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Environmental Engineering II
Design Project Report

Desalination of Seawater By Reverse Osmosis

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Introduction and Objectives

The subject of this document is desalination of seawater by reverse osmosis (RO). The objective of this document is to present a complete set of notes for the design of a reverse osmosis system sized for coastal municipal use. This document introduces the theoretical principles of reverse osmosis, delineates the information needed to design a reverse osmosis system, explains how to obtain such information, summarizes the general procedures for design, and provides a design example.

Reverse osmosis is considered the most contemporary, energy-efficient method of desalination available today. Prior to undergoing reverse osmosis, seawater typically endures three treatments:

► It is cleansed of suspended solids by a filter of known pore size – typically 0.5 microns;

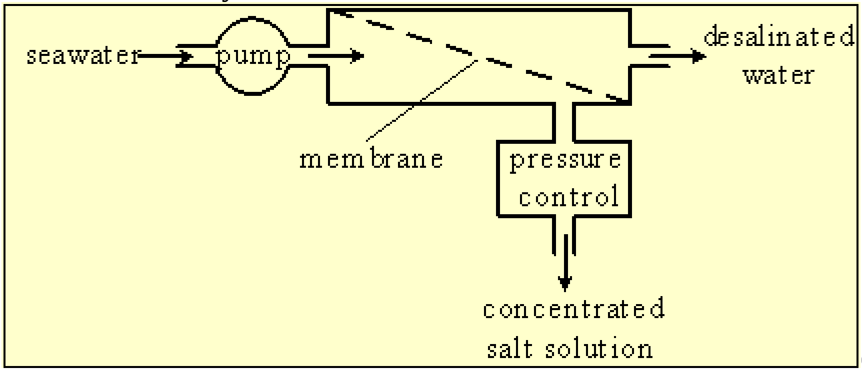
► Its pH is elevated in order to encourage the removal of weak acids such as boron and silica;

► It is mechanically pressurized in order to both maintain the design flow rate and overcome the osmotic pressure produced naturally by saline water. Seawater normally requires mechanical pressure in the range of 800 – 1200 psi, based on its salinity and the type of membrane used for reverse osmosis. The vendor of the membrane specifies the appropriate mechanical pressure (Sourcebook).

Reverse osmosis itself separates seawater into clean product water and highly saline reject water (brine). The focus of this document is reverse osmosis by spiral-wound thin-film composite membranes. These membranes typically consist of an ultra-thin polyamide barrier layer, a microporous polysulphone interlayer, a high-strength support web [not shown], and a non-woven web base layer, as depicted below:

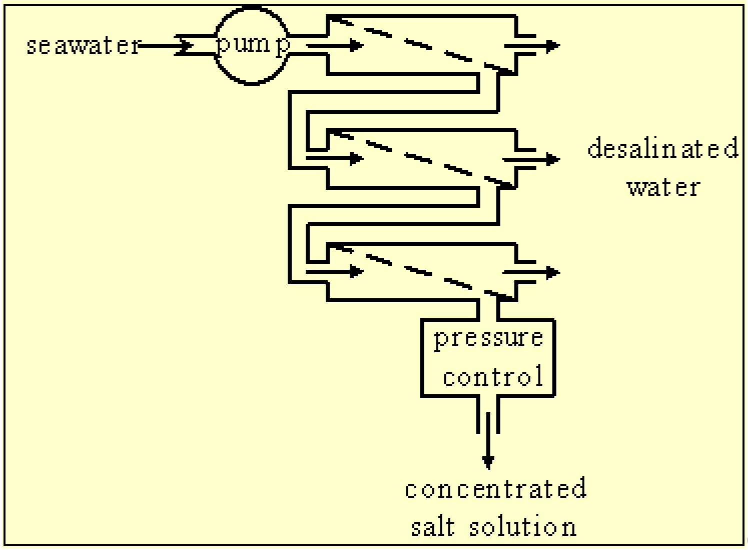
(Filmtec)

