Energy Recovery Devices in Desalination Applications

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Abstract

Membrane desalination is a pressure-driven process. A significant amount of the energy imparted into the feedwater flowing to the reverse osmosis (RO) membranes leaves the membranes in the concentrated reject water. A number of devices have been developed to recover pressure energy from the reject stream of seawater RO processes. Turbine-based, centrifugal energy recovery devices have been employed since the early 1980s. These devices are still in use where inexpensive power is available. However, it is the widespread adoption of positive-displacement “isobaric” energy-recovery devices since 2002, together with improved membrane performance, that has made membrane desalination an affordable and widely-accepted technology deployed around the world.

Isobaric energy recovery devices such as the ERI PX Pressure Exchanger® device can reduce the energy consumption of a seawater RO system by as much as 60% compared to a system with no energy recovery device or by as much as 30% compared to a system with a centrifugal energy recovery device. Since energy prices are rising and energy consumption can comprise as much as 75% of the total operating costs of a seawater RO plant, it has become almost inconceivable to build a seawater RO process without using isobaric energy recovery technology.

However, acceptance of these devices in brackish RO processes has not been as rapid. With membrane feed pressures of 28 bar or 400 psi or less and water recovery rates of up to 85%, brackish RO processes have as little as one quarter the energy in their reject streams compared to a seawater RO processes of similar permeate capacity. Nevertheless, isobaric energy recovery devices do save energy in brackish systems and can provide quick payback, especially in relatively high salinity, low recovery applications or where the cost of power is high. Improved devices developed specifically for brackish applications offer better performance at a lower capital cost. In addition, isobaric energy recovery devices provide significant operating flexibility by maintaining high energy transfer efficiency performance over a wide range of flow rates and membrane recovery rates.

The author presents an overview of energy recovery devices for RO applications. Process energy consumption and operational flexibility are discussed. Cost benefit analyses are provided for example seawater and brackish systems to identify best available energy recovery technologies for various RO operating conditions.

Keywords

desalination; efficiency; energy recovery device; reverse osmosis

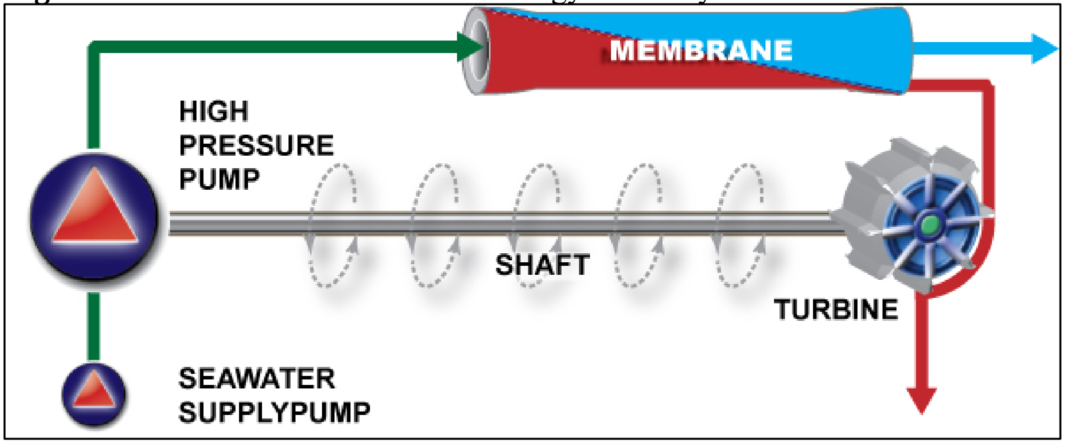
INTRODUCTION

Membrane desalination processes use hydraulic pressure to overcome the osmotic pressure of saltwater to force purified water through a semi-permeable membrane filter. The natural osmotic flow of water from purified water to saltwater is reversed, hence the name “reverse osmosis” or RO. A significant amount of the energy in the feedwater pumped to the RO membranes leaves the membranes in the concentrated reject water. In seawater RO processes, where the salinity of the feedwater typically ranges from 3 to 4% and membrane feed pressures typically exceed 65 bar or 900 pounds per square inch, the energy in the reject stream is substantial enough that its effective and efficient recovery largely determines the financial viability of the process. In brackish RO processes, where the salinity of the feedwater typically ranges from 0.05 to 1% and membrane feed pressures from 10 to 28 bar, the energy in the reject stream is less but nevertheless presents an opportunity for energy recovery.

