 217–227. [An original article describing the development of membranes with low surface energy by surface modifying macromolecules for oil-water treatment]

Hanemaaijer J.H, van Medevoort J, Jansen A.E, Dotremont C, van Sonsbeek E, Yuan T, De Ryck L. (2006). Memstill membrane distillation-a future desalination technology. *Desalination* 199, 175–176. [An excellent original article on the development of membrane distillation]

Holt J.K, Park H.G, Wang Y, Stadermann M, Artyukhin A.B, Grigoropoulos C.P, Noy A, Bakajin O. (2006) Fast mass transport through sub-2-nanometer carbon nanotubes. *Science* 312, 1034–1037. [An innovative original research article presenting the uses of carbon nanotubes membrane for desalination and gas separation]

Hummer G, Rasaiah J.C, Noworyta J.P. (2001) Water conduction through the hydrophobic channel of a carbon nanotube. *Nature* 414, 188–190. [The spontaneous and continuous filling of carbon nanotube by chain of water molecules explains by molecular dynamic simulation.]

Karla A, Garde S, Hummer G. (2003) Osmotic water transport through carbon nanotube membranes. *Proceedings of the National Academy Science U.S.A.* 100, 10175–10180. [The phenomenological behavior of carbon nanotube transport is explained by molecular dynamic simulation.]

Kesting R.E. (1971). *Synthetic polymeric membranes*, pp. 122–123, McGraw-Hill: New York, NY, USA. [An excellent book describing the phase inversion process thoroughly]

Kim Y, Rana D, Matsuura T, Chung W.-J. (2009) Influence of surface modifying macromolecules on the surface properties of poly(ether sulfone) ultra-filtration membranes. *Journal of Membrane Science* 338, 84–91. [The structure-performance relationship of surface membranes by surface modifying macromolecules is highlighted.]

Loeb S, Sourirajan S. (1963). Sea water demineralization by means of an osmotic membrane. *Advances in Chemistry Series* 38, 117–132. [This is the pioneering landmark article describing desalination of seawater using reverse osmosis membrane made of cellulose acetate.]

Park H.B, Freeman B.D, Zhang Z.-B, Sankir M, McGrath J.E. (2008). Highly chlorine-tolerant polymers for desalination. *Angewandte Chemie* 120, 6108–6113. [A recent article for the development of RO membranes from polymers other than cellulose acetate and polyamide]

Petersen R.J. (1993). Composite reverse osmosis and nanofiltration membranes. *Journal of Membrane Science* 83, 81-150 [An excellent review article for the preparation of TFC membranes by interfacial in-situ polymerization]

Rana D, Kim Y, Matsuura T, Arafat H.A. (2011). Development of antifouling thin-film-composite membranes for seawater desalination. *Journal of Membrane Science* 367, 110–118. [Recent original research on the development of antibiofouling membranes by surface modification]

Rana D, Matsuura T, Narbaitz R.M. (2006). Novel hydrophilic surface modifying macromolecules for polymeric membranes: Polyurethane ends capped by hydroxy group. *Journal of Membrane Science* 282, 205–216. [Various surface modifying macromolecules are synthesized and their chemical structure - filtration performance relationship is discussed.]

Rana D, Matsuura T. (2010). Surface modifications for anti-fouling membranes. *Chemical Reviews* 110, 2448–2471. [An authoritative and comprehensive review on surface modification of polymeric membranes to develop anti-fouling membranes]

Sourirajan S. (1970). *Reverse osmosis*. Academic Press: New York, NY, USA. [This pioneering landmark book gives an overview of reverse osmosis process.]

Van der Bruggen B, Vandecasteele C. (2002). Distillation vs. membrane filtration: Overview of process evolutions in seawater desalination. *Desalination* 143, 207–218. [A state-of-art review article describing traditional desalination processes with lower cost effectiveness by introducing alternative eco-friendly energy]

References

Abdel-Jawad M, El-Sayed E.E.F, Ebrahim S, Al-Saffar A, Safar M, Tabtabaei M, Al-Nuwaibit G. (2007). Fifteen years of R&D program in seawater desalination at KISR, part II. RO system performance. *Desalination* 204, 403–415.

