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Future of the osmotic processes

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ABSTRACT

Osmotic processes are widely utilized in water–ion separation applications. These include purification of low salinity water, desalination of brackish and seawater and reclamation of wastewater. The advantage of application of pressure driven membrane separation processes is obvious when comparing energy requirements of membrane processes with other desalination technologies. It is possible that future improvement of water permeability of current reverse osmosis (RO) membranes could bring some additional reduction of energy use of membrane desalination. However, for seawater desalination, any significant future reduction of energy requirement is limited by osmotic pressure of the concentrate and apparent coupling of water and salt transport. For current commercial RO membranes the increase of water permeability is associated with increase of salt transport and increased permeate salinity. The nominal salt rejection of commercial seawater membranes is about 99.85%. In order to maintain the same permeate salinity at lower feed pressure, membranes with higher water permeability have to maintain the same salt transport rate, which translates to a proportionally reduced salt passage, i.e. increased salt rejection. It is not very likely that current membrane manufacturing methods could bring additional improvement of salt rejection, which is today frequently above 99.9% for the flat sheet membranes. A new osmotic process that could bring a meaningful reduction of energy of seawater desalination is forward osmosis (FO). FO requires low pressure for recirculation of seawater and draw solution, but does not require high feed pressure to generate sufficient net driving pressure (NDP) to drive water through the membrane. FO utilizes osmotic pressure gradient to extract low salinity water from seawater. Under conditions of availability of low temperature waste heat, FO could desalt seawater at energy requirement less than 50% of the energy required by the current RO seawater desalination technology. The major obstacle for commercial implementation of FO to water desalination is lack of suitable commercially available membranes. The same obstacle, unavailability of suitable membranes, is facing another promising osmotic process: pressure retarded osmosis (PRO). Potentially, PRO could be a significant source of renewable energy, utilizing low salinity–high salinity water mixing energy to generate hydraulic gradient that would drive turbine and generate electric power. Detailed energy generating system configurations have been developed for PRO by S. Loeb and others in the past. However, due to difficulty of manufacturing of suitable membranes, the PRO technology verification experiments have been limited to laboratory conditions only. This paper includes information on current status of reverse osmosis as applied to desalination and wastewater treatment. Process configurations and areas of potential future improvement are discussed. Forward osmosis and pressure retarded osmosis process configurations and projected operating parameters of commercial systems are presented. Performance and configuration requirements of suitable membranes for FO and PRO are discussed.

Keywords: Reverse osmosis; Membranes; Osmotic process

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Dedicated to Prof. Sidney Loeb (1916–2008). December 14, 2009, Sede-Boker, Israel

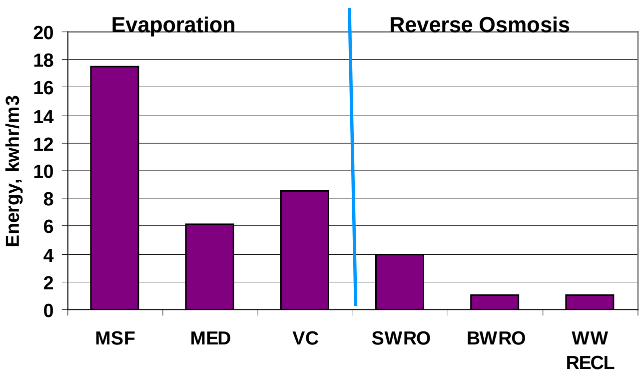
1. Introduction

Osmotic processes are widely utilized in water–ion separation applications. These include purification of low salinity water, desalination of brackish and seawater and reclamation of wastewater. The advantage of application of pressure driven membrane separation processes is obvious when comparing energy requirements of membrane processes with other desalination technologies as shown in Fig. 1.

It is possible that future improvement of water permeability of current reverse osmosis (RO) membranes could bring some additional reduction of energy use of membrane desalination. However, for seawater desalination, any significant future reduction of energy requirement is limited by osmotic pressure of the concentrate and apparent coupling of water and salt transport. For current commercial RO membranes the increase of water permeability is associated with increase of salt transport and increased permeate salinity. The nominal salt rejection of commercial seawater membranes is about 99.85%. In order to maintain the same permeate salinity at lower feed pressure, membranes with higher water permeability have to maintain the same salt transport rate, which translates to a proportionally reduced salt passage i.e. increased nominal salt rejection.

