SWRO Membrane Design with Isobaric Energy Recovery Devices

Authors

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Abstract

The great majority of medium and large seawater reverse osmosis (SWRO) desalination plants being designed and built today use isobaric energy recovery devices (ERDs) to minimize energy consumption. Isobaric ERDs transfer pressure from the high-pressure concentrate reject from the SWRO membranes to low-pressure seawater by placing the streams into contact in pressure-equilibrating chambers. This positive-displacement mechanism provides high hydraulic transfer efficiency but also allows some mixing of concentrate into the seawater, thereby increasing the salinity of the membrane feed stream. The amount of salinity increase is both a characteristic of the particular ERD and a function of the ratio of concentrate and seawater flow rates. The ionic composition of the concentrate in SWRO membranes operating without an ERD is a function of the seawater composition, the seawater properties and the membrane rejection performance. When these components operate together, the mixing affect is compounded and species mass balance calculations must be performed iteratively to estimate the composition of the streams and the corresponding system performance. The authors present the considerations and computations necessary for incorporating isobaric ERD mixing performance into membrane projection programs. Particular attention is paid to the tracking of trace species such as boron and silica.

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Introduction

Seawater reverse osmosis (SWRO) technology consumes far less energy today than it did just a few years ago. Advances in membrane technology have reduced the pressure required to drive reverse osmosis while isobaric energy recovery devices (ERDs) maximize process efficiency and provide operational flexibility. Together, these developments have made SWRO the least expensive and most reliable source of fresh drinking water in many parts of the world [1].

Reduction of the required operating pressure, together with improved rejections, have been primary forces driving the expansion of RO (reverse osmosis) and NF (nanofiltration). A comparison of the water permeability of a leading commercial RO membrane such as FILMTEC™ FT30 membrane shows that in the relatively short history of RO as a commercial process, water flux has increased from 43 liters per square meter per day per bar (L/m^2/day/bar) reported by Cadotte [2] in 1981 to values of 201 L/m^2/day/bar for the current XLE membrane and even approaches 295 L/m^2/day/bar for some FT30 derivatives used in nanofiltration. While the first 8-inch seawater elements were able to produce only 15.1 cubic meters of permeate per day (m^3/d) or 4000 gallons per day (gpd) and 99.2% rejection, major changes in membrane productivity and element design have resulted in current experimental seawater elements able to produce 47 m^3/d (12,500 gpd) and with 99.7% rejection under the same conditions [3].

ERDs have been employed in SWRO applications since the early 1980s to recover pressure energy from the concentrate reject stream of the SWRO membranes and return it to the membrane feed stream. Early ERDs were centrifugal devices that were limited in capacity and had a maximum net transfer efficiency of typically less than 80% at their best efficiency point [4]. More recently, isobaric ERDs, including piston-type work exchangers and the rotary PX Pressure Exchanger® device, have been developed to provide unlimited capacity and an operating efficiency of up to 98% [5]. The positive displacement pressure transfer mechanism used in these devices is similar to that in reciprocating pumps and assures high efficiency despite flow and pressure variations. Isobaric ERDs are employed in hundreds of desalination plants worldwide including the three largest SWRO plants in operation today.

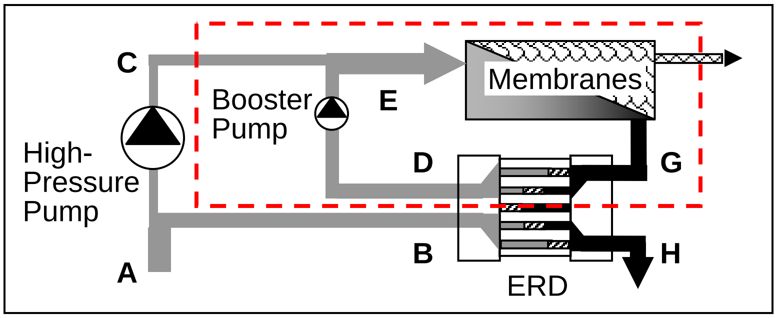
In all commercially available isobaric ERDs, some contact between the concentrate and seawater streams occurs inside the device. As a result, these streams mix slightly, thereby increasing the salinity of the membrane feed stream. The amount of salinity increase is a characteristic of the particular ERD and a function of the ratio of concentrate and seawater flow rates. The ionic composition of the concentrate feeding the ERD from the SWRO membranes is a function of the feedwater composition, feedwater properties, membrane rejection and membrane permeability. The salinity increase caused by the ERD is compounded by the membranes. Precise SWRO system design requires that species mass balance calculations must be performed iteratively to estimate the composition of the streams and the corresponding system performance.