Abu Tarboush B.J. (2008). Preparation of Thin-Film-Composite Polyamide Membranes for Desalination Using Novel Hydrophilic Surface Modifying Macromolecules. M.A.Sc. Thesis, Department of Chemical and Biological Engineering, University of Ottawa: Ottawa, Canada.

Abu Qdais H.A, Batayneh F. (2002). The role of desalination in bridging the water gap in Jordan. *Desalination* 150, 99–106.

Akkad A.A. (1990). Conservation in the Arabian Gulf countries. *Journal of American Water Works Association* 82(5), 40–50.

Alcamo J, Florke M, Markler M. (2007). Future long-term changes in global water resources driven by socio-economic and climatic changes. *Hydrological Sciences Journal* 52, 247–275.

Al-Sahlawi M.A. (1999). Seawater desalination in Saudi Arabia: Economic review and demand projections. *Desalination* 123, 143–147.

Al Sajwani T.M.A. (1998). The desalination plants of Oman: past, present and future. *Desalination* 120, 53–59.

Amjad Z. (1993). *Reverse osmosis: Membrane technology, water chemistry and industrial applications*, Van Nostrand Reinhold: New York, USA.

Antrim B, Liu B, von Gottberg A. (2007). World's largest spiral element – history and development. *Desalination* 178, 313–324.

Ashkelon - Ashkelon seawater reverse osmosis (SWRO) plant, Israel. <http://www.water-technology.net/projects/israel/> accessed on 15 October 2010.

Baker R.W. (2004). *Membrane technology and applications*, John Wiley & Sons: Chichester, UK.

Baker R.W, Barss R.P. (1988). Composite membrane for reverse osmosis. US Patent 4 772 391.

Banat F, Jwaied N. (2008). Economic evaluation of desalination by small-scale autonomous solar-powered membrane distillation units. *Desalination* **220**, 566–573.

BBC News (8 December 2009) - Mapping future water stress. <http://news.bbc.co.uk/2/hi/science/nature/7821082.stm> accessed on 15 October 2010.

Belfer S, Purinson Y, Fainshtein R, Radchenko Y, Kedem O. (1998). Surface modification of commercial composite polyamide reverse osmosis membranes. *Journal of Membrane Science* **139**, 175–181.

Bessenasse M, Kettab A, Moulla A.S. (2010). Seawater desalination: Study of three coastal stations in Algiers region. *Desalination* **250**, 423–427.

Borgnia M, Nielsen S, Engel A, Agre P. (1999). Cellular and molecular biology of the aquaporin water channels. *Annual Review of Biochemistry* **68**, 425–458.

Bouguecha S, Dhahbi M. (2002). The role of membrane technologies in supplying drinking and industrial water in Tunisia: Conventional process and new trends. *Desalination* **151**, 75–86.

Boussu K, De Baerdemaeker J, Dauwe C, Weber M, Lynn K.G, Depla D, Aldea S, Vankelecom F.J, Vandecasteele C, Van der Bruggen B. (2007). Physico-chemical characterization of nanofiltration membranes. *ChemPhysChem* **8**, 370–379.

Cadotte J.E. (1981). Reverse osmosis membranes. US Patent 4 277 344.

Darwish M.A, Elsayed A.A, Elsayed M.M, Aly S.E. (1981). Lecture notes on desalination: A short course, King Abdul Aziz University Press: Jeddah, Saudi Arabia.

Dreizin Y, Tenne A, Hoffman D. (2008). Integrating large scale seawater desalination plant within Israel's water supply system. *Desalination* **220**, 132–149.

Ebrahim S.H, Abdel-Jawad M.M, Saffar M. (1995). Conventional pretreatment system for the Doha reverse osmosis plant: Technical and economic assessment. *Desalination* **102**, 179–187.

Edalat A. (2008). Implementation of ISO 14001:2004 (environmental management system standard) for reverse osmosis desalination plants for the first time in Iran. *Desalination* **220**, 57–64.

