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Desalination by forward osmosis: Identifying performance limiting parameters through module-scale modeling

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ABSTRACT

In this study, we analyze the effects of membrane properties, namely water permeability, solute permeability, and structural parameter, on the overall performance of an FO membrane module to extract water from simulated seawater (0.6 M NaCl). By considering the thermodynamic limit of operation, we demonstrate that the maximum achievable water recovery is practically independent of membrane properties, and higher maximum water recovery is achievable with counter-current compared to co-current mode. Analysis of the module-scale model indicates that reducing the support layer structural parameter offers substantial reductions in the membrane area required to achieve a specified water recovery. For example, a 25% reduction of the structural parameter of a state-of-the-art thin-film composite (TFC) membrane (from 400 to 300 μm) yields a sizable 20% reduction in membrane area. In contrast, quintupling the water permeability coefficient (from 2.0 to 10.0 L m^{-2} h^{-1} bar^{-1}) of a modern TFC membrane generates only a modest 10% saving in membrane area. In addition, because of the permeability-selectivity trade-off that governs current polymeric membranes, doubling the water permeability coefficient would cause crippling ~7-fold increases in forward and reverse solute permeation. This quantitative study models the potential performance of a module-scale FO desalination process and firmly highlights the need to prioritize the reduction of support layer mass transport resistances over water permeability increases in membrane development.

1. Introduction

Seawater desalination accounts for a rapidly increasing portion of global freshwater production [1,2]. Currently, reverse osmosis (RO) and multi-stage flash (MSF) separation are the most extensively employed desalination processes. Despite steady technological advances over the years, MSF remains highly energy intensive and RO still requires a substantial amount of high-grade energy in the form of electricity [3,4]. Recent studies have highlighted the inherent link between water and energy sustainability and emphasized the need to produce water in a manner which minimizes the use of high quality energy resources [4–6]. Emergent technologies such as forward osmosis (FO) and membrane distillation which can utilize low-grade waste energy are, therefore, of increasing importance in desalination [6–12]. FO desalination systems have a wide range of potential water production and purification applications, from hybrid FO–RO schemes for agricultural water that exploit the lower fouling propensity of FO [13], to shale gas water recycling systems that utilize the ability of FO to treat the highly saline waters produced during hydraulic fracturing [14,15].

FO desalination comprises two stages: first, water is extracted from a saline feed stream into a draw solution and, second, the draw solute is separated from the diluted draw stream to recover the extracted water [1]. In the first stage, the saline feed solution is contacted with a high osmotic pressure draw solution in a membrane module. Driven by the chemical potential gradient, water permeates from the feed solution across the semipermeable membrane into the draw solution. In the second stage, product water is separated from the draw stream in a closed cycle, thus regenerating the initial draw solution. Various separation processes may be employed to recover water from the draw stream [8,15–17]. For example, thermolytic draw solutes, such as ammonia–carbon dioxide, may be stripped using low temperature distillation [8].

In order for FO desalination to be cost-effective, membranes need to achieve a high average water flux whilst maintaining an adequate rejection of salts and contaminants [1,7]. Currently, tailored thin-film composite (TFC) membranes, consisting of a thin polyamide active layer on a polysulfone–polyester fabric support layer, have demonstrated consistently high FO performance by providing the optimal

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combination of high water permeability, low solute permeability, and low support layer resistance to water transport [18–21]. Novel membranes, based on materials ranging from carbon nanotubes to graphene to aquaporin proteins, could potentially achieve greater water permeabilities and solute rejections, and are the subject of active research [22–26]. Innovative fabrication techniques are also being investigated in attempts to further lower the mass transport resistance of FO membrane support layers and enhance productivity [20,27–31].

Previous studies have investigated the trade-off between water and solute permeability of the membrane active layer [32,33] and the effect of morphology and microstructure on concentration polarization within the membrane support layer [28,34–38]. These studies concentrate on the theoretical and mechanistic understanding of the mass transport phenomena in FO and thus offer limited perspectives on overall FO system performance. At present, the advantages of improving membrane properties (water permeability and solute rejection of the active layer and mass transport resistance of the support layer) at module level have not been quantitatively analyzed. Module-scale modeling enables the determination of system-level performance parameters, including water recovery, solute leakage, and membrane area. In addition, incorporating the effects of local flow rate and concentration variations is imperative when assessing the impact of concentration polarization, which is exponentially dependent on the local water flux [39]. Therefore, module-scale FO analyses provide important practical insights on the economic viability of the process and can guide the design and implementation of FO desalination plants. In addition, understanding the potential benefits of advances in membrane technology on FO module performance will be integral in steering future membrane development.