A new osmotic process [1] that could bring a meaningful reduction of energy of seawater desalination is forward osmosis (FO). FO requires low pressure for recirculation of seawater and draw solution, but does not require high feed pressure to generate sufficient net driving pressure (NDP) to drive water through the membrane. FO utilizes osmotic pressure gradient to extract low salinity water from seawater. Under conditions of availability of low temperature waste heat, FO could desalt seawater at energy requirement less than 50% of the energy required by the current RO seawater desalination technology. The major obstacle for commercial implementation of FO to water desalination is lack of suitable commercially available membranes.

The same obstacle, unavailability of suitable membranes, is facing another promising osmotic process [2,3]: pressure retarded osmosis (PRO). Potentially, PRO could be a significant source of renewable energy, utilizing low salinity–high salinity water mixing energy to generate hydraulic gradient that would drive turbine and generate electric power. Detailed energy generating system configurations have been developed for PRO by S. Loeb and others in the past. However, due to difficulty of manufacturing of suitable membranes, the PRO technology verification experiments have been limited to laboratory conditions only.



MSF – multistage flash, MED – multieffect distillation, VC – vapor compression, SWRO – seawater reverse osmosis, BWRO – brackish water reverse osmosis, WWRECL – wastewater reclamation

Fig. 1. Energy requirements of desalination processes.

2. Reverse osmosis membranes

The vast majority of commercial reverse osmosis membranes are manufactured as a flat sheet and package in a spiral wound membrane element configuration.

Almost all commercial flat sheet membranes have composite configuration, as shown in Fig. 2. The membrane consists of 150 μ polyester fabric backing, 50 μ porous polysulfone support and 1000–2000 Å membrane separation barrier.

The key separation properties of the membrane: water permeability and salt rejection are determined mainly by the structure of the top layer, the membrane barrier.

The schematic configuration of the spiral wound membrane element is shown in Fig. 3.

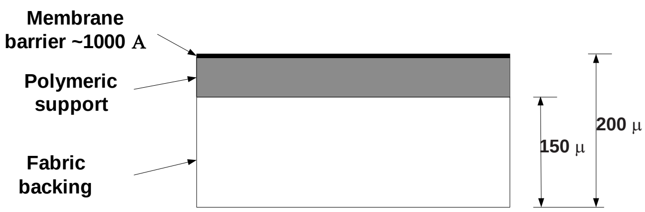


Fig. 2. Configuration of flat sheet composite membranes.

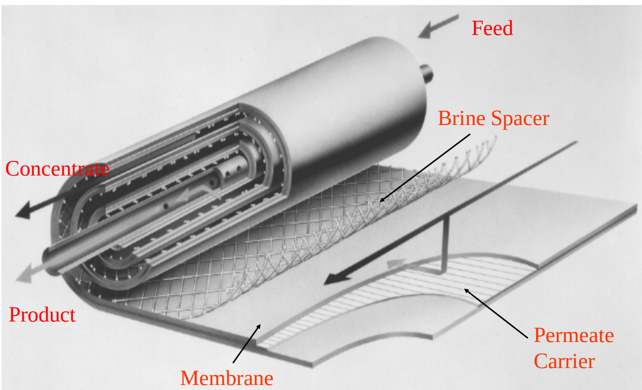


Fig. 3. Schematic configuration of the spiral wound element.

The configuration consists of number of membrane envelopes, attached by one side to the perforated permeate central tube. The membrane surfaces are separated by a polypropylene net, the brine spacer.

The standard length of spiral wound membrane elements is 1 m. The element diameter is either 200 mm or 400 mm. The 200 mm diameter membrane elements contain 37–41 m^2 of active membrane area. The 400 mm diameter elements contain about 4 times active membrane area of the 200 diameter elements.

3. Applications

The membrane elements are manufactured in three basic categories related to feed water salinity:

- Nanofitration membranes
- Brackish membranes
- Seawater membranes

Membranes belonging to different categories have the same physical dimensions and similar membrane area per element. They differ in the transport properties: water permeability and salt transport as shown in Table 1.

Each main category of membrane elements encompasses relative wide range of permeate flow and salt rejection. Membrane elements in the nanofiltration group have the highest water permeability and also a widest range of salt rejection.

