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Seawater reverse osmosis with isobaric energy recovery devices

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Abstract

The world increasingly depends on desalting seawater or brackish water for producing suitable and sustainable supplies of potable water for local populations, tourism, agriculture and industry. The energy cost component of desalinating seawater has historically been a large factor (up to 70%) of the total cost. There is a limit to the amount of available energy and an environmental consequence associated with every kilowatt consumed. Along with the older style centrifugal energy recovery devices (ERDs), there has been a recent proliferation of ERDs that employs positive displacement mechanisms. These “pressure-equalizing” or isobaric ERDs transfer the energy from the membrane reject stream directly to the membrane feed stream. This direct, positive displacement approach results in a net transfer efficiency of up to 97%. This efficiency advantage makes it possible to dramatically improve the performance of seawater reverse osmosis (SWRO) plants by reducing their energy consumption by as much as 60% compared to systems operating without energy recovery. In addition to energy savings, isobaric ERDs offer significant benefits to SWRO plant designers and operators. These include unlimited capacity, reduced high-pressure pump costs, high efficiency and operational flexibility. The PX pressure exchanger isobaric ERD provides the additional benefits of maintenance-free operation, fail-safe operation, corrosion avoidance, low vibration, ease of control and long life. Although the author of this paper is directly associated with Energy Recovery, Inc., a leading company in isobaric ERD technology, the principles and theories presented in this paper are applicable to all devices that are based on the positive displacement, isobaric chamber approach.

Keywords: SWRO; Desalination; Pressure exchanger; Energy recovery device

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1. Introduction

The desalination market has grown dramatically in recent years, and seawater reverse osmosis (SWRO) technology is leading this growth. SWRO plants have increased in both number and capacity. The largest SWRO plant in the world today is five times larger than the largest plant ten years ago, and another doubling is expected in the next two years. Several market factors have propelled this growth, and incremental improvements in membrane and pump technology have helped make plant operation more reliable and cost effective. But the technological breakthrough most responsible for reducing SWRO energy costs and enabling large-scale SWRO plants has been the development of isobaric energy recovery devices (ERDs).

The power required to drive the high-pressure pump(s) is typically the largest component of the operating cost of SWRO systems. Most of the pressure energy in the feedwater flowing to the SWRO membranes leaves the membranes with the brine reject water. A number of devices have been developed to recover pressure energy from the brine reject stream [1]. These ERDs fall into two general categories: centrifugal and isobaric devices. Centrifugal ERDs, including Pelton wheels, turbochargers and reverse-running pumps, are limited in capacity and have a maximum net transfer efficiency of approximately 82%. Furthermore, these devices are usually optimized for a narrow range of flow- and pressure-operating conditions such that their efficiency declines with seasonal or operational changes. Isobaric ERDs, including piston-type work exchangers and the rotary PX Pressure Exchanger™ device, provide unlimited capacity and a maximum operating efficiency of approximately 97%. 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. Higher ERD capacity is achieved by operating multiple units in parallel, similar to membranes.

In addition, SWRO systems with centrifugal ERDs require high-pressure pumps sized to handle the full membrane feed flow. In SWRO systems with isobaric ERDs, the ERD provides only the brine portion of the feed, thus the high-pressure pump pressurizes only the quantity of water that results in permeate.

The following sections focus on the design and operation of SWRO systems equipped with isobaric ERDs. The reader is directed elsewhere for more detailed discussion of the relative merits of isobaric and centrifugal ERDs [2,3] or to the manufacturer’s literature for design and operational details of specific devices.

2. Design

Optimum SWRO system design requires consideration of many factors including system capacity, capital and operating costs, maintenance requirements and equipment reliability. This section focuses on system capacity and operating cost calculations.

2.1. High-pressure pump capacity

In SWRO systems with isobaric ERDs, the high-pressure pump must only be large enough to supply the combined flow rate of the permeate, ERD leakage or lubrication, and other volumetric loss at the operating pressure of the membranes. The relationship between high-pressure pump flow and permeate flow is illustrated in Fig. 1[*].