The objective of this study is to model a module-scale forward osmosis unit operation and examine the effects of key membrane transport parameters on performance. First, we consider the thermodynamic limits of water recovery for both co- and counter-current flow in an FO process. Second, we introduce mass transport across a differential FO membrane element and discuss the performance limiting phenomena. We then develop a module-scale process model to simulate an FO membrane unit and examine the contributions of active layer, support layer, and boundary layer mass transport resistances to the membrane area required to achieve a specified water recovery. Lastly, we investigate the effects of different operating conditions, specifically, feed and draw flow rates and concentrations, on the membrane area requirement. The findings of this study can serve to guide the design and development of forward osmosis systems by identifying the parameters that offer the largest potential improvements in process performance.

2. Upper limit of water recovery

An FO module consists of a low concentration feed stream and a high concentration draw stream separated by a semi-permeable membrane, commonly in a spiral-wound or tubular/hollow fiber configuration [40]. Driven by the osmotic pressure gradient, water permeates across the membrane from the feed stream to the draw stream [41]. Similarly, draw solutes are transported down a concentration gradient from the draw stream to the feed stream, while feed solutes permeate into the draw stream. The primary objective of an FO process is to recover water from the feed stream into the draw stream. Fig. 1 shows schematics of two configurations of an FO process: co-current and counter-current.

Throughout this study, both the feed and draw solutes are taken to be NaCl and osmotic pressures are approximated using the van't Hoff equation, $\pi = \upsilon c R_g T$, where υ is the van't Hoff dissociation factor ($\upsilon = 2$ for NaCl), R_g is the universal gas constant, T is the absolute solution temperature, and c is the molar salt concentration. The accuracy of the van't Hoff osmotic pressure approximation decreases substantially at

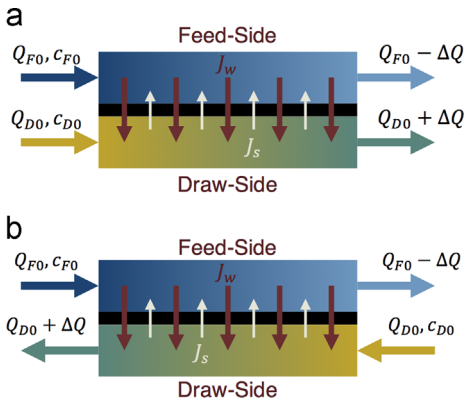

Fig. 1. Schematic of a FO module operating in (a) co-current and (b) counter-current mode. Water permeates from the feed-side to the draw-side with a local flux of J_w. The permeation flow rate, ΔQ, is the integral of J_w across the membrane area of the entire module. Draw solute leaks from the draw-side to the feed-side with a molar flux of J_S^R. Feed solute permeates from the feed-side to the draw-side with a molar flux of J_S^F. The net solute flux comprising J_S^R and J_S^F from the draw-side to the feed-side is J_S. The volumetric flow rate and molar concentration of the streams are denoted by Q and c, respectively.

solute concentrations above 1.5 M [42]. However, in this study the feed and draw concentrations at the membrane-solution interface range from 0.6 M to 1.4 M. In this region, errors in the van't Hoff approximation are under 3% [43] (OLI Systems, Morris Plains, NJ). In addition, we neglect hydraulic pressure drop along the membrane module, as these are small in comparison to the osmotic pressure differences across the membrane. By applying these assumptions, two streams are in equilibrium with each other when they have the same concentration. Thin-film composite (TFC) polyamide membranes governed by solution-diffusion were utilized in the membrane modules for all model analysis. Other module-scale effects, such as configuration of the membrane elements, are not considered in this investigation.

We define the water recovery, R, and the feed flow rate fraction, ϕ, in terms of the volumetric rate of water permeation across the membrane, ΔQ, and the initial feed and draw flow rates, Q_{F0} and Q_{D0}, respectively:

$$R = \frac{\Delta Q}{Q_{F0}} \tag{1}$$

$$\phi = \frac{Q_{F0}}{Q_{F0} + Q_{D0}} \tag{2}$$

Recovery, R, is the fraction of water extracted from the saline feed and is, thus, an important performance parameter in desalination processes.

Water flux across the membrane, J_w, is proportional to the osmotic pressure difference and can be expressed using the membrane water permeability coefficient, A, and feed and draw concentrations at the membrane-solution interface, $c_{F,m}$ and $c_{D,m}$, respectively [40]:

$$J_w = A(\pi_{D,m} - \pi_{F,m}) = \upsilon A R_g T (c_{D,m} - c_{F,m}) \tag{3}$$

Because concentrations $c_{F,m}$ and $c_{D,m}$ vary along the length of the membrane module, J_w denotes the local water flux. Similarly, the local net solute flux, J_s, is expressed using the membrane solute permeability coefficient, B [38,44]:

$$J_s = B(c_{D,m} - c_{F,m}) \tag{4}$$

Since both the draw and feed solutes are NaCl, J_s represents an aggregate of the reverse solute flux (RSF) of draw solute into the