ENERGY RECOVERY DEVICES FOR HIGH PRESSURE HYDRAULIC APPLICATIONS

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ABSTRACT

Membrane desalination is a pressure-driven process. A significant amount of the energy imparted into the water fed to the reverse osmosis (RO) membranes leaves in the concentrated reject water. A number of devices have been developed to recover pressure energy from this reject stream. Turbine-based, centrifugal energy recovery devices (ERDs) have been employed since the early 1980s. These devices are still in use in low-pressure RO processes or where inexpensive power is available, such as in Saudi Arabia. It is, however, the widespread adoption of positive-displacement “isobaric” ERDs since 2002, together with improved membrane performance, that has made desalination an affordable, and widely accepted, technology deployed around the world. Most seawater RO plants, and an increasing number of brackish water RO plants, being designed and built today utilize positive-displacement energy recovery devices such as the ERI PX Pressure Exchanger device to save energy.

Although most isobaric ERDs were designed for membrane desalination applications, they can potentially be applied to any high-pressure fluid application to recovery pressure from a waste or reject stream and use it to pressurize another stream. The mechanics of the PX Pressure Exchanger device are described in detail in consideration of its suitability for other high-pressure hydraulic applications.

Keywords: energy recovery, positive displacement, pressure exchanger, pump, reverse osmosis

INTRODUCTION

Four decades ago President John F. Kennedy said, "If we could produce fresh water from salt water at a low cost that would indeed be a great service to humanity and would dwarf any other scientific accomplishment." Until the advent of high-performance reverse osmosis membranes in the 1980s, distillation was the only available means to desalinate seawater. But the exceedingly high cost of brine-compatible equipment, the high maintenance requirements and energy costs exceeding \$3 per 1000 gallons (\$/kgal) have made municipal drinking water desalination of water by distillation impossible in most of the world.

Reverse osmosis desalination systems pump salt water to sufficient pressures to overcome the osmotic pressure of the water and force desalinated water through a selective membrane. Operating pressures depend on the salinity of the feedwater and the membrane characteristics, but typically range from 800 to 1,000 pounds per square inch (psi) for seawater RO. The volume of the concentrated reject stream from seawater RO systems is at least half the volume of the high pressure seawater fed to the membranes, therefore, recovery of energy from the reject stream has a significant impact on seawater RO plant economics. Energy recovery is also beneficial in brackish RO systems, but because of the lower salinity, the osmotic and operating pressures are lower and the conversion or recovery rate higher. These reduce the pressure and volume of the reject stream, respectively, relative to seawater RO processes, making energy recovery less important in brackish RO systems.

ENERGY RECOVERY DEVICES

A number of devices have been developed to recover pressure energy from the membrane reject stream and return it to the feed of the RO process. Turbine-based, centrifugal energy recovery devices, 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.

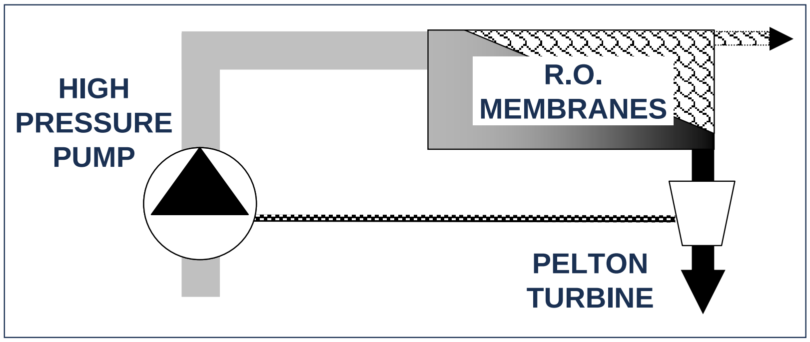

Figure 1: RO Process with a Turbine ERD

The membrane concentrate is ejected at high velocity through one or more nozzles onto a turbine wheel. The turbine, 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. The component efficiencies range from 70% to a maximum of 90%. Therefore, the overall efficiency of a turbine ERD is typically 50 to 75%.[1]

Energy consumption in the high-pressure portion of 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 net useful energy recovered by the turbine from the hydraulic energy in the high-pressure pump discharge and dividing by the pump and motor efficiency. Efficient, modern seawater RO plants operating with turbine ERDs can typically produce desalinated water for less than $1.00/kgal.

