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Reverse osmosis and osmotic power generation with isobaric energy recovery

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ABSTRACT

Current state-of-the-art seawater reverse osmosis processes require isobaric energy recovery devices to minimize energy consumption and total operating costs. These "pressure-equalizing" devices efficiently recover pressure energy from the reject concentrate stream of the reverse osmosis process. The use of isobaric energy recovery devices in SWRO processes provides a great deal of flexibility in the design and operation of the plant. In a properly designed application, membrane flux and recovery can be dynamically changed without a significant total process energy efficiency penalty. The high efficiency and flexibility of isobaric energy recovery devices makes them logical solutions for other membrane processes such as brackish RO systems and pressure retarded osmosis. Pressure retarded osmosis, sometimes referred to as osmotic power, is a membrane process for generating energy from the osmotic potential between two feed streams such as seawater and fresh water. The process, invented by Sidney Loeb in 1973, will see its first full-scale prototype within 2009. Isobaric ERDs play a pivotal roll in making the pressure retarded osmosis process economically viable. This paper will illustrate how isobaric energy recovery devices work and chart the technological advances they have made through the years. The application of the isobaric ERDs, and specifically the ERI PX device, to reverse osmosis and pressure retarded osmosis processes will be discussed in detail.

Keywords: Reverse osmosis; Osmotic power; Energy recovery devices; Forward osmosis; Pressure retarded osmosis

1. Introduction

Dr. Sidney Loeb played a pivotal role in the development of membrane separation technology. Together with Dr. Srinivasa Sourirajan, he invented the cellulose acetate polymer reverse osmosis membrane at the University of California Los Angeles in 1959. Dr. Loeb put these membranes to work in Coalinga, California in 1965 in the first membrane desalination process to provide municipal water supply. He was a tireless advocate for the use of the reverse osmosis process for water desalination in Israel where he spent the latter part of his life. Dr. Loeb continued to explore possible applications for semi-permeable membranes and patented a means to generate electricity with them.

In the practical application of both the reverse osmosis and power generation process, isobaric energy recovery devices play an important role. These devices were acknowledged by Dr. Loeb and the European Desalination Society who, in 2006, presented the first Sidney Loeb award for innovation to the inventor and developers of the PX Pressure Exchanger isobaric energy recovery device. This paper describes reverse osmosis and osmotic power generation processes with isobaric energy recovery as a means to pay tribute to Dr. Loeb and his pioneering work.

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2. Reverse osmosis

Reverse osmosis is a water desalination process wherein the osmotic pressure of a salt water solution is overcome with hydraulic pressure, forcing nearly pure water through the membrane and leaving concentrated brine behind. The cellulose acetate membrane developed by Dr. Loeb and Dr. Sourirajan had an anisotropic structure of a very thin "skin" on a relatively thick porous support layer that provided both good water permeation and high salt rejection. The anisotropic structure made RO desalination feasible and is used in these membranes to this day.

Further membrane innovations improved salt rejection and water permeation. These advances lowered membrane feed pressure requirements and, as a result, reduced energy consumption. However, in modern seawater reverse osmosis (SWRO) systems, an operating pressure of between 60 and 70 bar is still 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 had historically limited the deployment of large-scale SWRO to regions where power was inexpensive and abundant.

SWRO systems, however, consume far less energy today than they did just a few years ago. Improved membranes, increased pump efficiencies and the implementation of energy recovery devices (ERDs) have dramatically increased the energy efficiency of SWRO. The energy requirement for SWRO can be as low as 1.6 kWh/m^3, making the process energy-competitive with many traditional fresh water supply sources [1,2].

3. Energy recovery devices

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, such as Francis turbines, Pelton turbines or turbochargers, which were limited in capacity and had a maximum net transfer efficiency of typically less than 70% at their best efficiency point [3].

Pressure equalizing tanks were first developed for application as energy recovery devices (ERDs) for reverse osmosis desalination shortly thereafter by Bowie Keefer of Seagold Industries [4]. They were dubbed "isobaric" devices to describe the pressure-equalizing function of the tanks or chambers. The positive displacement pressure transfer mechanism used in these devices is similar to that in reciprocating pumps, assuring high efficiency despite flow and pressure variations. As a result, most SWRO plants being designed and built today utilize isobaric ERDs including three of the four largest SWRO plants currently in operation [5]. This process is illustrated in Fig. 1.

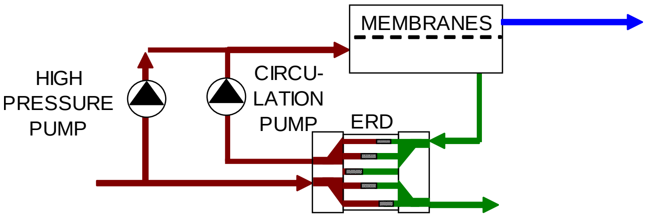

Fig. 1. Reverse osmosis with isobaric ERD.

