HISTORY AND CURRENT STATUS OF MEMBRANE DESALINATION PROCESSES

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Contents

Summary

It is important to review the history of the past to provide a vision for the future. It is therefore the objective of this paper to review the history of the development of membrane processes for water desalination and its current status. Research and development efforts in RO desalination over the past four decades has resulted in a 44% share in world desalination production capacity, and an 80% share in the total number of desalination plants installed worldwide (Greenlee et al., 2009).

Today, RO membrane technology is the leading desalination technology. It is applied to a wide variety of salty water and wastewater. New developments in energy recovery and innovations in pretreatment technology have improved the reliability and energy consumption of the RO technology. This article reviews the history and current state of the RO technology.

1. Introduction

Desalination of seawater or brackish water can be achieved by a number of processes some of which are dependent mainly on thermal energy and some on mechanical/electrical energy. Table 1a shows a summary of the technical and cost parameters of the major commercial desalination processes. Among the thermal processes are the multistage flash (MSF), the multiple effect distillation (MED) and the thermal vapor compression (TVC) process. Theses processes have a history of high reliability but also high energy consumption. Those processes that depend on mechanical/electrical energy are the mechanical vapor compression (MVC) process and the reverse osmosis (RO) process. The RO process has the lowest energy consumption among all other processes but it suffers from relatively lower reliability than the other processes. For seawater desalination, it is necessary to reduce the total dissolved solids (TDS) content from 35,000 to 47,000 mg/L down to less than 500 mg/L.

Energy used	**Thermal**		**Mechanical**	
Process	MSF	MED/TVC	MVC	RO
State of the Art	Commercial	Commercial	Commercial	Commercial
World Wide Capacity 2004 (Mm^3/d)	13	2	0.6	6
Heat Consumption (kJ/kg)	250 – 330	145 - 390	--	--
Electricity Consumption (kWh/m^3)	3 – 5	1.5 – 2.5	8 - 15	2.5 - 7
Plant Cost ($\$/m^3/d$)	1500 - 2000	900 - 1700	1500 - 2000	900 -1500
Time of Commissioning (months)	24	18 - 24	12	18
Production Unit Capacity (m^3/d)	< 76000	< 36000	< 3000	< 20000
Conversion Freshwater/Seawater	10 – 25%	23 – 33%	23 – 41%	20 – 50%
Max. Top Brine Temperature (°C)	90 – 120	55 - 70	70	45 (max)
Reliability	Very high	Very high	high	Moderate (for seawater)
Maintenance (Cleaning per year)	0.5 - 1	1 - 2	1 - 2	Several times
Pre-treatment of water	simple	simple	very simple	demanding
Operation requirements	simple	simple	simple	demanding
Product water quality (ppm)	< 10	< 10	< 10	200 - 500

Source: AQUA-CSP, DLR 2007

Table 1a. Technical and economic information of major desalination processes

Membrane desalination processes rely on the ability of membranes to differentiate between and selectively separate water and salts. The most common application for membrane desalination used throughout the world is RO. Osmosis is a process which uses a semipermeable membrane to separate solutions of different concentration. The solvent flows at a faster rate than the dissolved solids from the side of low concentration to the side with higher concentration.

The history of desalination is centuries long and dates back more than two thousand years. The historical records show that some civilizations such as Egyptians, Persians, and Greeks studied obtaining fresh water from seawater. Hippocrates, a well-known philosopher, stated that "vapor produced from seawater when condensed is no longer salty" and taught his students the concept of desalting. The Arabs, on the other hand, developed a distiller called "alembic" which was very similar to a single-effect distillation process known today. The alembic was used to refine perfumes and other high value products. Japanese sailors used earthenware pots to boil seawater and bamboo tubes to collect the condensate. Following early research and development efforts, there has been an exponential increase in desalination capacity installed both globally and nationally since 1960. Desalination plants, for purposes ranging from municipal water supply to industrial applications, are now in place in many countries. Many of these plants primarily utilize membrane technology and treat brackish water and seawater.

