UNIVERSITIES COUNCIL ON WATER RESOURCES
JOURNAL OF CONTEMPORARY WATER RESEARCH & EDUCATION
ISSUE 132, PAGES 3-10, DECEMBER 2005

Overview of Desalination Techniques

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The objective of this chapter is to present an overview of current and future technologies applied to the desalination of brackish and seawater to produce freshwater for supplementing drinking water supplies. Discussion of detailed design concepts and processes of desalination and applications to other impure waters such as wastewater is beyond the scope of this chapter. Where appropriate, references for further reading are introduced.

There are three basic categories of water purification technologies that are used for desalination: membrane technologies, distillation processes (thermal technologies), and chemical approaches. Some water purification plants use a combination of these technologies. Membrane technologies are the most common technology of desalination in the United States, while thermal technologies are not widely used in the United States. A brief overview of thermal technologies is included in this chapter. Chemical approaches include processes such as ion exchange, which is considered impractical for treating waters with high levels of dissolved solids. The chapter also includes a summary of new technologies under research and development for possible applications to desalination.

Membrane Technologies

A membrane is a thin film of porous material that allows water molecules to pass through it, but simultaneously prevents the passage of larger and undesirable molecules such as viruses, bacteria, metals, and salts (American Water Works Association 1999). Membranes are made from a wide variety of materials such as polymeric materials that include cellulose, acetate, and nylon, and non-polymeric materials such as ceramics, metals and composites. Synthetic membranes are the most widely used membranes in the desalination process and their use is growing at a rate of 5-10% annually (Krukowski 2001).

In general, membrane treatment processes use either pressure-driven or electrical-driven technologies. Pressure-driven membrane technologies include reverse osmosis (RO), nanofiltration (NF), ultrafiltration, and microfiltration (Table 1) (Duranceau 2001). Reverse osmosis, and to some extent nanofiltration processes, are considered effective in salt removal. Electrical-driven membrane technologies that are effective with salt removal include electrodialysis (ED) and electrodialysis reversal (EDR). In 2003, the U.S. EPA issued the Membrane Filtration Guidance Manual (U.S. EPA 2003). Membrane configuration refers to the arrangement of individual elements (cartridges) in a membrane treatment process. Chapter 2 of the EPA report (U.S. EPA 2003) documents an extensive overview of membrane filtration design and configuration. The AWWA Manual M46 documents detailed information about applications of synthetic membranes to desalination (American Water Works Association 1999).

Membrane technologies applicable to desalination are briefly described below.

Table 1. Characteristics of Applications of Pressure-Driven Membrane Processes

Membrane Process	Applied Pressure psi (kPa)	Minimum Particle Size Removed	Application (type, average removal efficiency %)
Microfiltration	4-70 (30-500)	0.1-3 µm	- Particle/turbidity removal (>99%) - Bacteria/protozoa removal (>99.99 %)
Ultrafiltration	4-70 (30-500)	0.01-0.1 µm	- Particle/turbidity removal (>99 %) - Bacteria/protozoa removal (>99.999 %) - TOC removal (<20%) - Virus removal/(partial credit only)
Nanofiltration	70-140 (500-1000)	200-400 daltons	- Turbidity removal (>99%) - Color removal (>98%) - TOC removal (DBP control) (>95%) - Hardness removal (softening) (>90%) - Synthetic organic contaminant (SOC) removal (500 daltons and up) (0-100%) - Sulfate removal (>97%) - Virus removal (>95%)
Hyperfiltration (Reverse Osmosis)	140-700 (1000-5000)	50-200 daltons	- Salinity removal (desalination) (>99%) - Color and DOC removal (>97%) - Radionuclide removal (not including radon) (>97%) - Nitrate removal (85 to 95%) - Pesticide/SOC removal (0 to 100%) - Virus removal (>95%) - As, Cd, Cr, Pb, F removal (40 to >98%)

Source: Duranceau 2001

Reverse Osmosis

Reverse Osmosis (RO) is a physical process that uses the osmosis phenomenon, i.e., the osmotic pressure difference between the saltwater and the pure water to remove salts from water (Figure1). In this process, a pressure greater than the osmotic pressure is applied on saltwater (feedwater) to reverse the flow, which results in pure water (freshwater) passing through the synthetic membrane pores separated from the salt. A concentrated salt solution is retained for disposal. The RO process is effective for removing total dissolved solids (TDS) concentrations of up to 45,000 mg/L, which can be applied to desalinate both brackish water and seawater.

