

Desalination of Seawater

AWWA MANUAL M61

First Edition

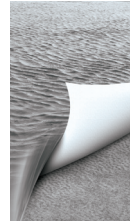


**American Water Works
Association**

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Chapter 1

Seawater Desalination Overview

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INTRODUCTION

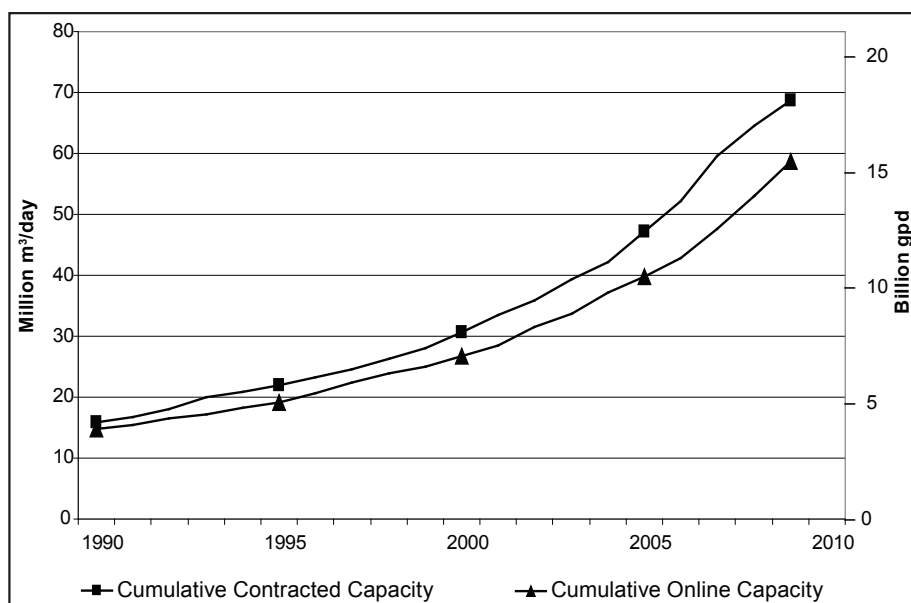
As worldwide fresh water supplies become increasingly stressed and world populations continue to grow, seawater desalination has become an increasingly sought-after alternative for new water supply in coastal areas. While three-quarters of the globe is covered with water, less than 0.3 percent is considered a renewable freshwater supply. More than half of the population in the United States lives within 50 miles (80 kilometers) of a coast, so the use of seawater as a source for potable water production is of great interest, especially in areas with stressed and overdrawn freshwater resources. Historically, the high cost of desalination has made it less attractive than freshwater supplies, even where those freshwater supplies were hundreds of miles away (i.e., Southern California).

As desalination becomes more economical, its use for municipal water supply has increased dramatically. Figure 1-1 shows that the worldwide desalination capacity more than doubled between 2002 and 2010. In the United States, most desalination facilities treat brackish water or are membrane softening plants; however, seawater desalination plants currently outnumber brackish water plants by 60 percent worldwide (GWI 2009).

Table 1 lists some of the more than two dozen seawater desalination plants built and operated in the United States. The majority of these facilities are industrial with a capacity of less than 1 million gallons per day (mgd) or 3.8 megaliters per day (MLD). In addition, a number of these plants are used intermittently because of the high cost of operation or problems experienced during operation. As coastal municipalities in the United States

begin to consider implementing larger seawater facilities, it is essential to ensure that these are constructed and operated in an efficient and reliable fashion without adversely impacting fragile coastal environments. Large capacity, highly efficient seawater desalination facilities have been successfully implemented within the last five years in Australia, Singapore, Spain, and several countries in the Middle East. In the United States, there are currently more than two dozen new seawater projects in various stages of development, primarily in California, Texas, and Florida.

The purpose of this manual of practice is to identify lessons learned from recent studies and seawater desalination projects around the world, and to use these to provide guidance for seawater desalination facilities that are reliable, economical, and environmentally sound.



Source: Global Water Intelligence 2010, data reproduced from DeSalData.com/Desalination Markets

Figure 1-1 Global growth of desalination facilities

Table 1-1 Operational seawater desalination facilities in the United States

Diablo Canyon, CA (0.6 mgd or 2.3 MLD)	Tampa, FL (25 mgd or 95 MLD)
Gaviota, CA (0.4 mgd or 1.5 MLD)	Stock Island, FL (2 mgd or 8 MLD)
Morro Bay, CA (0.6 mgd or 2.3 MLD)	Marathon, FL (1 mgd or 4 MLD)
Moss Landing, CA (0.5 mgd or 1.9 MLD)	Kauai, HI (0.2 mgd or 0.8 MLD)
Monterey Bay Aquarium, CA (0.04 mgd or 0.15 MLD)	Swansea, MA (2 mgd or 8 MLD)
Sand City, CA (0.3 mgd or 1 MLD)	Brockton, MA (5 mgd or 19 MLD)
Avalon, CA (0.1 mgd or 0.4 MLD)	

Courtesy of Greg Wetterau

DESALINATION TECHNOLOGIES OVERVIEW

Desalination processes can be divided into two broad categories: membrane separation and thermal evaporation. Membrane-based desalination processes typically employ mechanical pressure, electrical potential, or a concentration gradient as the driving force across a semi-permeable membrane barrier to achieve physical separation. Thermal desalination processes employ heat to evaporate the water from a salt solution, and the water vapor is then condensed and recovered.