The construction of a desalination plant will impact on the terrestrial, marine and atmospheric conditions of the local environment. Guidance documents developed by the California Coastal Commission (Seawater Desalination and the California Coastal Act, March 2004), the United Nations Environmental Program (UNEP/MAP/MEDPOL-2003) and the World Heath Organisation (WHO, 2008) describe how design and construction approaches can mitigate likely impacts. The impact of desalination plants on the marine environment can be mitigated with careful design and diligent operation. The efficient production of potable water by desalination of seawater is a global objective. Many countries world wide have active Research and Development (R&D) programs. The research is focused on mitigating fouling and reducing the energy requirements for seawater desalination plants. Various options for reducing the energy requirements and eliminating membrane fouling, the "perennial problem " include alternative desalination processes (such as forward osmosis) and the development of new generation membrane materials for reverse osmosis systems. Some promising technologies, such as the nanocomposite , carbon nano-tube and biomimetic membranes are still in the developmental stage. Membrane distillation is also being investigated. The aim of this article is to review the historical developments and brings to light the current status of RO technology.

2. RO Process Fundamentals

2.1 Osmosis and Reverse Osmosis

RO is a pressure-driven diffusion-controlled membrane process; on the same principle is based Nanofiltration (NF), a partial membrane softening process capable of removing bivalent ions (calcium, magnesium, etc.), dissolved organic matter as well as the compounds responsible for tastes and odours in water (see Figure 1). RO removes most ions regardless the valence (sodium, chlorides, etc.) mainly on the basis of a solubility-diffusivity mechanism. An RO membrane typically rejects all of the molecules over 150 molecular weight and a percentage of those between 25 and 150 MW. Other pressure-driven membrane processes, such as Microfiltration (MF) and Ultrafiltration (UF) are based on sieving mechanisms. Thus, whereas MF and UF are destined for raw water clarification/disinfection, RO and NF are used to remove environmental micro-pollutants, organic matter and dissolved salts.

Osmosis is a natural phenomenon in which a solvent (usually water) passes through a semipermeable barrier from the side with lower solute concentration to the higher solute concentration side. As shown in Figure 1, water flow continues until chemical potential equilibrium of the solvent is established. At equilibrium, the pressure difference between the two sides of the membrane is equal to the osmotic pressure of the solution. To reverse the flow of water (solvent), a pressure difference greater than the osmotic pressure difference is applied (see Figure 1); as a result, separation of water from the solution occurs as pure water flows from the high concentration side to the low concentration side. This phenomenon is termed reverse osmosis (it has also been referred to as hyperfiltration).

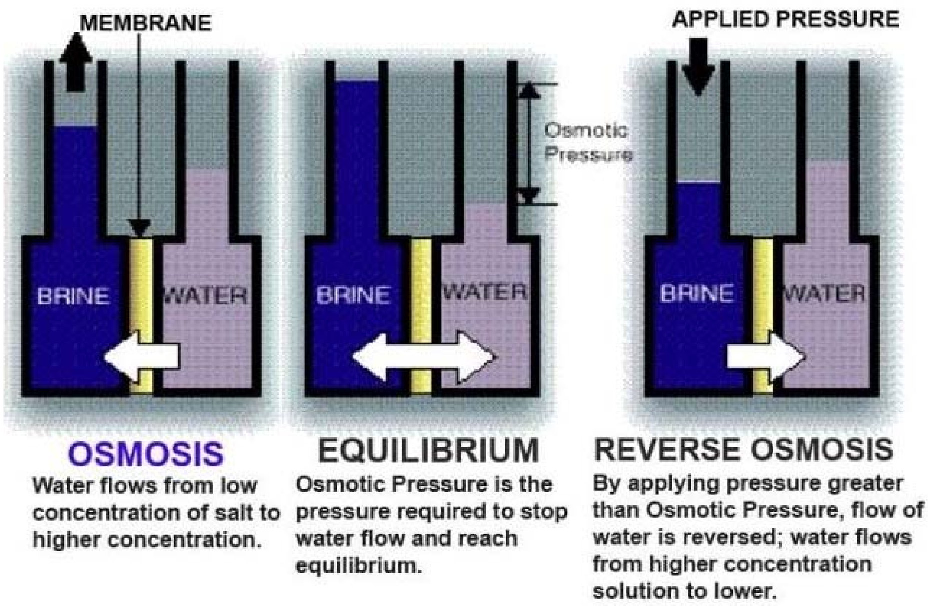

Figure 1 Osmosis ,equilibrium and reverse osmosis

A reverse osmosis membrane acts as the semipermeable barrier to flow in the RO process, allowing selective passage of a particular species (solvent, usually water) while partially or completely retaining other species (solutes). Desalination techniques are applied to raw water of various qualities in addition to seawater. Brackish water, river water, waste water and even treated drinking water from municipal supply are subject to desalination. The definitions of different categories are as follows:

a) Seawater: 15,000-50,000 mg/L TDS
b) Brackish water: 1,500-15,000 mg/L TDS
c) River water: 500-3,000 mg/L TDS
d) Pure water: less than 500 mg/L TDS
e) Waste water (untreated domestic): 250-1000mg/L TDS
f) Waste water (treated domestic): 500-700 mg/L TDS

