Introduction to Desalination Technologies

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Definition and brief history

Desalination can be defined as any process that removes salts from water. Desalination processes may be used in municipal, industrial, or commercial applications. With improvements in technology, desalination processes are becoming cost-competitive with other methods of producing usable water for our growing needs.

During World War II, it was felt that desalination technology - ‘desalting’ as it was called then - should be developed to convert saline water into usable water, where fresh water supplies were limited. Subsequently, “The Saline Water Act” was passed by Congress in 1952 to provide federal support for desalination. The U.S. Department of the Interior, through the Office of Saline Water (OSW) provided funding during the 1950s and 60s for initial development of desalination technology, and for construction of demonstration plants. Desalination is a relatively new science that has developed to a large extent during the latter half of the 20th century, and continues to undergo technological improvements even at the present time.

It is interesting to note that one of the first seawater desalination demonstration plants to be built in the United States was at Freeport, Texas in 1961. Dow, in cooperation with the U.S. Department of the Interior built a 1 million gallons per day (mgd) long tube vertical distillation (LTV) plant at a cost of $1.2 million, that produced water for the City of Freeport and for Dow operations. The plant was officially opened on June 21, 1961 by then President John F. Kennedy, by pressing a button from the White House. Vice President Lyndon Johnson attended the inaugural event in Freeport.

During his speech to dedicate the desalination plant, President Kennedy said “No water resources program is of greater long-range importance than our efforts to convert water from the world’s greatest and cheapest natural resources – our oceans – into water fit for our homes and industry. Such a break-through would end bitter struggles between neighbors, states and nations”. Those statement are true even today, more than 40 years later.

Desalination Technologies

A desalination process essentially separates saline water into two parts - one that has a low concentration of salt (treated water or product water), and the other with a much higher concentration than the original feed water, usually referred to as brine concentrate or simply as ‘concentrate’.

The two major types of technologies that are used around the world for desalination can be broadly classified as either thermal or membrane. Both technologies need energy to operate and produce fresh water. Within those two broad types, there are sub-categories (processes) using different techniques. The major desalination processes are identified in Table 1.

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Table 1. Desalination Technologies and processes

Thermal Technology	Membrane Technology
Multi-Stage Flash Distillation (MSF)	Electrodialysis (ED)
Multi-Effect Distillation (MED)	Electrodialysis reversal (EDR)
Vapor Compression Distillation (VCD)	Reverse Osmosis (RO)

Thermal and membrane capacity on a worldwide basis was about 7 billion gallons per day (bgd) in early 2000, with about 50% in thermal processes and 50% in membrane technologies. This is total installed capacity since the early 1950s, and not all of that capacity may be in operation. On a global basis, desalination capacity increased at almost 12 percent per year, from 1972 through 1999. There have been over 8,600 desalination plants installed worldwide, with approximately 20 percent of them in the U.S., the largest number of any country in the world. In terms of capacity however, the U.S. ranks second globally (U.S. Department of the Interior, 2003).

Thermal Technologies

Thermal technologies, as the name implies, involve the heating of saline water and collecting the condensed vapor (distillate) to produce pure water. Thermal technologies have rarely been used for brackish water desalination, because of the high costs involved. They have however been used for seawater desalination and can be sub-divided into three groups: Multi-Stage Flash Distillation (MSF), Multi-Effect Distillation (MED), and Vapor Compression Distillation (VCD).

Multi-Stage Flash Distillation (MSF)

This process involves the use of distillation through several (multi-stage) chambers. In the MSF process, each successive stage of the plant operates at progressively lower pressures. The feed water is first heated under high pressure, and is led into the first ‘flash chamber’, where the pressure is released, causing the water to boil rapidly resulting in sudden evaporation or ‘flashing’. This ‘flashing’ of a portion of the feed continues in each successive stage, because the pressure at each stage is lower than in the previous stage. The vapor generated by the flashing is converted into fresh water by being condensed on heat exchanger tubing that run through each stage. The tubes are cooled by the incoming cooler feed water. Generally, only a small percentage of the feed water is converted into vapor and condensed.