In Fig. 1, a dashed-line box is drawn around the high-pressure pump, the membrane array and the high-pressure portion of the ERDs. Nearly all the water that enters the box to feed the high-

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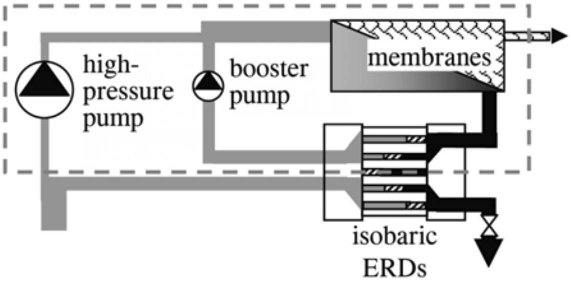

Fig. 1. Schematic diagram of the SWRO system.

pressure pump leaves as permeate. A small amount of water — typically less than 2% of the permeate volume — passes through the seals of the ERD. High-pressure pump flow and permeate flow remain nearly equal regardless of membrane pressure or booster pump flow rate.

In addition to reducing the required size of the high-pressure pump, isobaric ERDs allow the system designer to specify the capacity of the ERDs independent of the capacity of the high-pressure pump. This decoupling has enabled several recent SWRO innovations such as pressure center designs [4]. This decoupling also allows the system designer and operator to vary membrane recovery and membrane flux rate independently as described below. Such flexibility is important for obtaining optimal performance from each piece of equipment and for maintaining design productivity throughout a plant's life.

2.2. Energy consumption

The energy required to desalinate with an SWRO system can be expressed in terms of the specific energy — the energy required per unit output of permeate — and calculated with the following equivalent equations:

$$SE = \left(E_{HP} + E_{BP} + E_{SP}\right)/Q_P \tag{1}$$

$$SE = \Big[Q_{HP}\left(P_{HP} - P_F\right)/\eta_{HP} + Q_{BP}\left(P_{HP} - P_{BPI}\right)/\eta_{BP} + Q_{SP}P_F/\eta_{SP}\,/Q_P\Big] \tag{2}$$

where SE is the SWRO system specific energy, E_{HP} the high-pressure pump energy consumed, E_{BP} the booster pump energy consumed, E_{SP} the supply pump energy consumed, Q_P the permeate flow rate, Q_{HP} the high-pressure pump flow rate, P_{HP} the high-pressure pump outlet pressure, P_F the high-pressure pump feedwater pressure, η_{HP} the high-pressure pump and motor efficiency, Q_{BP} the booster pump flow rate, P_{BPI} the booster pump inlet pressure, η_{BP} the booster pump and motor efficiency, Q_{SP} the booster pump flow rate,and η_{SP} the supply pump and motor efficiency.

Many published comparisons of SWRO energy consumption with different ERDs present only the energy consumed by the high-pressure and booster pumps. This is partly because of the significant variation in pretreatment and supply pumping requirements. However, it is important to consider supply pump energy consumption when comparing devices because of potentially significant differences in low-pressure water consumption.

Between 1% and 2.5% of the brine flow to an isobaric ERD is consumed as leakage or lubrication flow. The exact lubrication flow rate depends upon system pressure, temperature, seawater and brine flow rates, and device characteristics. This flow is supplied by the high-pressure pump and implicitly appears in the above equation as the difference between Q_{HP} and Q_P.

2.3. Overflush

In a piston-type isobaric ERD, the chambers transition from high- to low- pressure as the piston contained in the chamber moves back and forth. A control system is used to manipulate valves and coordinate the timing of the pressure transitions and the piston movement in each chamber with that in other chambers. Each cycle of the piston can be thought of as a batch process. The control system coordinates these batch processes to accommodate the continuous flow of brine from the membranes. Often water must be bypassed or dumped during each cycle to maintain coordination between all the chambers in an array. This loss of pumped and treated water is called overflush. The PX Pressure Exchanger rotary ERD operates automatically and continuously with no overflush.

2.4. Mixing

In all commercially available isobaric ERDs, some contact between the brine and seawater streams occurs inside the device. As a result, these streams mix slightly. The ratio of the volume of brine that transfers into the seawater to the flow rate of the seawater, known as volumetric mixing, can be calculated with the following equation:

$$M = \left(S_{HP\mathrm{out}} - S_{FW}\right) \Big/ \left(S_{HP\mathrm{in}} - S_{FW}\right) \tag{3}$$

where M is the volumetric mixing, $S_{HP\mathrm{out}}$ the salinity of the high-pressure water leaving the ERD, S_{FW} the salinity of the system feedwater, and $S_{HP\mathrm{in}}$ the salinity of the high-pressure brine.