2.2 Fundamentals of Pressure-Driven Membrane Processes

Reverse osmosis (RO) and nanofiltration (NF) technologies are pressure-driven membrane separation processes aimed to recover water from a saline solution pressurized to a point greater than the osmotic pressure of the solution. In essence, the membrane filters out the salt ions from the pressurized solution, allowing only the water to pass. The RO and NF processes use hydraulic pressure to force pure water from saline feed water through a semipermeable membrane. The membranes used in the RO process are generally either made from polyamides or from cellulose sources. Cellulose acetate membranes in both flat sheet and hollow fine-fiber configuration are still manufactured. The composite polyamide flat sheet product of several manufacturers dominates modern membrane technology. New chemical formulas are constantly being developed. Unfortunately, many fail to meet the basic criteria for commercial success: stable performance for a long period of time, inexpensive to make with high yields, and repeatable characteristics.

As shown in Figure 1, purification by RO consists of placing a semi-permeable membrane in contact with a saline solution under a pressure higher than the solution osmotic pressure, typically 50 to 80 bar for seawater. A typical RO system is shown in Figure 2. The feed is pressurized by a high pressure pump and is made to flow across the membrane surface. Part of this feed, the permeate, passes through the membrane which removes the majority of the dissolved solids. The remainder together with the rejected salt emerges from the membrane modules as a concentrated reject stream, still at high pressure. In large plants, the reject brine pressure energy is recovered in a turbine or pressure exchanger. The primary objective of RO feed water pretreatment is to ensure that the RO membrane is not adversely affected by fouling, scaling or chemically and physically degraded. Fouling refers to particulate matter such as silt, clay, suspended solids, biological slime, algae, silica, iron flocs and other suspended matter that adheres to and accumulates on the membrane surface or even within the membrane matrix .Scaling is referred to as the buildup of a mineral salt layer on the membrane surface due to both direct surface crystallization and deposition of precipitated salt crystals onto the membrane surface. Fouling typically occurs in the lead membrane elements (i.e., initial stages) and progresses gradually toward the tail elements

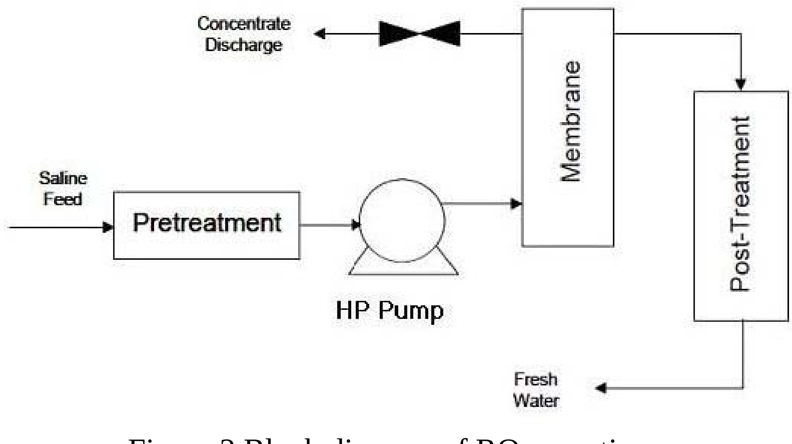

Figure 2 Block diagram of RO operations

Pressurizing the saline water accounts for most of the energy consumed by RO. Since the osmotic pressure, and hence the pressure required to perform the separation is directly related to the salt concentration, RO is often the method of choice for brackish water, where only low to intermediate pressures are required. The operating pressure for brackish water systems ranges from 15 – 25 bar and for seawater systems from 54 to 80 bar (the osmotic pressure of seawater is about 25 bar). A typical recovery value for a seawater RO system is only 40%.

