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What is next for forward osmosis (FO) and pressure retarded osmosis (PRO) ☆

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ABSTRACT

This short review summarizes our understanding and perspectives on FO and PRO processes and meaningful R&D in order to develop effective and sustainable FO and PRO technologies for water reuse and osmotic power generation.

Contents

1. Introduction

Technologies to produce clean water and clean energy have received worldwide attention due to water scarcity, highly fluctuating oil prices and global warming. Forward osmosis (FO) and pressure retarded osmosis (PRO) have received extensive attention during the last decade as emerging technologies for water reuse and seawater desalination, and power generation, respectively. The purposes of this short review are to summarize what we have learned in the last decade and to share our understanding and perspectives on FO and PRO in order to conduct meaningful R&D, and develop useful FO and PRO technologies for clean water and clean energy production.

Basically, FO takes advantage of naturally (osmotically) induced water transport across a semi-permeable membrane from a low

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osmotic pressure solution to a high osmotic pressure solution [1–5]. Ideally, the semi-permeable membrane allows water to pass through it but rejects all salts or unwanted elements. The high salinity solution performs as the draw solution, which has a higher osmotic pressure than the feed solution, to induce water flow across the membrane from the feed solution to itself. Thus, FO requires less energy to transport a net water flow across the membrane compared with pressure-driven membrane processes such as reverse osmosis (RO). However, in contrast to RO, the product of FO is not a potable water but a diluted draw solution, a mixture of the respective draw and feed solutions. Therefore, a second step of separation must be utilized to extract clean water and to regenerate the draw solution.

The second step of separation may be energy intensive depending on the draw solutes and the recycle process. Therefore, for clean water production, one must consider the energy consumptions of both the FO process and the draw solute regeneration in order to make a fair comparison between FO and other water production technologies. Otherwise, the conclusion could be biased and misleading [6–8]. Nonetheless, FO may be more cost-effective than pressure-driven membrane processes for water reuse if the regeneration of draw solutes is not needed. Thus, R&D on FO should prioritize those processes and applications without recycling draw solutes.

The idea of osmotic energy generation (PRO) was proposed about 70 years ago, but most of the early research studies were suspended owing to the absence of effective membranes [3,4,6,9], which are the heart of osmotic power systems. The estimated global osmotic energy using ocean and river water as feeds is high [9]. Statkraft of Norway built the first PRO prototype plant in 2009 using seawater and river water as feeds but terminated it in 2014 possibly due to technology immaturity such as membrane limitations, fouling, limited salinity gradient between seawater and river water, and small power output [10].

2. What is next for FO?

2.1. FO membrane development

There are a few comprehensive reviews on the progress of FO membrane development [2,3,6]. Basically, most FO membranes were fabricated by traditional phase inversion [6] and thin-film composites (TFC) via interfacial polymerization methods [11,12]. FO membranes made from the layer-by-layer method have been investigated but their reverse salt fluxes tend to be high [13,14]. Using hydrophilic materials as substrates for FO membranes is essential to enhance water flux [15,16]. Recently, TFC FO membranes synthesized on nano-fiber [17] and multi-bore [18] substrates with good mechanical properties have also been demonstrated. Future R&D should focus on innovation membranes with minimal fouling and internal concentration polarization (ICP). So far, double skinned FO membranes, consisting of a dense RO skin and a loose RO skin, have shown promise with reduced fouling and ICP [19,20].

2.2. FO for water reuse

Because of no hydraulic pressure involved and low fouling propensity [21–23], FO may be more cost-effective and superior in direct fertigation [24,25] and produced water reuse [16,26–31] if the recycled water is for industrial reuse. Using fertilizers as draw solutions, directly drawing water from brackish or sea water for agriculture purposes, can significantly simplify fertigation processes with lower costs. It has a great potential for water-scarcity countries to farm salt-tolerant agricultural crops. Recently, oil–water separation has received special attention due to the large amounts of discharged oily wastewater from hydraulic fracturing and petrochemical industries. So far there is no effective method to treat stable emulsified oily wastewater. Promising results with reasonable fluxes, high oil rejections of >99% and low fouling characteristics have been demonstrated using single- and double-skinned FO membranes with sulfonated polymers facing the oil–water feed [20,30]. This may provide new insight into how to treat the oily-wastewater. Besides, since the wastewater from hydraulic fracturing contains surfactants and other chemicals, a hybrid forward osmosis–membrane distillation (FO–MD) system with a high water recovery has also been demonstrated to treat oily wastewater containing petroleum, surfactant, NaCl and acetic acid [31].

So far, FO still has difficulties in being a cost-effective technology for direct seawater desalination because of its high energy consumption and lack of effective draw solutes with minimal reverse fluxes. Despite many advances in draw solutes made recently [32–35], challenges still exist to (1) minimize the reverse flux of draw solutes, (2) alleviate ICP and (3) find facile regeneration methods. However, FO exhibits potential for impactful environmental applications and enrichment of high value-added pharmaceutical products.