In addition to 200 mm diameter (8”) elements, the 400 mm diameter (16”) are being implemented commercially. The salt and water transport properties of large diameter elements are basically the same as of 200 mm diameter elements.

4. Nanofiltration

Transport properties of nanofiltrtaion membranes have been developed to as an industry response to various application requirements:

- High water permeability and salt rejection in the range of 90–95% for partial reduction of salinity and hardness in potable applications.
- Very low rejection of inorganic ions combined with very high rejection of dissolved organics for color reduction in applications
- Specialty nanofiltration membranes for industrial applications. Their performances usually include selective high rejection of divalent ions combined with high passage of other constituents.

Nanofiltration systems operate at low pressures and high recovery rates. Usually feed pressure is in the range 7–10 bar and recovery rate of 85–90%. Some NF systems operate at much higher recovery rate, reaching up to 98% [4].

The main directions of nanofiltration process improvement are efforts to tailor separation properties of the membranes to specific applications and reduction of the parasitic friction pressure loses in the membrane unit.

Development of selective rejection nanofiltration membranes has been partially successful. These include NF membranes used presently for color removal [4], pesticide rejection [5,6] and preferential sulfate reduction [7].

Future targets for selective rejection membranes are micropollutants, treatment of low salinity water with minute concentration of pharmaceutical and personal care compounds.

One of current developments that address pressure losses in the pressure vessels array is the central port pressure vessel design, also called optiflux configuration [9]. In this configuration, feed water is delivered to the pressure vessels at both ends and the concentrate is collected through the central ports. The feed–concentrate path flow length in the pressure vessel is only half of the path length in the conventional configuration. The average feed flow rate is reduced by 50% as well. The central port configuration results in operation of membrane elements at much higher recovery rate per membrane element (and lower concentrate flow rate) than it has been practiced in the past, resulting in apparent higher concentration polarization. Small, number of commercial systems, utilizing central port pressure vessels, is in operation, claiming stable performance and up to 20% reduction of feed pressure.

Table 1
Representative performance of commercial membrane elements

Membrane type	Nanofiltration	Brackish RO	Seawater RO
Dimension, mm	Φ 200 L 1000	Φ 200 L 1000	Φ 200 L 1000
Membrane area, m^2	37–41	37–41	37–41
Test pressure, mPa	0.5	1.0–1.5	5.5
Test feed salinity, ppm NaCl	500	1,500	32,000
Nominal salt rejection, %	50–95	99.0–99.6	99.6–99.8
Nominal permeate flow, m^3/d	21–47	41–49	24–34
Water permeability, m/s/Pa	$(1.4–3.2)\times10^{-11}$	$(1.4–1.7)\times10^{-11}$	$(2.8–3.9)\times10^{-12}$
Salt transport, m/s	$(3.5–150)\times10^{-7}$	$(0.5–1.5)\times10^{-7}$	$(1.5–4.2)\times10^{-8}$

5. Brackish RO

Brackish RO systems operate at higher pressure and lower recovery rate then it is common in nanofiltration applications. Feed pressure could be in the range of 15–20 bar. The recovery rate is determined by the concentration of scale forming constituents in the feed water, usually it is in the range of 70–85%.

The major challenge of brackish RO application is disposal of high salinity concentrate stream. Therefore, recovery rate is important issue for brackish systems. So far progress in developing feasible solutions for concentrate disposal has been minimal. Selective passage through membrane of scale forming constituents could be a solution. However, the requirement of high rejection rate of brackish membranes imposes very difficult restrictions on the development process of suitable selective passage membranes.

6. Wastewater reclamation

Membrane used in RO units operating in wastewater reclamation plants are usually the same type as used in RO brackish water systems. Vast majority of the systems utilize membrane filtration as feed water pretreatment. Performances of RO membranes in this application are quite stable, provided that potential bacterial grow in membrane elements is effectively controlled with presence of chloramines.

Future requirement, as it has been discussed for NF applications, includes membrane with selectively high rejection of micropollutants.

Another evolving trend is system configuration that includes membrane bioreactor (MBR) followed by RO as shown in Fig. 4.

Implementation of the MBR + RO configuration could result in significant improvement of the economics of the overall process. Elimination of dedicated membrane pretreatment (MF/UF), would result in considerable reduction of equipment and operating cost of the wastewater reclamation process.

