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GUEST COLUMN

Forward osmosis: an emerging technology for sustainable supply of clean water

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Nowadays, inadequate access to clean water has become one of the most pervasive problems due to the rapidly expanding global population and thus the exponentially growing demand in water and food supply, industry and social life (Shannon et al. 2008). Problems with water have called out for a large number of researchers to pay more attention to water sustainability and put forth effort to explore more robust technologies for wastewater treatment and desalination in addition to improving the efficiency of the current water production and distribution systems (Sikdar 2011). Among many potential solutions, membrane processes such as reverse osmosis (RO), nanofiltration (NF), ultrafiltration (UF), and microfiltration (MF) have found their overwhelming applications in water industry. However, these technologies are either chemically or energetically intensive, thus are castigated for high cost due to substantial chemical and energy consumptions as well as high fouling propensity which requires frequent backwash or cleaning.

Forward osmosis (FO), utilizing the natural phenomenon of osmosis, is an emerging membrane process driven by the osmotic pressure gradient created across a semipermeable membrane by two flowing streams of varying concentration (i.e., the draw solution and the feed). Hence, the energy required to transport water across the membrane is almost negligible. Far from being so, FO creates much less problem of fouling and cleaning (Mi and Elimelech 2010). By virtue of these unique features, FO distinguishes itself from other membrane processes for sustainable supply of clean water. An example of the FO unit for wastewater treatment is shown in Fig. 1.

In the FO process as illustrated, the draw solution (an aqueous solution of magnetic nanoparticles covered with thermosensitive polymer) (Ling et al. 2011) and the feed (wastewater) partitioned by the membrane flow co-currently through corresponding channels. The draw solution, having a higher osmotic pressure than the feed, draws water from the feed and flows back to the reservoir. As it continuously takes clean water from the feed, the draw solution in the reservoir becomes diluted. A regeneration process is connected to the reservoir to re-concentrate the draw solution as well as to produce clean water. A portion of the diluted draw solution is pre-heated with the aid of solar panel or waste heat and traverses a magnetic field. Upon heating, the magnetic nanoparticles covered with thermosensitive polymers change their surface property from hydrophilic to hydrophobic and are easily seized by the magnetic field or other filtration processes. As a result, clean water freely passes through and is collected as the product. The trapped magnetic nanoparticles are then sent back to the reservoir to replenish the draw solution.

The 1st key component of the FO unit is the membrane material which should be semipermeable, i.e., allowing water to permeate through while blocking all the solutes in the draw and feed solutions. A tremendous amount of research has been conducted on the molecular design of new membrane materials with superior FO performance and great progress has been achieved in the past 5 years. To date, several types of FO membranes have been reported such as (1) flat sheet membranes made of cellulose esters (Wang et al. 2010a; Zhang et al. 2010); (2)

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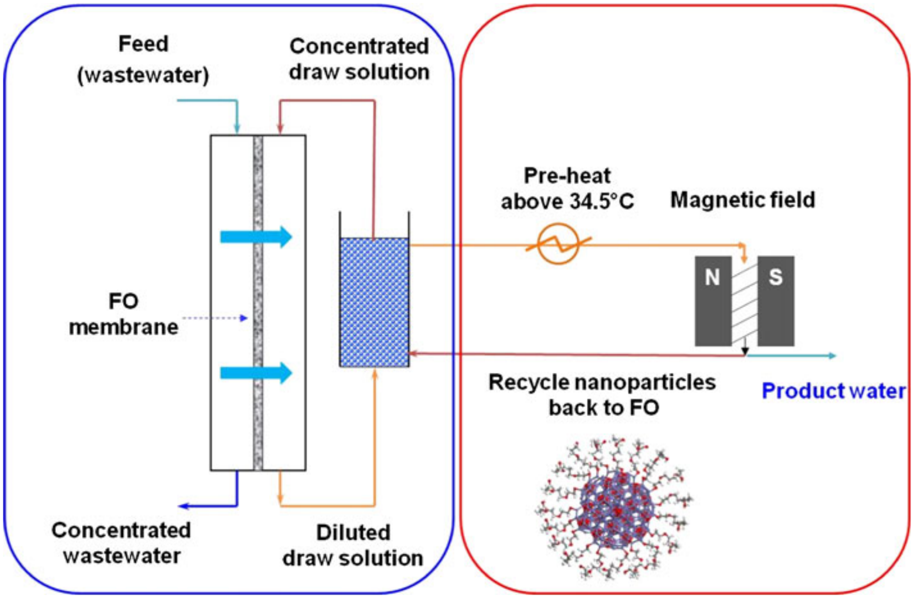

