Emergence of Forward Osmosis and Pressure-Retarded Osmotic Processes for Drinking Water Treatment

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Description of Emerging Processes

Approximately 97 percent of the Earth's water takes the form of salt water in oceans, seas, and lakes. Because of a worldwide water shortage, a need exists for alternative desalination technologies that can produce inexpensive, reliable, and sustainable sources of water for the world's growing population, as well as to meet its industrial and agricultural needs. Green energy is available wherever one finds a river that flows into a sea, equivalent to the energy contained in a 900-ft-high waterfall[1]. Desalination technologies, such as reverse osmosis (RO) and electrodialysis reversal (EDR), have proven to be effective in removing a number of dissolved contaminants from water and wastewater supplies, but require a significant electrical demand and often experience fouling problems uncommon with more conventional water and wastewater treatment methods[2]. Forward osmosis (FO) and pressure-retarded osmosis (PRO) are emerging membrane separations technologies that have the potential to be innovative, sustainable, and affordable alternatives to RO and EDR because of their ability to utilize the green energy available in natural systems[3].

Both FO and PRO rely on osmotically-driven water flux across a semi-permeable dissolved solids rejecting membrane. The term "osmosis" describes the natural diffusion of water through a semi-permeable membrane from a solution of a lower concentration to a solution with a higher concentration. These three technologies (RO, FO, and PRO) are common in that they use semi-permeable membranes to separate dissolved solutes from water. The semi-permeable membrane acts as a barrier that allows small molecules such as water to pass through, while rejecting larger molecules like salts, organics, and proteins, as well as viruses, bacteria, and other pathogenic material. Both FO and PRO exploit the osmotic pressure difference that develops when a semi-permeable membrane separates two solutions of different concentrations. Instead of employing hydraulic pressure as the driving force for separation in the RO process, FO and PRO use the osmotic pressure gradient across the membrane to induce a net flow of water through the membrane into what is referred to as the "draw" solution, thus efficiently separating the freshwater from its solutes. Driven by an osmotic pressure gradient, FO and PRO do not require significant energy input as in the comparable case of RO.

In osmosis, the osmotic pressure itself is the driving force for mass transport. The osmotic potential depends on the molar concentration, not the weight of dissolved species. Both FO and PRO use the osmotic pressure differential $\Delta\pi$ across the membrane, rather than hydraulic pressure differential Δp (as in RO). The FO process results in dilution of a highly concentrated stream. The concentrated solution on the permeate side of the membrane is the driving force in the FO process. The flux direction of the permeating water in FO, PRO, and RO is demonstrated in Figure 1[2,3,4]. The governing equation describing water transport through FO and PRO membranes, and the volumetric flux of water into the draw solution compartment of osmotic pumps, can be described by the Kedem–Katchalsky equation as shown below[5]:

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$$F_w = k_w(\Delta p - \Delta\pi)$$

Where is the water flux, is the water mass transfer coefficient, is the applied pressure, and is the osmotic pressure. For FO, is zero; for PRO .

In FO application for desalination and water treatment, the active layer of the membrane faces the feed solution and the porous support layer faces the draw solution. However, in PRO application, the porous support

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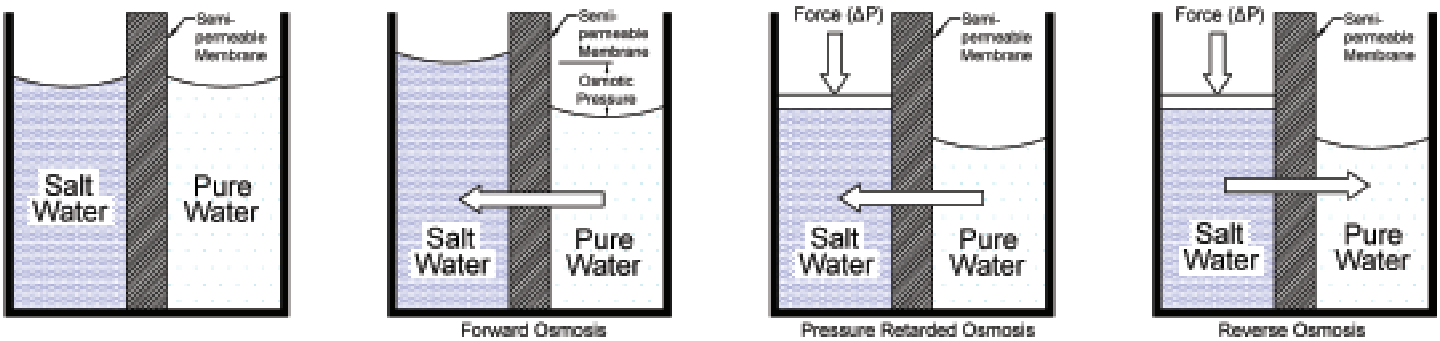