Following reverse osmosis, the product water undergoes only a final pH adjustment (from roughly 5 to just over 7) before it is ready for municipal use (Sourcebook). The following diagram depicts the typical structure of a reverse osmosis system:



(Lachish)

Reverse osmosis systems vary in size based on the demand for product water. Large systems, such as those designed for municipalities, typically feature membranes in series or stages, as depicted below:



(Lachish)

In the interest of brevity, this document does not describe in extensive detail the pre- and post-reverse osmosis treatments listed above. These treatments are standard to many industrial processes and subject to little interpretation.

Theoretical Principles

Reverse osmosis removes dissolved salts from seawater, which is defined as water with a total dissolved solids (TDS) concentration of 10,000 – 45,000 mg/L. Reverse osmosis typically yields product water of TDS concentration less than 500 mg/L and brine of TDS concentration greater than 35,000 mg/L. The maximum allowable concentration of TDS in drinking water is typically 500 mg/L (Sourcebook).

Certain chemical and physical properties of seawater (feedwater) determine the performance characteristics of a reverse osmosis system. A reverse osmosis system is characterized by its rate of product water recovery vs. rate of brine rejection. The most important chemical property of feedwater is salinity and the most important physical property is temperature.

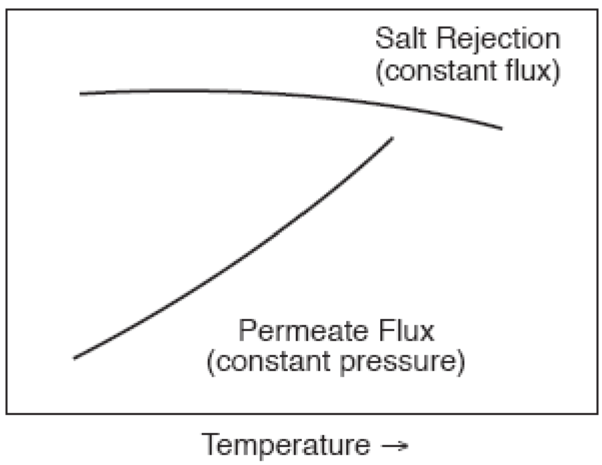
The salinity (dissolved salts concentration) of a feedwater is of primary importance because it suggests the appropriate rejection rate : recovery rate ratio. Typically, this ratio is 6:1. High-salinity feedwater requires a high rejection vs. recovery rate ratio in order to prevent membrane fouling (Hagopian).

Other chemical properties of feedwater TDS, namely molecular weight and charge, affect the rate of rejection vs. recovery. Molecules in feedwater are rejected if they are larger than the molecular weight cut-off (MWCO) for a given membrane; conversely, molecules in feedwater are recovered if they are smaller than the MWCO. The MWCO for a membrane typically ranges from 100 – 500 grams (Fundamentals).

Since the molecular weight of dissolved salts in water is significantly lower than the low typical MWCO value – the molecular weight of sodium (Na^+) is 23 grams and the molecular weight of chloride (Cl^-) is 35.5 grams – one may assume that reverse osmosis does not effectively filter dissolved salts from seawater. However, this assumption is incorrect. By the phenomenon of hydrogen bonding, described further below, dissolved salt molecules align with water molecules to form molecules of great enough "apparent size" (combined molecular weight) to almost always satisfy the MWCO. It is by hydrogen bonding that the reverse osmosis membranes remove 90 – 99 percent of dissolved salts from seawater (Fundamentals).

The phenomenon of hydrogen bonding is based on the polarity of the water molecule. Water is a polar molecule (has oppositely charged ends) so water molecules have the ability to align, positive to negative end, with both themselves and other polar molecules (including Na^+ and Cl^-). The charge of a polar molecule determines its tendency to align with water molecules – strongly charged polar molecules such as Fe^{2+} align with water molecules more readily than weakly charged polar molecules such as Na^+. This ability to align prompts individual water and dissolved salt molecules to combine into one molecule of sufficient "apparent size" (Fundamentals).