ENERGY SAVINGS WITH ENERGY RECOVERY DEVICES

A number of devices have been developed to recover pressure energy from the reject stream of RO processes. Turbine-based, centrifugal energy recovery devices (ERDs), such as Pelton turbines or hydraulic turbochargers, have been employed since the 1980s. A typical RO process with a turbine is illustrated in Figure 1.

Figure 1. RO Process with a Turbine Energy Recovery Device.



The membrane concentrate is ejected at high velocity through one or more nozzles onto a turbine wheel. The turbine, mechanically coupled to the high-pressure pump shaft, assists the motor in driving the pump that pressurizes the RO system. Because energy is transformed twice, once by the turbine and once by the pump impeller, energy is lost. The water-to-water transfer efficiency of a turbine ERD system is the product of the turbine and impeller efficiencies which range from 70% to a maximum of 90%. Therefore, the overall efficiency of the ERD is typically 60 to 75%.

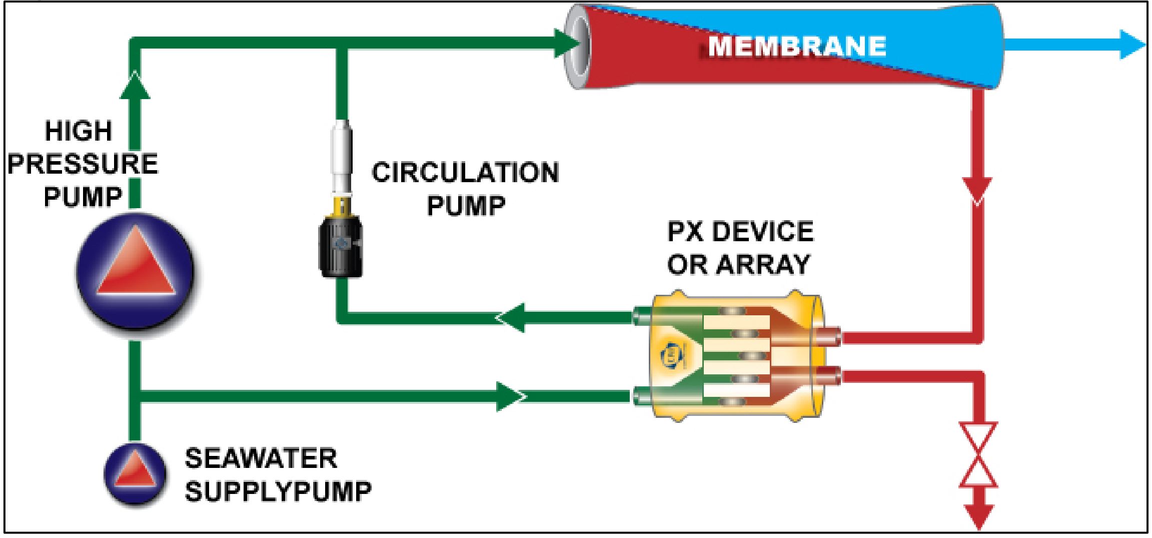
Energy consumption in an RO system equipped with a turbine ERD is the energy required by the high-pressure pump motor. It can be computed by subtracting the energy recovered by the turbine from the hydraulic energy in the high-pressure pump discharge and dividing by the pump and motor efficiency as illustrated in Equation 1.