Thermal technologies were the only options available for seawater desalination until reverse osmosis (RO) membranes were developed in the early 1960s. Since then, RO membrane processes have steadily been improved, and the efficiency has increased to the point that they are now the technology of choice for most seawater desalination applications. An exception to this is the Middle East, where low energy costs allow for thermal desalination to remain relatively competitive.

Besides the established desalination technologies, there are several newer technologies that are nearing commercialization or undergoing active research and development. A discussion of the established membrane and thermal technologies is presented first in this manual, followed by a brief discussion of developing technologies. The remaining chapters in this manual focus on pressure-driven membrane applications, as this presently has the most applicability to seawater desalination in the United States.

MEMBRANE SEPARATION

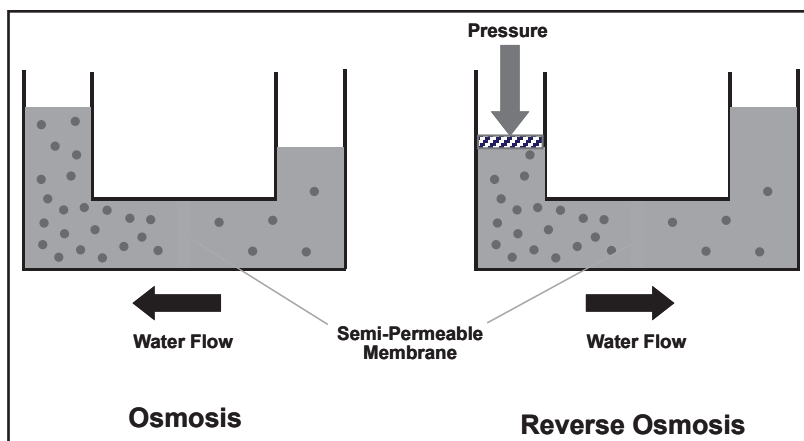
Membrane desalination technologies have been designed around the ability of semi-permeable membranes to selectively permit or minimize the passage of certain ions. Three fundamental driving forces can be used in membrane desalination systems including pressure, electric potential, and concentration gradient. RO and nanofiltration (NF) are pressure driven processes. Electrodialysis (ED) and electrodialysis reversal (EDR) are electric potential driven processes. Forward osmosis (FO) is a concentration-driven process.

Membrane-based seawater desalination processes have typically applied only RO. Although NF and ED/EDR are also mature technologies and can be used for desalination, ED/EDR are typically not cost competitive for desalination of seawater (Amjad 1993), and NF is not ordinarily considered for seawater desalination for potable water production. However, a novel approach employing two-pass (NF) configuration has been developed and tested for seawater desalination by the Long Beach Water Department in California. Similarly, FO is a developing technology and has not yet been commercialized for large-scale applications.

Reverse Osmosis (RO)

Desalination through RO is a well-established and nonproprietary unit process that currently represents the state-of-the-art of desalination technology for a number of reasons. In addition to the ability to reject a variety of contaminants, RO treatment generally has lower energy consumption, lower feed water flows, and no thermal impacts in the concentrate discharge in comparison to thermal desalination processes. Improvements in membranes and energy recovery devices used for seawater RO (SWRO) have improved the overall process efficiency thereby lowering the costs associated with treatment.

Reverse osmosis is based on overcoming the natural phenomenon of osmotic pressure, which occurs when a semi-permeable membrane separates two solutions with different concentrations of ions. The osmotic pressure created by the concentration gradient drives the flow of water from the dilute solution to the concentrated solution, until chemical equilibrium is established. The flow of water can be reversed with the application of an external hydraulic force (pressure) if this force is greater than the osmotic pressure. Figure 1-2 illustrates the basic concepts of osmosis and reverse osmosis.



Courtesy of Sandeep Sethi

Figure 1-2 Basic concept of osmosis and reverse osmosis

RO membranes are designed to retain salts and low-molecular weight solutes while allowing water to pass through. The original asymmetric cellulose acetate (CA) membranes, developed in the 1960s, were less permeable than modern thin-film composite (TFC) membranes and required a higher driving pressure, in excess of 1200 pounds per square inch (psi) or 8.3 megapascals (MPa) for seawater at typical operating fluxes. Additionally, the ability of CA membranes to reject salts was originally less than current materials.