To avoid the losses associated with the energy-transformation inherent in turbine ERDs, engineers developed positive-displacement isobaric devices for RO. These devices have been widely deployed since about 2002. They place the RO reject and filtered feedwater in contact inside pressure-equalizing, or isobaric, chambers. There are currently two commercially available types of isobaric ERDs including several piston-type work exchangers and the rotary PX Pressure Exchanger (PX) device. Piston-type devices have large chambers, pistons separating the concentrate and feed water, and valves and control systems to switch flow between the chambers and limit the travel of the pistons. The PX device has small chambers, no pistons and no direct controls.[2]

A simplified process flow diagram of an RO process with isobaric ERDs is shown in Figure 2. Concentrate rejected by the membranes (stream G) flows to the ERD(s), driven by a circulation pump. The ERDs replace the concentrate with feedwater from the low-pressure supply system (streams A and B). The pressurized feedwater (stream D) merges with the discharge of the high-pressure pump (stream C) to feed the membranes (stream E). Water leaves the process as permeate from the membranes (stream F) or as spent low-pressure concentrate from the ERDs (stream H).

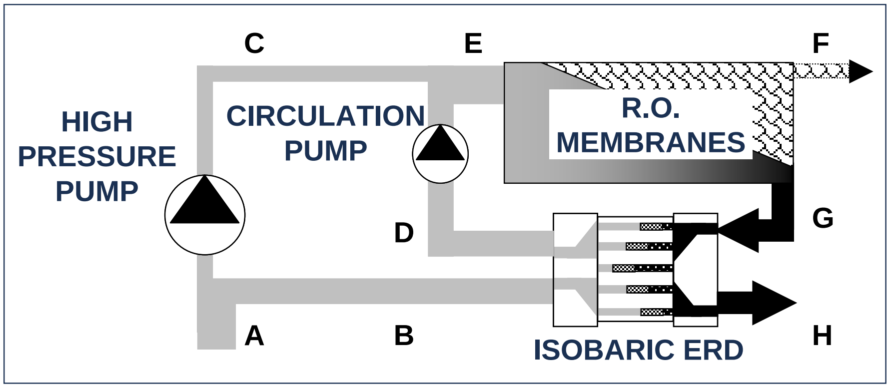

Figure 2: Simplified Diagram of an RO Process with Isobaric ERDs

ENERGY CONSUMPTION CALCULATION

The energy required to operate the high-pressure portion of an RO system equipped with isobaric ERDs is the sum of the high-pressure pump and circulation pump energy consumption. This is expressed in terms of the energy required per unit output of permeate or the specific energy:

$$SE_{PX} = Q_{HP}\left(P_{HP} - P_F\right)/\left(\eta_{HP} Q_P\right) + Q_{CP}\left(P_{HP} - P_{CPI}\right)/\left(\eta_{CP} Q_P\right)$$

where:

SE_{PX} = specific energy

Q_P = permeate flow rate

Q_{HP} = high-pressure pump flow rate

P_{HP} = high-pressure pump outlet pressure

P_F = high-pressure pump feedwater pressure

η_{HP} = high-pressure pump and motor efficiency

Q_{BP} = circulation pump flow rate

P_{CPI} = circulation pump inlet pressure

η_{CP} = circulation pump and motor efficiency

Typical values for a seawater RO process are given in Table 1 with reference to the stream locations in Figure 2. Plant energy consumption calculated with Equation 1 also appears in Table 1.

