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Membranes and processes for forward osmosis-based desalination: Recent advances and future prospects

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ABSTRACT

Forward osmosis (FO) is an increasingly important technology that has been deemed promising for addressing the global issue of water scarcity. Rapid progress over the past decade has been marked by significant innovations in the membrane development and process design. The key idea is to develop next-generation membranes through advanced membrane fabrication methods as well as hybrid systems where the FO process can really value-add. As such, this article provides an overview of the various FO membrane designs, in particular, the thin-film composite, surface-modified, and mixed matrix and biomimetic membranes. The pros and cons of each type of membranes are discussed together with the strategies used to optimize membrane properties such as structural parameter (*S*), water permeability (*A*) and salt permeability (*B*) to achieve enhanced FO performances. Furthermore, we also discuss the roles of FO in the various hybrid systems and evaluate the potential of these hybrid systems for desalination. Lastly, we provide our perspectives, especially in the area of membrane fabrications and FO hybrid systems, to shed light on the future research directions for harnessing the true potential of FO for desalination.

1. Introduction

Global water scarcity is an escalating problem that is driven by increasing population, emerging economies and compounding effects from climate changes [1,2]. Addressing this problem requires innovative technologies that provide energy-efficient and cost-effective solutions to recover potable water from unconventional water sources such as seawater, brackish groundwater and wastewater [2]. Today, the most robust and widely used desalination technology is the reverse osmosis (RO) process [3]. RO is a membrane-based process that utilizes a semi-permeable membrane to oppose and surpass the osmotic pressure of the saline solution to produce clean water. It is a thermodynamically non-spontaneous process, where a transmembrane pressure (TMP) is essential to provide the driving force for mass transport across the membrane [4]. The large intrinsic osmotic pressure of the seawater implies that a high hydraulic pressure is necessary for the RO process. To this end, RO is still considered an energy- and cost-intensive process despite the fact that the low energy consumption has already been realized by advances in the technology [5,6].

Forward osmosis (FO) for desalination emerges with the promise of overcoming the challenges of pressure-driven membrane processes [7]. In FO, spontaneous water permeation across a semi-permeable membrane occurs, which is driven by a chemical potential difference (osmotic gradient) arising from a concentrated draw solution (DS) and a diluted feed solution (FS). Since an external hydraulic pressure is not necessary, FO offers the advantages of lower energy demand (i.e., reduced capital and operational costs) as well as less irreversible membrane fouling as compared to the RO process [8,9]. Due to these reasons, FO has attracted immense attention within the membrane community which sees research efforts intensifying over the past decade, especially within the last 5 years (Fig. 1).

Over this period, significant progress has been made in the FO technology [10]. Herein, we aim to cover this progress from two main aspects namely, membrane design and hybrid FO system. Our arguments for these two aspects are as follows. First, the key to a successful FO technology depends largely on the membrane itself [11]. Suitable membranes were once thought to be lacking as conventional asymmetric RO membranes turned out inappropriate for FO application given their lower than expected fluxes [7]. However, the success of the HTI (Hydration Technologies Inc.) membranes had inspired a burgeoning growth in FO membrane design given a better understanding of the desired characteristics of FO membranes. There are now more focused research efforts in the direction of thin film composite (TFC) membranes to develop membrane substrates with optimized

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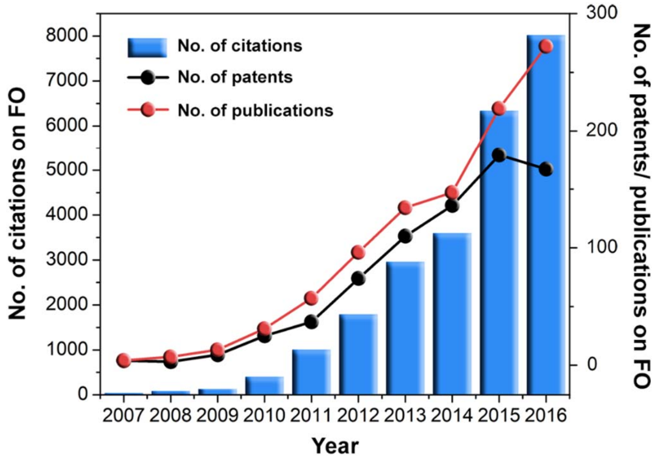

Fig. 1. Number of citations, patents and publications on forward osmosis over the past ten years. The number of citations and publications are based on data from Web of Science, while data for the number patents are obtained from SciFinder.

parameters to mitigate internal concentration polarization (ICP) [12] and thin and robust selective layers for high FO performance and fouling control [13,14]. Meanwhile, the emerging novel materials which have high capacities to create synthetic nanochannels are utilized in membrane designs to further boost membrane performances [15,16]. Polymeric membranes, in particular, play an instrumental role and act as a versatile platform to facilitate all these efforts [11]. Second, hybrid FO system has become a topic of discussion recently as water treatment and desalination cannot be achieved with a standalone FO process [17], but it is possible to pair the FO process with another separation process to regenerate the diluted DS and/or employ FO as a pre-treatment for desalination [18]. Correspondingly, many studies have demonstrated the potential to lower the energy demand of desalination as compared to conventional desalination processes, or the increased capacity of the desalination process to handle feed water of high concentration with hostile trace contaminants [17]. To create an even larger impact, a good draw solute is crucial in facilitating easy recovery of the product water. Conventional inorganic draw solutes, which main purpose is to create a DS with a higher osmotic pressure than FS, are non-responsive in nature [19]. The use of ammonia and carbon dioxide solution as an easily re-generable DS has sparked great interest in the research of responsive draw solutes [20,21]. In recent years, ‘smart’ draw solutes that are responsive towards temperature, pH, electro-magnetic field or light have been vigorously pursued, motivated by the desire to regenerate diluted DS and recover the product water in an energy-saving and cost-effective way [22].

