KEY POINT: In the US, Australia, Europe, and many other locations, almost all seawater desal applications utilize Reverse Osmosis (RO) or Nanofiltration (NF) membrane technology.

SUMMARY

- Desal membrane processes include:
  - Reverse Osmosis (RO)
  - Nanofiltration (NF)
  - Electrodialysis (ED)
  - Electrodialysis Reversal (EDR)

RO and NF are classified as pressure-driven membrane processes. ED and EDR are electrically driven.

- In the US, almost all desal applications utilize RO or NF (Mickley 2006).

- The use of ED or EDR is not as common for municipal drinking water treatment. These methods remove salts from the feedwater but do not remove many other particles and are therefore not considered filters (USEPA 2005). Further, ED and EDR are not economically viable to seawater desal due to its high salinity. We therefore focus on RO/NF technology in this document and throughout the PIM.

- Both RO and NF utilize the principle of reverse osmosis to accomplish desal. They are essentially the same process with different degrees of salt rejection. In RO and NF, water passes through the membrane while its constituents are rejected. Thus, they are both considered “barrier technologies” for the purpose of removing pathogenic microorganisms

- RO is very efficient for rejecting a wide variety of contaminants. The salt rejection properties of NF are more modest. NF can be used as softening process and pretreatment to RO.

- RO is the most versatile technology, and has been demonstrated as the most economically viable option for a wide range of applications and feed water quality. NF is commonly used for specialty applications in which the more robust salt rejection properties of RO are unnecessary.
STRATEGIES

The following sections briefly describe the principle of RO, and the state of current RO and NF membrane technology.

Principle of RO

As the name suggests, the principle of RO is predicated on the reversing the osmotic flow of a system via applied pressure (USBR 1998, USEPA 2005). The process is illustrated in a series of diagrams in Figure 1 below.

The diagram on the left shows the natural phenomenon of osmosis, in which water flows from a dilute to a more concentrated solution across a semi-permeable membrane, which allows the passage of water but rejects dissolved solids. The driving force for osmosis is proportional to the difference in concentration of dissolved solids between the two solutions separated by the semi-permeable barrier.

In the middle diagram, osmotic equilibrium is achieved when the concentrations of the two solutions are equal. The difference in height of the two water columns is the osmotic pressure of the system. It is this pressure that must be overcome to force the migration of water against the osmotic gradient, as shown in the diagram on the right. When a pressure in excess of the osmotic pressure is applied to the more concentrated solution, water flows backwards across the membrane, creating a dilute solution that is very low in total dissolved solids (TDS) and leaving behind a concentrated solution that is high in TDS.
Figure 1. Illustration of osmosis and reverse osmosis

RO membrane systems

RO membrane systems used for desal include the following components:

- High-pressure feed pumps
- RO membrane trains
- Energy recovery devices
- Desalinated water conditioning systems

Following pretreatment (e.g., coagulation and filtration), the filtered water is conveyed by transfer pumps from a filtrate water storage tank, through cartridge filters, and into the suction pipe of high pressure RO feed pumps. The cartridge filters are designed to retain particles of 1 to 20 microns that have remained in the source water after pretreatment. The main purpose of the cartridge filters is to protect the RO membranes from damage.
In addition, in lieu of conventional pretreatment and cartridge filters, microfiltration (MF) and ultrafiltration (UF) pretreatment systems for RO are beginning to gain more popularity (Xu et al. 2009, MMWD 2007, Pankratz year unknown, Stedman 2009).

The high-pressure feed pumps are designed to deliver feed water to the RO membranes at the pressure required for membrane separation of fresh water from salts (typically 55 to 80 bars, or 800 to 1200 psi, for seawater). Required feed pressure is site-specific and is mainly determined by the source water salinity and the configuration of the RO system.

The semi-permeable membranes used in RO systems reject dissolved solids primarily on the basis of charge, size, and shape of the contaminants. Larger, more highly charged constituents are more efficiently removed than smaller species that carry fewer charges. Because size and shape are difficult to quantify at the molecular level, the concept of molecular weight cut-off (MWCO) is often used as criteria for the removal abilities of RO membranes, with the underlying assumption that molecular weight is a rough estimate for size.

Typically, an RO membrane is expected to remove 90 percent of a constituent that is highly charged or larger than the MWCO. Manufacturers may make proprietary modifications to the membrane chemistry to generate products that are either more or less efficient for removal of certain contaminants. Although the precise rejection for each constituent in the feed water varies with each specific product, as a general rule most RO membranes remove in excess of over 98-99 percent of all ionic species.

Energy recovery is now a key component of membrane desal processes. The pressurized concentrate stream has inherent energy that is “lost” if the concentrate is simply treated or disposed of without any attempt to recover that energy. Due to the high-pressure operation of SWRO (often up to 1,200 psi), the concentrate is more pressurized in this application compared to brackish water desal applications, and thus energy recovery is more feasible and very desirable. For more information this process, refer to the related PIM cell discussion on energy recovery.

NF membrane systems

Similar to the RO process, the NF process also uses semi-permeable membranes and a driving force of hydraulic pressure. NF was developed in the mid-1980’s and is characterized as a “looser” membrane that is intentionally designed to be less efficient for removing monovalent ions such as sodium (Na⁺), potassium (K⁺), and chloride (Cl⁻), while maintaining high rejection of multivalent ions such as calcium (Ca²⁺), magnesium (Mg²⁺), and organic substances (USEPA 2005). Thus, NF allows more salt passage across the membrane, and is sometimes called a “softening membrane.” Because the pressure (and thus the energy) required for desal via RO is proportional to the difference in TDS between the two sides of the semi-permeable membrane, this feature of NF allows hardness to be effectively removed at a lower operating cost than RO.
(due to lower energy requirements). Similar to RO, energy recovery is possible with NF using typical energy recovery devices.