		A	B	C	D	E	F	G	H
FLOW	gpm	5000	2973	2027	2973	5000	2000	3000	3000
PRESSURE	psi	25	25	870	838	870	0	853	15
SALINITY	ppm	34,000	34,000	34,000	35,437	34,849	207	57,943	56,520

SYSTEM PARAMETERS

PX units/Array	qty	12
Unit Flow	gpm	250
Lubrication	%	0.9%
Total Lubricant	gpm	27
PX Unit Efficiency	%	96%
Conversion	%	40%

CIRCULATION PUMP

Efficiency	%	80%
Power	kW	52

HIGH PRESSURE PUMP

Efficiency	%	80%
Power	kW	933

SYSTEM PERFORMANCE

Specific Energy	kWh/1000 gal	8.21
Specific Energy	kWh/cubic meter	2.17

Table 1: Example Seawater RO System Performance Data

In an RO system equipped with PX devices, the flow rate through the high pressure pump is approximately equal to the permeate flow rate as indicated in Table 1. This means that the high pressure pump only pumps the amount of water that leaves the system as permeate. The majority of the water circulated through the membranes is moved by the circulation pump. Because the circulation pump imparts minimal pressure, is consumes very little energy: approximately 6% of the energy consumed by the high pressure pump. This aspect of PX technology benefits RO operation by reducing the required size and energy consumption of the high pressure pump and by allowing a plant to operate affordably at a low conversion rate. Lower conversion rates correspond with lower membrane pressures and longer membrane life.[3]

PX DEVICE MECHANICS

The PX device facilitates pressure transfer from the high pressure brine reject stream to the low-pressure seawater feed stream. It does this by putting the streams in direct, momentary contact in the ducts of a rotor. The rotor is fit into a ceramic sleeve between two ceramic end covers with precise clearances that, when filled with high pressure water, create an almost frictionless hydrodynamic bearing. At any given instant, half of the rotor ducts are exposed to the high-pressure stream and half to the low pressure stream. A schematic representation of the ceramic components of the PX device and the flow paths through it is provided in Figure 1.

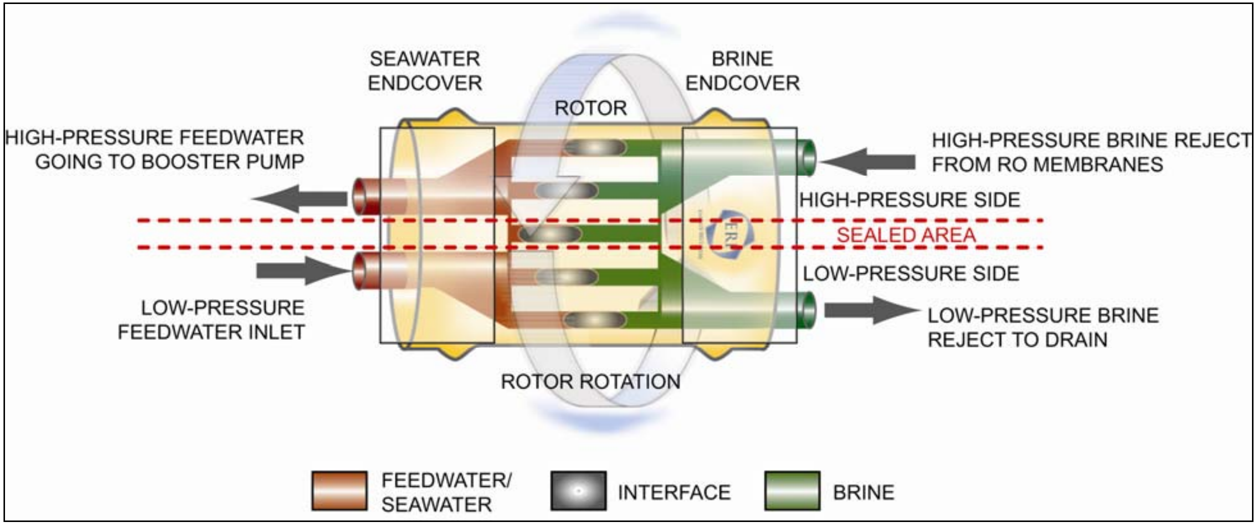

Figure 3: PX Device Diagram

As the rotor turns, the ducts pass a sealing area that separates high and low pressure. The ducts that contain high pressure are separated from the adjacent ducts containing low pressure by a seal formed with the rotor's ribs and the ceramic end covers. To minimize flow through this seal, the gap between the mating parts is extremely narrow. One of the primary engineering challenges for making the PX device work is creating a gap which does not change over a long service life despite temperature variations and fluctuating high hydrostatic and hydrodynamic forces.