Therefore, in this review, we commence by first highlighting the basic principles and identifying the main challenges pertaining to the FO process. By drawing on our expertise in membrane fabrication and engineering, we then shortlist the key progress in FO membrane developments since 2010. Particularly, our discussion centers around the various types of FO polymeric membrane fabrication and modification methods with a strong emphasis in tuning the structural parameters of membrane substrates, engineering flat sheet and hollow fiber membrane configurations as well as designing and optimizing TFC and mixed matrix membranes to achieve enhanced FO performances. Next, recent advancements in hybrid FO systems for desalination are provided. Notably, the design strategies on developing hybrid systems are put into the perspective of finding the right fit for FO to harness its full potential for desalination. Lastly, we discuss the future prospects of membrane innovations and hybrid systems as well as how crucial they are in shaping the position of FO for desalination.

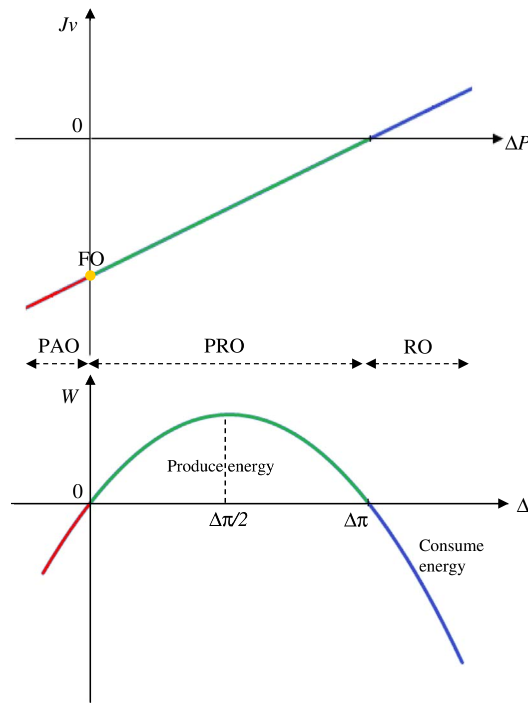

Fig. 2. Water flux J_v (upper) and energy production W (lower) as a function of hydraulic pressure ΔP for PAO/FO/PRO/RO processes.

2. Basic principles and challenges of FO

Since FO utilizes the osmotic pressure difference across the membrane active layer as the driving force to draw the water flow from the FS (low concentration) side to the DS (high concentration) side, the hydraulic pressure difference across the membrane (ΔP) is almost equal to zero as described in Fig. 2. In addition to FO, the figure also shows the flux-pressure relationship of reverse (RO), pressure retarded osmosis (PRO) and pressure assisted osmosis (PAO), where ΔP is above zero. When hydraulic pressure is applied to the more concentrated solution side, the process becomes PRO ($\Delta P <$ osmotic pressure difference ($\Delta\pi$)) or RO ($\Delta P > \Delta\pi$). In contrast, PAO is operated by applying hydraulic pressure on the lower concentrated solution side. Compared with the conventional RO separation, FO/PRO/PAO does not separate fresh water during the process. Instead, the permeated water flows to the DS side and a further process is required to separate the water from the dissolved solutes if clean water as the end product is desired.

The DS, formed by homogeneously dissolving or dispersing draw solutes in water, plays a key role in an FO process. By capitalizing on the osmotic pressure difference generated by a concentrated DS and a dilute FS, the water is driven out from the FS to the DS to realize the separation. Hence, one of the most critical characteristics required of the DS is to have a high osmotic pressure, in addition to other desired qualities including high diffusion coefficient to reduce ICP, low reverse diffusion to the FS, low/no toxicity, chemically stable and cost-effectiveness [22]. More importantly, the DS must be easily regenerated/concentrated (when purified water extraction from the DS or draw solute regeneration is required) as it is strategic towards the design of the FO applications and the hybrid systems eventually adopted [7,22]. Further discussion on the draw solutes can be found in Section 4.

On the other hand, the membrane is the key to a highly efficient FO system. During an FO process, the actual driving force (real osmotic pressure gradient across the membrane active layer) is significantly lower than the osmotic pressure difference between the bulk FS and the bulk DS, primarily due to the presence of ICP effect in the membrane support layer [7] (illustrated in Fig. 3), i.e., either through dilution of DS on the DS side (Fig. 3a) or accumulation of solutes on the FS side