Since most of the energy losses for RO result from releasing the pressure of the concentrated brine, large scale RO systems are now equipped with devices to recover the mechanical compression energy from the discharged concentrated brine stream with claimed efficiencies of up to 95% . In these plants, the energy required for seawater desalination has now been reported to be as low as 9 kJ/kg or 9 MJ/m^3 which is equivalent to 2.5 kWh/m^3 product.

Raw feed water, either from a seawater intake or a beach well, is filtered through a dual or multi-media filter to remove particulate matter. Acid for pH correction and/or anti-scalant are added as appropriate to prevent scale depositing on the membrane surface. A safety cartridge filter of 5-10 microns is used to further protect the membranes. The feed is then passed to the high-pressure pump, which increases the pressure to 50 – 80 bar depending on salinity and other factors. Many plants operate with 40 –45% of the feed water being recovered as potable water. The 55 –60% is rejected at very high pressure. In early designs this was discharged to atmosphere through a reducing valve. This wastes all the pressure energy, which is expensive. Later designs included various systems to recover this energy. These include, reverse running pumps, Pelton wheels and more recently pressure or work exchangers. Some of these have efficiencies of up to 96% and have resulted in plants where energy consumption has been reduced to 2.5 – 3 kWh/m^3 (see Figure 3).

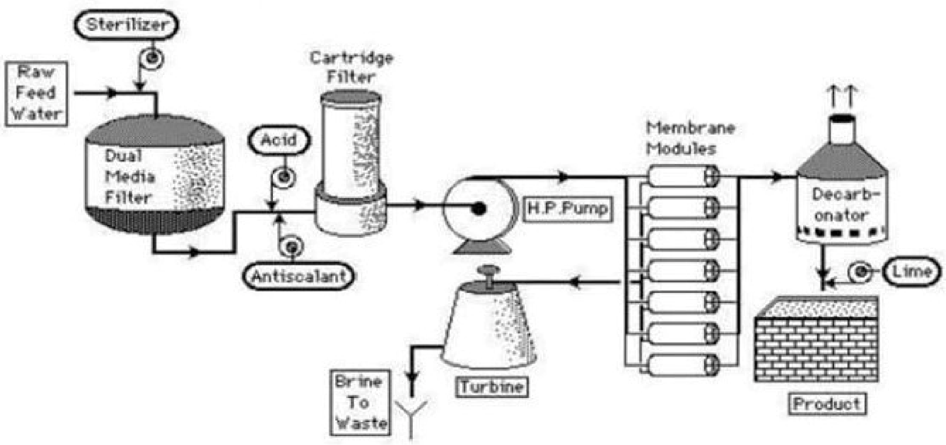

Figure 3 Seawater RO process with energy recovery

3. Feedwater Contaminants

The feed water salinity for desalination facilities ranges from approximately 1000 mg/L TDS to 60,000 mg/L TDS, although feed waters are typically labeled as one of two types: seawater or brackish water. Although most seawater sources contain 30,000–45,000 mg/L TDS, seawater reverse osmosis membranes are used to treat waters within the TDS range 10,000 – 60,000 mg/L. Brackish water reverse osmosis membranes are used to treat water sources (often groundwater sources) within a range of 1000–10,000 mg/L TDS. The feed water type can dictate several design choices for a treatment plant, including desalination method, pretreatment steps, waste disposal method, and product recovery (the fraction of influent water that becomes product)

Seawater and brackish waters contain substantial quantities of minerals, organic carbon and microbial contaminants, and they can also be impacted by waste discharges. Table 1b (Al-Mutaz, 2000) provides information on the typical mineral composition of seawaters. Brackish water contains lesser amounts of salts. Special technologies are required to convert these waters into drinking water that would be safe and desirable to consume.

	Normal	**Eastern**	**Arabian Gulf**	**Red Sea**
Constituent	**Seawater**	**Mediterranean**	**At Kuwait**	**At Jeddah**
Chloride ($C1^{-1}$)	18,980	21,200	23,000	22,219
Sodium (Na^{+1})	10,556	11,800	15,850	14,255
Sulfate (SO_4^{-2})	2,649	2,950	3,200	3,078
Magnesium (Mg^{+2})	1,262	1,403	1,765	742
Calcium (Ca^{+2})	400	423	500	225
Potassium (K^{+1})	380	463	460	210
Bicarbonate (HCO_3^{-1})	140	--	142	146
Strontium (Sr^{+2})	13	--	--	--
Bromide (Br^{-1})	65	155	80	72
Boric Acid (H_3BO_3)	26	72	--	--
Fluoride (F^{-1})	1	--	--	--
Silicate (SiO_3^{-2})	1	--	1.5	--
Iodide (I^{-1})	<1	2	--	--
Other		--	--	--
Total Dissolved Solids	34,483	38,600	45,000	41,000