Cellulose acetate membranes utilized an asymmetric structure while the TFC contained multiple layers made from different materials. In the asymmetric configuration, the membrane consists of the same material throughout with a dense layer at the top and porous layer beneath. In contrast, the TFC membrane consists of a thin but dense layer of one material over a porous support consisting of a different material.

Currently, there are a variety of modified and improved blends of CA membranes available to the desalination industry, but these membranes are rarely used in large-scale desalination applications. CA membranes can tolerate continuous exposure to low concentrations of chlorine (0.1 to 0.5 mg/L at 25°C), which is an advantage for biofouling control in seawater applications. They are, however, susceptible to hydrolysis, which compromises the membrane's salt rejection performance. Hydrolysis of CA membranes is accelerated if the operating pH is less than approximately 4 or greater than approximately 7 and temperatures are greater than 30°C (Mallevalle et al. 1996). Therefore, pH depression into this range is needed for seawater desalination with CA membranes.

The development of TFC membranes provided greater salt rejection and higher water production per unit membrane area. TFC membranes are made by combining a thin, dense membrane film with a porous underlying material that provides structural support. The thin film typically consists of aromatic polyamide (PA) and the bottom support layer is typically polysulfone. Most of the solute rejection occurs at the thin nonporous film, and its small thickness can significantly reduce the pressure required to drive water through it in comparison to CA membranes. TFC membranes are stable over a broad pH range (2-11) and can withstand temperatures as high as 45°C. However, unlike the CA membranes, they are susceptible to degradation by strong oxidants such as free chlorine. Although the degradation rate caused by free chlorine is a function of pH, membrane materials generally deteriorate upon exposure to chlorine (sometimes catastrophically).

High pressures are required to overcome the osmotic pressure of the salts and minerals, and the resistance from the membrane material, and other associated system losses.

SWRO membranes are typically operated at feed pressures of approximately 800 to 1,000 psi (5.5 to 6.9 MPa). RO membranes are capable of rejecting contaminants as small as 0.1 nm; however, the process of water transfer is mostly diffusion controlled rather than convection controlled as with microfiltration and ultrafiltration. In addition to the effects of the major ion matrices, mass transfer of ions through RO membranes is also impacted by broader water quality characteristics, such as temperature and pH.

The amount of water recovered using SWRO membranes ranges from 35 to 60 percent, and commercially available SWRO membranes typically reject 99.5 to 99.8 percent of the total dissolved solids (TDS) in the feed water. However, removal of a few constituents, such as boron, is sometimes not as great as might be required (see Chapter 2). If product water goals are not met, additional treatment may consist of two-pass RO, in which a portion or all of the permeate produced in the first pass is treated again in a second pass. New membranes with improved boron rejection are currently being developed by SWRO manufacturers to avoid the need for two-pass treatment; however, other water quality goals besides boron may also impact the need for a two-pass system. An optimized SWRO design will therefore depend on the feed water quality, system operating conditions, and specific finished water quality requirements.

Because membrane processes are based on physical separation, they do not require thermal energy to vaporize the water (with the exception being membrane distillation, discussed later in this chapter). As a result, the energy consumption for treatment components of an SWRO plant typically falls in a range of 10 to 20 kilowatt-hours (kWh)/1,000 gallons (2.6 to 5.3 kWh/m³). In comparison, total energy used for thermal desalination treatment processes can range from 10 to 40 kWh/1,000 gallons (2.6 to 10.6 kWh/m³), depending on the unit processes.

Energy recovery devices are increasingly used in SWRO applications. These devices can recover from 25 to over 45 percent of input energy for SWRO. Examples of such devices as presented in Chapter 3, include Pelton wheels, work exchangers, pressure exchangers, and hydraulic turbo-exchangers.

One of the greatest challenges for membrane desalination processes is fouling and scaling of the membranes. Fouling can occur as a result of inadequate pretreatment or measures for reduction of particulate, colloidal, or organic matter to tolerable levels, or biological growth in the membrane pressure vessels. Scaling results from precipitation of sparingly soluble salts in the system and tends to be less of a concern in seawater desalination than in brackish water systems, which run at higher recoveries. Compounds such as calcium carbonate, calcium sulfate, silicate, barium sulfate, and strontium sulfate in the feed water may, however, contribute to limiting the recovery of the RO process. Acid or scale inhibitors (also known as *antiscaleants*) may be added to reduce alkalinity and prevent formation of scale, allowing for higher recovery than otherwise possible. As a result of high levels of particulates and the generally aerobic state of seawater, SWRO plants require comprehensive pretreatment and chemical conditioning of the feedwater for successful operation.

Nanofiltration (NF)

Nanofiltration is typically used to soften water and remove disinfection by-products (DBP) precursors such as dissolved organic matter. NF is typically not used for seawater desalination, although unique configurations of two-pass NF have been successfully used to desalinate seawater.