In RO processes equipped with isobaric ERDs, the high-pressure pump and permeate flow rates are nearly equal. Therefore, the high-pressure pump is sized to the permeate flow rate, not to the full membrane feed flow rate. Clearly this reduces both the capital and operating cost of the high-pressure pump.

With the acceptance of highly efficient energy recovery devices as standard equipment on large SWRO plants, the need for lower operating pressures and hence higher flux membranes was reduced. Previously membrane manufacturers worked to increase membrane flux almost exclusively as the main way to try to reduce the overall cost of water production by reducing operating pressures and thus saving energy. However this changed when plant designers could recover much of the pressure in the brine stream and convert it in to useful energy. Membrane suppliers could then develop or tailor membrane chemistry for better rejection of chloride, boron or other salts without the design restraint of maintaining high flux values [6].

4. Pressure retarded osmosis

In the 1970s, Dr. Loeb patented a process for converting osmotic potential-energy into electrical energy [7]. Named pressure retarded osmosis (PRO), the process is essentially reverse osmosis in reverse. A semi-permeable membrane separates two solutions having different concentrations, osmotic pressures, and hydrostatic pressures. Water permeates from the low to the high osmotic and hydrostatic pressure side. Water can be released from the high osmotic and hydrostatic pressure side through a hydroturbine at a flow rate equal to the permeate rate. This is osmotic power generation. The process is illustrated in Fig. 2.

In an osmotic power process, the permeation of water simultaneously dilutes the concentrated solution and concentrates the dilute solution such that the osmotic driving force is constantly diminishing along with the permeate rate, which decreases proportionately to the approach of the osmotic pressure difference to the hydraulic pressure difference. A means to replace or re-concentrate the

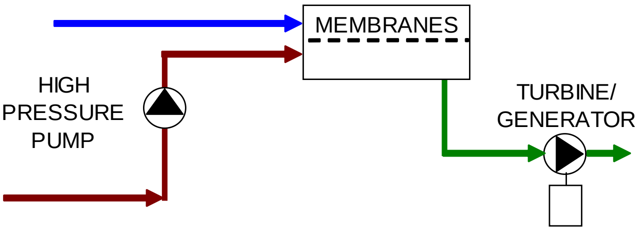

Fig. 2. Basic osmotic power process.

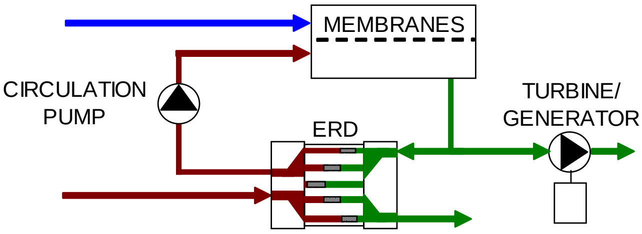

Fig. 3. High-efficiency osmotic power process.

high osmotic and hydrostatic pressure side is necessary to make the process operate continuously. A pump could be used to pressurize concentrated water for delivery to the high-pressure side of the membrane as illustrated in Fig. 2. However, the energy required for the pump would have to be drawn from the energy generated with the hydroturbine, and the mechanical and hydraulic losses would make the overall process impractical.

5. Isobaric energy recovery devices for PRO

Dr. Loeb later proposed a more efficient means to supply fresh concentrated water to the high-pressure side of the membrane using two tanks [8,9]. A portion of the pressurized dilute water is directed to a tank filled with low-pressure concentrate. The pressure in the tank quickly equilibrates. Additional inflow of the dilute water displaces the concentrate toward the membranes. Once the interface between the dilute and concentrate reaches the tank's discharge, the flow of the dilute water can be switched to a second tank of low-pressure concentrate. The first tank is refilled with low-pressure concentrate, discharging the dilute water to the environment or to a regeneration process. Thus, if the process control and switching mechanism is seamless, the flow of concentrate to the membrane and the flow of dilute water from the membrane can be continuous. The operation of the two tanks and the switching mechanism is essentially identical to the device proposed by Keefer and that of modern isobaric ERDs.