With reference to Figure 3, seawater from a supply pump flows into a rotor duct on the left side at low pressure. This flow expels brine from the duct on the right side. After the rotor turns past a sealing area, high-pressure brine flows into the right side of the duct, compressing and expelling the seawater. Pressurized seawater then flows to a circulation pump. This pressure exchange process is repeated in each duct with every rotation of the rotor, so that the ducts are continuously filling and discharging. About 20 revolutions are completed every second.

The PX rotor contains no pistons or barriers. When the rotor is not spinning, flow passes directly through the device making PX operation during RO startup and shutdown almost automatic. Mixing between the brine and seawater streams is limited by the aspect ratio of the rotor ducts which are long and narrow. The PX is designed so that the interface between the brine and seawater in a duct never reaches the end of the rotor before the duct is sealed. Supplying up to 5% extra seawater to the PX flushes the rotor and reduces the mixing effect.

Like reciprocating pumps, the positive-displacement pressure transfer mechanism used in isobaric ERDs delivers high, constant efficiency despite pressure and speed/flow rate variations. Efficiency ranges from 96 to 98% in standard PX devices operating at seawater RO pressures. As a result, most seawater RO plants being designed and built today utilize PX technology. Many plants built with centrifugal ERDs have been retrofitted or their operators are considering converting to isobaric devices to reduce energy consumption and increase production capacity.[3]

PX technology achieves superior energy transfer performance and reliability in desalination applications because of the following features:

> ***Ceramic:*** The high-impact-resistant aluminum oxide ceramic used in the PX device is the same material used in bullet-proof sheathing. Gaps between mating parts can be extremely

narrow because of the stiffness and hardness of the ceramic. This material is ideal for salt water applications because, unlike metals, it never corrodes and it maintains exceptional dimensional stability.

Positive Displacement: The PX device applies a positive displacement mechanism. Therefore, its efficiency is very high and constant over a broad range of flows and pressures. This characteristic differs from centrifugal devices whose performance declines as flows and pressures shift away from peak design operating conditions, similar to the performance of a centrifugal pump.

Single Moving Part: The rotor is the only moving part in the PX device. Driven by the flow, it floats on a seawater-lubricated hydrodynamic bearing and requires no periodic maintenance. Rotor speed adjusts automatically to maintain constant mixing and pressure transfer performance.

PX DEVICE INSTALLATIONS AND APPLICATIONS

PX technology is employed in hundreds of desalination plants around the world. Single devices are used in relatively small RO trains, while multiple PX devices are connected by manifolds to run in parallel to serve large trains. Examples of large seawater RO plants currently operating with PX technology include the 200,000 m^3/day plant in Hamma, Algeria plant[4] and the 140,000 m^3/day plant in Perth, Australia.[5]

Although it was developed specifically for membrane desalination applications, PX Pressure Exchanger technology can potentially be applied to any hydraulic pressure-recovery application. One such application is water elevation, such as is necessary in mining applications. The head pressure of a down-flowing stream could be used to pressurize an up-flowing stream with just the energy required to drive a small booster pump to overcome friction losses.

Another potential application is in high-pressure liquid-liquid heat transfer. A PX device could be used to depressurize a process stream prior to heat transfer and then repressurize the stream. This would reduce the pressure requirement and associated cost of the heat exchanger.

Another application currently under development is osmotic power technology.[6] Osmotic power consists of exposing a fresh water stream to a salt water stream across a semi-permeable membrane. The osmotic pressure that results is used to drive a turbine and generate electricity. The diluted pressurized salt water waste and fresh seawater are run through the PX device to recover the pressure energy. As in desalination application, the PX device serves as a seal for the high-pressure portion of the process.

CONCLUSIONS

Many desalination plants being designed and built today save energy by utilizing isobaric energy recovery devices, such as the ERI PX Pressure Exchanger device. Isobaric ERDs save energy by reducing the water that must be pressurized by the high-pressure pump. Seawater RO systems equipped with isobaric ERDs consume 15 to 30% less energy than comparable systems equipped with turbine ERDs such as Pelton turbines. Although it was developed specifically for membrane desalination applications, PX technology can potentially be applied to any hydraulic pressure-recovery application.

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