Fig. 1 Schematic of a forward osmosis unit

single- and dual-layer hollow fibers based on polybenzimidazole (PBI) (Wang et al. 2007; Yang et al. 2009), cellulose acetate (CA) (Su et al. 2010; Su and Chung 2011) or poly (amide–imide) (Setiawan et al. 2010); (3) thin film composite (TFC) polyamide membranes (Wang et al. 2010b; Yip et al. 2010; Widjojo et al. 2011); (4) layer-by-layer assembly (Qiu et al. 2011); and (5) biomimetic membranes (Wang et al. 2012). To maximize the water flux, most FO membranes are designed of asymmetric structures with a thin dense active layer on a porous sublayer. One challenge arising from this design is the internal concentration polarization (ICP) inevitably occurring within the sublayer (i.e., dilution effect of the draw solution or concentration effect of the feed) regardless of running the draw solution along the sublayer (FO mode) or running the feed along the sublayer (pressure retarded osmosis (PRO) mode). The immediate impact of ICP is a significant drop in the net driving force, and one cannot expect a very high water flux once ICP is developed. Very interesting studies targeting at this issue are from Wang et al. (2010a) and Zhang et al. (2010) whose experimental results show that ICP can be largely reduced by forming a highly porous support layer. An additional contribution of these studies is the concept of the double-dense layer structure that reduces fouling. In general, TFC polyamide membranes offer a greater water flux than those phase inversion membranes. So far, the highest water flux for seawater desalination is about 15 L/m^2 h reported by Widjojo et al. (2011) based on 2.0 M NaCl draw solution and flat TFC polyamide membranes in the PRO mode. Further increment in the water flux for seawater desalination is difficult even if the pure water permeability of membranes is raised due to the increasingly limiting effect of the flux-dependent ICP, which calls for a better design of the sublayer or a completely new membrane structure. In addition, considering the fact that two solutions are involved in the FO process, the thin polyamide layer of such TFC membranes might be damaged with the flow of water from the sublayer to the active layer during either regular operation or frequent backwashing. An interesting study from Qiu et al. (2011) is the formation of FO membranes using layer-by-layer (LBL) polyelectrolytes. Although these LBL membranes generate water flux comparable to those from TFC membranes, the very low retention to the draw solutes suggests that the present designs may not be useful for practical applications. Wang et al. (2012) successfully developed biomimetic FO membranes embedded with Aquaporin Z and a very encouraging water flux of 145 L/m^2 h was achieved based on a 2.0 M NaCl draw solution and DI water feed in the PRO mode. But the preparation procedure is very complicated and it is hard to scale up.

Another key component is the draw solution. Desired draw solutions should at least meet three basic criteria; namely, (1) high osmotic pressure which may induce a high water flux; (2) minimal diffusion through the membranes to avoid possible contamination of the feed and to lower the replenishing cost; (3) easy regeneration with low energy consumption. From a practical point of view, inorganic salts such as NaCl, though frequently used, are not desirable draw solutes because of easy passage through most membranes and high energy cost to recycle. Ammonium bicarbonate may be also not suitable since even a trace level of residuals may deteriorate the taste of the product water. Recently, we have successfully developed unique draw solutes based on functionalized magnetic nanoparticles, organic compounds, and polyelectrolytes (Ling et al. 2010; Ge et al. 2011, 2012). The greatest strength of these newly-designed draw solutes is that they can be easily and almost completely separated from water through UF/NF (Ling and Chung 2011) or magnetic field compared with conventional salts. For example, the draw solution containing 0.12 g/mL polyacrylic acid sodium salt (Mw ~ 1,800 Da) generates a water flux of 7.5 L/m^2 h in the 1st FO test and generates a comparable water flux of 7.3 L/m^2 h after 9 times regeneration (Ge et al. 2012). With sound experimental evidence, we are confident that the regenerated draw solutes work very well and the performance loss is nearly negligible. These pioneering studies have largely pushed forward the transformation of FO from a scientific concept to a feasible technology. One thing we should note is that the draw solution should offer an osmotic pressure much higher than 27 atm (osmotic pressure of seawater) for seawater desalination in order to achieve acceptable water flux. To regenerate the draw solution after the desalination process would require a lot of energy. Therefore, at the present-day membrane and draw solute technologies, FO is more practical and economical for wastewater treatment and desalination of water sources of low salinity.