Reverse osmosis needs energy to operate the pumps that raise the pressure applied to feedwater. The amount of pressure required directly relates to the TDS concentration of the feedwater. For brackish water, the pump pressure requirement is between 140 and 400 psi. For seawater, pumps may need to generate up to 1200 psi. Therefore, the TDS concentration of the feedwater has a substantial effect on the energy use and the cost of the product water.

Two common types of membranes used in RO process for desalination include Cellulose Acetate (CA) membranes and Non-CA membranes. Cellulose Acetate membranes were developed in the 1960s and various modified and improved blends of CA membranes are currently used in the desalination process. The CA membrane has a relatively smooth surface that is resistant to fouling. It is theorized that if the membrane surface is rather smooth, the material that may cause fouling

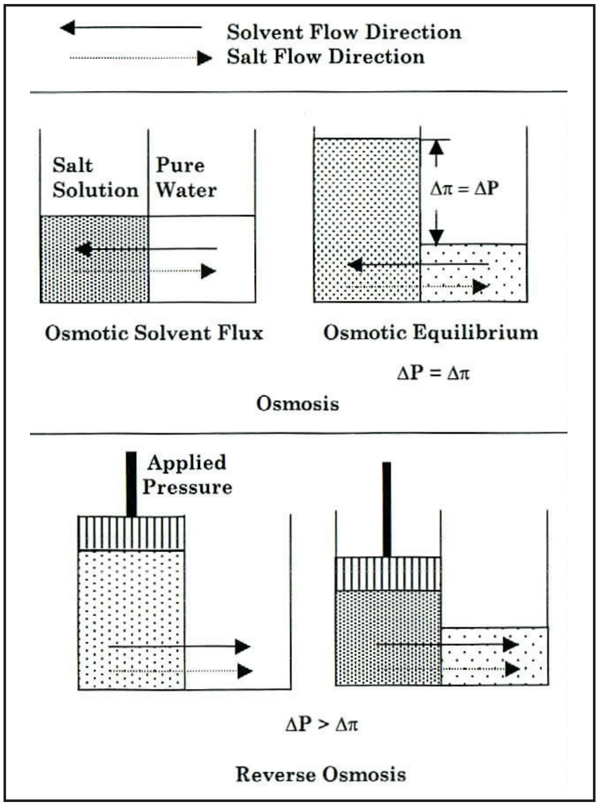

Figure 1. Reverse Osmosis vs. Osmosis
Source: Krukowski 2001

cannot deposit in the membrane crevices (Nicolaisen 2002).

Non-CA membranes, typically called "thin-film composite membranes" include aromatic polyamide (PA) membranes and composite membranes using common organic materials such as polysulfone. These membranes have a higher flux rate (volume of freshwater per membrane surface area) and, compared to CA membranes, allow passage of lower salt concentration. Non-CA membranes are more stable over a broader pH range than the CA membranes, but are susceptible to degradation by chlorine (El-Dessouky and Ettouney 2002).

Pre-treatment of feedwater is essential in order to protect the RO membrane, reduce energy costs, and increase salt retention. It should be free of large particles, organic matter, bacteria, oil and grease. Typical pre-treatment involves multimedia, cartridge, and sand filtration to remove larger particles, organic matter and other materials; and adding chemicals to prevent the formation of precipitates and scaling of the membrane. Often, pH adjustment is also needed. Certain membrane materials are sensitive to oxidants such as chlorine; therefore, additional chemicals may be needed in order to remove the oxidants from the feedwater prior to membrane treatment. Post-treatment of RO permeate may also be needed depending on the intended use of the product water. For example, carbon dioxide and soda ash may be added to increase alkalinity of the treated water and to reduce corrosiveness of the product water.