7. Seawater RO

RO seawater desalination is the most challenging application in respect of applied pressure and requirements of salt rejection. Feed pressure is in the range of 55–80 bar. Recovery rate of seawater RO units is in the range 40–50%. The upper limit of recovery rate is dictated by the required feed pressure.

Seawater salinity is in the range of 32,000–45,000 ppm TDS. This feed salinity and range of recovery rate translates to an average feed salinity in the membrane unit of 50,000–65,000 ppm TDS. The practical limit of product water salinity produced by membrane unit is seawater RO plant is 300–350 ppm. Therefore, in a single pass system configuration salt passage of seawater membranes cannot exceed 0.4–0.5% (99.4–99.5% salt rejection) over the entire "membrane life" period.

Since the initial development of seawater composite polyamide membrane, the initial effort was to develop membrane products with increasingly higher salt rejection (Fig. 5). More recently, the R&D efforts were directed to produce seawater membranes with higher perme-

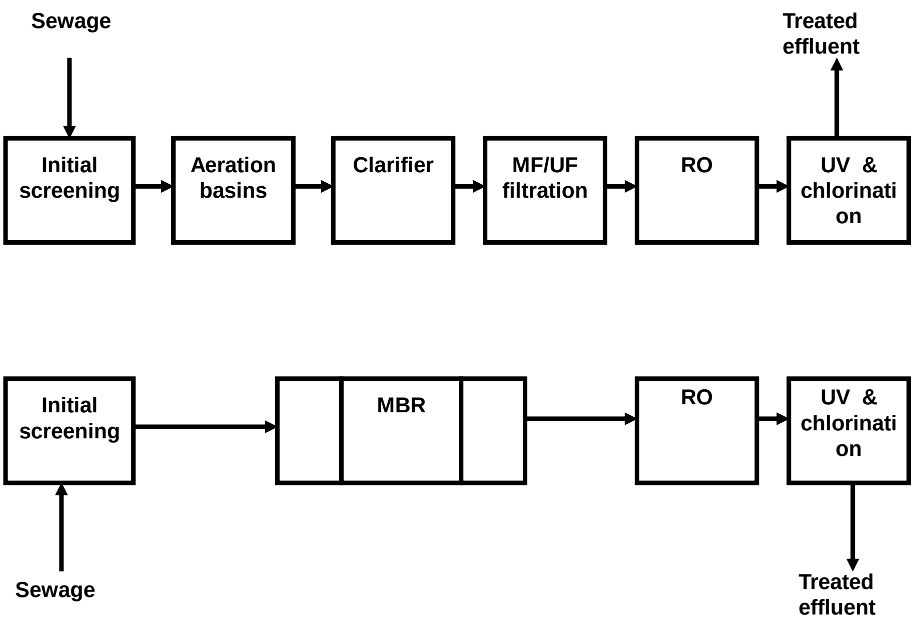


Fig. 4. Advanced treatment of municipal effluents. Wastewater biological treatment followed by membrane filtration, followed by RO (upper diagram). MBR followed by RO (lower diagram).

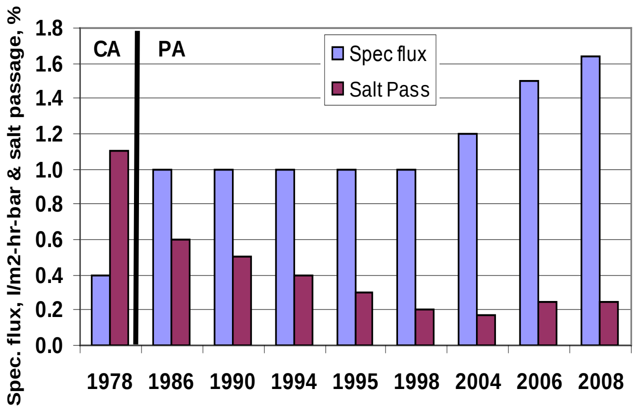


Fig. 5. Evolution of permeability and salt passage of seawater composite polyamide membranes.