Figure 1. Solvent flows in FO, PRO, and RO.

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layer faces the feed solution and the active layer of the membrane faces the draw solution. The chemical potential, which is determined by the osmotic pressure difference across the membrane, is the effective driving force in making energy and fresh water. This potential is usually lower than the potential generated by the osmotic pressure difference between the bulk feed and bulk draw solution due to external concentration polarization[6].

The main advantages of using FO and PRO are that they can be operated at low or no hydraulic pressure and they possess a high rejection of a wide range of contaminants. Since the only pressure involved in the FO and PRO processes is due to flow resistance in the membrane module, it may have a lower membrane fouling tendency than pressure-driven membrane processes. The ideal material of membranes for FO and PRO would have a high active-layer density and result in high solute rejection; the thin membrane film, having minimum porosity of the support layer, would minimize internal concentration polarization, and therefore, provide a higher water flux. In addition, it would be desired that the membrane be hydrophilic for enhanced flux and reduced membrane fouling; an important aspect of these alternative membranes would be high mechanical strength to sustain hydraulic pressure when used for PRO.

Different module configurations for these membrane technologies include plate-and-frame, spiral-wound, tubular, and bag configuration[2]. Plate-and-frame modules are the simplest devices for packing flat sheet membranes and can be constructed in different sizes and shapes, ranging from lab-scale to full-scale systems. The limitations of plate-and-frame elements are lack of adequate membrane support and low packing density. Spiral-wound configurations have been successfully modified for FO mode by placement of an additional glue line at the center of the membrane envelope that provides a path for the feed to flow inside the envelope. The feed flows into the first half of the perforated central pipe, is then forced to flow into the envelope, and then flows out through the second half of the perforated central pipe. The limitation of spiral-wound FO configuration is the difficulty to induce flow into the permeate channels for the purpose of cleaning or backwashing[7]. In practical applications, hollow fibers for continuously operated FO and PRO processes may have some advantage as compared to the other configuration. This is because they can support high hydraulic pressure without deformation and can be easily packed in bundles directly inside a pressure vessel. Also, hollow fiber membranes do not need a thick support layer as in flat sheet RO membranes, thereby reduce internal concentration polarization and enhance membrane performance.

With PRO, the water potential between fresh water and sea water corresponds to a pressure of 26 bars. This pressure is equivalent to a column of water (hydraulic head) of 885 feet (270 meters) high[8]; however, the optimal working pressure is only half of this, ranging from 11 to 15 bar[9]. This method of generating power was invented in 1973 by Professor Sidney Loeb at the Ben-Gurion University of the Negev, Beersheba, Israel[10]. This concept was not realized until the world's first osmotic plant, with capacity of 4 kW, was opened by Statkraft in November 2009, in Tofte, Norway[11,12]. It is estimated that, each year, 12 TWh could be generated in Norway, sufficient to meet 10 percent of the country's total demand for electricity, and 1600 TWh could be generated worldwide[13].

In one study, the use of a custom-made and laboratory-scale membrane module enabled the collection of experimental PRO data. Results obtained with a flat-sheet cellulose triacetate (CTA) FO membrane, and NaCl feed and draw solutions, closely matched model predictions[4]. Maximum power densities of 2.7 and 5.1W/m^2 were observed for 35 and 60 g/L NaCl draw solutions, respectively, at 970 kPa of hydraulic pressure[4]. The authors report that "power density was substantially reduced due to internal concentration polarization in the asymmetric CTA membranes, and to a lesser degree, to salt passage. External concentration polarization was found to exhibit a relatively small effect on reducing the osmotic pressure driving force."