Nanofiltration uses semi-permeable membranes and a driving force of hydraulic pressure; however, in comparisons to RO, NF membranes typically have a higher molecular weight cut-off (MWCO). NF membranes remove a high percentage (90 to 98 percent) of divalent ions (i.e., those associated with hardness) but removal of monovalent ions is somewhat limited (typically 60 to 85 percent).

Because a higher concentration of monovalent ions can pass through the NF membrane, the osmotic pressure is lower compared to RO. This, combined with a more permeable membrane skin layer, reduces the hydraulic pressure requirements to 500 to 700 psi (3.4 to 4.8 MPa) for seawater applications. Recognizing these advantages, the Long Beach Water Department (California, United States) has developed and patented an innovative two-pass nanofiltration method for the desalination of seawater. This will be discussed further in Chapter 3.

Electrodialysis (ED) / Electrodialysis Reversal (EDR)

ED and EDR processes use ion-selective membranes and an electrical potential as a driving force to separate charged species from water. Pressure driven systems (RO and NF) selectively pass water through a membrane and retain dissolved salts in the concentrate. In contrast, ED and EDR use an electrical potential to draw dissolved ions through a set of membranes (cations to one side, anions to the other), while the deionized water passes between the membranes and is ultimately recovered.

An electrodialysis stack consisting of alternating layers of cationic and anionic ion-selective flat-sheet membranes creates channels of desalted product water and concentrated reject water. Cations migrate to the cathode and anions migrate to the anode while cation-selective membranes allow only cations to pass and anion-selective membranes allow only anions to pass. The net effect is to remove the salt from every other cell.

A modification of the ED process, EDR, periodically reverses the polarity of the applied electrical potential on the stack to minimize the effects of inorganic scaling and fouling by switching product channels into concentrate channels and vice versa. This allows the EDR system to operate at higher recoveries compared to ED.

ED/EDR processes are typically not used for seawater desalination because with higher salinities, the ED/EDR process generally becomes less efficient than other membrane-based desalination technologies. Additionally, bacteria, nonionic constituents, and residual turbidity are not affected by this process and therefore remain in the product water, requiring additional treatment before drinking water standards are met. Because ED/EDR are not typically used for seawater desalination, these processes will not be discussed further in this manual.

THERMAL EVAPORATION

Thermal desalination technologies work by evaporating water from a saline solution and then condensing the vapor (steam) to produce distilled water. All large-scale thermal processes involve heating water to its boiling temperature to produce the maximum amount of water vapor. The pressure of the system is typically decreased so that the temperature required for boiling is reduced. Commercially available distillation systems are designed to allow for “multiple boiling” in a series of vessels that operate at successively lower temperatures and pressures.

Thermal technologies that are used for desalination include multistage flash (MSF), multiple effect distillation (MED), and vapor compression (VC). MSF and MED systems typically use direct heat exchange from steam as the energy source for evaporation, while VC systems use the heat from the compression of the vapor as the energy source for evaporation. Thermal processes can produce water with very low salt concentrations (TDS levels of 10 mg/L or less) from TDS levels as high as 60,000-70,000 mg/L TDS; however, there are limitations associated with distillation processes for seawater desalination.

One of the most significant limitations of thermal technologies is the energy requirement of the vaporization step. High levels of salts result in boiling point elevation, and the energy required to vaporize seawater ranges from around 25 to 100 kWh/1000 gal of fresh water produced (Wade 2001). It should be noted that these thermal energy requirements are

in addition to the electrical energy required for the other aspects of the process. Often, large distillation plants are coupled with steam or gas turbine power plants, making use of low grade heat to reduce power input requirements. Thermal technologies are more commonly used in the Middle East, where energy costs are relatively low, the large land requirements are not cost prohibitive, and ecological permitting requirements are less stringent. There has long been interest in using solar energy as a source of heat for accomplishing the evaporation in distillation, but suitable technologies for a large-scale project are not yet available.

Operational issues for thermal desalination include corrosion and scaling. Because seawater is highly corrosive in nature, special alloys, such as cupronickel alloys, aluminum, and titanium, are used most commonly in desalination with distillation processes. These special alloys contribute significantly to the capital cost of a distillation plant, particularly with the large surface area required for efficient distillation. The scaling of sparingly soluble salts at elevated temperatures on the inner walls of pipes and equipment is another operational issue that reduces the heat transfer efficiency of the heat exchangers, increasing the overall energy required for distillation. Also, additional permitting concerns may arise because concentrate discharged from a thermal distillation process has a higher temperature than the ambient water in the discharge location. While the cost of thermal desalination is often considerably higher than RO, very little pretreatment is required ahead of thermal processes, and the product water quality is extremely high (less than 10 mg/L TDS), avoiding the need for additional treatment to address boron, chloride, or bromide concerns.