2.3. FO for the removal of toxic ions and concentration of pharmaceutical products

Heavy metal contamination is a severe environmental issue because of an exponential increase of heavy metal compound usage in various industries. Since heavy metals cannot be metabolized by the body or decomposed naturally, they accumulate inside the body and cause severe body dysfunction. Hence, the removal of toxic heavy metal ions from wastewater is a top priority for many countries. Nano-filtration (NF) has been used for heavy metal removal, but it suffers from high fouling tendency and insufficient rejections.

FO has been proposed to remove boron and arsenic [36–41]. By using a novel bulky hydroacid complex as the draw solute to minimize reverse solute flux, FO has been demonstrated to effectively remove heavy metal compounds such as $Na_2Cr_2O_7$, Na_2HAsO_4, $Pb(NO_3)_2$, $CdCl_2$, $CuSO_4$, $Hg(NO_3)_2$ from wastewater [38]. High water fluxes were harvested with heavy metals rejections of more than 99.5%. In addition, the rejections were maintained at 99.5% when a more concentrated draw solution (1.5 M) or feed solution (5000 ppm) was utilized. Interestingly, rejections greater than 99.7% were still achieved by operating the FO process at 60 °C. These remarkable performances may create new FO applications to treat heavy metals-laden wastewater. However, one must find a disposable draw solute, such as RO brine or an energetic and economic favorable method to recycle draw solutes for this application to minimize the overall process cost.

The demands for pharmaceuticals and proteins are steadily increasing. Athermal enrichment methods are preferred because these products are labile and heat sensitive. Membrane technology has gained importance in biotechnology due to its mild operational conditions and superior separation abilities [42]. However, pressure-driven membrane processes are usually energy intensive, and severe membrane fouling is often encountered. In contrast, FO not only consumes less energy but also has much more reversible fouling. Nevertheless, the high reverse salt fluxes during FO processes using conventional draw solutes such as NaCl may denature the feed proteins. To overcome this, using dual-FO systems and bulky draw solutes with minimal reverse fluxes is recommended for pharmaceutical and protein enrichments [43,44].

2.4. System integration

Although FO may not as cost-effective as RO for seawater desalination, an integration of FO and RO, as shown in Fig. 1,

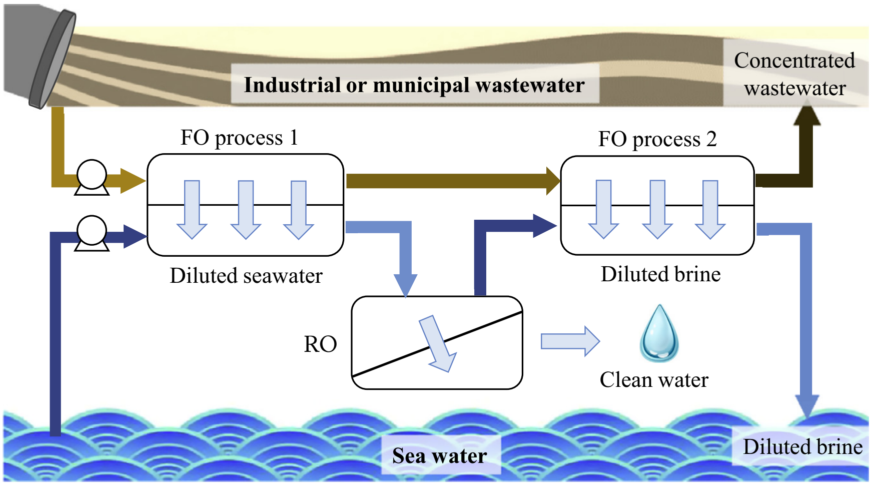

Fig. 1. FO and RO integration for seawater desalination.

may offer a better alternative for seawater desalination with a lower energy consumption and a higher water recovery [45–48]. By integrating FO and RO, additional feed water can be drawn from wastewater to lower the concentration of seawater before it enters the seawater reverse osmosis (SWRO) plant. As a result, SWRO can be operated at a lower pressure. In addition, the SWRO retentate can be re-diluted with the aid of another FO process and directly discharged.

FO and MD integrations are worthy of further studies with the aid of waste heat or solar energy because high water recovery and water purity can be obtained simultaneously. However, up to the present, only limited studies have focused on FO–MD systems for wastewater recycling [31,49–51].

3. What is next for PRO?

3.1. PRO membrane development

Compared to FO membranes, the development of PRO membranes has evolved more slowly because of the high pressure applied on the draw solution [3,6,52]. Most FO membranes may collapse or be severely deform during PRO operations [53]. Spacers are needed for PRO flat-sheet membrane modules to maintain flow channels and improve mass transfer. The feed spacers not only cause hydraulic pressure losses along the flow channels but also inevitably deform PRO membranes under high pressure operations [54,55]. As a consequence, the reverse salt fluxes and internal concentration polarization (ICP) are drastically increased and result in substantial reductions in both water flux and power density. Moreover, the burst pressure of flat sheet membranes is highly dependent on the spacer design [56]. Therefore, identification of spacers such as tricot fabric feed spacers, compatible with PRO membranes, is of paramount importance for the development of effective flat-sheet PRO membrane modules [56]. In contrast, no spacers are needed in PRO hollow fiber modules due to the mechanically self-supported nature of hollow fibers. However, deformation of hollow fibers also happens in PRO hollow fiber modules and the deformations of inner-selective and outer-selective hollow fibers under high PRO pressures are different. Hence, different strategies on material selection, membrane morphology formation and macrovoid distribution must be incorporated in the design in order to produce highly robust PRO hollow fiber membranes [57–59].