Applications

The FO application has thus drawn much attention, with applications developed in various fields, such as desalination, wastewater treatment, and pharmaceutical and juice concentration, and even power generation and potable-water reuse in space. Recent studies of applications of FO in the field of wastewater treatment and water purification include treatment of landfill leachate, concentration of dilute industrial wastewater, potable reuse of wastewater in advanced life support systems, and concentration of liquids from anaerobic sludge digestion at a domestic wastewater treatment facility.

Desalination and Water Purification

To date, the only viable commercial drinking water application for FO has been developed by Hydration Technology Innovations, which has developed a small water purification bag (hydration bag), used mostly by the military[14]. The bag is made of a semipermeable FO membrane and contains a solid glucose draw solution. When immersed in contaminated water from puddles and ponds, purified water diffuses into the bag, slowly diluting the solid draw solution to produce a potable drink. With sufficient contact time, such water will permeate the membrane bag into the draw solution, leaving the undesirable feed constituents behind. The diluted draw solution may then be ingested directly. Typically, the draw solutes are sugars, such as glucose or fructose, which provide the additional benefit

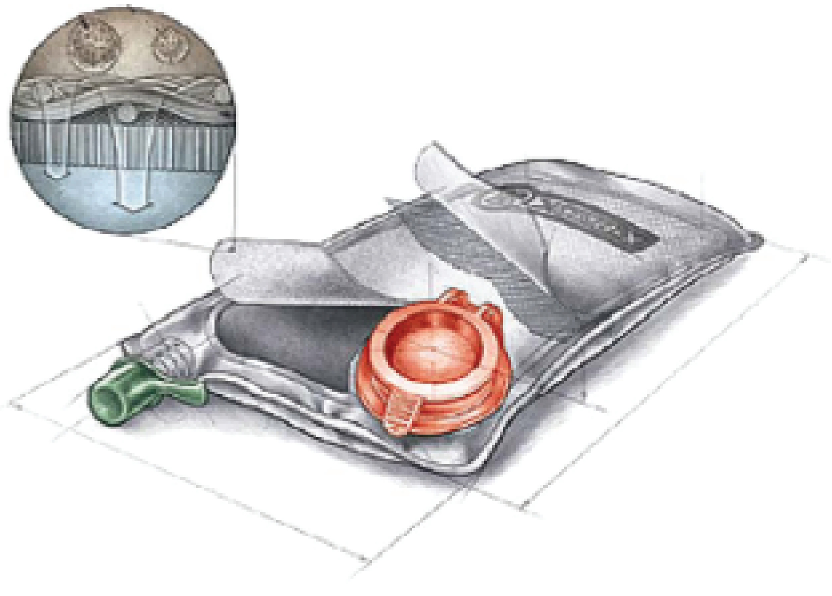

Figure 2. Illustration of a water hydration bag.

