Desalination 309 (2013) 125–140

Contents lists available at SciVerse ScienceDirect

Desalination

journal homepage: www.elsevier.com/locate/desal

Revised external and internal concentration polarization models to improve flux prediction in forward osmosis process

Chien Hsiang Tan [1], How Yong Ng *

Centre for Water Research, Department of Civil and Environmental Engineering, Faculty of Engineering, National University of Singapore, Block E1A #02-19, 1 Engineering Drive 2, 117576, Singapore

HIGHLIGHTS

► Previous FO modified ECP model can only account for NaCl or KCl as draw solute.
► Previous ECP model under-predicted the ECP effect on flux for other solutes.
► Using dilution/suction in ECP model improved flux prediction.
► ICP model improved by using solute resistivity constant.
► The revised ECP and ICP models improved accuracy of flux prediction for FO process.

ARTICLE INFO

Article history:
Received 14 March 2012
Received in revised form 12 September 2012
Accepted 14 September 2012
Available online 24 October 2012

Keywords:
Forward osmosis
External concentration polarization
Internal concentration polarization
Diffusivity
Solute resistivity constant
Modeling

ABSTRACT

Previous modified external concentration polarization (ECP) model can only accurately account for the ECP effect of the forward osmosis (FO) process with NaCl or KCl as the draw solute, when Schmidt number (*Sc*) values are less than 800 and water fluxes are low. However, for other solutes (i.e., $MgSO_4$, $MgCl_2$, $CaCl_2$ and glucose) that have considerable variation of solutes diffusivities with concentration and high *Sc* values, the previous modified ECP model under-predicted the effect of ECP on flux. To improve accuracy of flux prediction, the previous ECP model was revised to include dilution/suction and property (diffusivity) variation effects. The modified ICP model was also improved by considering a solute resistivity constant, K_s, that is specific to each membrane for each draw solute used, due to different degree of interactions of different solutes with the porous matrix membrane material. The revised ECP and ICP models, proposed in this study, improved the overall accuracy of flux prediction for the FO process when different draw solutions were considered. The overall FO model was verified by data obtained from laboratory-scale experiments and the appropriate FO models could be selected based on the feed and draw solutes under both pressure-retarded-osmosis and forward-osmosis mode of operation.

1. Introduction

The forward osmosis (FO) process has recently been actively studied and has shown great potential in its application in various fields, particularly in seawater desalination and wastewater treatment [1–5]. Numerous studies have demonstrated that performance of the FO process can be compared with other membrane processes [2,5] with additional advantages such as lower fouling potential [4,5], higher water recovery [6] and low energy consumption [7]. However, the lack of an improved FO membrane and an ideal draw solution, whereby water molecules can be separated easily and economically from the diluted draw solution in order to regenerate and reuse the draw solution in the FO process, challenged the progress of the FO technology. Hence, more studies on the performance of FO membrane and various draw solutions need to be conducted to provide a more quantitative comparison. In addition, FO process modeling is a very important tool for process design and performance projection.

FO membrane transport modeling allows researchers to predict water flux for an FO operation with different FO membranes, feed and draw solutions, and operating conditions without actually conducting a physical experiment. This is especially vital when selecting a draw solution and for scaling-up of the FO process. The challenge of predicting flux for the FO process effectively and accurately is the selection of an accurate model suitable for a wide range of testing conditions, which requires relatively low computational power. In membrane process modeling, especially for FO, the external concentration polarization (ECP) effect, the internal concentration polarization (ICP) effect and

* Corresponding author. Tel.: +65 65164777; fax: +65 67744202.
E-mail address: howyongng@nus.edu.sg (H.Y. Ng).
[1] Tel.: +65 65164777; fax: +65 67744202.

0011-9164/$ – see front matter
http://dx.doi.org/10.1016/j.desal.2012.09.022

the membrane permeability have to be considered and their models have to be developed separately before combining them to allow for accurate flux prediction in an FO process.

All membrane processes suffer from ECP effect at the membrane interfaces that are in contact with the bulk fluids because a thin layer of fluid at the interface can get polarized. Within this thin layer of fluid, transport of water and other solutes are only based on advection (perpendicular to the membrane surface) and molecular diffusion. The first ECP model used to describe the impact of ECP in FO process was established by McCutcheon and Elimelech [8]. They adopted the ECP models typical used in reverse osmosis and ultrafiltration [9,10] for modeling the ECP effect in FO. Their results are accurate for ECP layer that is developed under lower bulk NaCl concentration regime. Tan and Ng subsequently used a modified film-model, which is developed from the boundary-layer concept, to describe the ECP effect at low to high bulk NaCl concentration with much success [11]. However, the use of the above ECP models for other FO draw solutes were not accounted for.

The ICP effect exhibits a more severe impact on the reduction of water flux in the FO process than the ECP effect due to the fact that there is also an axial flow of a salt solution within the porous layer of the asymmetric FO membrane, creating the ICP. The solutes that enter and exit the porous layer are brought about by advective water flux and direct diffusion, and since minimal amount of solute can penetrate the dense selective layer, it will result in back diffusion and the buildup of solute within the porous layer leading to the formation of the ICP effect. For ICP modeling, a previously developed model using the convective-diffusion model had been used [8,12,13]. It was noted in Tan and Ng that the earlier ICP model over-predicted the water flux in the FO process mainly due to the simplified assumptions used to describe the model [11]. An extension to the ICP model was proposed by introducing the diffusivity of NaCl as a function of its concentration to determine the solute resistance coefficient that was independent of the solute diffusivity. And this modified model performed superior to the previous ICP model in terms of flux prediction [11]. Likewise for the modified ICP model, only NaCl solution was taken into account and no other draw solutes were considered.