$$\text{Energy Consumption} = \frac{Q_{HP} \times P_{HP} - Q_R \times P_R \times \eta_T \times \eta_{HP}}{\eta_{HP} \times \eta_{HPM}} \tag{1}$$

Q_{HP} is the high-pressure pump flow rate, P_{HP} is the high-pressure pump differential pressure, η_{HP} is the high-pressure pump efficiency, Q_R is the turbine flow rate, P_R is the turbine differential pressure, η_T is the turbine efficiency and η_{HPM} is the high-pressure pump motor efficiency. Pelton turbines discharge at atmospheric pressure so P_R is, effectively, the membrane reject pressure.

Isobaric energy recovery devices employ a positive-displacement energy transfer mechanism to transfer pressure from the high-pressure reject stream to a low-pressure seawater stream from the supply pump. They have been widely employed in seawater RO processes since 2002. These devices achieve energy-transfer efficiencies of up to 98% (Sanz and Stover, 2007). A typical process configuration for an RO system equipped with isobaric ERDs is illustrated in Figure 2.

Figure 2. RO Process with an Isobaric Energy Recovery Device.



A seawater RO process equipped with PX Pressure Exchanger® isobaric ERDs is shown in Figure 3.

Figure 3. Seawater SWRO Process with PX Pressure Exchanger ERDs.

Isobaric ERDs transfer pressure from the high-pressure brine reject to a portion of feed water by putting them in direct contact in pressure-equilibrating or isobaric chambers. Concentrate rejected by the membranes flows to the isobaric ERD(s), driven by a circulation (booster) pump. The ERD replaces the concentrate with feedwater. Pressurized feedwater merges with the discharge of the high-pressure pump to feed the membranes. Some mixing occurs between the concentrate and feedwater in the ERD resulting in a slight increase in the membrane feed salinity and a corresponding increase in the membrane feed pressure.

Energy consumption in an RO system equipped with isobaric ERDs is the sum of the energy consumed by the high-pressure pump and circulation pump motors. It can be computed using Equation 2.

$$\text{Energy Consumption} = \frac{Q_{HP} \times P_{HP}}{\eta_{HP} \times \eta_{HPM}} + \frac{Q_{CP} \times P_{CP}}{\eta_{CP} \times \eta_{CPM}} \qquad (2)$$

Q_{CP} is the circulation pump flow rate, P_{CP} is the circulation pump pressure and η_{CP} is the circulation pump efficiency, η_{CPM} is the circulation pump motor efficiency and the rest of the variables were defined above. It should be noted that the efficiency or performance of the isobaric ERD is not directly included in the energy consumption equation, rather it appears implicitly as a reduction in the high-pressure pump flow rate, Q_{HP}.

Pressure, flows and energy consumptions for an example seawater RO process equipped with no ERD, a turbine ERD or an array of isobaric ERDs are listed in Table 1. In Table 1, "recovery rate" is the membrane water recovery rate defined as the ratio of the permeate flow rate to the membrane feed flow rate. The high-pressure pump discharge pressure, assumed to be equal to the membrane feed pressure in Table 1, is a function of recovery rate for a given membrane design, feedwater salinity and feedwater temperature (ROSA, 2007).

Table 1. Seawater RO Process Energy Consumption Comparison.

		No ERD	Turbine ERD	Isobaric ERD
Permeate Flow	(m^3/hr)	227	227	227
Recovery Rate	(%)	40	40	40
High-Pressure Pump Flow	(m^3/hr)	568	568	231
High-Pressure Pump Pressure	(bar)	68	68	69
High-Pressure Pump Energy	(kW)	1421	847	600
Turbine Efficiency	(%)	--	83	--
Circulation Pump Flow	(m^3/hr)	--	--	338
Circulation Pump Pressure	(bar)	--	--	2
Circulation Pump Energy	(kW)	--	--	30
Total Energy	(kW)	1421	847	629

