Journal of Membrane Science 465 (2014) 159–166

Contents lists available at ScienceDirect

Journal of Membrane Science

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

Effect of hydraulic pressure and membrane orientation on water flux and reverse solute flux in pressure assisted osmosis

Yoontaek Oh [a], Sangho Lee [b], Menachem Elimelech [c], Seockheon Lee [d,e,*,*], Seungkwan Hong [a,e,*]

[a] School of Civil, Environmental & Architectural Engineering, Korea University, 1-5 Ga, Anam-dong, Seongbuk-gu, Seoul 136-713, Republic of Korea
[b] School of Civil and Environmental Engineering, Kookmin University, 861-1 Jeongneung-dong, Seongbuk-gu, Seoul 136-702, Republic of Korea
[c] Department of Chemical and Environmental Engineering, Yale University, New Haven, CT 06520-8286, United States
[d] Center for Water Resource Cycle (CWRC), Korea Institute of Science and Technology, Hwarangno 14-gil 5, Seongbuk-gu, Seoul 136-791, Republic of Korea
[e] Energy Environmental Policy and Technology, Green School, Korea University-KIST, Seoul 136-701, Republic of Korea

ARTICLE INFO

Article history:
Received 7 August 2013
Received in revised form
9 March 2014
Accepted 5 April 2014
Available online 13 April 2014

Keywords:
Forward osmosis (FO)
Pressure assisted osmosis (PAO)
Membrane orientation
Water flux
Reverse solute flux

ABSTRACT

Forward osmosis (FO) is an emerging technology that has received much global interest due to its potential applications in wastewater reclamation and seawater desalination. One of the major challenges to overcome is the detrimental effects of concentration polarization (CP), which reduce the effective osmotic pressure driving force and thus decrease productivity of the FO process. In this study, pressure assisted osmosis (PAO) was investigated as a method to increase the effective driving force and water flux by combining an osmotic pressure driving force with an additional hydraulic pressure. Experiments were carried out to examine the efficiency of the PAO process using a bench-scale setup specially designed to prevent membrane deformation under the applied hydraulic pressure. Results showed that PAO water flux increased with increasing the applied hydraulic pressure in FO mode (i.e., active layer facing the feed solution). The measured water fluxes were in good agreement with predictions based on a model developed to describe the water flux in PAO operation. However, the PAO water flux was lower than model predictions in PRO mode (i.e., active layer facing the draw solution). This observation is attributed to the spacer 'shadow effect' and the resulting reduction in the effective membrane area by the spacers. The results also showed that reverse solute flux decreased with increasing the applied hydraulic pressure in both FO and PRO modes. Although applying hydraulic pressure to FO increases energy consumption, the higher water flux in PAO reduces the number of membrane modules for the FO process. In addition, control of the driving force is easier in PAO than FO, leading to flexibility in system design and operation. Based on these results, a possible combination of FO and RO system with PAO was proposed for allowing higher energy efficiency in seawater desalination.

Published by Elsevier B.V.

1. Introduction

Increasing concern over the limited supply of fresh water from conventional sources has increased the need to develop alternative water sources, including the reuse of wastewater and seawater desalination. Forward osmosis (FO) is an emerging membrane technology that can be used to produce clean water from these alternative water sources. FO is driven by the osmotic pressure difference across a semi-permeable membrane, and has received much interest in recent years because of the wide range of potential applications [1–3]. Compared with pressure-driven membrane processes, FO may offer several advantages, including lower use of electric energy, high rejection of contaminants, and low membrane fouling tendency [4]. Examples of potential FO applications include wastewater treatment [5–7], seawater/brackish desalination [8,9], and energy generation using salinity gradients [10–16].

However, there are several limitations that prevent large-scale applications of the FO process. One critical limitation is the phenomenon of concentration polarization (CP), which reduces the effective osmotic pressure driving force across the membrane, thereby lowering water flux. Of particular importance is the internal concentration polarization (ICP) within the support layer of FO membranes, which results in a marked decrease in the osmotic pressure driving force compared to external concentration polarization (ECP). Due to ICP, the FO water flux and productivity

* Corresponding author. Tel.: +82 2 3290 3322; fax: +82 2 928 7656.
** Co-corresponding author. Tel.: +82 2 958 5829; fax: +82 2 958 5839.
E-mail addresses: seocklee@kist.re.kr (S. Lee), skhong21@korea.ac.kr (S. Hong).

http://dx.doi.org/10.1016/j.memsci.2014.04.008
0376-7388/Published by Elsevier B.V.

are generally lower than those of pressure-driven membrane technologies, such as reverse osmosis (RO). Because CP is inherent of the FO process and cannot be eliminated, it is of paramount importance to better understand the phenomenon and to develop methods to reduce its deleterious effects on the FO process.

In this paper we investigate a new FO operation, pressure assisted osmosis (PAO), which incorporates the FO and RO processes. In PAO, in addition to the osmotic pressure driving force originating from the draw solution, hydraulic pressure is also applied to increase the driving force for water transport. The additional hydraulic pressure on the feed side was shown to not only increase permeate water flux, but also reduce reverse solute flux. We focused on the performance of PAO, with an emphasis on the effect of hydraulic pressure and membrane orientation. Based on the results obtained, we proposed a possible process innovation incorporating PAO for seawater desalination.