Today, high performance PRO flat-sheet membranes that can withstand hydraulic pressures up to 22 bar with corresponding power density of 18 W/m^2, and hollow fiber membranes that can withstand hydraulic pressures up to 20 bar with corresponding power density of 27 W/m^2 using seawater brine (1.0 M NaCl) and deionized water as feeds, have been developed [60,61]. These PRO performances are superior to others reported in the literature. Moreover, outer-selective PRO hollow fiber membranes, which may have a less pressure drop along the fiber, have been demonstrated [59,62]. Fouling in PRO membranes is more complicated than that in FO because the feed stream faces the porous substrates in PRO operations. In addition, the reverse salt flux may facilitate fouling and complicate fouling mechanisms [63–66]. Accordingly, hollow fiber membranes with anti-fouling properties for osmotic power generation have been designed by grafting hyperbranched polyglycerol and zwitterionic polymers on polyethersulfone hollow fiber membranes [67,68]; even though, PRO membranes with higher power density, capacity to withstand greater pressures and better anti-fouling properties are urgently needed.

3.2. Feed streams: seawater vs. RO brine

For the Statkraft PRO pilot, it required two long pipes to transport seawater and river water to the PRO pilot and extensive pretreatments were conducted to remove foulants and scalants from both feeds [10]. A high pressure pump was employed to pressurize the seawater. Since the salinity gradient between seawater and river water is relatively low, there is no substantial gain in economic and energy when balancing the energy produced from the

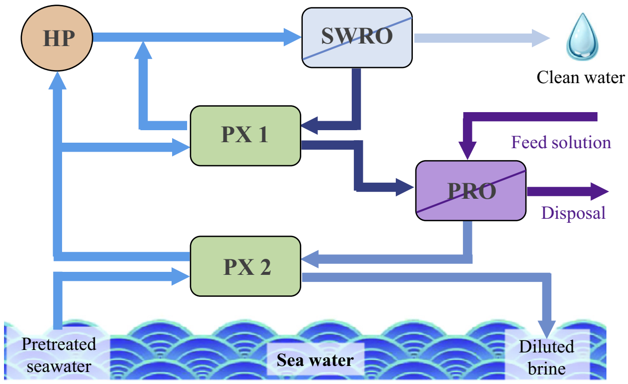

Fig. 2. PRO and RO integration for seawater desalination.

PRO plant and the energy consumed in pretreatments, pumping the feeds and pressurizing the seawater compartment.

Therefore, future PRO studies should focus on the use of either (1) retentates from both SWRO and wastewater reuse RO (WWRO) or (2) SWRO retentate and river water as feeds. Not only can these feed streams create much greater osmotic energy, but also save some of the pre-treatment costs. This is because RO retentate has been well pre-treated in its previous processes, which will significantly reduce the membrane fouling in the PRO step. In addition, since the RO retentate is already under a high pressure, it is unnecessary to have an additional pump to pressurize the high pressure compartment as in the case of using seawater and river water as the feed pair for PRO.

3.3. Integration of RO, PRO and pressure exchanger

If SWRO retentate is used as the draw solution, then the salinity gradient between the SWRO retentate and river water is much greater than that between seawater and river water (about 7.9–8.5 vs. 3.5 wt% NaCl). The PRO plant may be able to raise its operational pressure from 13.5 bar for the feed pair of seawater and river water to 20–35 bar depending on RO brine concentration [6,52]. This will significantly increase the production of osmotic energy, but also bring tremendous challenges for the design of PRO membranes with very high mechanical strength to withstand the higher operational pressure. Nevertheless, the integration of osmotic power generators and SWRO plants can (1) make seawater desalination less energy dependent and more sustainable and (2) alleviate the disposal and environmental issues of waste RO brine.

Fig. 2 illustrates the integration of pressure exchangers (PX) with a SWRO plant and a PRO unit. The 1st pressure exchanger not only transmits energy from the highly pressurized RO retentate to the feed seawater but also discharges the highly pressurized and concentrated RO retentate as the draw solution for the subsequent PRO operation. The 2nd pressure exchanger takes advantages of the diluted and pressurized RO brine to pressurize the feed seawater. As a result, the high pressure pump for SWRO requires less energy to pressurize the seawater feed.

Many experiments on integrated RO–PRO–PX systems [69,70] and theoretical calculations on their energy consumption have been reported [71–74]. Various design strategies for pressure exchanger devices were also proposed [73–77]. Once the osmotic power generator is fully integrated with the SWRO plant with the aid of pressure exchangers, it is envisioned that seawater desalination will become much more energy-efficient and cost-effective and this integration will entirely revolutionize the desalination industry and future osmotic energy production.

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