Sustainable Desalination of Seawater

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ABSTRACT

The demand for fresh water continues to grow, driven by increasing population densities in urban areas that lack sufficient fresh water and an increasing global need for water for agriculture and industry. One of the ways to meet this demand for fresh water is desalination – removing dissolved salt from seawater. With the abundance of seawater on the planet, desalination is an attractive and viable long-term option. There are now 13,080 desalination plants in operation around the world according to the International Desalination Association. In California alone, some 20 seawater desalination plants have been proposed, including a $300 million facility near San Diego.

Seawater reverse osmosis is an advanced desalination process used to filter water in which seawater is forced through a semi-permeable membrane, producing pure water on one side and concentrated brine on the other. The process, however, has historically been energy-intensive because of the high pressures that must be attained for it to work effectively. Recent technological advances, including the development of energy recovery devices, have dramatically improved the energy efficiency and reduced cost. Early energy recovery devices were only 50% to 75% efficient but newer ones can recover up to 98% of the energy from the high-pressure membrane reject stream.

This paper describes seawater reverse osmosis processes, reviews the technologies used to minimize energy consumption and contrasts their efficacy. It also examines the role of energy recovery devices in improving the energy efficiency of high pressure water application beyond desalination.

Keywords: desalination, seawater, energy, ERD, ERI

1 INTRODUCTION

Water scarcity is recognized as a significant problem throughout the world. Yet the demand for fresh water continues to grow, driven by the need for drinking water to satisfy the world's growing population, changing weather patterns, an increasing need for water for agriculture and industry and the concentration of populations in urban areas that lack sufficient fresh water resources. Humanity now uses more than half of the available surface fresh water on earth. In 2003, the United Nations Population Fund predicted that global consumption will increase by 40% by 2025. A study conducted by the International Water Management Institute projects that by 2025, 33% of the population of the developing world will face severe water shortages. The uneven geographic distribution of fresh water supplies compounds this problem; at least 300 million people live in regions that already have severe water shortages. By 2025, the number could be 3 billion.

Existing water resource infrastructures are being strained in many regions, in part because of changing weather patterns and surface water availability. A relevant example comes from Australia, where the Serpentine Dam was constructed in 1961 to supply water to the city of Perth. At the time, Serpentine Dam had a 98% assured yield of 51 million cubic meters per year but its yield has since been de-rated on three occasions down to 15 million cubic meters per year. Indeed, by 2006 it was mostly a dry dam basin with a yield of just five million cubic meters per year. For another example, the Governor of California recently declared a statewide drought emergency. State officials say California's water supply remains critically low because of three dry winters in a row, restrictions on water pumped from the Sacramento-San Joaquin River Delta and a population that has grown by 9 million since the last drought in 1991. Mandatory water rationing may be implemented this summer for the first time in history.

Climate change will likely increase the demand for fresh water and further disrupt existing water supply resources. Temperatures are expected to increase by 0.3 deg C per decade.[7] Results from Australia, from the Melbourne Water Climate Change Study, estimate that this increase will cause an 8% reduction or possibly as high as an 11% reduction in rainfall by 2020. Climate change is expected to increase the ratio of rain to snow, delay the onset of the snow season, accelerate the rate of spring snowmelt and shorten the overall snowfall season, leading to more rapid and earlier seasonal runoff. According to the United Nations Intergovernmental Panel on Climate Change, "increases in average atmospheric temperature accelerate the rate of evaporation and demand for cooling water in human settlements, thereby increasing overall water demand." In addition, rising sea levels may exacerbate seawater intrusion problems in coastal aquifers or rivers that communities currently depend on for water.

Water scarcity can be addressed, in part, through conservation and recycling as well as through better use of conventional resources. Modern seawater desalination technology is a sustainable new source of fresh water, however, that should be a component of any program designed to address long-term water supply needs.

2 SEAWATER REVERSE OSMOSIS

Reverse osmosis is a water desalination process that produces drinking water by forcing seawater against a semi-permeable membrane, producing pure water on one side and concentrated brine on the other. Reverse osmosis is widely used around the world; indeed, reverse osmosis processes accounted for 59% of contracted desalination capacity as of September 2008, having grown at a rate of 17% per year since 1990.

