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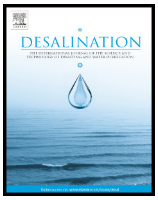

A statistics-based forward osmosis membrane characterization method without pressurized reverse osmosis experiment

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HIGHLIGHTS

- A statistics-based FO membrane characterization method was developed.
- The statistical approach finds FO membrane parameters using ICP and ECP models.
- Consideration of ECP helps to determine more accurate FO membrane parameters.
- The parameters from the FO method predict the FO membrane behavior fairly well.
- Pressurized RO experiment may not need to obtain FO membrane characteristics.

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ABSTRACT

A simple forward osmosis (FO) membrane characterization method was developed based on the combination of a single FO test and a statistical approach to avoid the pressurized reverse osmosis (RO) test, which may damage the tested FO membrane or misread the membrane characteristics. The single FO test measures water and reverse solute flux (J_w and J_s, respectively) in the active layer facing feed solution (AL-FS) mode using deionized water as feed and sodium chloride as draw solute. The statistical approach finds the most appropriate water permeability (A), salt permeability (B), and the resistance to salt diffusion within the support layer (K_{ICP}) of the tested FO membrane to predict J_w and J_s using both internal concentration polarization (ICP) and external concentration polarization (ECP) models. Verifications using various experimental results in this work and other literatures reveal that the developed FO membrane characterization method determines more reliable parameters (A, B, and K_{ICP}) than the conventional characterization method based on the RO experiment to predict the experimental J_w and J_s in FO processes. Consideration of ECP helps to determine more accurate FO membrane parameters (especially K_{ICP}), but it is difficult to properly model ECP suitable for the tested FO membrane channel.

1. Introduction

Pressure-driven membranes have been widely used in the field of water purification, wastewater reclamation, and desalination. These membrane processes use hydraulic pressure as the driving force for water transport through the membrane. Especially in reverse osmosis (RO) process, extensive electric energy is required for the operation, hence the need for an alternative approaches to water desalination inquiry, considering limitations on feed water recovery [1]. Forward osmosis (FO) is one of the most attractive emerging membrane technologies. FO uses a concentrated solution called draw solution (DS) to generate high osmotic pressure, which pulls water across a semi-permeable membrane from the feed solution with low osmotic pressure. The difference in osmotic pressure between DS and feed creates the natural driving force. FO process has some advantage of lower energy requirements and membrane fouling potential, compared to hydraulic pressure-driven membrane processes such as RO [2].

One of the most successful applications of the FO process is seawater desalination using ammonia–carbon dioxide as DS and low-grade heat as DS recovery and fresh water production [3]. On the other hand, for the past few years, some hybrid FO systems have been studied for various applications including seawater and brackish water desalination (about 60%), wastewater treatment (about 13%) or both (i.e. simultaneously, about 13%) [4]. Direct fertigation, protein concentration or dewatering of RO concentrate, and harvesting the microalgae for further biodiesel production are other applications of FO process [5–7]. Another recent study investigated the possibility of dual-stage Forward osmosis/Pressure

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retarded osmosis (FO/PRO) for the osmotic dilution of shale gas wastewater [8].

Regardless of these various possible applications of FO processes, it is very difficult to find a full-scale FO application in the world mostly due to poor performance of the current-level FO membranes [4]. A full-scale simulation of an FO application with the current-level FO membrane characteristics as input parameters revealed that the predicted average flux was very low because of the concentrated feed and the diluted DS in full-scale operation [9]. The low flux problem may be solved by enhancing the process design [10], but the fundamental solution to this problem is to develop the FO membrane with high performance. Fortunately, the efforts to develop the FO membrane with better performance keep going on [11–14], which may lead the promising future of the FO process.

It is very crucial to obtain accurate FO membrane properties not only for developing better membranes but also for predicting the full-scale performance of an FO process. When describing the FO membrane properties, three parameters, the pure water permeability (A), solute permeability (B), and the resistance to salt diffusion within the support layer (K_{ICP}) are commonly used. In order to describe the water and reverse solute fluxes in FO process, these three parameters are typically used and thus regarded as the standard criteria for FO membrane characterization [15].

The general methods for evaluating FO membrane properties involve at least two separate independent experiments [16–18]. Firstly, the parameters related to the active layer of the FO membrane (i.e., A and B) are measured by applying hydraulic pressure in RO mode experiments. Subsequently, the resistance to salt diffusion within the support layer (K_{ICP}) is determined by FO mode experiments.

FO membrane is generally manufactured to reduce the resistance to salt diffusion within the support layer (K_{ICP}) to decrease the effect of internal concentration polarization (ICP) [16,18,19]. The support layer of FO membrane is thinner, less tortuous, and more porous than that of RO membrane, which may result in the reduction in physical resistance [20]. The physically weak support layer could be damaged by hydraulic pressure applied in RO experiment to analyze water and solute permeability of FO membrane [15,21]. Moreover, membrane compaction and deformation problems caused by hydraulic pressure may lead to obtain less accurate FO membrane characteristics [22]. Thus, it is recommended to confirm mechanical stability of the FO membrane by pure water permeability test with hydraulic pressure [23]. In summary, the conventional RO filtration test to determine FO membrane characteristics may be problematic, which is the motivation of this study.