The most important physical characteristic of feedwater is temperature. Temperature greatly affects the rate of rejection vs. recovery for the system. Chilled feedwater causes the pores of a membrane to shrink, which yields a high rate of rejection. Heated feedwater causes the pores of a membrane to expand, which yields a low rate of rejection. A high rate of rejection ensures highly sanitary product water, which is imperative if the water is intended for human consumption. Otherwise, a high rate of rejection is not preferred – a high rate of recovery takes precedence in the interest of energy efficiency and productivity. The following figure illustrates how temperature influences both the rate of rejection and rate of recovery:



(Filmtec)

Information Needed for Design

In order to design a reverse osmosis treatment system, the following information is needed:

1. The feedwater source;
2. The feedwater quality;
3. The feedwater TDS or dissolved salts concentration;
4. The maximum allowable product water TDS concentration;
5. The required product water flow rate;
6. The number of elements in each pressure vessel;
7. The temperature of the incoming feedwater.

How to Obtain Information Needed for Design

The information needed for design is either given or may be obtained experimentally:

► The feedwater source is given;
► The feedwater quality is given;
► The feedwater TDS or dissolved salts concentration is given;
► The maximum allowable product water TDS concentration is given;

► The required product water flow rate is given;
► The number of elements in each pressure vessel is given;
► The temperature of the incoming feedwater may be obtained on-site using of a thermometer.

General Design Procedure
The following design procedure is generally appropriate for municipal reverse osmosis systems.

1. Determine the required brine flow rate based on the required product water flow rate:
   required brine flow rate = 6(required product flow rate)
2. Determine the unadjusted required feedwater flow rate based on the required brine flow rate and required product flow rate:
   unadjusted required feedwater flow rate = required brine flow rate + required product flow rate
3. [Reverse osmosis design calculations are typically based on a feedwater temperature of 25° Celsius.] Determine the adjusted required feedwater flow rate.
   a. Determine the temperature correction factor based on the temperature of the incoming feedwater.
   b. Determine the adjusted required feedwater flow rate, Q, of the incoming feedwater:
      Q = unadjusted flow rate * temperature correction factor
4. Select membrane type based on the TDS or dissolved salts concentration.
5. Select the membrane element diameter based on the membrane type and required product water flow rate.
   a. Record the maximum product water TDS concentration that corresponds with the selected membrane element diameter.
6. Select a membrane product from a vendor based on the intended use of the product water, feedwater source, and membrane element diameter.
   a. Record the following membrane product specifications:
      i. Active membrane surface area
      ii. Product water flow rate
   b. [For the purpose of designing the preliminary treatment] Record the operating conditions upon which these membrane product specifications are based:
      iii. Feedwater pH
      iv. Operating pressure
7. Record the following membrane element properties based on feedwater source, feedwater quality, and membrane element diameter:
   a. Silt Density Index (SDI)
   b. Maximum recovery rate
   c. Target rate of recovery
   d. Maximum allowable product water flow rate
   e. Minimum allowable reject water flow rate
   f. Maximum allowable feedwater flow rate
8. Determine the minimum required number of membrane elements:
   no. elements = Q / (target rate of recovery * active membrane area)
9. Determine the required number of pressure vessels:
   minimum required no. pressure vessels = no. elements / no. of elements in each pressure vessel
10. Arrange the pressure vessels into stages and verify that the system satisfies all design criteria (Filmtec).

Design Example
The following design example is based on input data typical of a small coastal municipality.