Reverse osmosis processes, however, can be energy-intensive because of the high pressures that must be attained for it to work effectively. In seawater reverse osmosis (SWRO) systems, an operating pressure of 870 to 1015 psi is required. Even at these pressures a maximum of approximately 50% of the available pure water can be extracted before the osmotic pressure becomes so high that additional extraction is not economically viable. The rejected concentrate leaves the process at nearly the membrane-feed pressure. The combination of the high required membrane-feed pressure and the high-volume reject stream has historically limited the deployment of large-scale SWRO to regions where power is inexpensive and abundant.

2.1 Turbine 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 (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.

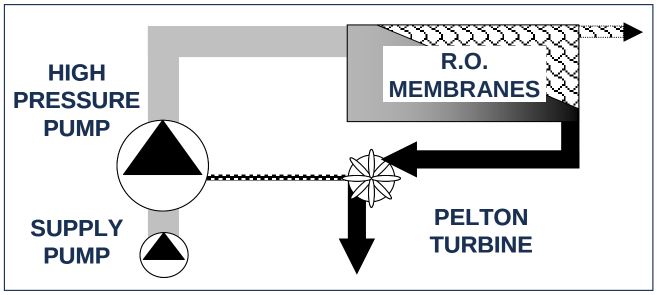

Figure 1: Reverse osmosis with a Turbine ERD

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. Energy is lost in a turbine ERD because it is transformed twice, once by the turbine and once by the pump impeller. 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%. The overall efficiency of a turbine ERD, therefore, is typically 50 to 75%.

2.2 Isobaric Energy Recovery Devices

Engineers developed isobaric ERDs to avoid the inefficiencies associated with the energy-transformation inherent in turbine ERDs. They place the RO concentrate reject and the seawater feed in contact inside pressure-equalizing, or isobaric, chambers. These innovative devices were introduced to large desalination plants in 2002 and have been deployed widely since.

A simplified flow diagram of an SWRO process with isobaric ERDs is shown in Figure 2. Concentrate rejected by the membranes flows to the ERD(s) driven by a circulation pump. The ERDs replace the concentrate with seawater. The pressurized seawater merges with the discharge of the high-pressure pump to feed the membranes. Water leaves the process as fresh water permeate from the membranes or as spent low-pressure concentrate from the ERDs. An energy recovery efficiency of 98% can be achieved with state-of-the-art isobaric ERDs.

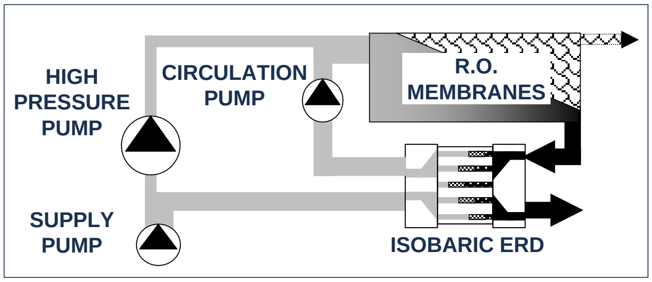

Figure 2: Simplified Diagram of an SWRO Process with Isobaric ERDs

The positive-displacement pressure transfer mechanism used in isobaric ERDs deliver high efficiency despite pressure and speed/flow rate variations. As a result, most SWRO plants being designed and built today utilize isobaric ERDs. 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. The largest SWRO trains operating today, 6.6 million gal/day in Hamma Algeria, are supplied with PX Pressure Exchanger devices.

2.3 SWRO Energy Consumption

Energy is consumed throughout the SWRO process for conveying and pressurizing water. A breakdown of energy use in a large state-of-the-art plant is shown in Figure 3. These data indicate that 68% of the power consumed in a

SWRO process goes to the high-pressure pumps that feed the RO membranes, even in modern plants using low-energy membranes and high-efficiency pumps.