Recovery rate is a major parameter for evaluating membrane effectiveness. Recovery is defined as the volume of freshwater produced as a percentage of the volume of feedwater processed. Typical recovery rates for RO systems can be 30 percent to 80 percent depending on the quality of feedwater, pressure applied, and other factors. Reverse osmosis membranes that operate at low pressures but maintain high recovery rates have been developed. Typically, these ultra low-pressure reverse osmosis membranes (ULPRO) are made of thin film composites of polymers, with an active surface layer that is negatively charged with improved fouling resistance properties (Ozaki et al. 2002, El-Dessouky 1989, Bertelsen 2005, Paulson 2004, Nicolaisen 2002).

Nanofiltration

A nanofiltration (NF) membrane works similar to reverse osmosis except that with NF, less pressure is needed (70 and 140 psi) because of larger membrane pore size (0.05 μm to 0.005 μm). Nanofiltration can remove some total dissolved solids, but is often used to partially soften water and is successful at removing solids, as well as dissolved organic carbon. For low TDS brackish waters, NF may be used as a stand-alone treatment for removing salts.

Electrodialysis and Electrodialysis Reversal

Electrodialysis (ED) utilizes electromotive force applied to electrodes adjacent to both sides of a membrane to separate dissolved minerals in water. The separation of minerals occurs in individual membrane units called cell pairs. A cell pair consists of an anion transfer membrane, a cation transfer membrane, and two spacers. The complete assembly of cell pairs and electrodes is called the membrane stack (Figure 2). The number of cells within a stack varies depending on the system. The spacer material is important for distributing the water flow evenly across the membrane surface.

The ED process is effective with salt removal from feedwater because the cathode attracts the sodium ions and the anode attracts the chloride ions. The required pressure is between 70 and 90 psi (Brunner 1990). In general, ED has a high recovery rate and can remove 75% to 98% of total dissolved solids from feedwater.

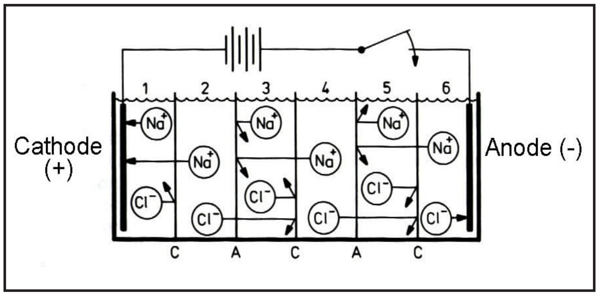

Figure 2. Electrodialysis Stack
Source: Brunner 1990

Electrodialysis reversal (EDR) is a similar process, except that the cation and anion reverse to routinely alternate current flow. In design applications, the polarity is reversed 4 times per hour, which creates a cleaning mechanism, and decreases the scaling and fouling potential of the membrane. EDR has a higher recovery rate (up to 94%) because of the feedwater circulation within the system and alternating polarity.

ED and EDR can remove or reduce a host of contaminants from feedwater and the process is not as sensitive to pH or hardness levels in feedwater. The EDR process is adaptable to various operation parameters, requires little labor, and the maintenance costs are generally low (American Water Works Assocation 1999). However, when using ED and EDR technologies for desalination, treatment cost is directly related to the TDS concentration in feedwater. These technologies are best used in treating brackish water with TDS up to 4000 mg/L and are not economical for higher TDS concentrations (Brunner 1990). The city of Washington, Iowa is currently operating a 1.1 MGD capacity ED plant that successfully removes 50% of the TDS in the water (Hays 2000), while the city of Suffolk, Virginia is operating a 3.75 MGD EDR plant which treats brackish water (TDS range 460-500 mg/l) (Younos 2004).