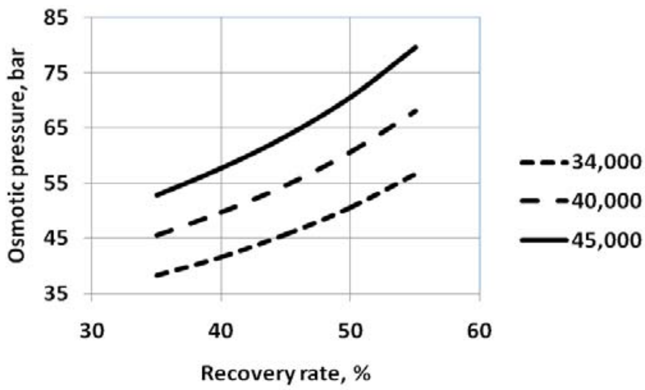


Fig. 7. Osmotic pressure of the RO concentrate vs recovery rate for representative salinity range of seawater.

ability. This is in order to enable operation at lower feed pressure and to reduce required process energy.

The available potential for pressure reduction in seawater RO systems is illustrated in data presented in Figs. 6 and 7.

It is evident from graph in Fig. 6 that RO unit has to operate at feed pressure sufficiently high to result in concentrate pressure that is higher then the osmotic pressure of the concentrate. This is to provide sufficient net driving pressure at the concentrate end of the membrane unit.

The osmotic pressure of the concentrate is function of feed salinity and recovery rate as shown for representative seawater salinities in Fig. 7.

The feed pressure difference over the osmotic pressure that has to be maintained in the RO unit for a given flux rate is function of membrane permeability. The offering of commercial seawater membranes includes relatively wide range of water permeabilities. Water permeability of various membrane element can be compared based on their nominal permeate flow, if the membrane elements have the same membrane area and are tested at the same test conditions, which is presently the case in RO membrane industry.

The present offering of seawater membranes by major membrane manufacturer is summarized in Table 2.

The results listed in Table 2 indicate similar performance of membrane elements from different manufacturers and quite narrow distribution of salt rejection.

The summary of nominal values of permeate flux and salt passage of commercial elements, shown in a graphic form in Fig. 8, suggests that is possible to manufacture highly permeable seawater membranes within a narrow range of salt passage, i.e. there is only a marginal correlation between permeate flux and salt passage.

However, translation of nominal elements performance data into water and salt transport values indicates a different picture, as illustrated in Fig. 9.

According to information presented in Fig. 9, there is a clear trend in commercial membranes of increasing salt transport with increased water permeability, a coupling of water and salt transport. This phenomenon has significant implication on utilization of high permeability membranes in seawater RO systems.

Permeate water produced in seawater RO unit is corrosive and require chemical stabilization. The stabilization process involves addition of hardness and adjustment

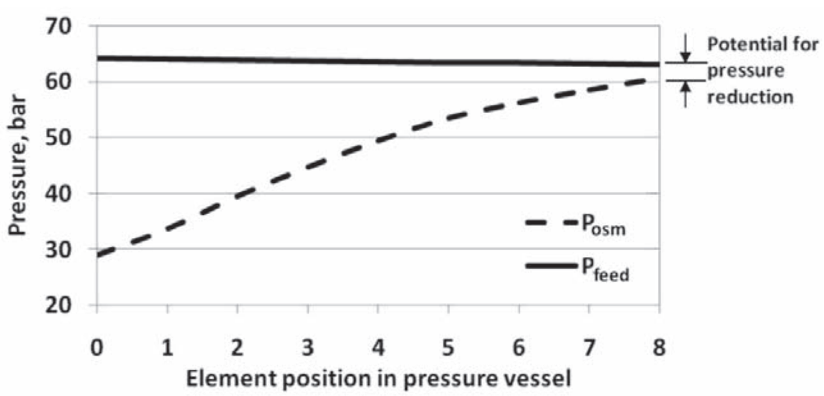


Fig. 6. Changes of osmotic pressure and feed pressure along a seawater RO memebrane unit. Feed salinity, 40,000 ppm TDS, recovery rate 50%.