m^3/hr = cubic meters per hour, kW = kilowatts

Isobaric ERDs can reduce the energy consumption of a seawater RO system by as much as 60% compared to a system with no ERD or by as much as 30% compared to a system with a turbine ERD. If the cost of power is $0.08/kWh, application of isobaric ERDs in the system illustrated in Table 1 would save approximately $550,000 per year compared to a system with no ERD or over $150,000 per year compared to a system with a turbine ERD. The corresponding payback for installing isobaric ERDs, a circulation pump and peripheral equipment would be approximately 4 months. This payback estimate does not consider the capital cost savings associated with the smaller high-pressure pump required in RO systems with isobaric ERDs.

Financial considerations such as this have made it almost inconceivable to build a seawater RO process without using isobaric ERD technology. Many SWRO processes built with turbines have been retrofit with isobaric ERDs to either reduce the energy required to produce the same amount of permeate or to increase the amount of permeate that can be produced with the same high-pressure pump (Stover and Cameron, 2007).

ERDS IN BRACKISH REVERSE OSMOSIS SYSTEMS

Brackish water can be found where seawater and fresh water merge, for example, in marine estuaries or in underground aquifers near coastlines. Because the salinity is lower, the osmotic pressure and the corresponding membrane feed pressure of a brackish RO process are lower than that of a seawater RO process. Equipment for brackish RO systems is typically rated for a maximum service pressure of 28 bar or 400 psi. In addition, brackish RO processes are often operated at higher recovery rates than seawater processes, thereby reducing the flow rate of the reject stream. Pressure, flows and energy consumptions for an example brackish RO process are listed in Table 2.

Table 2. Brackish RO Process Energy Consumption Comparison.

		No ERD	Turbine ERD	Isobaric ERD
Permeate Flow	(m^3/hr)	200	200	200
Recovery	(%)	60	60	60
High-Pressure Pump Flow	(m^3/hr)	333	333	201
High-Pressure Pump Pressure	(bar)	21	21	22
High-Pressure Pump Energy	(kW)	257	192	163
Turbine Efficiency	(%)	--	83	--
Circulation Pump Flow	(m^3/hr)	--	--	132
Circulation Pump Pressure	(bar)	--	--	2
Circulation Pump Energy	(kW)	--	--	10
Total Energy	(kW)	257	192	173

In the brackish RO process illustrated in Table 2, isobaric ERDs reduce energy consumption by 33% compared to a system with no ERD. If the cost of power is \$0.08/kWh, the corresponding cost savings with isobaric ERDs would be approximately \$67,000 per year. Although the energy savings is less than can be achieved with ERDs in a seawater RO system, isobaric ERDs for brackish applications are less expensive. A payback of 19 months is possible for an isobaric ERD system of the capacity required for the RO process described in Table 2. The corresponding payback for a turbine system is estimated to be 16 months with an estimated annual savings of \$52,000. Although payback is shorter with a turbine ERD, the savings that can be achieved with over the life of a plant is greater with an isobaric ERD.

Figure 4 presents the estimated payback time for a brackish RO system equipped with isobaric ERDs using the system capacity and cost assumptions described above.

Figure 4. Estimated Payback Time for a System Equipped with Isobaric ERDs.