El-Sadek A. (2010). Water desalination: An imperative measure for water security in Egypt. *Desalination* **250**, 876–884.

Environmental Protection Agency (2002). Title 40 CFR: Protection of the Environment, Ch. 1, Part 143 (National Secondary Drinking Water Regulations), US Environmental Protection Agency, National Archives and Records Administration. <http://www.epa.gov/lawsregs/search/40cfr.html> accessed on 15 October 2010.

Fang Y, Pham V.A, Matsuura T, Santerre J.P, Narbaitz R.M. (1994). Effect of surface-modifying macromolecules and solvent evaporation time on the performance of polyethersulfone membranes for the separation of chloroform/water mixtures by pervaporation. *Journal of Applied Polymer Science* **54**, 1937–1943.

Fibiger R.F, Colucci M.J, Forgach D.J, Wessling R.A, Schmidt D.L. (1990). Rejection enhancing coatings for reverse osmosis. US Patent 4 894 165.

Freger V. (2003). Nanoscale heterogeneity of polyamide membranes formed by interfacial polymerization. *Langmuir* **19**, 4791–4797.

Freger V. (2004). Swelling and morphology of the skin layer of polyamide composite membranes: An atomic force microscopy study. *Environmental Science Technology* **38**, 3168–3175.

Freger V, Gilron J, Belfer S. (2002). TFC polyamide membranes modified by grafting of hydrophilic polymers: An FT-IR/AFM/TEM study. *Journal of Membrane Science* **209**, 283–292.

Fritzmann C, Löwenberg, J, Wintgens, T, Melin T. (2007). State-of-the-art of reverse osmosis desalination. *Desalination* **216**, 1–76.

Ghosh A.K, Jeong B.-H, Huang X, Hoek E.M.V. (2008). Impacts of reaction and curing conditions on polyamide composite reverse osmosis membrane properties. *Journal of Membrane Science* **311**, 34–45.

Global Water Intelligence (2008). WTD seals contract for Iran's largest ever desal plant. **9**(9), September.

Global Water Intelligence (2009). Israel's desal desperation. **10**(1), January.

Glückauf E. (1965). On the mechanism of osmotic desalting with porous membranes, In Proc. First Int. Conf. on Water Desalination, Vol. 1, pp. 143–156, Office of Saline Water, U.S. Dept. of Interior: Washington, DC, USA.

Glueckstern P. (1999). Design and operation of medium- and small-size desalination plants in remote area: New perspective for improved reliability, durability and lower costs. *Desalination* **122**, 123–140.

Glueckstern P, Priel M. (1998). Advanced concept of large seawater desalination systems for Israel. *Desalination* **119**, 33–45.

Glueckstern P, Priel M, Gelman E, Perlov N. (2008). Wastewater desalination in Israel. *Desalination* **222**, 151–164.

GWRC (2008). Global Water Research Coalition (GWRC), Water and Energy – Report of the GWRC Research Strategy Workshop, Draft, May.

Hadadin N, Qaqish M, Akawwi E, Bdour A. (2010). Water shortage in Jordan – Sustainable solutions. *Desalination* **250**, 197–202.

Hafez A, El-Manharawy S. (2002). Economics of seawater RO desalination in the Red Sea region, Egypt. Part 1. A case study. *Desalination* **153**, 335–347.

Hirose M. (2005). Highly permeable composite reverse osmosis membrane and method of producing the same. US Patent 6 837 381.

Hirose M, Ikeda K. (1996). Method of producing high permeable composite reverse osmosis membrane. US Patent 5 576 057.

Hirose M, Ito H, Maeda M, Tanaka K. (1997). Highly permeable composite reverse osmosis membrane, method of producing the same, and method of using the same. US Patent 5 614 099.

Hydranautics, (2007). Hydranautics, Press release: Integrated membrane solutions at work in Southern Spain, <http://www.membranes.com/press/Escombreras.Jan%202007.pdf> accessed on 15 October 2010.

Hyung H, Kim J.-H. (2006). A mechanistic study on boron rejection by sea water reverse osmosis membranes. *Journal of Membrane Science* **286**, 269–278.