Table 2
Nominal performance of RO seawater membrane elements. Nominal test conditions: feed salinity 32,000 ppm TDS, recovery rate 8%, feed pressure 5.5 MPa

Manufacturer	Nominal salt rejection, %	Nominal permeate flow, m^3/d	Active membrane area, m^2/element
Manufacturer # 1	99.80	24.6	37.2
Manufacturer # 1	99.80	34.0	37.2
Manufacturer # 2	99.80	22.7	37.2
Manufacturer # 2	99.80	28.4	37.2
Manufacturer # 2	99.70	42.6	37.2
Manufacturer # 3	99.75	22.7	37.2
Manufacturer # 3	99.75	24.6	37.2
Manufacturer # 3	99.75	28.4	37.2
Manufacturer # 3	99.80	34.0	37.2

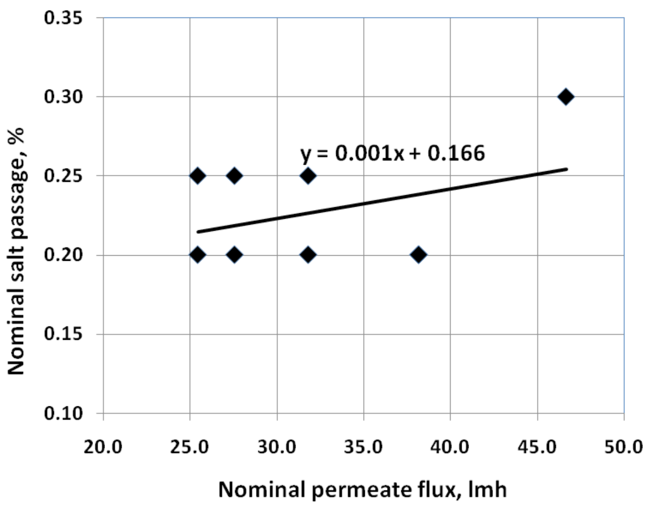


Fig. 8. Nominal permeate flux and salt passage of commercial SWRO membrane elements.

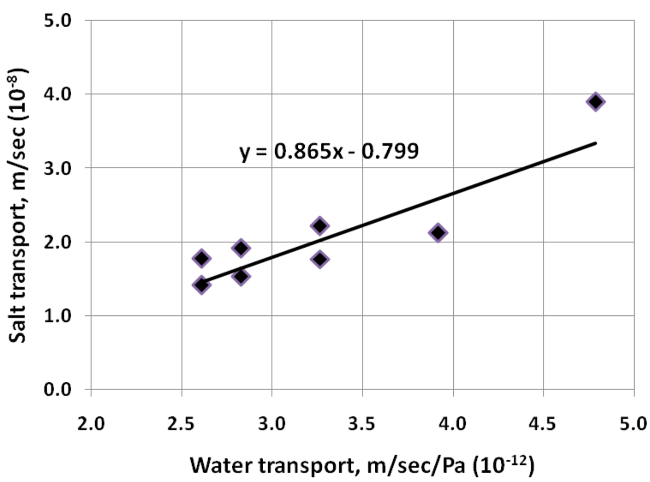


Fig. 9. Water and salt transport properties of commercial SWRO membrane elements.

of water pH. This permeate water treatment results in increase of permeate salinity by about 100 ppm of TDS. Therefore, permeate salinity, produced in commercial desalination system for potable applications has to be below 350 ppm TDS.

Compared to a nominal test conditions, membrane elements operate in field at lower average permeate flux and higher feed salinity. In field conditions the average flux is in the range of 13.6–15.3 $l/m^2/h$, regardless of membrane permeability. This flux rate is about half of the nominal permeate flux (compared to test conducted at the nominal test conditions). Therefore the dilution of salt passing through the membrane is much lower and product salinity is higher. Based on the salt transport value, it is possible to calculate the nominal salt rejection of a membrane that is required for production of permeate of a target salinity. The results of calculations for target permeate salinity of 300 ppm TDS are shown in Fig. 10.

The upper curve in Fig. 10 corresponds to membrane performance at an average flux rate of RO system of 14.6 $l/m^2/h$. This flux rate is middle of a range of an average permeate flux values in RO systems operating on surface source seawater (open intake). The rejection values required for commercial membranes of high permeability are becoming quite high above nominal flux rate of 30 $l/m^2/h$. However, if commercial seawater system could operate reliably at higher flux rate, the required salt rejection would be lower as illustrated on the lower curve in Fig. 10 for flux rate of 29 $l/m^2/h$.

The general conclusion of the above evaluation is that if seawater RO systems can be designed to operate at a higher average permeate flux rate, then higher permeability membranes could be utilized and produce permeate at required salinity. This approach would result in smaller, less expensive, membrane unit but with a similar power usage as it is today.