Information Needed For Design

1. The feedwater source: seawater
2. The feedwater quality: microfiltered
3. The feedwater dissolved salts concentration: 32,000 mg NaCl/L
4. The maximum allowable product water TDS concentration: 500 ppm
5. The required product water flow rate: 140 gpm
6. The number of elements in each pressure vessel: 6
7. The temperature of the incoming feedwater: 25˚ C

Design Procedure

1. Determine the required brine flow rate based on the required product water flow rate:
   required brine flow rate = 6(required product flow rate) = 840 gpm
2. Determine the unadjusted required feedwater flow rate based on the required brine flow rate and required product flow rate:
   unadjusted required feedwater flow rate = required brine flow rate + required product flow rate = 980 gpm
3. [Reverse osmosis design calculations are typically based on a feedwater temperature of 25° Celsius.] Determine the adjusted required feedwater flow rate.
   a. Determine the temperature correction factor (TCF) based on the temperature of the incoming feedwater: TCF = 1.0
   b. Determine the adjusted required feedwater flow rate, Q, of the incoming feedwater:
      Q = unadjusted flow rate * TCF = 980 gpm
4. Select membrane type based on the TDS or dissolved salts concentration: membrane type = seawater high rejection (SWHR)
5. Select the membrane element diameter based on the membrane type and required product water flow rate: membrane element diameter = 8 inches
   a. Record the maximum product water TDS concentration that corresponds with the selected membrane element diameter: maximum product water TDS concentration = 500 ppm
6. Select a membrane product from a vendor based on the intended use of the product water, feedwater source, and membrane element diameter: membrane product = FILMTEC SW30HR-380
   a. Record the following membrane product specifications:
      i. Active membrane surface area: 380 ft^2
      ii. Product water flow rate: 6000 gpd = 4.2 gpm
   b. [For the purpose of designing the preliminary treatment] Record the operating conditions upon which these membrane product specifications are based:
      i. Feedwater pH: 8
      ii. Operating pressure: 800 psi
7. Record the following membrane element properties based on feedwater source, feedwater quality, and membrane element diameter:
   a. Silt Density Index (SDI): <5
   b. Maximum recovery rate: 13 percent
   c. Target rate of recovery: 8.8 gfd
   d. Maximum allowable product water flow rate: 8800 gpd = 6.1 gpm
   e. Minimum allowable reject water flow rate: 16 gpm
   f. Maximum allowable feedwater flow rate: 70 gpm
8. Determine the minimum required number of membrane elements:
   minimum required no. elements = Q / (target rate of recovery * active membrane surface area) = 62.8 ~ 63

9. Determine the required number of pressure vessels:
   no. pressure vessels = no. elements / no. of elements in each pressure vessel = 10.5 ~ 11
11. Arrange the pressure vessels into stages and verify that the system satisfies all design criteria:

Design Parameter	Design Criteria	Stage No.			Sum
		1	2	3	
Flow Rate By Stage (gpm)					
Feedwater		980	854	753	
Product Water		126	101	62	
Reject Water		854	753	691	
No. Vessels	11	5	4	2	11
Flow Rate By Vessel (gpm)					
Feedwater		196	214	377	
Product Water		25.2	25.2	31.2	
Reject Water		171	188	345	
Rate of Recovery By Element (%)	<13	12.9	11.8	8.3	
No. Elements	>63	30	24	12	66
Flow Rate By Element (gpm)					
Feedwater	<70	32.7	35.6	62.8	
Product Water	<6.1	4.2	4.2	5.2	
Reject Water	>16	28	31	58	
Product Water TDS (ppm)	<500	<500	<500	<500	

Concluding Remarks

The information presented above is sufficient to design a reverse osmosis treatment system for a coastal municipality. Practical application of this design information is entirely feasible; however, users of this design process are encouraged to conduct physical testing of any RO treatment system following its construction to ensure proper functionality. Reverse osmosis is progressing rapidly as a technology and its implementation is becoming increasingly feasible for coastal municipalities worldwide. Coastal municipal planners are encouraged to consider reverse osmosis technology for all their freshwater needs.

References

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