Multi-stage flash distillation plants have been built since the late 1950s. Some MSF plants can contain from 15 to 25 stages, but are usually no larger than 15 mgd in capacity. MSF distillation plants can have either a ‘once-through’ or ‘recycled’ process. In the ‘once-through’ design, the feed water is passed through the heater and flash chambers just once and disposed of, while in the recycled design, the feed water for cooling is recycled. Each of these processes can be structured as a ‘long tube’ or ‘cross tube’ design. In the long tube design (built at Freeport in 1961), tubing is parallel to the concentrate flow, while in the cross tube design, tubing is perpendicular to the concentrate flow.

MSF plants are subject to corrosion unless stainless steel is used extensively. In addition to corrosion, MSF plants are also subject to erosion and impingement attack (U.S. Bureau of Reclamation, 2003). Erosion is caused by the turbulence of the feed water in the flash chamber, when the feed water passes from one stage to another.

Distillation processes produce about 3.4 billion gpd globally, which is about 50 percent of the worldwide desalination capacity. MSF plants provide about 84 percent of that capacity. Most of those plants have been built overseas, primarily in the Middle East, where energy resources have been plentiful and inexpensive.

Multi-Effect Distillation (MED)

The MED process has been used since the late 1950s and early 1960s. Multi-effect distillation occurs in a series of vessels (effects) and uses the principles of evaporation and condensation at reduced ambient pressure. In MED, a series of evaporator effects produce water at progressively lower pressures. Water boils at lower temperatures as pressure decreases, so the water vapor of the first vessel or effect serves as the heating medium for the second, and so on. The more vessels or effects there are, the higher the performance ratio. Depending upon the arrangement of the heat exchanger tubing, MED units could be classified as horizontal tube, vertical tube or vertically stacked tube bundles

There have been several MED plants built in the U.S. and overseas. Three low-temperature MED plants with a combined capacity of 3.5 mgd have been operating successfully in St. Thomas, U.S. Virgin Islands, where desalinated water is the principal water supply source (Krishna, 1989). The MED units are operated by the Virgin Islands Water and Power Authority. Steam from the power plant is directed to the evaporators in the desalination units. Product water is obtained as condensate of the vapor from each vessel. Several MED plants are found overseas, both in the Caribbean and in the Middle East.

Vapor Compression Distillation

The vapor compression distillation (VCD) process is used either in combination with other processes such as the MED, or by itself. The heat for evaporating the water comes from the compression of vapor, rather than the direct exchange of heat from steam produced in a boiler (Buros, 2000). Vapor compression (VC) units have been built in a variety of configurations. Usually, a mechanical compressor is used to generate the heat for evaporation. The VC units are generally small in capacity, and are often used at hotels, resorts and in industrial applications.

Membrane Technologies

Membrane technologies can be subdivided into two broad categories: Electrodialyis/Electrodialysis Reversal (ED/EDR), and Reverse Osmosis (RO).

Electrodialysis (ED) and Electrodialysis Reversal (EDR)

Electrodialysis (ED) is a voltage-driven membrane process. An electrical potential is used to move salts through a membrane, leaving fresh water behind as product water. ED was commercially introduced in the 1960s, about 10 years before reverse osmosis (RO), Although

ED was originally conceived as a seawater desalination process, it has generally been used for brackish water desalination.

ED depends on the following general principles:

- Most salts dissolved in water are ions, either positively charged (cations), or negatively charged (anions).
- Since like poles repel each other and unlike poles attract, the ions migrate toward the electrodes with an opposite electric charge
- Suitable membranes can be constructed to permit selective passage of either anions or cations.