Fouling is an important issue for FO although it is not as serious as pressure-driven membrane processes. Both sides of FO membranes may have fouling such as scaling, colloidal fouling, or organic fouling depending on the ingredients in the draw and feed solutions. Fouling in the FO process is almost fully reversible and the membrane can be easily cleaned by way of simple physical cleaning (Mi and Elimelech 2010). However, when the FO tests are conducted in the PRO mode, some foulants might get stuck in the porous membrane matrix and are difficult to be completely washed out, leading to a usually much more severe fouling compared to the FO mode. A general and well-recognized fact of the FO process is that PRO mode generates a higher water flux than FO mode due to more serious influence of ICP. For this reason, a lot of works tend to present experimental observations based on the PRO mode. This is meaningless and somewhat misleading. In most cases, the foulants are in the feed, thus it is preferable to run FO with the feed against the active layer in order to alleviate fouling. For wastewater treatment and desalination, more research on FO membrane fouling and cleaning needs to be conducted under different membrane orientations since many substances are present and some of them may induce fouling.

The feasibility of using FO for wastewater treatment and desalination has been verified in a number of studies (Cornelissen et al. 2008; Li et al. 2011; Phuntsho et al. 2011). Among these innovative trials, one representative example is the osmotic membrane bioreactor (OMBR), which combines activated sludge treatment and FO with a post RO process for wastewater treatment (Cornelissen et al. 2008). The basic idea is to replace UF/MF membranes in the current MBR system with FO membranes by employing an external draw solution to provide driving force in the form of osmotic pressure difference. Since FO membranes offer a much higher selectivity than UF/MF membranes, the treated effluent would contain much less dissolved organic content and the efficiency of biological degradation is enhanced due to prolonged retention time for organic matter (Xiao et al. 2011). Also, the FO membranes in OMBR are expected to be less susceptible to fouling compared with the UF/MF membranes in traditional MBR. Since the treated effluent from OMBR has better quality, membrane fouling in the subsequent RO process can be minimized. To make OMBR commercially viable, more membrane materials and draw solutions should be evaluated and the possible influence of draw solute leakage on the biological system should be investigated.

In summary, with the tremendous research progress in membrane materials and draw solutions, FO has shown great potential in a variety of applications. Especially, FO is thought to be a promising technology for sustainable supply of clean water. Despite these broad prospects, FO researchers have to find out sound solutions to several important questions before mass application of FO technologies. (1) How much energy is consumed in order to run a FO unit? No doubt, the FO process itself consumes very little amount of energy since it normally runs at atmospheric pressure. However, another process (e.g. RO) is essential to re-concentrate the diluted draw solution after it extracts some water from the feed and this extra process would consume much more energy than the FO process. To evaluate the energy consumption of a FO unit for any specific applications, the draw solution regeneration process must be also considered. (2) How to effectively and completely remove the draw solutes from the product water? For the draw solution regeneration, the efficiency to separate the draw solutes from water using UF, NF or magnetic separator is still not high enough. It may not be a big issue to reach discharge standard if a certain amount of draw solutes remains in the produced water. In case of drinking water production, however, the quality of the product water has to meet a very high standard. Thus, the problem of residual draw solutes needs to be taken very seriously although the concentration may be very low. (3) How much water flux is reasonable? As to FO membranes, researchers are pursuing high water flux and high rejection to the draw and feed solutes. In fact, there is a trade-off relationship between permeability and selectivity for polymeric membranes (Geise et al. 2011). Namely, it is very difficult to simultaneously enhance water flux and solute rejection to a great extent. Besides, high water flux suggests increased fouling propensity as well as more severe concentration polarization. To design a good FO membrane, one needs to consider the uniqueness of the specific application. For example, high water flux is preferable for water reuses while high rejection may not be necessary. On the other hand, high rejection must be the first priority if the FO membrane is used for drinking water production. Much more research needs to be conducted before FO can play an important role in the sustainable supply of clean water for mankind.

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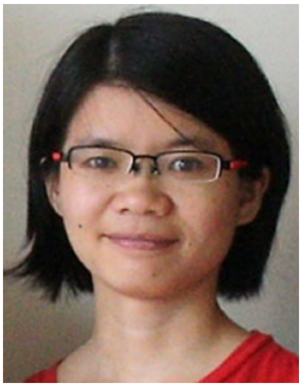

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