Source: Al-Mutaz, 2000

Table 1b. Major Ion Composition of Seawater (mg/liter),

4. General Characteristics of Membranes

A *membrane* is a thin piece of material, often in the form of a sheet, but sometimes in other configurations, typically of the order of 0.1 mm in thickness, which forms a physical barrier between two fluids whilst maintaining a degree of communication between them [Hanbury and Hodgkiess 1995]. A crucial feature of membranes is the tendency for a particular membrane to be more permeable to some species than to others. This is the property which is utilized in desalination technology. Some types of membranes, called "*ion-exchange membranes*", are most permeable to ions- either negatively-charged 'anions' or positively-charged 'cations'. For other membranes, selective permeability is based mainly on species size rather than electric charge.

Some *"driving force"* is needed to cause species to move through a membrane in order to achieve the required separation. Important examples of such driving forces are: concentration difference, electrical potential difference, pressure difference or temperature difference. In fact, the flux (flow rate across a membrane per unit area) in a membrane is in direct proportion to the driving force. In reverse osmosis (RO) systems, water molecules are forced through a suitable membrane by application of pressure difference. The driving forces for different membrane processes are shown in Table 2 . The characteristics of the different pressure-driven membranes are listed in Table 3.

Membrane separation is governed by both the chemical nature of the membrane polymer and the physical structure of the membrane. The desired separation (rejection) attainable with a particular membrane depends on the relative permeability of the membrane for the solution components.

Driving Force	Separation Process
Potential difference (Voltage)	Electrodialysis, Electrosynthesis, Bipolar
Pressure difference	Reverse Osmosis, Nanofiltration, Ultrafiltration, Microfiltration, Gas Separation, Haemofiltration
Temperature difference	Membrane Distillation, Pervaporation,
Concentration difference	Dialysis, Haemodialysis, Gas Contacting

Source: M.E. Williams, 2003

Table 2 Driving forces for the different membrane processes

Separation Process	Pore Size	Operating Pressure (KPa)	Substances Removed	Comperitor Processes
Microfiltration	0.1 - 10 μm	140 – 5,000	Bacteria, viruses, larger colloidal particles, precipitates and coagulates	Ozonation, chlorination, sand-bed filtration, bioreactors, coagulation
Ultrafiltration	10 – 1,000Å 1,000 – 500,000 Da	200 – 1,000	High molecular weight proteins, large organic molecules and pyrogens	Sand-bed filtration, bioreactors and active carbon treatment
Nanofiltration	2 – 70 Å 180 – 10,000 Da	550 – 1,400	Large divalent and some monovalent ions, colourants and odorants	Lime/soda softening and io exchange
Reverse Osmosis	1 to 70 Å	1,400 – 7,000	All of the above in addition to monovalent ions	Evaporation, freezing and Electrodialysis

Source: Report of critical analysis on the desalination technologies, MEDINA Project no. 036997, May 2007

Table 3 Technical description of pressure-driven membrane operations

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Biographical Sketch

Ali M. El-Nashar received the B.Sc. (Mech. Eng.) from Alexandria University (Egypt) in 1961 and Ph.D. (Nuclear Engineering) from London University (UK) in 1968. He has been a faculty member at several universities in Egypt, UK and USA and was appointed professor of mechanical engineering at Florida Institute of Technology (USA) and Mansoura University (Egypt). He was a research fellow at Clemson University (USA) during the period 1971 to 1976. He has worked as consultant for different industrial and UN organizations among which Dow Chemical Co. (USA), Ch2M-Hill Co. (USA), Science Application Co. (USA), UNEP, Technology International Co. (USA). He is member of the ASME, ISES and IDA and editor of the International Desalination and Energy journals. He has worked at the Research Center of the Abu Dhabi Water and Electricity Authority (UAE) as manager of the desalination and cogeneration section which pioneered development work on solar desalination for ADWEA for 20 years. He has been associated with the International Centre for Water and Energy Systems, Abu Dhabi, UAE.