Volumetric mixing is a function of the mixing characteristics of the specific ERD and the ratio of seawater and brine fed to the device but is independent of the membrane recovery rate. Mixing increases the membrane feed salinity to slightly above the salinity of the system feed. The ratio of the increase in membrane feedwater salinity to the system feedwater salinity — the salinity increase — can be estimated by mass balance using the following equation:

$$\begin{aligned} SI = \Bigg\{ & S_{FW} \times \left[1 - M \times \left(1 - R - L\right)\right] - \\ & -S_P \times \left[\frac{R \times M \times (1 - R - L)}{(1 - R)}\right] 1 \Big/ \\ & -\left[\frac{M \times (1 - R - L)}{(1 - R)}\right]\Bigg\} \end{aligned} \tag{4}$$

where SI is the salinity increase, R the membrane recovery, L the ratio of the ERD lubrication flow rate to the brine flow rate, and S_P the permeate salinity. Alternately, salinity increase can be very closely approximated with the following empirical equation:

$$SI \cong R \times M \times 1.025 \tag{5}$$

Eqs. (4) and (5) are based on the simplifying assumption that only one ionic couple is present, namely sodium chloride. Eqs. (3) through (5) apply at “balanced flow” when the high- and low-pressure flows through the ERD are equal.

2.5. Membrane performance

SWRO membrane performance is a function of a number of variables including membrane type, feedwater temperature, salinity and dissolved solids composition, permeate quality requirements, and membrane flux and membrane conversion or recovery rate. The composition of the membrane feedwater is affected by mixing in the ERD, and thus is a function of the composition of the brine reject flowing from the membranes. Because membrane selectivity varies with membrane type, flux and ion type, the composition of the brine differs from the composition of the feedwater, and those differences vary with system operating conditions. Therefore, an accurate prediction of membrane performance would require concurrent consideration of ERD

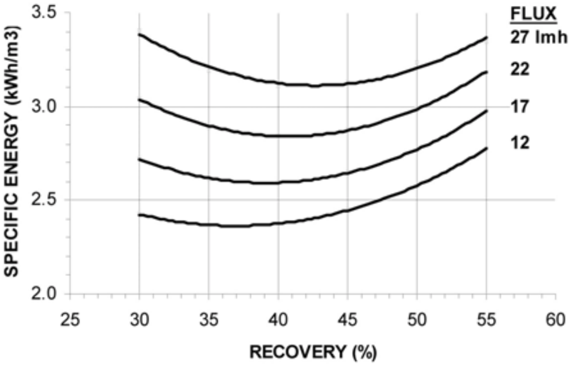

Fig. 2. Case Study: SWRO system specific energy vs. membrane variables.

mixing. Unfortunately, at the time of this writing, no commercially available membrane projection model allows the system designer to account for ERD mixing.

An approximate membrane design can be developed by ignoring individual ion selectivity and balancing and solving Eq. (4) to estimate the bulk membrane feed salinity. The membrane projection model can then be run to provide an estimate of the membrane operating and discharge pressures. These process parameters and Eq. (2) can then be used to estimate energy consumption. The relationship between SWRO system specific energy consumption, membrane recovery and membrane flux for a typical system is illustrated in Fig. 2.

In Fig. 2, specific energy is expressed in units of kilowatt hours per cubic meter of permeate (kWh/m^3) and flux in units of liters of permeate per square meter of membrane surface per hour (lmh). The estimated specific energy data presented in Fig. 2 were derived using a conventional membrane projection model, efficiency data from commercially available pumps, Eq. (4) and published operating data for the PX-220 Pressure Exchanger device. Specific energy was calculated with Eq. (2) above. These data indicate that lower flux rates and lower recovery rates generally result in lower system energy consumption and that an optimal minimum specific energy occurs between approximately 35% and 45% recovery.

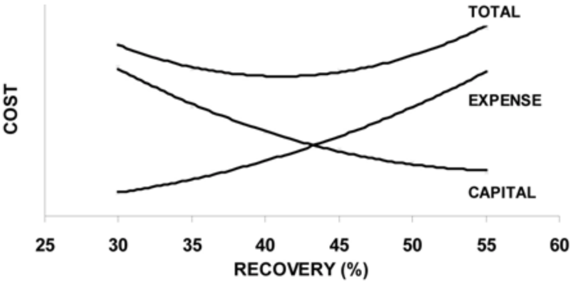

Fig. 3. Overall plant cost optimization diagram.