2. Modeling water flux

Following the general equation for FO presented by Lee et al. [13], McCutcheon and Elimelech [17] derived the following simplified equations to predict the water flux, J_w, in FO in the presence of ECP and ICP:

$$J_w = A\left[\pi_{D,b}\exp(-J_wK) - \pi_{F,b}\exp\left(\frac{J_w}{k}\right)\right] \quad \text{(for FO mode)} \tag{1}$$

$$J_w = A\left[\pi_{D,b}\exp\left(-\frac{J_w}{k}\right) - \pi_{F,b}\exp(J_wK)\right] \quad \text{(for PRO mode)} \tag{2}$$

$$K = \frac{t\tau}{\varepsilon D} = \frac{S}{D} \tag{3}$$

Here, A is the membrane pure water permeability, $\pi_{D,b}$ and $\pi_{F,b}$ are the draw and feed solution bulk osmotic pressures, respectively, K is the solute resistance to diffusion within the porous support layer, k is the mass transfer coefficient in the boundary layer at the active layer side of the membrane, t, τ, and ε are the thickness, tortuosity, and porosity of the support layer, respectively, D is the bulk diffusion coefficient of the draw solute, and S is the structural parameter of the membrane. The mass transfer coefficient k is obtained from

$$k = \frac{ShD}{d_h} \tag{4}$$

where Sh is the Sherwood number and d_h is the membrane channel hydraulic diameter. The Sherwood number for a rectangular membrane channel can be obtained as described elsewhere [16].

In Eqs. (1) and (2), the solute resistivity, K, and mass transfer coefficient, k, are the key factors that control the permeate water flux, J_w. Choi et al. proposed new equation for combined system of FO and RO as below [18].

$$J_w = A\left(\Delta P + \pi_{D,b}\exp\left(-\frac{J_w}{k_D}\right) - \pi_{F,b}\exp\left(\frac{J_w}{k_F}\right)\right) \quad \text{(for FO mode)} \tag{5}$$

where ΔP is the transmembrane applied hydraulic pressure, and k_F and k_D are the mass transfer coefficients for ECP and ICP, respectively. Note that in this equation, k_F and k_D are equivalent to k and $1/K$ in Eqs. (1) and (2).

It is noteworthy that the total water flux in PAO is not simply the sum of the water fluxes by FO and RO (i.e., $J_w = J_{w,FO} + J_{w,RO}$). Actually, the increased water flux by the applied hydraulic pressure decreases effective osmotic pressure due to enhanced ICP as predicted by the $\pi_{D,b}\exp(-(J_w/k_D))$ term in Eq. (5).

For our experiments with deionized (DI) water feed in FO and PRO modes, the equations for water flux simplify to

$$J_w = A(\Delta P + \pi_{D,b}\exp(-J_wK)) \quad \text{(for FO mode)} \tag{6}$$

$$J_w = A\left(\Delta P + \pi_{D,b}\exp\left(-\frac{J_w}{k}\right)\right) \quad \text{(for PRO mode)} \tag{7}$$

Here, we neglected the osmotic pressure term of feed side because DI water was used as feed solution ($\pi_{F,b} = 0$). Further, the concentration of salt in feed solution caused by reverse solute flux was extremely small compared to draw solution concentration, even at the end of the experiment; hence, this assumption (i.e., $\pi_{F,b} = 0$) is acceptable in our experiments.

3. Material and methods

3.1. Membrane

Commercially available FO membranes (HTI, Albany, OR) made of cellulose triacetate (CTA) were used in this study. They are flat sheet membranes with an asymmetric structure. Polyester woven mesh is embedded in the membrane structure to improve mechanical strength. Basic information on this membrane is given elsewhere [19].

3.1.1. Membrane characterization

The A and B coefficients were measured using an identical membrane sample. The two coefficients were measured every time when a membrane was replaced by a new sample after each run.

3.1.2. Membrane orientation

Generally, two membrane orientation modes exist in the FO process: one with the active layer facing the feed solution (FO mode) and the active layer facing the draw solution (PRO mode). Membrane orientation is important because water flux behaviors are different for different membrane orientations, even with identical concentrations of draw solution (i.e., identical osmotic pressure) [20]. In our experiments, when the applied pressure was over 20.7 bar (300 psi) in PRO mode, the membrane was damaged. On the other hand, membrane damage was not observed in FO mode, even at 27.6 bar (400 psi). For this reason, the maximum applied pressures were set to 13.8 bar (200 psi) in PRO mode and 20.7 bar (300 psi) in FO mode, respectively, in our experiments.

3.2. Spacer and new test cell

Fig. 1 shows the schematic of the specially fabricated cell and spacer design used in our experiment. Spacers are composed of two different materials. One is a porous stainless steel spacer, 1.75 mm in thickness, that allows water to pass freely. The width and length of the spacer are designed to fit the channel dimensions in the test cell. The other spacer is a tailored permeate carrier, which is used in commercially available spiral wound RO membrane modules (Hydranautics Inc.). Four sheets of permeate carrier are used to fill the remaining channel. These two types of spacers are placed on both the feed and draw solution channels of the test cell.

The spacers play a very important role in our experiments. In PRO experiments, for example, when general diamond shape plastic mesh spacers were used, the membrane underwent severe deformation by the applied hydraulic pressure on the feed side. This membrane deformation phenomenon has been reported recently [11,16]. In our experiments, the same phenomenon was observed and salt rejection decreased remarkably because the