Discussion

The quality of feedwater is a determining factor for deciding which type of membrane process to use. Surface water (as compared to groundwater) represents the most variable water quality, particularly in terms of particle loadings and turbidity. Some problems associated with using membranes may include short design life; membrane cleaning (backwashing or chemical treatment); high membrane replacement costs; low resistance to chlorine, and lack of resistance to fouling.

Fouling is a primary factor affecting water productivity and occurs when the membrane pores are blocked due to residual buildup. The primary mechanisms of fouling are scaling, plugging, adsorption and bio-fouling caused by biological growth. Fouling control requirements and methods are briefly described below (Duranceau 2001):

- All RO/NF membrane systems require scaling control and it is achieved by addition of acid and/or antiscalent to feedwater.
- All RO/NF membrane systems require plugging control and it is achieved by maintaining feedwater turbidities below 0.2 NTU and silt density index (SDI) below 2.0.
- Bio-fouling can be controlled by adding free chlorine (either gas chlorine or hypochlorite solution) at the front of the plant, and may be followed by adding a de-chlorinating agent to protect against oxidation damage to the membrane; bio-fouling can also be controlled by adding monochloramine (NH_2Cl) or other bactericidal agents.

Water treatment processes in the future may readily employ integrated membrane processes that can effectively treat fresh, brackish, and saltwater. In addition, risk assessments relative to security and supply vulnerability may also influence the selection of membrane processes (Dykes and Conlon 1989). Current research focuses on developing high-pressure membranes with high recovery rates in order to improve energy consumption and cost performance (Magara et al. 2000). Other studies focus on developing fouling-resistant membranes, which will extend membrane life and reduce cleaning and energy costs (Van der Bruggen and Vandecasteele 2002).

Ion Exchange Technologies

The ion exchange technologies for water treatment are often used for water softening among other applications. The ion-exchange system can best be described as the interchange of ions between a solid phase and a liquid phase surrounding the solid. Chemical resins (solid phase) are designed to exchange their ions with liquid phase (feedwater) ions, which purify the water. Resins can be made using naturally-occurring inorganic materials (such as zeolites) or synthetic materials. Modern ion-exchange materials are prepared from synthetic polymers tailored for different applications. Ion-exchange technologies applied to desalination are rather complex. For details, readers can explore available publications (Arden 1997, Sengupta 1995). Briefly, saltwater (feedwater) is passed over resin beads where salt ions from the saltwater are replaced for other ions. The process removes Na^+ and Cl^- ions from feedwater, thus producing potable water. Ion exchange can be used in combination with reverse osmosis processes such as blending water

Table 2. Summary of processes of typical thermal technologies

Technology	Brief Description – Advantages and Disadvantages	Feedwater
Solar Distillation(SD)	A pond of saltwater with a clear lid takes advantage of solar heat. The saltwater evaporates and condenses on the lid. The brine stays in the pool and condensation forms potable water Low energy costs, low material and equipment costs / requires large amounts of land and direct sunlight, low productivities	SW/BW
Multistage-Flash	Combination of many flashing stages. One flashing stage: Saltwater traveling through tubes is cooler than the vapor surrounding the tubes. Heat exchange preheats the saltwater. The saltwater is emptied to the brine pool, where it evaporates and fills the vapor space that preheats the incoming saltwater. The vapor is condensed to form potable water, and the brine becomes the feed water for the next stage Proven reliable for years, can operate using waste thermal energy, can handle large capacities / requires highest amount of energy of all technologies	SW
Multiple Effect Evaporation(MEE)	Combination of many effects. One effect: Saltwater is sprayed overtop of hot tubes. It evaporates and the vapor is collected to run through the tubes in the next effect. As the cool saltwater is sprayed over the vapor filled tubes, the vapor condenses and is collected as potable water. The resulting brine collects in the bottom of each effect, and is either circulated to next effect or exited from system Requires less energy than MSF, can operate using waste thermal energy, can handle large capacities / high amounts of energy, scaling on tubing	SW
Thermal Vapor Compression(TVC)	Works as first effect of multiple effect evaporation. The steam jet ejector is used to compress the vapor for the tubes in the first effect. A condenser is responsible for condensing the vapor to the final productIncreases MEE performance ratio when combined with MEE.	SW
Mechanical Vapor Compression(MVC)	Works the same as thermal vapor compression except that mechanical compressors are used instead of steam jet ejectors Meet needs in remote areas, transportable.	SW/BW
Adsorption Vapor Compression	Pressure differences occur between two tanks as a fluid mixture is transferred between them. This drives the heat exchange for evaporation and condensation of saltwater to form potable water Heat is released from an exothermic reaction between blending of feed water with a solution such as LiBr, which preheats the feed water that is sent to the evaporator	SW/BW