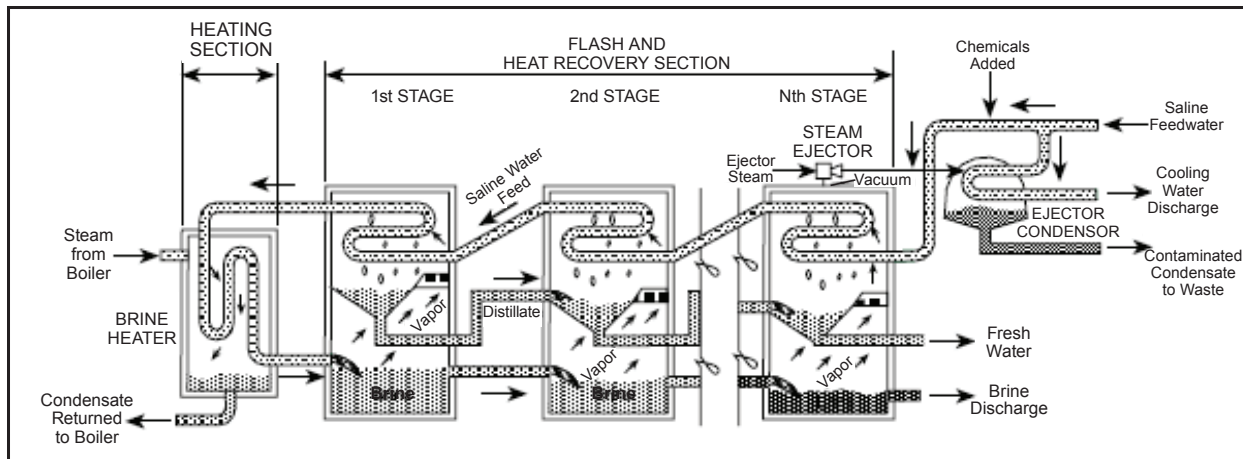
Multistage Flash Distillation (MSF)

MSF accounts for the greatest installed thermal distillation capacity worldwide. In the MSF process, water is heated in a series of stages, each with successively lower pressures and temperatures. Typically, MSF plants can contain from 15 to 25 stages. Vapor generation or boiling caused by reduction in pressure is known as *flashing* (illustrated in Figure 1-3). As the water enters each stage through a pressure-reducing nozzle, a portion of the water is flashed to form vapor. In turn, the flashed water condenses on the outside of the condenser tubes and is collected in trays. As the vapor condenses, the latent heat is used to preheat the seawater that is being returned to the main heater, where it will receive additional heat before being introduced to the first flashing stage. The condensate collected in each stage forms the product, and the whole process is driven by a subatmospheric pressure gradient through the stages.

Evaporation or flashing of a small portion of the feed continues in each successive stage at a lower pressure. The MSF process generates and condenses vapor in the same stage or effect. The range of recoveries for conventional MSF desalination processes is limited to about 10 to 30 percent for seawater desalination.

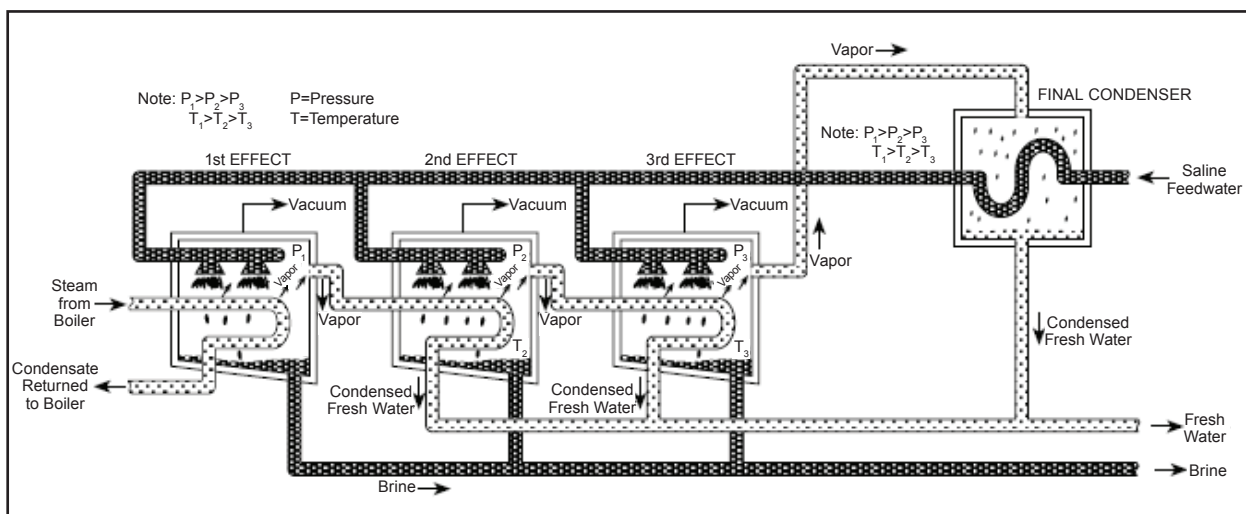
Multiple Effect Distillation (MED)