The objective of this work is to develop an FO membrane characterization method without pressurized RO experiment. Instead of carrying out the pressurized RO filtration tests, a simple statistical approach is introduced to find the most appropriate FO membrane characteristics (i.e., A, B, and K_{ICP}) using mass transfer model for FO process. Recently, a similar approach to the objective of this study was already developed [19]. This method consists of a single FO test and a least-squares nonlinear regression, using A, B, and structural parameter (S) as regression parameters. It shows better prediction performance than the conventional method using both RO and FO tests. However, the mass transfer model used in this method neglects the effect of external concentration polarization (ECP). According to the recently published literatures, the ECP effect is not negligible compared to ICP [9,10] and the FO membrane characteristics cannot be accurately measured without considering ECP [24,25]. Thus, an advanced FO membrane characterization method should adopt the FO mass transfer model accounting for not only ICP, but also ECP. The FO mass transfer model used in this study considers the ICP within the support layer and the external concentration polarization (ECP) in the boundary layers faced the active and support layers of the tested membrane. In the FO membrane characterization method developed in this work, a single FO test produces water and solute flux data and the FO mass transfer model accounting for both ICP and ECP determines the most fitted FO membrane characteristics (i.e., A, B, and K_{ICP}). The FO membrane characteristics determined by this method were verified using the experimental water and solute flux data obtained from the experiments in this study and other literatures [13,26–34], and the comparison between this method and the prior FO membrane characterization method based on a single FO test [19] was carried out in terms of predictability and the effect of the consideration of ECP.

2. Materials and methods

2.1. Materials

FO membrane used in this study was FO8040 which is thin-film composite (TFC) membrane and provided by Toray Chemical Korea, Inc. Lab-scale crossflow FO and RO systems described in Fig. 1 were used in this study. The FO cells have two symmetric channels on both sides of the membrane for co-current flows of the feed and draw solutions. The channel dimensions in the cell are 110 mm in length, 60 mm in width, and 1 mm in height. Membrane surface and cross-sectional flow areas are then 6.6×10^{-3} m^2 and 6.0×10^{-5} m^2, respectively. Mesh spacers were inserted within both channels to improve support of the membrane as well as to promote turbulence and mass transfer. The FO cell was also used in the pressurized filtration test in the RO system.

Draw solute used in this study was sodium chloride (NaCl) from Daejung chemical & metals, Co., Ltd. (Korea). NaCl is one of the most preferred draw solutes because (1) it is rejected to a large extent (>95%) by the membrane, (2) it is able to expect a high osmotic pressure, (3) it has nearly constant diffusivity over the range of concentrations applied (e.g., the diffusivity of NaCl ranges from 1.472 to 1.526×10^{-9} m^2/s [35], and (4) it is easily quantifiable in the feed by conductivity measurements to determine J_s [19].

2.2. RO and FO filtration test

Prior to each filtration test, the lab-scale RO and FO systems were flushed with deionized water for 30 min and the feed reservoir was filled with deionized water at a constant temperature of 23 °C.

RO filtration tests were carried out to directly determine water and salt permeability (A and B). Deionized (DI) water was use as feed water and water flux (J_w) was measured at different applied pressure ranged from 2 to 5 bar. The applied pressure did not exceed 5 bar in this study to prevent FO membrane damages and deformation caused by thin and elastic structural characteristics. Unlike the general RO filtration test discussed elsewhere [36], the pre-compaction process was skipped in this work, which is because the compaction may alter the water and salt permeability of the tested FO membrane. The water permeability (A) was then determined by dividing the water flux by the applied hydraulic pressure, ΔP (i.e., $A = J_w/\Delta P$).

On the other hand, feed solution with salt concentration which leads approximately 1 bar of osmotic pressure (1380 mg l^{-1} as NaCl) was used to determine salt permeability (B). Water flux and salt rejection rate was measured at total applied pressure of 5 bar. Observed salt rejection, R, was determined from the difference in feed (c_f) and permeate (c_p) salt concentrations (i.e., $R = 1 - c_p/c_f$). The conductivity of feed and draw sides was measured with a calibrated conductivity meter (Mi 180 Bench Meter; Martini Instrument, USA) to determine concentrations using molar concentration-conductivity relation. The rejection values for each sample are the average of three different measurements, each collected over about 30 min. The solute permeability coefficient, B was determined from [37,38].

$$B = J_w \left(\frac{1-R}{R} \right) \exp\left(-\frac{J_w}{k_f} \right), \tag{1}$$

where J_w and k_f correspond to the permeate flux and the mass transfer coefficient of NaCl in the feed solution, respectively. The mass transfer

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