Sources: El-Dessouky and Ettouney 2002, El-Dessouky et al. 2000 treated by ion exchange with RO product water to increase water production.

Thermal Technologies

Thermal technologies are based on the concept of using evaporation and distillation processes. Modern thermal-based technologies are mostly developed as dual-purpose power and water desalination systems. These technologies are applied to desalination of seawater. Some common processes include multi-stage flush (MSF), which is widely used in the Middle East, as well as vapor compression (VC) and some variation of those technologies. Table 2 provides a brief overview of types, advantages and disadvantages of various thermal technologies.

Desalination Technologies of Future

Several new technologies are being researched with potential for future applications to desalination. For example, electrodeionization (EDI) is a combination of ion exchange and electrodialysis. Other new technologies include combinations of membrane/ distillation technologies, and freezing. Table 3 shows a brief summary of developing technologies.

Table 3. Summary of processes of desalination technologies under research and development

Technology	Brief Description – Advantages and Disadvantages	Feedsource
Electrodeionization(EDI)	EDI is a combination of ion exchange and electrodialysis. Electric charge is applied to plates outside of membranes with resin beads between them. Saltwater passes between membranes. Saltwater ions take place of ions on resin then are pulled out through membranes in front of electrically charged plates. Water passes through resin and is free from ions, thus producing purified water Can produce ultra-pure water	BW
Membrane Distillation(MD)	A temperature difference occurs on opposing sides of the membrane. Differences in vapor pressure drive the system and only vapor passes through the membrane. Salt is not vaporized so it cannot pass through pores Requires high amounts of energy / not fully developed	Researched using 15,000-300,000 mg/L TDS
Freeze Separation(FS)	Freezing of saltwater forms pure water ice crystals, which have to be separated from brine and then melted to get potable water Less energy required than evaporation techniques / not fully developed	SW
Capacitive Deionization(CDI)	Salt water passes through plates coated with carbon aerogel material. Carbon aerogel absorbs ions, thus producing potable water Applicable to special needs / not fully developed.	BW
Rapid Spray Evaporation(RSE)	Saltwater is sprayed through nozzles at high velocity. As it exits, it is vaporized and salt is not, thus producing potable waterPotential to process brine and high salinities, can use waste energy, high recovery / not used for large applications	Brine/SW/BW
Freezing With Hydrates(FH)	A saltwater vapor/gas mixture is cooled. Hydrates are formed and separated from the brine. Hydrates are decomposed to form potable water and the hydrate former gasPotential for future use because of research of hydrates developing / still being researched and not developed	SW
Vacuum Distillation(VD)	By subjecting saltwater to vacuum, the boiling temperature is reduced. Saltwater is vaporized at lower temperatures and is condensed to form potable waterLow amounts of energy, ability to run off of waste energy, no scaling because of low temperatures / being researched and not developed	Researched using 32,100 mg/L TDS

Sources: El-Dessouky and Ettouney 2002, El-Dessouky et al. 2000

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