The MED process, like the MSF process, uses multiple vessels (or effects) arranged in series with reduced ambient pressure in each subsequent effect. Typically, 8 to 16 effects are used in MED to minimize the energy consumption. The feed water is distributed on the outside of the evaporator tubes in a thin film (see illustration in Figure 1-4) to promote rapid boiling and evaporation. Steam is condensed on the colder inside surface. Vapor produced by evaporation is condensed in a way that uses the heat of vaporization to heat the remaining saline solution at a lower temperature and pressure in each succeeding effect, allowing water to undergo multiple boiling without supplying any additional heat after the first effect. Thus, the vapor produced in each effect is used to heat the feed water in the next effect. This not only reduces the energy required for distillation but also the overall electrical power consumption. As a result, energy costs for operating an MED plant are lower than that of an MSF plant.



Source: Buros 2000 Water Desalting Planning Guide. Reprinted with permission of John Wiley & Sons, Inc.

Figure 1-3 Multistage flash distillation



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Figure 1-4 Multiple effect distillation

The steam generated in the final effect is typically at a pressure and temperature too low to be of further use. MED systems normally condense this steam using an external cooling source to remove the heat of condensation.

Energy is required in an MED system as follows: (1) to create steam of sufficient pressure to drive evaporation in the first stage; (2) to power vacuum systems to reduce the boiling pressure in the downstream effects (if operated at low temperatures); (3) to pump influent water through the heat exchangers to the evaporator(s), to recirculate the concentrate within each evaporator stage, and to pump the condensate and concentrate through the heat recovery prior to exiting the system; (4) cooling water to condense the steam from the final stage. Energy efficiencies may be gained via the combination of the evaporator systems with available low-pressure or waste steam/heat sources or by the

addition of efficiency enhancement devices to the conventional MED system. The range of recoveries for conventional MED is limited to approximately 20 to 35 percent for seawater desalination.

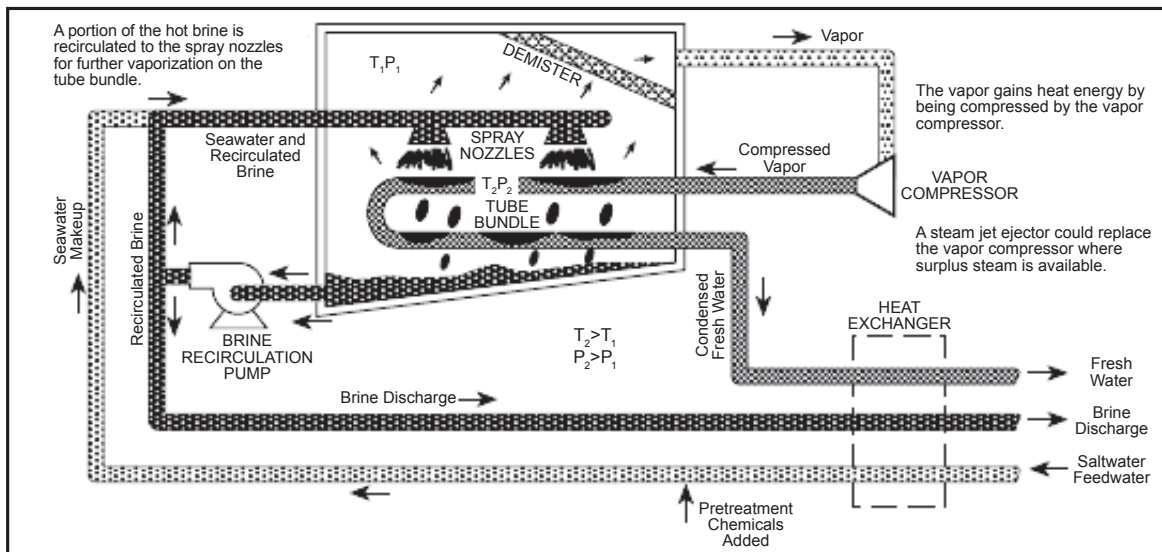
Vapor Compression (VC)

Heat for evaporation in VC systems is provided by one of two approaches: mechanical vapor compression (MVC) or thermo vapor compression (TVC); an illustration of the former is provided in Figure 1-5. MVC systems use electricity while TVC systems use high-pressure steam to compress the water vapor created from distillation to higher pressure and temperature, so that it can be returned to the evaporator and used as a heat source. The vapor compression process is well established and is used for seawater desalination as well as treating RO concentrate for residuals management. Vapor compression systems typically have recoveries in the range of 40 to 50 percent for seawater desalination.

NOVEL DESALINATION PROCESSES IN DEVELOPMENT

Forward Osmosis

As in the case of RO and NF, FO employs a semi-permeable membrane to separate water from a saline solution; however, instead of using external hydraulic pressure to create the driving force for water transport through the membrane, the FO process employs a natural pressure gradient provided by a higher salinity “draw” solution (such as ammonium carbonate or specially prepared magnetic nanoparticles). The higher osmotic pressure of the draw solution causes water to move toward it through a membrane. Freshwater is then separated from the draw solution using an additional separation process, which can vary depending on the nature of the draw solute. The separated draw solutes are either recovered and reused in the FO process or discharged.