The resulting osmotic power process with isobaric energy recovery is illustrated in Fig. 3. The similarity between this process and a reverse osmosis process with an isobaric ERD is clear. Concentrate is supplied to the ERD at low pressure. A portion of diluted discharge from the membranes is also fed to the ERD. The ERD transfers the pressure of the diluted water to the concentrate. A circulation pump is used to move water through the membranes and the ERD in a high-pressure loop. The ERD makes osmotic power feasible by facilitating efficient renewal of the high-pressure loop with fresh concentrate after it is diluted with water permeating through the membranes. The function of the isobaric ERD, therefore, is to seal the high-pressure portion of the process, remove diluted water and replace it with fresh concentrate.

Isobaric ERDs were recognized by Loeb for their ability to reduce the size of the hydroturbine and reduce the role of the concentrate pump to that of a circulation pump instead of a pressurizing pump. Both of these changes dramatically increase the overall efficiency of a potential PRO process. However, a suitable membrane does not yet exist for the process.

6. PRO membranes

Considerable research has been dedicated to the development of a suitable membrane for PRO. As of the date of this writing, practical, sustainable osmotic power generation has yet to be demonstrated. Not surprisingly, the technical challenge of a suitable membrane for PRO was anticipated by Dr. Loeb [9].

In PRO, the concentrate is diluted by the permeate, especially in the immediate vicinity of the membrane surface. In addition, salts in the dilute solution tend to be carried to the dilute side interface of the membrane along with the mass flow of the permeate, thus increasing the concentration and osmotic pressure on that side of the membrane and decreasing the osmotic pressure driving force. This is concentration polarization, well-understood in RO. However, RO membranes only suffer concentration polarization on the salt-water side. The structural side contains mostly permeate and any dissolved species that diffuse through the membrane are swept away by the flux of permeate. Therefore, concentration polarization practically occurs only on one side of the membrane. The polarization boundary layer thus created is minimized by agitation of the concentrate. However, because the concentration polarization on the dilute side of a PRO occurs in the structural layer, agitation does not minimize the boundary layer. The result is reduced osmotic driving force.

7. PRO and forward osmosis process development

A significant research and development effort to produce a PRO process is underway by the Norwegian utility Statkraft [10, 11]. The goal of the effort is to use seawater and fresh water to generate power. A pilot plant is being built near Oslo to generate 2–4 kW of power with approximately 2,000 m^2 of membrane.

Other research efforts are focused on the development of a forward osmosis (FO) process. FO uses an osmotic driving force to extract water from water containing dissolved species including salt water. It employs a “draw solution” with a higher osmotic potential than the salt water, but it operates at a low hydraulic pressure. FO may be a first step toward the creation of a PRO membrane, one that allows researchers to address the problem of concentration polarization on both sides of the membrane without having to address the structural requirements of a high-pressure PRO process.

An example FO process uses a drinkable, sugar-based solid to draw permeate from a salt water or dirty water source through the wall of a pouch made with FO membrane. Such pouches are commercially manufactured by Hydration Technologies, Inc. However, the membrane used does not lend itself to high surface area deployment in the spiral or hollow-fine-fiber configurations required for RO and likely required for PRO.

For low-pressure FO applications, a hydrophilic membrane is required. Indeed, the membrane must be hydrophilic on both sides to make the process function. The cellulose acetate membranes originally developed by Dr. Loeb and later commercialized by others are hydrophilic but are relatively more expensive to manufacture than modern polyacrylate (PA) RO membranes. PA membranes are made of synthetic polymers that are hydrophobic. This is not a problem for most RO applications because the high operating pressure of the process wets the membrane. Efforts to develop hydrophilic PA membranes for low-pressure FO application are underway at the University of Texas, the University of Kentucky, Virginia Polytechnic Institute and State University and Membrane Technology and Research, Inc. [12–14]

Others working to develop forward osmosis processes include Oasys Water with Yale University [15,16] and Quantumsphere. Both intend to use engineered draw solutions from which extracted water can be separated with relatively low-temperature heat. The regenerated concentrated draw solution will be returned to the forward osmosis membranes in a closed loop. If the loop is sealed from the environment with an isobaric ERD, the pressure generated could be used to drive a hydroturbine. The basic process design was invented by Dr. Loeb and dubbed an osmotic heat engine. This name is appropriate because the overall result of the process is to concentrate the energy of a relatively low-temperature heat source into a purified water stream or electrical power. Both the Oasys Water and Quantumsphere processes require FO membranes that can withstand exposure to the draw solutions. However, because the osmotic potential of these engineered solutions far exceeds that of seawater, they could become important osmotic power processes once suitable membranes are developed.

8. Conclusions

It is said that great research generates more questions than it answers. In this regard and in many others, Dr. Sidney Loeb’s pioneering work is as important today as it was at the time it was carried out. The world has benefited for many years from seawater reverse osmosis technologies based on Dr. Loeb’s work. As PRO technology matures it will serve as an additional reminder of the importance of his work.

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