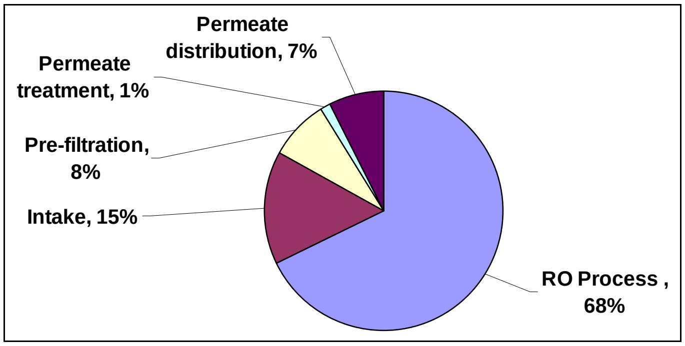

Figure 3: Estimated power consumption in a 50 million gal/day SWRO plant

The benefit of ERDs for SWRO process energy reduction is illustrated in Figure 4. Starting with the Jeddah 1 plant in Saudi Arabia which had no energy recovery and consumed over 8 kWh/m^3 in the SWRO portion of the process, SWRO energy consumption was first lowered by implementing Francis turbines as was done in Las Palmas, Gran Canaria, then by Pelton turbines as was done in Trinidad. It should be noted that the Pelton turbines in the Trinidad plant are very large and considered state-of-the-art. Nevertheless, the isobaric ERDs and other process improvements in operation in the Perth plant cut SWRO plant energy consumption from approximately 3.8 kilowatt hours per cubic meter of permeate produced (kWh/m^3)(14.4 kWh per 1000 gallons (kWh/kgal)) to 3.2 kWh/m^3 (12.1 kWh/gal) or about 16%.

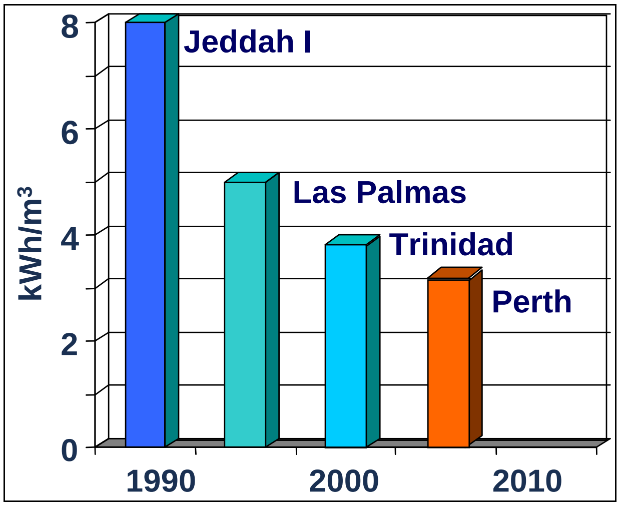

Figure 4: Improvements in SWRO energy consumption

The importance of isobaric ERDs for reduction of energy requirements and associated environmental impacts in SWRO technology received international recognition by desalination operators and users. The Energy Recovery, Inc. PX Pressure Exchanger device was awarded Environmental Contribution of the Year in 2007, in part because the energy savings demonstrated in Figure 4.

The energy requirements for modern SWRO were compared to those of conventional sources of water supply in Southern California by the Affordable Desalination Collaboration. Energy consumption for a small SWRO plant was measured as 3.1 kWh/m^3 (12 kWh/kgal) compared to the power required to convey surface water to Los Angeles: about 2.9 kWh/m^3 (11 kWh/kgal). However, regardless of the energy required, additional surface water capacity to meet increased demand in Southern California is simply not available. Therefore, the cost of seawater desalination was compared to the cost of alternative means of new supply. Specifically, the cost of a plant producing 50 million gallon of permeate per day with conveyance piping was compared to the cost of a comparable recycled water facility. The SWRO cost range was $2.38-2.80/kgal compared to $3.07/kgal for recycled water. In addition to the cost advantage of SWRO, other factors make it preferable to large-scale recycling including the unlimited availability of seawater, legal limits on use of recycled effluent and the challenge of overcoming the public’s aversion to “toilet-to-tap” reclaimed water.

2.4 SWRO Process Optimization

Isobaric ERDs provide high constant energy transfer efficiency over a wide range of flows and pressures. As a result, the membrane water recovery rate can be varied without increasing the energy required to produce a unit of permeate. This flexibility allows a process operator to optimize membrane performance as seasonal variations in the seawater occur or as the membrane elements age by adjusting the speed of the booster pump. Numerous best-efficiency operating points can be found which is a tremendous advantage for low-cost SWRO operation.