Source: Buross 2000 Water Desalting Planning Guide. Reprinted with permission of John Wiley & Sons, Inc.

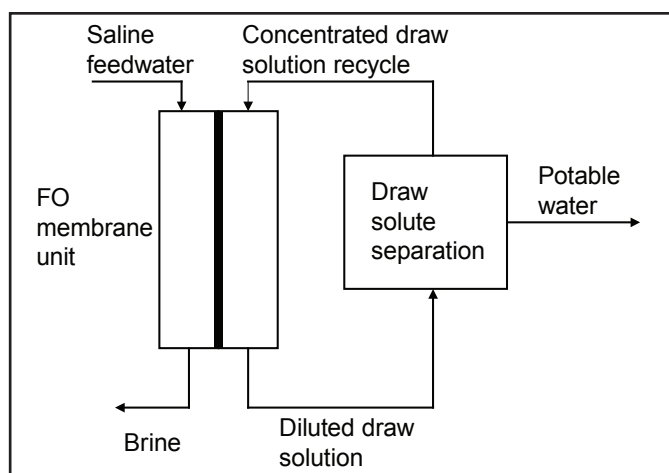
Figure 1-5 Vapor compression

Osmotic driving forces in FO can be significantly greater than hydraulic driving forces used in RO. The use of a suitable draw solution with very high osmotic pressure driving forces can be used in principle to generate high water fluxes and recoveries. The FO process, once fully developed and commercialized, is expected to have potential advantages in terms of relatively low fouling potential, low energy consumption, and simplicity. Identification of appropriate draw solutions and development of efficient membranes are two of the most pressing challenges for FO. An effective draw solute should have the following characteristics:

- High osmotic efficiency, meaning that it has to be highly soluble in water and have a low molecular weight in order to generate a high osmotic pressure.
- Nontoxic as trace amounts may be present in the product water.
- Chemical compatibility of the membrane.
- Easy and economical separation from recovered water.

Commercial RO membranes are not suited for the FO process because of relatively low product water fluxes. This low water flux is due mainly to internal concentration polarization within the porous support layer of the membrane, which alters the effective driving force across the active layer of the membrane, thereby limiting water flux. One of the important tasks for future research is the development of a semi-permeable FO membrane having high salt rejection and minimal internal concentration polarization to realize higher product water fluxes. Figure 1-6 illustrates the general process used in forward osmosis.

FO technology is still in development. Bench-scale FO units have been built and operated at Yale University laboratory (McCutcheon and Elimelech 2006) supported by Office of Naval Research (Award No. N000140311004). The draw solution employed in this study consists of highly concentrated ammonium carbonate, prepared by mixing ammonia and carbon dioxide gases. Upon heating (to approximately 60°C), ammonium carbonate decomposes back into ammonia and carbon dioxide gases, leaving behind the desalinated water. This separation needs to be essentially complete because of limits on ammonia in drinking water. Thermal recovery of ammonia and carbon dioxide from the draw solution requires energy, so the process may be suited for applications where low-grade heat is available.



Source: Water Research Foundation 2009. Reprinted with permission.

Figure 1-6 Schematic of forward osmosis desalination process

FO has also been studied for use as pretreatment for RO in several novel applications including water reclamation and nutrient recovery (Cath et al. 2005, Holloway et al. 2007). Several hybrid processes have also been developed including osmotic dilution prior to desalination, which reportedly can significantly reduce the energy demand of desalination in some applications (Lundin 2009). Finally, FO has been proposed as a method of energy generation in blending highly concentrated desalination brine with fresh wastewater flows prior to discharging into the ocean. Such an approach would employ two waste products to produce electrical power and reduce the overall energy footprint of the desalination facility.

Membrane Distillation

Membrane distillation (MD) is a hybrid process using principles of both membrane separation and thermal distillation. MD involves evaporation of water from a saline solution and transport of the water vapor through the pores of a hydrophobic membrane. The membrane allows water vapor to pass through but prevents the solution from passing through. Water vapor is transported across the membrane in response to a change in partial pressure across the membrane because of a thermal gradient. The clean vapor is subsequently carried away from the membrane and condensed as pure water either within the membrane package or in a separate condenser system.

MD differs from pressure-driven membrane technologies in that, rather than applying pressure to force liquid through a membrane, the driving force for desalination is the difference in vapor pressure of the liquid across the membrane. Increasing the temperature of the liquid increases the vapor pressure and results in increased membrane penetration rate. The efficiency of an MD process largely depends on the feed water quality, system design, and heat recovery from the permeate stream. MD has been reported to run at relatively low temperature (approximately 70°C) and thus can utilize waste heat or low-grade heat sources. The energy source for feedwater heating and/or for a vacuum system to sweep away the vapor may be low-grade thermal energy such as supplied by low-pressure steam, waste heat, solar energy, or geothermal energy.