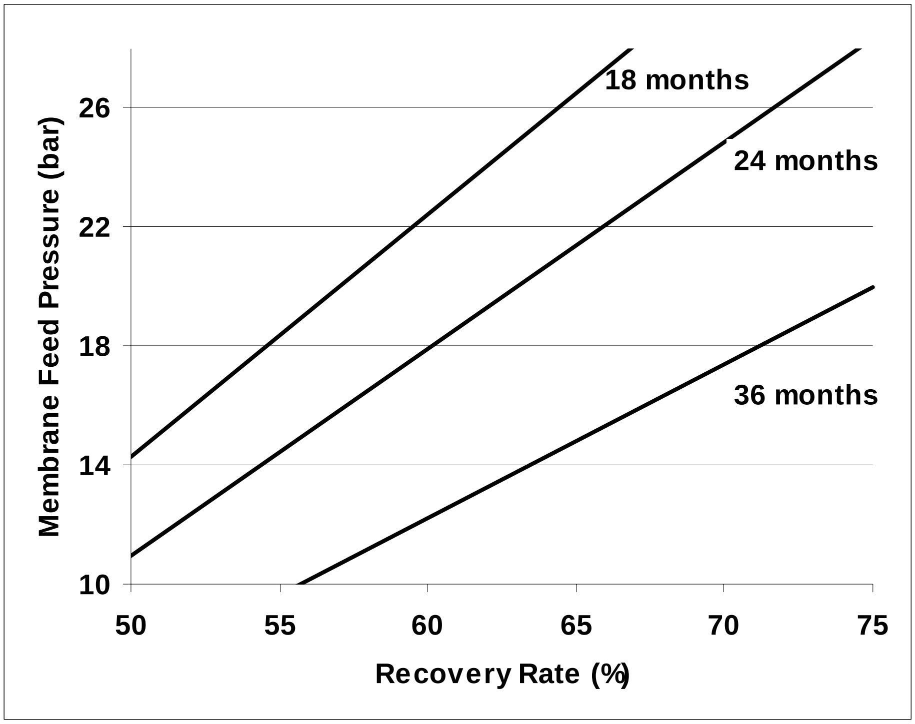


Figure 4 shows that energy savings depends strongly upon the membrane feed pressure and recovery rate. Higher membrane feed pressures and lower recover rates provide the fastest payback for isobaric ERD system installations.

OPERATIONAL FLEXIBILITY WITH ISOBARIC ERDS

Energy savings is not the only consideration important in the design and operation of RO systems with ERDs. As positive displacement devices, isobaric ERDs provide high, constant energy transfer efficiency over a wide range of flows and pressures. Therefore, the membrane water recovery rate can be adjusted without significantly increasing the energy required to produce a unit of permeate. Altering membrane recovery changes the flow rate to the energy recovery device array. Although the maximum flow rate through each energy recovery device is limited, additional units can be added as necessary to accommodate a wide range of membrane recovery rate variation.

An example of how membrane recovery rate can be altered in an RO system equipped with an isobaric ERD is given with reference to Figure 2 above. If the flow rate of the circulation 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 circulation pump is increased to double the flow rate of the high-pressure pump, the system will operate at 33% recovery. As membrane recovery is reduced, membrane pressure reduces and the load on the high-pressure-pump motor reduces. As recovery rate is increased, membrane pressure increases but the RO system requires less feedwater. Such adjustments in response to day-to-day variations in feedwater quality or over the course of the life of a plant can significantly benefit membrane performance.

For instance, if heavy fouling conditions occur, the recovery rate can be lowered, increasing membrane cross flow and reducing contaminant deposition and biological growth on membrane surfaces. This can be especially beneficial in brackish RO systems where the potential for biological growth and membrane fouling is high. Alternately, recovery can be increased when feedwater temperatures are high to minimize permeate salinity. In this way, an operator can manipulate and optimize RO system performance to achieve low energy consumption throughout the year. Flexible recovery and low-recovery operation are tremendous advantages for low-cost RO operation provided by isobaric ERD technology.

CONCLUSIONS

Energy recovery devices have become essential components in seawater reverse osmosis desalination systems because of the energy savings they provide. Although the energy savings they provide is less than in seawater RO systems, these devices also provide energy savings in brackish RO. Isobaric ERDs provide greater energy savings in either seawater or brackish RO systems than do turbine ERDs because they operate at higher water-to-water energy-transfer efficiencies. The cost savings benefit of isobaric ERDs in brackish RO systems depends upon the membrane feed pressure and recovery rate with faster payback in systems with high membrane feed pressures and lower recovery rates. In addition, isobaric ERDs facilitate operational flexibility by accommodating variable membrane water recovery rates.

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