Iijima S. (1991) Helical microtubes of graphitic carbon. *Nature* **354**, 56–58.

Jeong B.-H, Hoek E.M.V, Yan Y, Subramani A, Huang X, Hurwitz G, Ghosh A.K, Jawor A. (2007). Interfacial polymerization of thin film nanocomposites: A new concept for reverse osmosis membranes. *Journal of Membrane Science* **294**, 1–7.

Johnson D.R, Stutts K.J, Batzel D.A, Hallfrisch V.A, Anschutz J.E. (1994). Method of making thin film composite membranes. US Patent 5 368 889.

Kang G, Liu M, Lin B, Cao Y, Yuan Q. (2007). A novel method of surface modification on thin-film composite reverse osmosis membrane by grafting poly(ethylene glycol). *Polymer* **48**, 1165–1170.

Khawaji A.D, Kutubkhanah I.K, Wie J.-M. (2007). A 13.3 MGD seawater RO desalination plant for Yanbu industrial city. *Desalination* **203**, 176–188.

Khulbe K.C, Feng C.Y, Matsuura T. (2010). The art of surface modification in synthetic polymeric membranes. *Journal of Applied Polymer Science* **115**, 855–895.

Kim S.H, Kwak S.-Y, Suzuki T. (2005). Positron annihilation spectroscopic evidence to demonstrate the flux-enhancement mechanism in morphology-controlled thin-film-composite (TFC) membrane. *Environmental Science Technology* **39**, 1764–1770.

- Kim S.H, Kwak S.-Y, Sohn B, Park T.H. (2003). Design of TiO₂ nanoparticles self-assembled aromatic polyamide thin-film-composite (TFC) membrane as an approach to solve biofouling problem. *Journal of Membrane Science* **211**, 157–165.
- Kim S, Jinschek J.R, Chen H, Sholl D.S, Marand E. (2007) Scalable fabrication of carbon nanotube/polymer nanocomposite membranes for high flux gas transport. *Nano Letters* **7**, 2806–2811.
- Knepper M.A, Nielsen S. (2004). Peter Agre, 2003 Nobel Prize winner in chemistry. *Journal of the American Society Nephrology* **15**, 1093–1095.
- Koseoglu H, Kabay N, Yüksel M, Sarp S, Arar Ö, Kitis M. (2008). Boron removal from seawater using high rejection SWRO membranes – impact of pH, feed concentration, pressure and cross-flow velocity. *Journal of Membrane Science* **227**, 253–263
- Kranhold K. (2008). Water, water, everywhere.... The Wall Street Journal, January 17.
- Kuehne M.A, Song R.Q, Li N.N, Petersen R.J. (2001). Flux enhancement in TFC RO membranes. *Environmental Progress* **20** (1), 23–26.
- Kulkarni A, Mukherjee D, Gill W.N. (1996). Flux enhancement by hydrophilization of thin film composite reverse osmosis membranes. *Journal of Membrane Science* **114**, 39–50.
- Kurihara, M, Fusaoka, Y. (1999). Recent progress on separation membrane and outlook for future. *Membrane* **24**, 247–255.
- Kwak S.-Y, Jung S.G, Kim S.H. (2001a). Structure-motion-performance relationship of flux-enhanced reverse osmosis (RO) membranes composed of aromatic polyamide thin films. *Environmental Science Technology* **35**, 4334–4340.
- Kwak S.-Y, Kim S.H, Kim S.S. (2001b). Hybrid organic/inorganic reverse osmosis (RO) membrane for bactericidal anti-fouling.1. Preparation and characterization of TiO₂ nanoparticles self-assembled aromatic polyamide thin-film composite (TFC) membrane. *Environmental Science Technology* **35**, 2388–2394.
- Lashkaripour G.R, Zivdar M. (2005). Desalination of brackish water in Zehdan city in Iran. *Desalination* **177**, 1–5.
- Lawson K.W, Lloyd D.R. (1997). Membrane distillation. *Journal of Membrane Science* **124**, 1–25.
- Lee P.O. (2005). Water management issues in Singapore, paper presented at Water in Mainland Southeast Asia, 29 November - 2 December, Siem Reap, Cambodia, organized by the International Institute for Asian Studies, Netherlands and the Centre for Khmer Studies (CKM), Cambodia.
- Loeb S, Sourirajan S. (1961). Sea water demineralization by means of a semipermeable membrane. *Dept. Eng, UCLA, Los Angeles, CA, USA, Report No. 60-60*.
- Loeb S, Sourirajan S. (1964). High flow porous membranes for separating water from saline solutions. US Patent 3 133 132.
- Lokiec F, Kronenberg G. (2003). South Israel 100 million m³/y seawater desalination facility: Build, operate and transfer (BOT) project. *Desalination* **156**, 29–37.
- Lonsdale H.K, Merten U, Riley R.L. (1965). Transport properties of cellulose acetate osmotic membranes. *Journal of Applied Polymer Science* **9**, 1341–1362.
- Louie J.S, Pinnau I, Ciobanu I, Ishida K.P, Ng A, Reinhard M. (2006). Effects of polyether–polyamide block copolymer coating on performance and fouling of reverse osmosis membranes. *Journal of Membrane Science* **280**, 762–770.
- Mane P.P, Park P.-K, Hyung H, Brown J.C, Kim J.-H. (2009). Modeling boron rejection in pilot- and full scale- reverse osmosis desalination processes. *Journal of Membrane Science* **338**, 119–127.
- Matsuura T. (1994). *Synthetic membranes and membrane separation processes*. CRC Press: Boca Raton, FL, USA.
- McCutcheon J.R, McGinnis R.L, Elimelech M. (2005). A novel ammonia-carbon dioxide forward (direct) osmosis desalination process. *Desalination* **174**, 1–11.