2.6. Overall cost

Although Fig. 2 suggests that lower energy consumption can be achieved with a greater number of membranes, the SWRO system designer must also consider capital costs. System capacity can be optimized by incorporating all capital and operating costs into an optimization diagram of the type illustrated in Fig. 3.

2.7. Isobaric ERD cost comparison

Commercially available isobaric energy recovery devices operate with different efficiencies, lubrication flows and mixing rates. As described above, all these variables affect overall SWRO operating costs. Different devices can be compared by quantifying the pumping energy required to produce a given flow rate of desalinated permeate with an SWRO system equipped with the device. A comparison of a piston-type isobaric ERD and the ERI PX-220 device is presented in Fig. 4.

The piston-type ERD performance data presented in Fig. 4 are based recently published data for the DWEER* 1100 [5]. The differences

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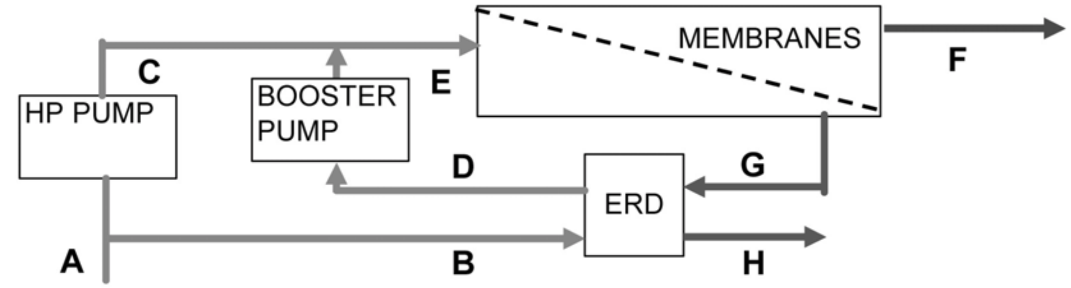
*DWEER is a trademark of DWEER Technology Ltd.



PX		A	B	C	D	E	F	G	H
FLOW	m^3/hr	1818	983	835	983	1818	818	1000	1000
	m^3/day	43636	23589	20046	23589	43636	19636	24000	24000
PRESSURE	bar	1.8	1.8	65.0	62.1	65.0	0.0	63.0	1.0
SALINITY	mg/l	40,500	40,500	40,500	42,593	41,615	350	75,378	73,321

DWEER		A	B	C	D	E	F	G	H
FLOW	m^3/hr	1848	1012	836	982	1818	818	1000	1030
	m^3/day	44356	24288	20068	23568	43636	19636	24000	24720
PRESSURE	bar	2.5	2.5	63.7	60.7	63.7	0.0	61.7	1.0
SALINITY	mg/l	40,500	40,500	40,500	41,000	40,766	350	73,834	72,386

Membrane Differential	bar	2.0
Recovery	%	45%
Temperature	°C	25
HP Pump Efficiency	%	78%
Booster Efficiency	%	77%
Cartridge Filter DP	bar	2.0
Supply Pump Efficienc	%	76%

ERD type		**PISTON**	**PX**
ERD units/Array	qty	5	23
Unit Flow	m3/hr	**200**	**43**
Overflush	%	3%	0%
Lubricant/Array	m3/hr	**18**	**17**
Lubrication	%	1.8%	**1.7%**
HP Differential Press	bar	1.0	**0.9**
LP Differential Press	bar	1.5	**0.8**
Volumetric Mixing	%	1.5%	6.0%
Salinity Increase	%	**0.7%**	**2.8%**
ERD Efficiency	%	**94%**	**96%**
HP Pump Power	kW	**1819**	**1876**
Booster Pump Powe	kW	**106**	**102**
Supply Pump Power	kW	**302**	**249**

Total Power	**kW**	**2227**	**2227**
Specific Energy	**kWh/m^3**	**2.72**	**2.72**

Fig. 4. Isobaric energy recovery device performance comparison.

between the performance of a piston-type ERD and the PX Pressure Exchanger rotary ERD are evident in the data in Fig. 4. No overflush is required with the PX device, but a 3% overflush associated with flow bypass between cycles is typical with a piston ERD. The salinity increase caused by the PX device is higher than caused by a piston ERD, and the result in the case illustrated in Fig. 4 is a 1.4 bar increase in operating pressure. The lubrication flow required by the two types of devices is almost identical and the high- and low-pressure differentials through the PX device are lower. As a result, the efficiency of the PX device is higher. When all these factors are considered, the specific energy consumption of SWRO systems equipped with these two different isobaric ERDs is the same despite differences in individual performance characteristics.