Notably, there is no formal definition of NF, and one manufacturer’s NF membrane may have similar rejection characteristics to another’s low-rejection RO membrane. Thus, rather than a distinct differentiation between NF and RO, the range of commercially available products embodies a spectrum of rejection capabilities with NF and RO at the low and high ends, respectively, and overlapping performance in the middle. Also, note that the use of the term “RO” in the literature can refer to technology utilizing the reverse osmosis process for desal, in general, and in this context includes NF, as well.

**State of current membrane technology**

In municipal applications, semi-permeable RO/NF membranes are bundled in an efficient spiral-wound configuration to maximize available surface area. The smallest bundle of membrane area is called an “element” (or a “module”). Elements numbering into the thousands for the largest capacity plants can be combined into a system to produce potable water.

RO and NF systems can be configured in various ways to meet site-specific treatment objectives and/or increase energy efficiency, as follows:

- **NF-NF:** A two-pass NF system (i.e., the “Long Beach Method”) may be able to accomplish seawater desal in a more energy efficient manner than a single pass of RO membranes.

- **NF-RO:** A pass of NF membranes may be used upstream of a pass of RO membranes to desalinate seawater more efficiently (Hassan et al. 1998).

- A **partial second pass of RO** may be used in cases in which the TDS concentration is extremely high (e.g., in the Persian Gulf or Red Sea) or levels of a specific contaminant that is not efficiently removed by RO (e.g., boron) must be further reduced beyond the capability of a single RO pass (Gorenflo et al. 2007).

Conceptual process designs can be created to model membrane functionality. The various RO and NF membrane element manufacturers have developed software to enable users to develop conceptual process designs using their respective proprietary membrane products. At a minimum, source water quality is a necessary input for these modeling programs. These programs are generally available for free public download at each of the respective manufacturers’ web sites, such as the ROPRO® Reverse Osmosis System Design Software Program developed by Koch Membrane Systems, and the IMSDesign developed for Hydranautics’ membrane products.
The design of RO elements is largely standardized, such that elements of similar size from any manufacturer can be used interchangeably. In addition to the three standard diameters for glass fiber reinforced housings (2.5-, 4- and 8-inch), membrane elements with larger diameters have been developed. Koch Membrane Systems, Inc. introduced the world's largest MegaMagnum® RO Element, with an element diameter of 18-inches (457.2 mm) and length of 61-inches (1549 mm). Hydranautics also developed new brackish and seawater 16-inch diameter RO elements. The larger membrane elements offer significant cost savings by reducing capital investments for construction and installation, as well as operation and maintenance costs. Larger membranes can also significantly reduce the footprint of the desal plant.

**BENEFITS & COSTS**

**Benefits**

- Membrane processes have a smaller footprint and are generally more economical than thermal processes.
- RO and NF systems can be configured in various ways to meet site-specific treatment objectives and/or increase energy efficiency.
- NF membrane systems have required less energy and therefore have lower operating costs than RO membrane systems.

**Costs**

- Power requirements comprise a substantial portion of the total cost to produce desalinated water. Thus, two variables for which small changes can significantly influence the cost of desal include the cost of energy and power consumption.
- The higher the TDS of the feedwater, the more expensive it is to desalinate using membrane processes. The energy necessary to accomplish RO is proportional to the TDS of the feed water.
- The warmer the feed water, the lower the cost of desalinating seawater using membrane processes. Because the heated water is less viscous, the pressure required to drive the feed water through the membranes is somewhat reduced, lowering energy consumption and, therefore, operating costs.
KEY UNCERTAINTIES

Although RO technology appears to be maturing, several major challenges remain, including membrane fouling. Membrane fouling leads to increases in energy use, and membrane degradation due to poor resistance to chlorine, other oxidants and chemicals.

In an attempt to reduce fouling, there has been a shift in recent years from producing the original cellulose acetate membranes to developing thin-film composite (TFC) membranes. Several variations of TFC membranes have been commercialized. Many of these developments have resulted from the addition of polymer to smooth the surface or surface modifications such as addition of different functional groups to change the surface charge. While these improvements reduce fouling, truly fouling-resistant membranes are yet to be realized. Thus, opportunities exist to modify existing or create new membrane formulations or alter surface characteristics to reduce fouling.

Currently, the most direct and effective way to protect against fouling is with effective pretreatment to remove suspended/colloidal matter and dissolved organic matter. As an alternative to fouling-resistant membranes, fouled membranes that could be cleaned easily with low-cost oxidants (e.g., chlorine) would be desirable. However, the state-of-the-art SWRO membranes cannot tolerate oxidants such as free chlorine, and they require chlorine removal from the feedwater before being processed by the RO modules. Consequently, biofouling can be another challenge that limits the performance of RO membranes.

Another limitation in RO desal is the relatively low recovery rate in seawater (up to about 60 percent), which results in large volumes of concentrate. Maximum recovery is limited by the mechanical pressure limitations of the materials in the membrane element whereas practical recovery (typically 45 percent for seawater) must consider optimization of other parameters such as solubility product limits and energy consumption. Several approaches for improvements to overall SWRO recovery are currently being investigated (Xu et al. 2009, Sethi et al. 2008, NRC 2008).

ADDITIONAL RESOURCES


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