In a saline solution, dissolved ions such as sodium (+) and chloride (-) migrate to the opposite electrodes passing through selected membranes that either allow cations or anions to pass through (not both). Membranes are usually arranged in an alternate pattern, with anion-selective membrane followed by a cation-selective membrane. During this process, the salt content of the water channel is diluted, while concentrated solutions are formed at the electrodes. Concentrated and diluted solutions are created in the spaces between the alternating membranes, and these spaces bound by two membranes are called cells. ED units consist of several hundred cells bound together with electrodes, and is referred to as a stack. Feed water passes through all the cells simultaneously to provide a continuous flow of desalinated water and a steady stream of concentrate (brine) from the stack.

In the early 1970s, the Electrodialysis Reversal (EDR) process was introduced (Buros, 2000). An EDR unit operates on the same general principle as an ED unit, except that both the product and concentrate channels are identical in construction. At intervals of several times an hour, the polarity of the electrodes is reversed, causing ions to be attracted in the opposite direction across the membranes. Immediately following reversal, the product water is removed until the lines are flushed out and desired water quality restored. The flush takes just a few minutes before resuming water production. The reversal process is useful in breaking up and flushing out scales, slimes, and other deposits in the cells before they build up. Flushing helps in reducing the problem of membrane fouling.

Because of the inherent characteristics of the electrical process used in ED units, they are normally used to desalinate brackish water, rather than high salinity water such as seawater. The few ED units that are located in Texas are those that are used in low-salinity applications such as surface water desalination (e.g. Lake Granbury and Sherman).

Reverse Osmosis (RO) and Nanofiltration (NF)

In relation to thermal processes**,** Reverse Osmosis (RO) is a relatively new process that was commercialized in the 1970s (Buros, 2000). Currently, RO is the most widely used method for desalination in the United States. The RO process uses pressure as the driving force to push saline water through a semi-permeable membrane into a product water stream and a concentrated brine stream. Nanofiltration (NF) is also a membrane process that is used for removal of divalent salt ions such as Calcium, Magnesium, and Sulphate. RO, on the other hand, is used for removal of Sodium and Chloride. RO processes are used for desalinating brackish water (TDS>1,500 mg/l), and seawater. The process is explained below:

Osmosis is a natural phenomenon by which water from a low salt concentration passes into a more concentrated solution through a semi-permeable membrane. When pressure is applied to the solution with the higher salt concentration solution, the water will flow in a reverse direction through the semi-permeable membrane, leaving the salt behind. This is known as the Reverse Osmosis process or RO process.

An RO desalination plant essentially consists of four major systems:

a) Pretreatment system
b) High-pressure pumps
c) Membrane systems
d) Post-treatment

Pre-treatment is very important in RO because the membrane surfaces must remain clean. Therefore, all suspended solids must be first removed, and the water pre-treated so that salt precipitation or microbial growth does not occur on the membranes. Pre-treatment may involve conventional methods such as a chemical feed followed by coagulation/flocculation/sedimentation, and sand filtration, or pre-treatment may involve membrane processes such as microfiltration (MF) and ultrafiltration (UF). The choice of a particular pre-treatment process is based on a number of factors such as feed water quality characteristics, space availability, RO membrane requirements, etc.

High pressure pumps supply the pressure needed to enable the water to pass through the membrane and have the salt rejected. The pressures range from about 150 psi for slightly brackish water to 800 - 1,000 psi for seawater.

The membrane assembly consists of a pressure vessel and a semi-permeable membrane inside that permits the feed water to pass through it. RO membranes for desalination generally come in two types: Spiral wound and Hollow fiber. Spiral wound elements are actually constructed from flat sheet membranes. Membrane materials may be made of cellulose acetate or of other composite polymers. In the spiral wound design, the membrane envelope is wrapped around a central collecting tube. The feed water under pressure, flows in a spiral path within the membrane envelope, and pure (desalinated) water is collected in the central tube. As a portion of the water passes through the membrane, the remaining feed water increases in salt content. A portion of the feed water is discharged without passing through the membrane. Without this discharge, the pressurized feed water would continue to increase in salinity content, causing super-saturation of salts. The amount of feed water that is discharged as concentrate, ranges from about 20 percent for brackish water to about 50 percent for seawater.