The authors seek to simplify the SWRO design process by presenting the considerations and equations necessary for incorporating isobaric ERD mixing performance directly into membrane projection programs. Although the authors are affiliated with Energy Recovery, Inc., a leading manufacturer of ERDs and the Dow/FilmTec, a leading supplier of reverse osmosis membranes, the work presented in this paper is intended to apply generally to all reverse osmosis membrane systems equipped with isobaric ERDs.

SWRO with Isobaric ERDs

A typical process configuration for an SWRO system equipped with an isobaric ERD is illustrated in Figure 1 below. Concentrate rejected by the membranes flows to the ERD, driven by a booster (circulation) pump. The ERD replaces the concentrate with seawater. This flow merges with the discharge of the high-pressure pump to feed the membranes. Water leaves the system as membrane permeate or as spent low-pressure concentrate from the ERD.

Figure 1 – Schematic of SWRO System with Isobaric ERD

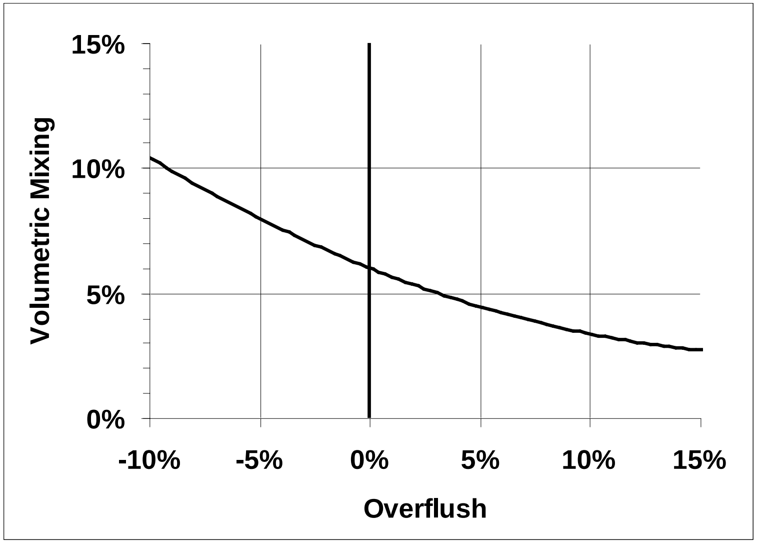


The isobaric ERD separates the high- and low-pressure streams and seals the high-pressure portion of the process. To illustrate how this affects SWRO system operation, a dashed-line box is drawn around the high-pressure portion of the process and through the ERD in Figure 1 above. Nearly all the water that enters the box from the high-pressure pump leaves as permeate. A small amount – typically less than 2% of the permeate volume – passes through the seals of the ERD as lubrication flow or leakage. High-pressure pump flow and permeate flow are always nearly equal regardless of membrane pressure or booster pump flow rate.

Within the ERD, pressure transfers directly from the concentrate to the seawater stream in pressure-equilibrating chambers. This positive-displacement mechanism provides high hydraulic-transfer efficiency but also allows some mixing of concentrate into the seawater, thereby increasing the salinity of the membrane feed stream. The degree of mixing is a characteristic of the particular ERD and a function of the ratio of concentrate and seawater flow rates to the ERD.

One means to reduce mixing in isobaric ERDs is to supply excess seawater to clear the chambers of any residual concentrate. Overflush reduces mixing in the ERD as illustrated in Figure 2 below. Zero overflush corresponds to “balanced flow” when the seawater inlet flow rate equals the seawater outlet flow rate. The axis labels in Figure 2 are further defined in the following section.

Figure 2 – Isobaric ERD Mixing versus Overflush



It is important to distinguish between leakage and mixing in isobaric ERDs. Leakage occurs primarily at the seals which are located at the ends of the isobaric chambers. High-pressure seawater leaks to low-pressure seawater and high-pressure concentrate leaks to low-pressure concentrate with no change in salinity. Mixing occurs within the isobaric chambers and does not change flow rates. The two phenomena are independent and unrelated.

Reverse Osmosis Design

To predict basic parameters like product quality and energy consumption for a planned RO installation, most of the RO-membrane manufacturers offer software programs. These programs are based on mass transfer terms, thermodynamics and fluid dynamics, and take specific characteristics of the particular RO membrane into account. To design a system, the feed water composition, the required product flow and quality, and the temperature have to be known. Having this basic information, the goal of the system designer is to minimize feed pressure and optimize the hydraulic distribution within the system to minimize fouling while maximizing the permeate quality and the system recovery.

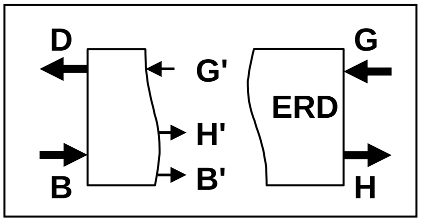
Especially in seawater applications with high feed water salinities, thus high osmotic pressures, the composition of the membrane feed stream has a substantial impact on energy consumption and product water quality. Therefore it is indispensable for the designer of an RO system to know the exact water composition in the entry of the RO-membrane. Due to the mixing of concentrate and feed water in the ERD, a small but not negligible recirculation of seawater around the RO system takes place. For example, for a TDS increase of 1% from 40,000 milligrams per liter (mg/L) to 40,400 mg/L, the concentration of ions will increase by approximately 1% and the required feed pressure increases by approximately 0.5 bar. It should be noted that for trace constituents, such as boron or silica, the affect of mixing on permeate water quality is hardly measurable.