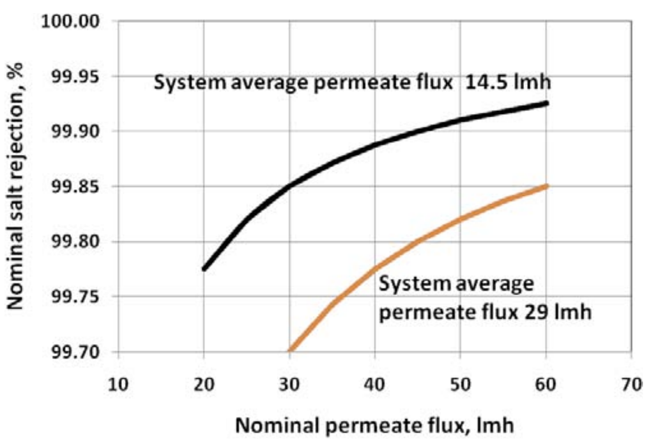


Fig. 10. Relation between nominal salt rejection and nominal permeate flux required for production of permeate of 300 ppm TDS salinity in a seawater RO system operating at recovery rate of 50% treating 40,000 ppm TDS seawater feed.

The above discussion was based on a single pass system configuration. In a two pass systems, utilization of higher permeability membranes in the first pass system can provide in some cases tangible economic benefits of lower total energy consumption.

Overall, the operational margins for additional reduction of energy requirement of seawater RO desalination process are quite limited. Additional decrease of feed pressure is limited by osmotic pressure of the concentrate. The high pressure pumps and energy recovery devices are close to the limits of possible efficiency. A new process approach is required.

Among new desalination processes, forward osmosis (FO) is the one with clear and understandable process concept [1]. It is a membrane process of desalination that utilizes difference of chemical potential at two sides of the membrane as a driving force for water transport. The FO process can be conducted at low seawater pressure. The energy requirement is limited to water recirculation and low temperature heat source for regeneration of draw solution. According to researchers developing this process and engineering estimation, the energy requirement of FO is less than half of energy requirement of seawater RO. Also, low pressure operation of all seawater loops in the FO process enables use of piping and hydraulic components made from polymeric materials that are less expensive then the high alloy steels utilized in seawater RO systems.

The FO process requires semipermeable membranes with transport and water–ion separation properties similar to the properties of the current commercial composite RO membranes.

Extensive research works conducted on the FO process indicate that major obstacle for commercialization of this process is phenomena of concentration polarization in membrane layers that support the salt rejection membrane barrier. There is a need for unsupported membrane. Unsupported commercial RO membranes exist today in a format of fine hollow fibers. However, their water permeability is quite low. Also the diameter of lumen of capillary RO fibers is very small, which would result in elevated energy requirement for recirculation. Apparently, currently efforts are being made by some membrane filtration manufacturers to develop large diameter capillary membranes of composite configuration with membrane barrier made of aromatic polyamide for NF applications. The FO process requires membranes with salt rejection similar to current seawater membranes. Therefore, significant improvement of salt rejection would have to be achieved to successfully manufacture large diameter capillary membranes suitable for the FO process.

The osmotic process of pressure retarded osmosis (PRO), which is projected to generate renewable energy, requires semipermeable membranes with transport properties and membrane module configuration very similar as required by the FO process. In the PRO process the flow of low salinity water through the membrane is in opposite direction then in the FO process, however, the adverse effect of concentration polarization is the same.

The situation that FO and PRO processes could utilize very similar membrane module configurations should increase probability of development and commercial implementation of suitable membrane devices for the above processes.

8. Summary

The most mature of the osmotic processes, the RO desalination technology evolved into very reliable and energy efficient salinity reduction process. Improvement of membrane transport properties is still possible. However, due to limitation of osmotic pressure and requirement of high salt rejection, the effect of membrane improvement on reduction of process energy will not be significant. The selective separation properties of the membrane could be improved. If such membranes will be developed it would open new areas of applications and in some cased could make the existing RO processes more efficient.

Commercial development of two new osmotic processes: forward osmosis and pressure retarded osmosis could result in significant reduction of energy requirement of seawater RO and possibly create a new source of renewable energy. Both processes require new special membrane and membrane module configuration. The task of development of such membranes will be difficult but seems possible.

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