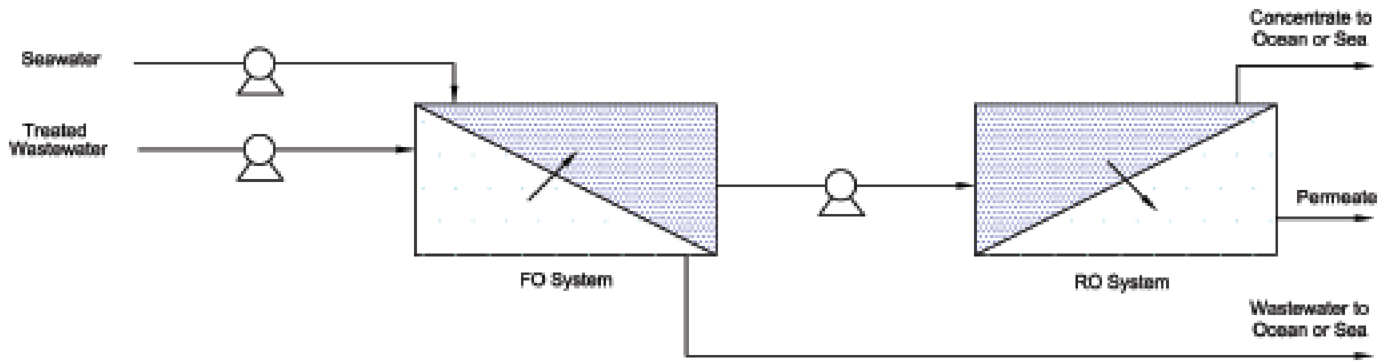

Figure 3. Schematic for an FO-RO for seawater and wastewater treatment.

of nutrition to the user of the FO device. A point of additional interest with such bags is that they may be readily used to recycle urine, greatly extending the ability of a backpacker or soldier to survive in arid environments. This process may also, in principle, be employed with highly concentrated saline feedwater sources such as seawater, as one of the first intended uses of FO with ingestible solutes was for survival in life rafts at sea. Figure 2 depicts an illustration of a water purification hydration bag. It is unclear whether this technology is economically scalable.

One of the start-up companies in this new commercial arena is Oasys Water Inc., which uses FO technology developed at Yale University [6,15]. The developers claim that its technology can produce desalinated water at less than half the cost and using 90 percent less energy than RO. This area of current research in FO involves the direct removal of draw solutes by thermal means. This process is typically referred to as the "ammonia–carbon dioxide" FO process, as the draw solutes are salts formed from the mixing of ammonia and carbon dioxide gases in water[6].

In this application, seawater is the feed, and the accompanying draw solution is formed by using highly soluble ammonia and carbon dioxide gases, which produces a strong enough osmotic pressure to extract water from seawater. These salts can reach high concentrations, particularly as the ratio of ammonia to carbon dioxide is increased. An especially convenient property of these salts is that they readily dissociate into ammonia and carbon dioxide gases if a solution containing them is heated. The diluted draw solution is heated to about 60ºC at 1 atm pressure to decompose the ammonia and carbon dioxide, and the product water is then recovered after degassing via distillation. Once the concentrated draw solution is used to affect separation of water from the FO feed solution, the diluted draw solution is directed to a reboiled stripper (distillation column) and the solutes are completely removed and recycled for reuse in the FO system[16]. An FO system of this type thereby affects membrane separation of water from the FO feed, using heat as its primary energy source. The quality of heat used by this process can be as low as 40°C. If FO of this type is used in a cogeneration environment (waste heat from a power plant, for example), its energy cost can be greatly reduced, compared to RO[17]. Full-scale application costs for this FO have yet to be documented.

QuantumSphere Inc. develops and manufactures proprietary high-performance catalysts that are used to increase the rate of chemical reactions[18]. They use a proprietary organic solution as a draw solution for seawater desalination. The diluted organic solution is then heated to cause the proprietary formulated organic solute to drop out. The processed water requires a final purification step through activated charcoal. Process energy costs are 70 percent less than traditional RO, the company claims. This last purification step suggests that there could be some issues with traces of organics in the purified water after removal of the organic solute. It is unclear whether or not the proprietary draw solution used in this process could obtain the necessary regulatory approvals for use in producing drinking water.

Wastewater Treatment

Another application of FO is treatment of impaired water and wastewater, with specific opportunities for direct potable reuse of treated sewage. Research carried out by the Colorado School of Mines, in Golden, Colo., has demonstrated the application that utilizes treated sewage, or another impaired water source, in a FO system to dilute seawater prior to desalination with RO, which is shown in Figure 3[19].