Memstill - Low cost water desalination. http://www.emf.nl/pdf/brochure_memstill.pdf accessed on 15 October 2010.

Mi W, Lin Y.S, Li Y. (2007) Vertically aligned carbon nanotube membranes on macroporous alumina supports. *Journal of Membrane Science* **304**, 1–7.

Mickols, W.E, Busch M, Maeda Y, Tonner J. (2005). A novel design approach for seawater plants. *IDA World Congress*: Singapore.

Mitra S.S, Sharma M.K, Rybar S, Bartels C, Pelegrin L. (2009). Fujairah SWRO-management of membrane replacement. *Desalination and Water Treatment* **10**, 255–264.

Morgan P.W, Kwolek S.L. (1996). Interfacial polycondensation II. Fundamentals of polymer formation at liquid interfaces. *Journal of Polymer Science, Polymer Chemistry Edition* **34**, 531–559.

Mukherjee D, Kulkarni A, Gill W.N. (1994). Flux enhancement of reverse osmosis membranes by chemical surface modification. *Journal of Membrane Science* **97**, 231–249.

PUB Singapore (2010). Water for all – meeting our water needs for the next 50 years.

PUB Singapore (2008). <http://www.pub.gov.sg/water/Pages/default.aspx> accessed on 15 October 2010.

Qtaishat M.R. (2008). Design of Novel Membranes for Desalination by Direct Contact Membrane Distillation. Ph.D. Thesis, Department of Chemical and Biological Engineering, University of Ottawa: Ottawa, Canada.

Rana D, Matsuura T, Narbaitz R.M, Feng C. (2005). Development and characterization of novel hydrophilic surface modifying macromolecule for polymeric membranes. *Journal of Membrane Science* **249**, 103–112.

Reverberi F, Gorenflo A. (2007). Three year operational experience of a spiral-wound SWRO system with a high fouling potential feed water. *Desalination* **203**, 100–106.

Reid C.E, Breton E.J. (1959). Water and ion flow across cellulosic membranes. *Journal of Applied Polymer Science* **1**, 133–143.

Riley R.L, Case P.A, Lloyd A.L, Milstead C.E, Tagami M. (1981). Recent developments in thin-film-composite reverse osmosis membrane systems. *Desalination* **36**, 207–233.