Recovery adjustment is illustrated with reference to Figure 5 below. 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. A booster pump flow increase automatically increases the flow rate of high-pressure reject to the ERDs. The flow rate of feedwater to the ERDs must be increased in proportion, but this increase requires very little energy because the feedwater is delivered at low pressure.

A high recovery rate means a high process yield. High-recovery operation reduces supply-pumping and pretreatment expenses and can keep an SWRO process running at design production levels if there are pretreatment system problems. However, operation at high recovery results in higher average concentrate salinities in the membrane elements, higher osmotic pressures and higher membrane feed pressures compared to operation at low recovery. In addition, supersaturation of the concentrate can result in more scaling and high membrane flux can result in more fouling. Reducing recovery reduces membrane pressure and the load on the high-pressure-pump motor. Low recovery operation is beneficial if heavy fouling conditions occur because membrane cross-flow is increased and contaminant deposition and biological growth on membrane surfaces is reduced. Such adjustments can significantly change membrane performance but have negligible affect on isobaric ERD performance which provides high efficiency regardless of flow rate or pressure. In this way, an operator can manipulate and optimize SWRO system performance to achieve low energy consumption throughout the year.

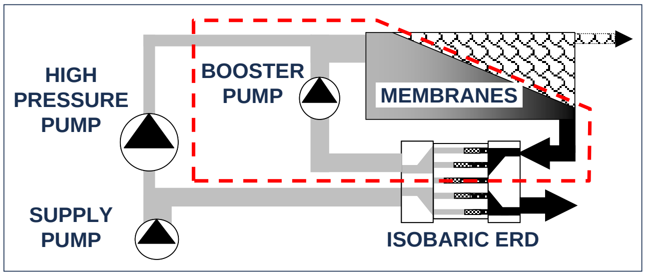

Figure 5: Schematic of SWRO system with Isobaric ERDs

2.5 Other Environmental Factors

Concern has also been raised about the potential environmental impact of concentrate discharges from desalination facilities. However, the majority of the known impacts are from thermal (distillation) facilities from which copper and other metals leached from the process are discharged. Membrane desalination facilities, which use significantly less metal and operate at much lower temperatures, do not cause such impacts. Nevertheless, some desalination plants assure zero environmental impact by discharging the seawater concentrate far out to sea in open currents. At the Perth desalination plant, for example, the concentrate pipeline extends 1,540 feet (470 meters) from shore. The velocity of the discharge is up to 13 feet per second (4 meters per second) through nozzles spaced at 16-foot (5-meter) intervals to ensure total mixing of seawater concentrate within 164 feet (50 meters) of each side of the pipeline.

Less concern has been raised about the environmental impacts of seawater intakes. Intake systems are designed to minimize the entrainment of solids and marine life that must be removed by the pretreatment system before the water flows to the SWRO process. Open intakes are ideally placed in flowing currents to assure uniform, clean feedwater and intake velocities are minimized to prevent entrainment. Beach wells and ocean-floor subsurface intakes are also widely employed.

3 ENERGY RECOVERY AND OTHER APPLICATIONS

PX technology is employed in hundreds of desalination plants around the world. Single devices are used in relatively small RO trains, while multiple isobaric ERDs are connected by manifolds to run in parallel to serve large trains. Although it was developed specifically for membrane desalination applications, isobaric ERD 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 is 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. An isobaric ERD depressurizes a process stream prior to heat transfer and then repressurizes the stream. This would reduce the pressure requirement and associated cost of the heat exchanger.

Yet another application currently under development is osmotic power technology. 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 isobaric ERD to recover the pressure energy. As in desalination application, the isobaric ERD serves as a seal for the high-pressure portion of the process. An osmotic power demonstration plant is currently being constructed in Norway and is expected to be in operation by summer 2009.

4 CONCLUSIONS

The global demand for fresh water continues to grow while supplies dwindle. Desalination of seawater with reverse osmosis membranes and energy recovery devices has become an affordable means of water supply. Many desalination plants being designed and built today save energy by utilizing isobaric energy recovery devices, such as the 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 15-30% 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.