With RO seawater desalination, most of the energy is used to overcome the osmotic pressure of the salt water, and this high osmotic pressure limits the amount of pure water that can be recovered. In coastal areas, treated wastewater is being discharged to the ocean, wasting a valuable resource. By using seawater as the draw solution, and passing wastewater through the FO membrane prior to ocean discharge, purified wastewater can be used to dilute seawater prior to feeding to an RO system for desalination[19]. The osmotic pressure of the seawater is then reduced, which lowers the energy required for desalination and improves water recovery. Disposal of RO concentrate to the ocean is of environmental concern and is strictly regulated; however, the use of FO and RO as a combined means may offer sustainable solutions for the treatment of sea water with treated wastewater streams that provide high quality waters suitable for the sustainable management of ocean discharges and water reuse.

Summary

The concept of utilizing the osmotic effect in many fields of science and engineering, including water and wastewater treatment, seawater/brackish water desalination, and electric power production, has received increasing attention over the last several years. Both FO and PRO have the potential to convert the osmotic pressure difference between fresh water (i.e., river water) and seawater to electricity. Moreover, they can recover energy from highly concentrated brine in seawater desalination. Nevertheless, relatively little research has been undertaken for fundamental understanding of the FO and PRO processes. Yet, the increasing attention in FO and PRO is directed towards membranes with improved properties that will make it possible to commercialize these processes in the near future.

Forward osmosis is a process that, like reverse osmosis, uses a semi-permeable membrane to affect separation of dissolved solutes from water. The driving force for this separation is an osmotic pressure gradient, such that

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a "draw" solution of high concentration (relative to that of the feed solution) is used to induce a net flow of water through the membrane into the draw solution, thus effectively separating the feed water from its solutes. In contrast, the reverse osmosis process uses hydraulic pressure as the driving force for separation, which serves to counteract the osmotic pressure gradient that would otherwise favor water flux from the permeate to the feed. The FO takes place when the hydraulic pressure difference is zero. The PRO will occur where the applied pressure difference is between zero and the flux reversal point, and RO will occur where the applied pressure difference is greater than the osmotic pressure difference (as shown in Figure 4), which serves as a good summary of the basis behind these differing osmotic-controlled systems. If a membrane is used that allows water molecules to pass through, but not the molecules of dissolved salts, and it is arranged with fresh water on one side and salt water on the other side as the water goes through the membrane, the water level on the salt water side will rise. This pressure difference can be used to generate a flow of water that will turn a turbine; consequently FO and PRO could be viable sources of renewable energy in the future[20].

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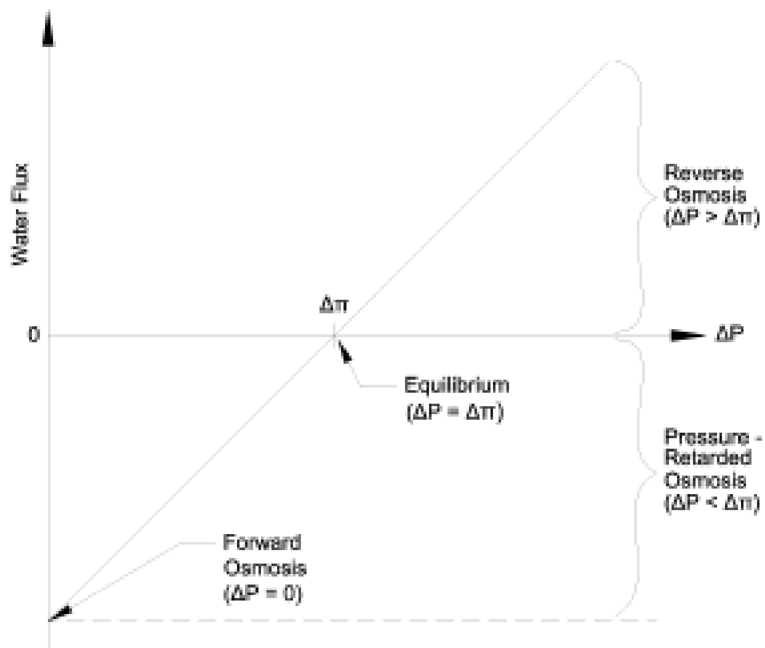

Figure 4. Graphical summary of the direction and magnitude of water flux as a function of applied pressure in FO, PRO, and RO (adapted from reference 20).