Rozelle L.T, Cadotte J.E, Cobian K.E, Kopp C.V. Jr. (1977). Nonpolysaccharide membranes for reverse osmosis: NS-100 membranes, in *Reverse osmosis and synthetic membranes, theory-technology-engineering* (ed. S. Sourirajan), pp. 249–261, National Research Council of Canada: Ottawa, Canada.

Saad M.A. (2004). Membrane desalination for the Arab world: Overview and outlook, First forum on water desalination and purification technology: Outlook for the Arab world, Marrakesh, Morocco, May 29-30.

Saad M.A. (2005). Membrane desalination for the Arab world: Overview and outlook. *Arab Water World* **29(1)**, 10–13.

Sanza M.A, Bonnelyea V, Cremerb G. (2007). Fujairah reverse osmosis plant: 2 years of operation. *Desalination* **203**, 91–99.

Schipper J.C. (2009). Water chemistry, fouling and scaling in reverse osmosis and nanofiltration: Short course conducted by the Middle East Desalination Research Center at Amman, Jordan, April 19-22.

Schultz R.D, Asunmaa S.K. (1970). Ordered water and the ultrastructure of the cellular plasma membrane, in *Recent progress in surface science, Vol. 3.* (eds. J.F. Danielli, A.C. Riddiford, M. Rosenberg), Academic Press: New York, NY, USA.

Sepahan (1977). Sepahan group document and contract. Urban and industrial water technology reports, 1977-2002.

Service R.F. (2006). Desalination freshens up. *Science* **313**, 1088–1090.

Sforca M, Nunes S.P, Peinemann K.V. (1997). Composite nanofiltration membranes prepared by in-situ polycondensation of amines in a poly(ethylene oxide-b-amide) layer. *Journal of Membrane Science* **135**, 179–186.

Sourirajan S, Matsuura T. (1985). *Reverse osmosis/ultrafiltration process principles*, pp. 802–805, National Research Council of Canada: Ottawa, Canada.

Sundet S.A. (1993). Morphology of the rejection surface of aromatic polyamide membranes for desalination. *Journal of Membrane Science* **76**, 175–183.

TNO - Purification of water and liquids. http://www.twanetwerk.nl/upl_documents/Schilthuizen.pdf accessed on 15 October 2010.

Tortajada C. (2006). Water management in Singapore. *Water Resources Development* **22**, 227–240.

Tran C.N, Maldonado A.C, Somanathan R. (1993). Thin-film composite membrane. US Patent 5 234 598.

Tran C.N, Maldonado A.C, Somanathan R. (1994). Method of making thin-film composite membranes. US Patent 5 358 745.

Tuas Singapore - Tuas seawater desalination plant – Seawater reverse osmosis (SWRO), Singapore. <http://www.water-technology.net/projects/tuas/tuas2.html> accessed on 15 October 2010.

Verissimo S, Peinemann K.V, Bordado J. (2006). Influence of the diamine structure on the nanofiltration performance, surface morphology and surface charge of the composite polyamide membranes. *Journal of Membrane Science* **279**, 266–275.

Wang K.Y, Chung T.-S. Qin J.-J. (2007). Polybenzimidazole (PBI) nanofiltration hollow fiber membranes applied in forward osmosis process. *Journal of Membrane Science* **300**, 6–12.

WTP - Water Treatment Plant (WTP) - Seawater desalination: Giving new lease of life to Middle East. <http://www.thewatertreatmentplant.com/sea-water-desalination.html> accessed on 15 October 2010.

Wavhal D.S, Fisher E.R. (2003). Membrane surface modification by plasma-induced polymerization of acrylamide for improved surface properties and reduced protein fouling. *Langmuir* **19**, 79–85.

Wittbecker E.L, Morgan P.W. (1996). Interfacial polycondensation 1. *Journal of Polymer Science, Polymer Chemistry Edition* **34**, 521–529.

Wu S, Xing J, Zheng C, Xu G, Zheng G, Xu J. (1997). Plasma modification of aromatic polyamide reverse osmosis composite membrane surface. *Journal of Applied Polymer Science* **64**, 1923–1926.