In this study, the first objective is to study the applicability of the modified ECP and ICP models used by Tan and Ng for FO flux prediction when other possible draw solutions are used [11]. For the second objective, it is expected that for the other draw solutions, dilution/suction parameter need to be considered when modeling the ECP effect to improve the accuracy of flux prediction; hence the modified ECP model will be revised to account for these effects. The third objective of this study is to develop a modified ICP model that takes into consideration the solute resistance coefficient of each solution, so as to take into account the interaction of solute with the porous matrix membrane material occurring within the ICP layer. Finally, both the revised ECP and ICP models will be combined to determine the accuracy of flux prediction in a FO process when different draw solutions are used.

2. Materials and methods

2.1. Feed and draw solutions

The feed and draw solutions were prepared using deionized (DI) water. The feed solution used, depending on the objectives of the experiments, was either DI water or 0.5 M NaCl solution. The draw solutions used for this study include NaCl, KCl, $MgSO_4$, $MgCl_2$, $CaCl_2$ and Glucose. The maximum concentration prepared for these draw solutions could be as high as 5.0 M, depending on their solubility. Solution properties including osmotic pressure were calculated using the software, StreamAnalyzer 2.0 (OLI systems Inc., Morris Plains, NJ), while dynamic viscosity, density and diffusivity were obtained from other published literature [14–22].

2.2. FO membrane

The FO membrane (Hydration Technologies Inc., Albany, OR) used was the same as the one used in Tan and Ng [11]. A detailed description and SEM images of the membrane are provided elsewhere [23].

2.3. Membrane orientation

The FO membrane was tested either in the PRO mode, also known as normal mode in Tan and Ng [11] (i.e., the dense selective layer of the membrane faces the draw solution while the porous layer faces the feed solution), or in the FO mode, also known as the reverse mode in Tan and Ng [11] (i.e., the dense selective layer facing the feed solution while the porous layer faces the draw solution) and as shown in Fig. 1. Other designation for membrane orientation was also used [24], but designations as above were used to keep in line with previous publications used herein for modeling comparison.

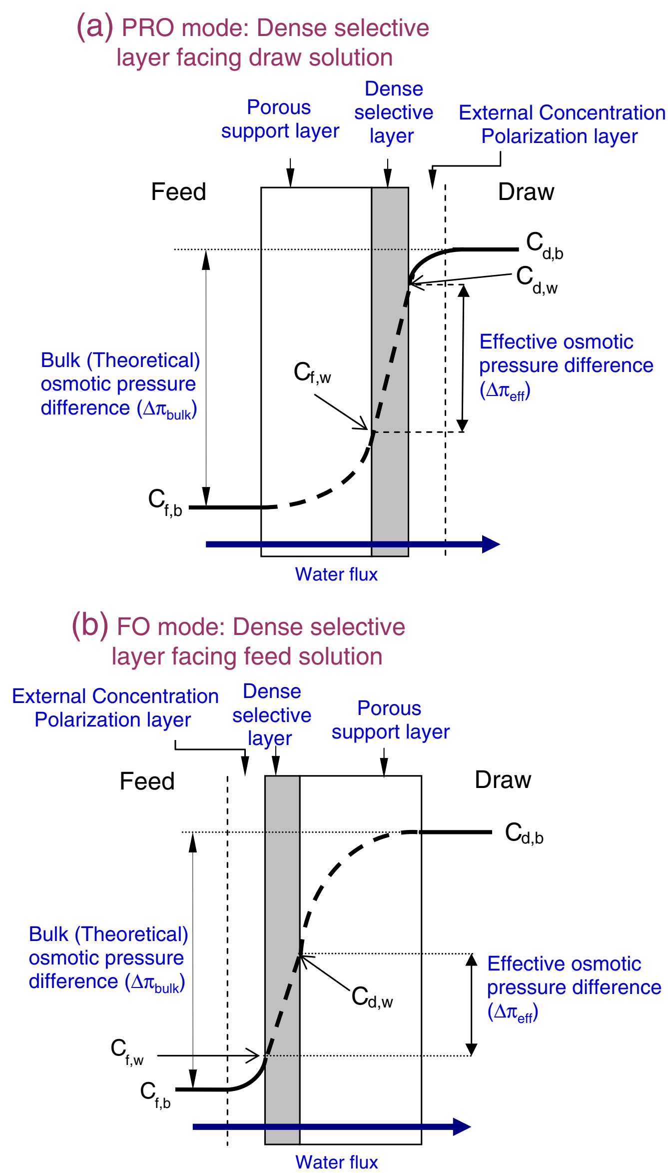

Fig. 1. Transport phenomenon and membrane orientation of the FO process using an asymmetric FO membrane. (a) PRO mode and (b) FO mode. Adapted from [11,24].