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A simple modeling approach for a forward osmosis system with a spiral wound module

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ABSTRACT

A simple but accurate prediction method for the performance of a commercial spiral wound forward osmosis (FO) module was developed. The method includes a fundamental model based on the internal and external concentration polarization (ICP and ECP) in the FO process, the module experiments with sodium chloride, and a fitting process to increase the accuracy of the model. Comparison between the ICP/ECP modeling results and the experimental data reveals that trans-membrane pressure is a key parameter to explain the difference between the modeling and experimental results. The draw solution (DS) channel heights in the module could be shrunk by trans-membrane pressure, and this hypothesis is strongly supported by a statistical analysis for the differential pressure and the accuracy of a modified model accounting for the effect of trans-membrane pressure. The modified model with trans-membrane pressure and other hydrodynamic factors as fitting variables predicts the performance of the spiral wound FO module accurately. The number of experimental data for the fitting process (i.e., trained data) to obtain a reliable prediction model was found to be around 30, and the modified model turns out to work reasonably well to predict not only the trained data but also the untrained data.

1. Introduction

Forward osmosis (FO) process is an attractive desalination process. Since it uses osmotic pressure gradient between draw solution (DS) and feed solution (FS), a very small mechanical pressure (compared to reverse osmosis (RO) process) is necessary to take pure water from FS. Behind this attractive point, there are two hidden issues in FO applications: (1) DS recovery, and (2) Scale-up. In FO processes, DS draws pure water from FS permeating through semi-permeable membrane. Thus, DS is diluted while FS becomes concentrated. If the objective of an FO process is to obtain fresh water, the diluted DS should be separated into the fresh water and re-concentrated DS, which is called DS recovery, the first issue. An independent desalting process such as heating [1] and reverse osmosis [2–3] is necessary for DS recovery, and several hybrid design options were introduced [4–5].

This paper focuses on the second issue, scale-up. If a full-scale FO system is designed with a realistic recovery rate (i.e., the ratio of permeate to FS flow rate), the actual osmotic pressure gradient will be decreased due to diluted DS and concentrated FS. Thus, the performance of full-scale FO applications may be overestimated without considering this scale-up effect. The model-based approaches have been carried out to expect the performance of full-scale FO applications [2, 6–10]. These works were based on the fundamental mechanisms of FO process such as internal and external concentration polarization (ICP and ECP) and the actual osmotic pressure difference between DS and FS was considered as a function of longitudinal position of FO membrane (or local recovery rate). The average water flux in a full-scale system was predicted using the model-based approach.

These modeling-based works assumed the scale-up as just enlarging a flat-sheet membrane. With this assumption, FS and DS are supposed to flow along each channel divided by the FO membrane in the same or opposite parallel directions. However, the real flow patterns of FS and DS in the spiral wound FO module are not that simple like the assumption [11–16]. For examples, the DS flows into a cylindrical tube inside the spiral wound module, and it is distributed the DS channel in a perpendicular direction to the FS flow direction. Thus, it is not sure that the FS and DS are uniformly distributed to several channels inside the module. In addition, it may happen that the channel heights are changed due to uneven pressure distribution.

Due to these reasons, some experimental data in a spiral wound FO membrane test are not easily explained by the fundamental theory of FO as shown in Fig. 1. Since pure water is used as FS and there exists no ECP in the FS side, the FS flow rate is not supposed to affect the water flux of the FO module. However, Fig. 1a shows that the water flux of the

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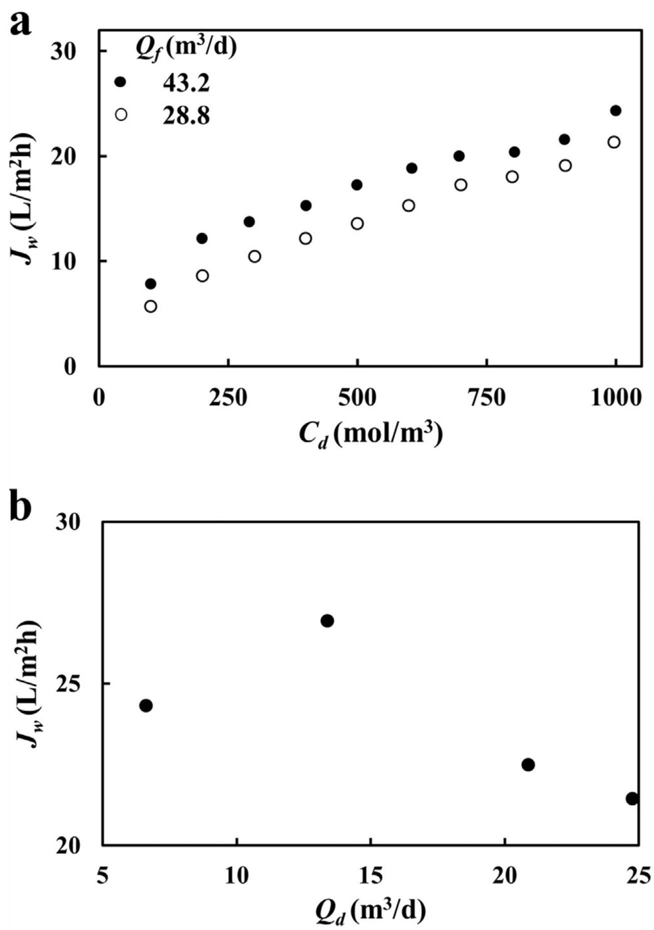