Yang H.L, Lin J.C.-T, Huang C. (2009). Application of nanosilver surface modification to RO membrane and spacer for mitigating biofouling in seawater desalination. *Water Research* **43**, 3777–3786.

Yuster S.T, Sourirajan S, Bernstein K. (1958). Seawater demineralization by the surface skimming process. *UCLA Report* **58-26**.

Biographical Sketches

Takeshi MATSUURA, received B.Sc. (1961) and M.Sc. (1963) from the Department of Applied Chemistry at the Faculty of Engineering, University of Tokyo. He received Doktor-Ingenieur at the Institute of Chemical Technology of the Technical University of Berlin (1965). He worked at the National Research Council of Canada from 1969 until he joined the University of Ottawa in 1992 as a professor and the chair holder of the British Gas/NSERC Industrial Research Chair. He served as a professor of the Department of Chemical Engineering (currently Chemical and Biological Engineering) and the director of the Industrial Membrane Research Institute (IMRI) until he retired in 2002. He was appointed to professor emeritus in 2003. He served also at the National University of Singapore (2003), University Technology Malaysia, Skudai, Malaysia, (2007, 2009, 2010) at Myongji University, Yongjin, Korea, (2008) as visiting professor. He received the Research Award of International Desalination and Environmental Association in 1983. He is a fellow of the Chemical Institute of Canada and a member of the North American Membrane Society. He has published over 300 papers in refereed journals, authored and co-authored 4 books and edited 6 books. A symposium of membrane gas separation was held at the Eighth Annual Meeting of the North American Membrane Society, May 18-22, 1996, Ottawa, to honor Dr. Matsuura together with Dr. S. Sourirajan. He received George S. Glinski Award for Excellence in Research from the Faculty of Engineering of the University of Ottawa in 1998.

Dipak RANA, is presently a Research Scientist in the Industrial Membrane Research Institute, Department of Chemical and Biological Engineering, University of Ottawa, Ottawa, Canada. Dr. Rana

has been a member of various prestigious organizations, like Indian Chemical Society; Society for Polymer Science, India; Society of Plastics Engineers, USA; American Chemical Society; etc, for long period. He was awarded Ph. D. in Science from Jadavpur University, Calcutta (presently Kolkata), when he was worked at the Indian Association for the Cultivation of Science, Calcutta, India. He received his Master in Chemistry with specialization in Physical Chemistry as well as his Bachelor with Honors in Chemistry from the University of Calcutta, India. Dr. Rana has published over 50 professional papers and book chapters.

Mohammed Rasool QTAISHAT, received his Ph.D. degree in Chemical Engineering from University of Ottawa, Canada in 2008. He joined University of Jordan, Jordan in 2009 as a faculty member in the Department of Chemical Engineering, his current position is assistant professor where he mainly teaches desalination courses for undergraduate and graduate level at both the university of Jordan and the German Jordanian university. He is the author or co-author of one US patent and many research papers and has given several presentations at scientific conferences. His current research interests include future desalination technologies as well as renewable energy. He was the recipient of 2008 Technology Venture Challenge Prize for innovation from Ontario Centre of Excellence. He also was the recipient of the best poster presentation award at the EUROMED 2008 conference for his work in membrane distillation. Dr. Qtaishat is a reviewer in many international journals and he is a member of several national and international scientific committees.

Gurdev SINGH, received his Degree and Ph.D in Civil Engineering at the National University of Singapore in 2003 and 2007, respectively. He is Research Engineer/Scientist at the Environmental and Water Technologies Centre of Innovation at Ngee Ann Polytechnic, Singapore. He previously worked at the Industrial Membrane Research Institute, University of Ottawa and the Nanoscience & Nanotechnology Initiative, National University of Singapore, where he developed his expertise on membrane science and technology before joining Ngee Ann Polytechnic in 2009. His present research interests concern: development of energy efficient and non-fouling membranes for membrane bioreactors, design and optimization of integrated membrane desalination systems e.g. membrane distillation and forward osmosis, design and development of filters for air purification and detoxification. He is author/co-author of about 20 publications in referred journals and several proceedings of international scientific conferences and workshops.