Accounting for recirculation requires an iterative approach to predict the impact of an ERD on an RO-system. The RO-design software by Dow/FilmTec, ROSA (**R**everse **O**smosis **S**ystem **A**nalysis) provides a recirculation stream built in and, accordingly, has the capability to resolve the compositions of the membrane feed, reject and permeate streams taking into account the compounding affects of recirculation and mixing. The recirculation stream together with a seawater bypass stream of equal flow rate can be used to emulate the mixing effect.

Incorporating ERD Mixing into Membrane Design

First, an expression for ERD mixing is derived in terms of the flow rates and salinities fed to the device(s). The ERD is divided and the left end is considered with reference to Figure 3 below. The bulk flow into the left end is low-pressure seawater in stream B and the bulk flow out is high-pressure seawater in stream D. Concentrate mixes into stream D as stream G' and an equal flow rate of seawater exits as stream H'. If the flow rate of stream B is greater than that of stream D, the excess seawater exits as stream B'.

Figure 3 – ERD Divided for Analysis



A mass balance around left end of ERD yields:

$$F_B C_B + F_{G'} C_{G'} = F_D C_D + F_{H'} C_{H'} + F_{B'} C_{B'} \tag{1}$$

where C_X is the concentration of an arbitrary species in stream X, F_X is the flow rate of stream X, $C_G = C_{G'}$, and $C_B = C_{H'} = C_{B'}$. The stream indices are defined in Figures 1 and 3 above. Define Overflush = OF ≡ $(F_B - F_D)/F_D$ such that $F_B = F_D(1+OF)$ and $F_{B'} \equiv F_B - F_D = (OF)F_D$. Define Mixing Flow = $F_M \equiv F_{G'} = F_{H'}$. Insert these relationships into Equation (1) and solve for Volumetric Mixing (VM):

$$\frac{F_M}{F_D} \equiv VM = \frac{C_D - C_B}{C_G - C_B} \tag{2}$$

Note that Overflush drops from the equation. This means that Equation (2) is an accurate expression of volumetric mixing even if overflush is applied. However, changing overflush changes volumetric mixing as indicated in Figure 2. Also note that Equation (2) is independent of the membrane recovery rate.

Define ERD Leakage = L ≡ $(F_G - F_D)/F_G$. Solve for F_D: $F_D = F_G(1 - L)$. Leakage flow is supplied by the high pressure pump. Permeate flow is related to high-pressure pump flow according to the following equation:

$$F_C = F_P \left[\frac{1 - (1 - L)(1 - R)}{R} \right] \tag{3}$$

where R is the Recovery Rate = F_P/F_E , F_C is the high-pressure pump flow rate, F_P is the permeate flow rate and F_E is the membrane feed flow rate.

Rearranging Equation (2), we derive an equation for Mixing Flow: $F_M = VM * F_D$ or

$$F_M = VM(1 - L)F_G \tag{4}$$

In the ERD, concentrate at a concentration of C_G and a flow rate of F_M exchanges with seawater at a concentration of C_B and a flow rate of F_M. Therefore, Equation (4) can be used in the membrane projection model to quantify the flow rate of the brine recirculation stream and the seawater bypass stream.

Conclusions

Developments in membrane and ERD technology have significantly reduced SWRO energy consumption and contributed to its widespread application for fresh water supply. Isobaric ERDs, which are used in the vast majority of new SWRO system designs, allow some mixing between the concentrate reject and the membrane feed. This paper has presented the equations necessary to quantify the mixing effect and provided a relatively simple means to take the mixing effect into account in the SWRO design process.

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References

[1] M. Busch and W.E. Mickols, Reducing Energy Consumption in Seawater Desalination, Desalination, 165 (2004) 299-312.

[2] J.E. Cadotte, Interfacially Synthesized Reverse Osmosis Membrane, US Patent 4,277,344, Patent and Trademark Office, Washington, D.C., July 7, 1981.

[3] W.E. Mickols, M. Busch, Y. Maeda, J. Tonner, A Novel Design Approach for Seawater Plants, IDA Conference, Singapore, 2005.

[4] R.L. Stover, Energy Recovery Devices for Reverse Osmosis, Everything About Water, November 2006, 40-45.

[5] R.L. Stover, Seawater Reverse Osmosis with Isobaric Energy Recovery Devices, Desalination 203 (2007) 168-175.