3. Operation

Although the energy consumption is similar in SWRO systems equipped with different ERD technologies, there are significant operational differences. Specifically, recovery variation, flux variation, system control, maintenance and device life differences should be considered.

3.1. Recovery and flux variation

Isobaric ERDs allow the SWRO system operator to vary membrane flux and recovery independently. This concept is illustrated with reference to Fig. 1. If the flow rate of the booster pump is set with a variable frequency drive to be equal to the flow rate of the high-pressure pump, the system will operate at 50% recovery. If the flow rate of the booster pump is increased to double the flow rate of the high-pressure pump, the system will operate at 33% recovery. Neither of these operations significantly changes the high-pressure pump flow rate nor the permeate flow rate. Membrane flux can also be adjusted independent of recovery, although less easily, by directly manipulating high-pressure pump or permeate flow or pressure using a control valve, variable frequency drive or an adjustable supply-booster pump. The decoupling of high-pressure-pump operation and ERD and booster-pump operation provides significant design and operational flexibility.

3.2. SWRO system and ERD control

An SWRO system generally need not be manipulated to sustain peak ERD performance because isobaric ERD efficiency varies little as a function of flow rate or operating pressure. Therefore, controls are required only for the operation of the ERD itself and for keeping the flows and pressures within the capacity limits of the ERD. A PX Pressure Exchanger device operates automatically such that only SWRO system flow and pressure controls are necessary. Specifically, one high-pressure flow meter and pressure gauge and one low-pressure flow meter and pressure gauge are required to operate a PX device array.

Piston-type ERDs require additional controls to operate valves and to limit piston movement. Each ERD in a piston-ERD array must be operated individually and in conjunction with the other devices in the array to minimize overflush/ bypass and to prevent excessive pulsations.

3.3. Maintenance

ERD maintenance must be considered in SWRO system operation because of the direct costs of the maintenance and because of the cost of the associated system downtime. The PX device requires no periodic maintenance. If a PX rotor stops spinning for any reason, water flows through the device unimpeded because there are no pistons or barriers in the flow paths through the device. Flow through a stopped rotor will cause higher salinity at the membranes, however, large SWRO systems that employ multiple PX devices can operate indefinitely and safely with one or more stopped rotors. This fail-safe design feature provides plant operators the latitude to postpone or schedule maintenance when convenient. The open flow channels through the PX device also facilitate easy startup and shutdown.

Piston-type isobaric ERDs do require periodic maintenance of the piston and the all the valves and subsystems necessary for device operation. Piston ERDs, which have barriers in the flow paths, can require immediate emergency maintenance in the event of device failure. Device failure can shutdown an SWRO system, and in plants with pressure-center or collector designs, an individual device shutdown can stop the entire plant. Lost uptime, if it occurs, is a significant cost.

3.4. Device life

Factors that adversely affect the longevity of SWRO equipment include corrosion, vibration and abrasion (wear). Pressure transfer in the PX device takes place in a ceramic rotor enclosed in ceramic components. This ceramic is the same material used in bullet-proof sheathing. It is approximately three times harder than steel and never corrodes in seawater. Vibration and pulsation are negligible. The single moving part in the PX device — the rotor — floats on a hydrodynamic bearing of seawater which prevents solid–solid contact and thereby avoids abrasion wear. This combination of physical and dynamic characteristics assures maximum device life. Metal components in other ERDs corrode, wear and fatigue which reduces performance and can eventually result in device failure. Specifically, valve wear manifests as excess leakage and piston wear as excess mixing. To prevent unexpected shutdowns, piston-type ERDs require periodic maintenance and component replacement.

4. Conclusions

Isobaric ERDs offer significant benefits to SWRO plant designers and operators. These include unlimited capacity, reduced high-pressure pump costs, high efficiency and operational flexibility. Among the commercially available isobaric ERDs, the PX Pressure Exchanger isobaric ERD provides the following advantages:

- minimal simple controls
- fail-safe operation
- maintenance free operation
- corrosion avoidance
- low vibration
- long life

These design and operational advantages have not only made isobaric ERDs the best choice for energy recovery in SWRO systems, they have also enabled the tremendous growth and success of SWRO for desalination applications.

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