Potential advantages of MD are the ability to use low-grade heat, minimal pretreatment needs, and negligible scaling or precipitation concerns. Challenges include need of waste heat for economic feasibility, membrane fouling, and membrane degradation due to loss of hydrophobicity. MD technology is currently in the development and demonstration phase.

A variety of arrangements and configurations can be used to induce the vapor through the membrane, collecting and condensing it as product water. Common to all concepts is that the feedwater directly contacts the membrane. Condensation can be achieved using one of four process configurations:

1. **Air-Gap Membrane Distillation.** This configuration, which is the most common and most versatile arrangement, provides an air gap after the membrane, followed by a cool surface for condensation to occur.
2. **Direct-Contact Membrane Distillation.** The cool condensing solution (pure water) directly contacts the membrane and condenses the vapor as it passes through the membrane, where the coolant liquid typically flows countercurrent to the feed water.
3. **Sweep-Gas Membrane Distillation.** A sweep gas pulls the water vapor out of the membrane gap for subsequent condensation outside of the membrane package.
4. **Vacuum Membrane Distillation.** Vacuum is applied to the membrane space to pull the water vapor out of the system.

Freeze/Thaw

The freeze/thaw approach to desalination is similar to thermal desalination in the fundamental concept of relying on a phase change to achieve separation. In the case of freeze/thaw, the phase change is from liquid to solid. Ice crystals exclude salt from their structure and the salt is then able to be separated as a brine from the ice. A key aspect of the process is that the energy required for the phase change from water to ice is less than one-seventh the energy that is required for the phase change from water to vapor (however, practical thermal desalination processes such as MSF and MED use much less energy than the heat of evaporation due to the use of multiple effects or stages as previously discussed). Challenges with freeze desalination include implementing the proper washing and separation of the crystals without premature melting and/or recontamination with the excluded salt. Different configurations of freeze/thaw desalination systems that have been developed include direct freezing, indirect freezing, and absorption (AWWA 2004).

Capacitive Deionization (CDI)

Carbon aerogel is an ideal electrode material because of its high electrical conductivity, high specific surface area, and controllable pore size distribution (Yang et al. 2001, Ying et al. 2002). The Lawrence Livermore National Laboratory (LLNL) began its research into carbon aerogels and capacitive deionization technology (CDI) in the late 1980s. LLNL developed and optimized carbon aerogel materials, which multiplied the effective surface area of the deionization electrodes by a factor of 60,000, dramatically improving their capacity to attract and hold charged water constituents.

In the process of capacitive deionization (CDI), the high salinity solution flows between the electrode pairs and ions are adsorbed onto the surface of the porous electrodes by applying a low voltage electric field thereby producing deionized water. The major mechanisms related to the removal of charged constituents during CDI are physisorption, chemisorption, electrodeposition, and/or electrophoresis. Unlike ion exchange, no additional chemicals are required for regeneration of the electrosorbent in this system. Adsorbed ions are desorbed from the surface of the electrodes by eliminating the electric field, resulting in the regeneration of the electrodes. The efficiency of CDI strongly depends on the surface property of electrodes, such as their surface area and adsorption properties.

CDI systems exhibit several advantages: a simple, modular, plate-and-frame construction, and low energy requirement. However, current challenges include the limited adsorption capacity of carbon aerogel electrodes, slow kinetics of transport of ions into and out of the highly porous electrodes, relatively high costs of the CDI modules, and the fouling potential of the aerogel surface caused by natural organic matter. CDI is still in the development stage with on-going bench and pilot tests.

Supercritical Desalination (SCD)

Recent research by the Wetsus, Centre of Excellence for Sustainable Water Technology in the Netherlands (Ingo et al. 2009) has looked at the use of supercritical conditions in water to promote desalination. Supercritical conditions are achieved at elevated temperatures and pressures, where the liquid and gas form of water both exist and are indistinguishable from each other. Supercritical water is an extremely poor solvent of inorganic salts, allowing dissolved salts to be removed through precipitation, producing a solid or near solid waste stream and a purified product. The purity of the product depends on the temperature and pressure of the supercritical fluid; however, SCD has been proposed as a pre-treatment step for RO in seawater desalination, where SCD is used to produce a water with TDS levels close to 3,500 mg/L using a pressure of 22 MPa (3,200 psi) and temperature of

approximately 350°C. Brackish water reverse osmosis (BWRO) membranes could then be used for further desalination, with the theoretical energy requirements being comparable with conventional SWRO, but with higher recoveries on the order of 70 to 80 percent. SCD technologies are still in development and have not been tested outside of the laboratory; however, these technologies may play a role in future desalination applications as they offer unique opportunities not currently available with either membrane- or evaporation-based technologies.

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