Fig. 1. Do spiral wound FO modules behave differently from the fundamental theory?: (a) Effect of FS flow rate and (b) DS flow rates on the water flux of FO 8040 module (Toray Chemical Korea, Inc.). Pure water and sodium chloride solution were used as FS and DS, respectively. The detailed information on the operation condition and results will be discussed in Section 3.2.

module increases at higher FS flow rates (e.g., the water flux was expected to be the same for both FS flow rates.). In addition, Fig. 1b shows the increased DS flow rates decrease the water flux of the module, which is totally opposite to the theory (e.g., the water flux was expected to increase at higher DS flow rates.). According to the theory, ECP in the DS side should get smaller with the increase in mass transfer resulting from the increased DS flow rates (i.e., the increase in cross-flow velocity in the DS side), which causes the increase in the water flux.

The experimental study using real FO modules is of critical importance because the FO module behaviours seem different from the well-known theory verified by lab-scale experiments and the module is a basic unit to design a full-scale process. Currently, three types of FO modules (spiral wound, flat sheet, and hollow fiber) have been developed and applied to pilot- or real-scale systems. The previous works about FO module experiments published so far [11–21] have reported the effects of draw solute, hydrodynamic factors (e.g., flow rates and mechanical pressures), and temperature on the water flux data observed in the three types of FO modules. Although these works reported real experimental data observed in their FO systems using real modules, their results are specific to each operation condition. For example, it is impossible for the findings from these studies to explain why FO 8040 module does not seem to follow the fundamental mechanism discussed above (Fig. 1).

Modeling FO module directly can be a good solution to understand the performance of the module. Gruber et al. presented a computational fluid dynamics (CFD) model for an FO module using an open source CFD code [22]. Understanding complicated flow patterns inside the module will help to design better modules. However, it should be better to have a simple and predictive model for FO modules in order to design a full-scale FO system. Recently, a few researches about modeling FO modules verified using experiments have been published [23–25]. These works developed a good predictive model for spiral wound and hollow fiber modules based on correlation with experimental results using parameters related to membrane and mass transfer as fitting variables. However, the module behaviours observed in Fig. 1 cannot be explained using their models because the fitting parameters used in these approaches are based from the fundamental FO mass transfer mechanisms such as ICP and ECP.

Sometimes, it could be better to use an empirical equation with important operation variables in order to develop better predictive models. Khayet et al. (2016) developed a second order polynomial equation with flow rates and temperatures as independent variables [26]. This type of approach works very well in terms of prediction accuracy, but it should need a number of data to obtain reliable model parameters to increase the accuracy. In addition, it may be difficult for the empirical model to explain the reason why the module behaviours seen in Fig. 1 happen although the empirical model may be able to predict this kind of peculiar pattern very well. This is because the model is not based on the fundamental FO theory.

Therefore, the objective of this study is to develop a simple and predictive model for an FO module to help an easy and reliable design of a full-scale FO system. A spiral wound FO module named FO 8040 (the 8″ spiral wound FO module made by Toray Chemical Korea, Inc.) is chosen for the study. In order to take the advantages of both fundamental and empirical models, the module-scale ICP and ECP model in the simplest form is developed and the error between the experimental and modeling data is expressed as an empirical equation using hydrodynamic parameters (e.g., FS flow rate, DS flow rate, and trans-membrane pressure) as fitting variables. Using the developed model, the characteristic performance of FO 8040 module will be discussed comprehensively. In addition, the minimal number of experimental data required to obtain the model parameters will be suggested to increase the applicability of the model in a real-filed application.

2. Materials and methods

2.1. Modeling a simple module-scale FO system

In order to develop a simple module-scale model, FO module was assumed to be a one-dimensional system consisting of FS side, FO membrane, and DS side as shown in Fig. 2, which was generally used to explain the concept of the internal and external concentration polarization (ICP and ECP) in literatures [27]. The water flux (J_w), reverse solute flux (J_s), hydraulic pressures (P_{FS} and P_{DS}), concentrations

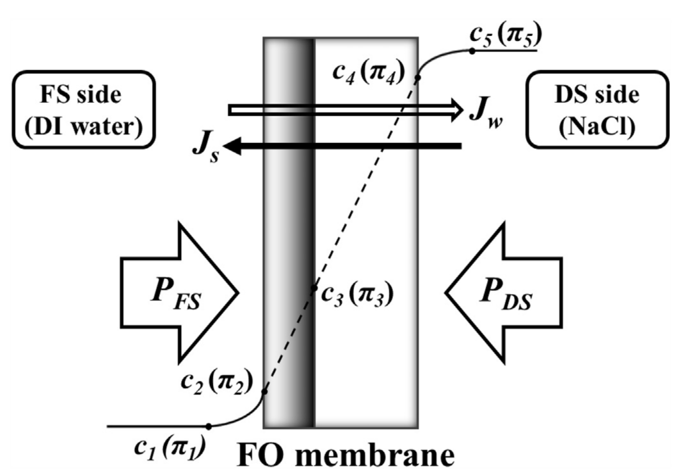

Fig. 2. Schematic of a one-dimensional FO system.