Figure 1- A cross-sectional view of a pressure vessel with a spiral-wound RO membrane

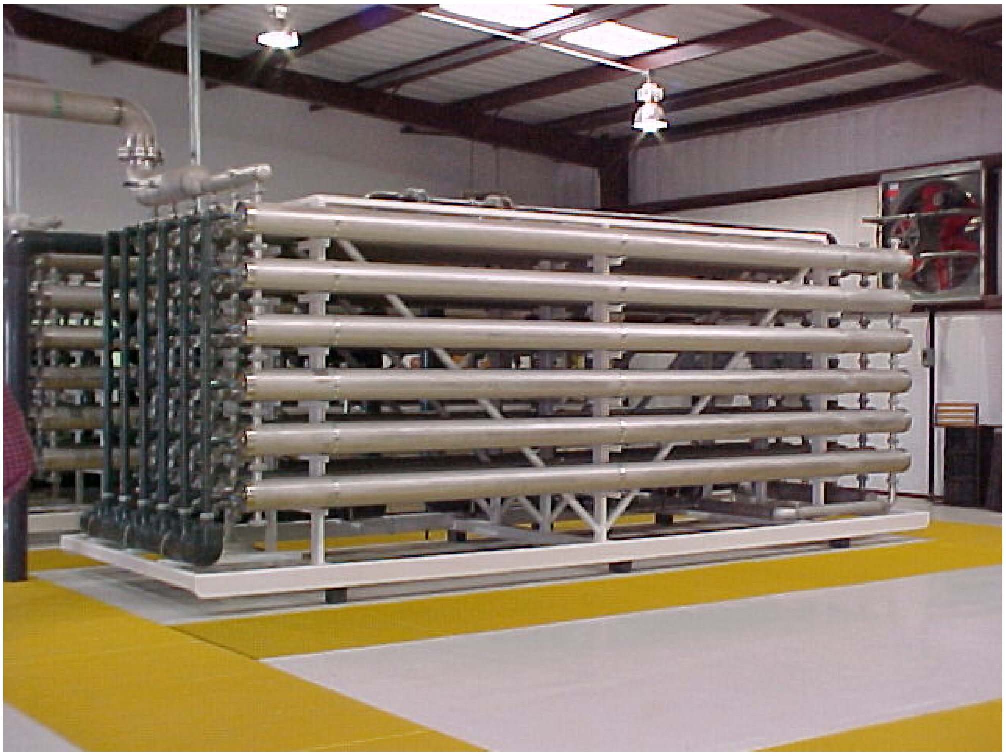

Figure 2-A water treatment plant using RO for desalination.

Another type of membrane is the hollow fiber design which places a large number of hollow fiber membranes in a pressure vessel. The pressurized saline water is introduced into the vessel along the outside of the hollow fibers. Under pressure, desalinated water passes through the fiber walls, and flows in the hollow fibers for collection. This type of design is not as widely used now as the spiral wound membranes for desalination.

Post-Treatment consists of stabilizing the water and preparing it for distribution. The post-treatment might consist of adjusting the pH and disinfection. If the desalinated water is being combined with other sources of water supply, it is very important to ensure similar water quality characteristics in both water sources.

Two developments have helped to reduce the operating cost of RO plants during the past decade: the development of more efficient membranes and the use of energy recovery devices. The newer membranes have higher flux (rate of water flow per unit area), improved rejection of salts, lower prices and longer service life (Buros, 2000).

It is now common to use energy recovery devices connected to the concentrate stream as it leaves the pressure vessel at about 20-50 psi less than the applied pressure from the high-pressure pump. The energy recovery devices are mechanical and consist of turbines, pressure exchangers or other devices that rotate and produce energy, thus assisting the RO process in reducing the overall energy needs. The energy recovered can be as high as 25-35 percent of the input energy for seawater RO (Oklejas, et al., 1996).

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