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Effect of operating conditions on osmotic-driven membrane performances of cellulose triacetate forward osmosis hollow fiber membrane

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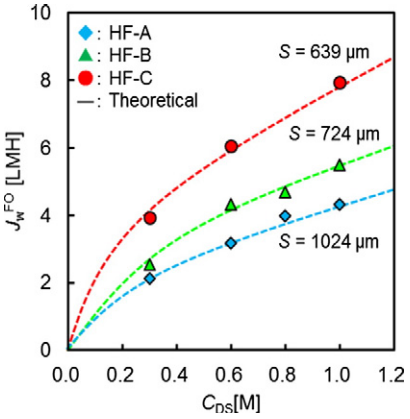
HIGHLIGHTS

- CTA-HF membrane module for approximately 700 HF membranes with diameters of less than 200 μm
- CTA HF membranes featured high J_w^{FO}/J_s^{FO}, exceeding 800 L/mol.
- The theoretical results agreed well with the experimental data in the obtained FO membrane.

GRAPHICAL ABSTRACT



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ABSTRACT

Recent development in forward osmosis (FO) membranes is promising in providing a versatile potential application for further advance in the water treatment and energy production sectors. Using FO hollow fiber membranes to achieve wide application of FO at an industrial level is advantageous because of their large specific membrane area and easy module construction for large-scale applications. In this study, three types of cellulose triacetate (CTA) hollow fiber (HF) forward osmosis membranes with diameters of less than 200 μm were evaluated under various operating conditions i.e., draw solution concentration, cross flow velocity, membrane orientation, and temperature. The osmotically driven performance evaluation revealed that the CTA HF membranes featured high water flux-to-reverse salt flux ratios, J_w^{FO}/J_s^{FO}, exceeding 800 L/mol. These values are much higher than those of commercial and reported FO membranes. The performance of the obtained FO membranes was also analyzed theoretically and the theoretical results agreed well with the experimental data.

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1. Introduction

Forward osmosis (FO) enables spontaneous transport of water molecules through a selective semi-permeable membrane from a lower concentration solution (feed solution: FS) to a higher concentration solution (draw solution: DS) by an osmotic pressure gradient. Recently, FO membrane processes have gain much research interest because of their versatile potential as an alternative membrane technology in areas such as hybrid desalination [1–3], wastewater treatment [4], enrichment of product [5,6], and energy production [7]. Recent developments in FO membranes have generated opportunities and potential for application at the industrial level. For example, Modern Water Inc. (UK) has constructed seawater desalination plants based on FO processes; the technology was named manipulated osmosis desalination (MOD) [8]. The MOD process involves an FO membrane, an osmotic agent (OA) as the draw solution (DS), a reverse osmosis (RO) recovery unit, and a supply pump. The hybrid system enables the production of drinking water via the RO recovery unit and pre-treatment of the RO process via the FO process. The major benefit of the FO pre-filtration hybrid system is the lower fouling propensity when compared with that of normal RO systems because the diluted OA solution comprises few foulants. The performance of the subsequent RO process remains mostly constant for more than 24 months without chemical cleaning [8]. Thus, the FO pre-filtration is ideal for desalination of highly polluted seawater with a high fouling potential.

Another example of a successful commercial FO product is SeaPack®, an emergency water resupply bag, which was developed by Hydration Technology Innovations (HTI) [9]. In this application, an edible DS (e.g., sugars or drinking powders) is packed in a sealed bag comprising a FO membrane. When SeaPack® is loaded into the water supply, such as rainwater, lake water, or river water, only pure water can be transported into the bag owing to the osmotic pressure difference, and the resulting diluted DS can be used for drinking purposes.

To achieve widespread use of FO processes, the development of FO membranes with high performance is required, because commercial RO membranes cannot be typically used as FO membranes. Examples of FO membranes include cellulose triacetate flat sheets [3,7,10–15], thin-film composite (TFC) flat sheets [14,16–27], biomimetic flat sheets [28-32], and TFC hollow fibers [33–37]. Recent numerous efforts have been made toward developing high-performance FO membranes, with a considerably higher water permeability than that of commercial FO membranes by tuning the support layer structure and the active layer characteristics [16–27,33–37]. However, for industrial applications, the development of large-scale FO membrane modules is required. Although both the flat sheet-based spiral-type module and hollow fiber (HF)-type module configurations have been trialed in large-scale experiments, the HF-type modules are more advantageous owing to their large specific membrane area and easy module construction [38–41]. HF membranes with smaller diameter can enable the fabrication of modules with larger effective membrane area. For example, commercially available FO spiral modules have an effective membrane area about 3.2 m^2 (diameter: 4 in., length: 40 in.) [42] and 17.6 m^2 (diameter: 8 in., length: 40 in.) [43]. On the other hand, HF membranes with the diameter of approximately 180 μm used in this study enable to provide a larger effective area over 60 m^2 of 5-inch scale module (diameter: 5 in., length: 26.9 in.) [44]. Although there are some reports about fabrication of HF FO membranes, those diameters were about 1 mm [34,35]. Therefore, the HF used in this study is one of smallest HF FO membrane promising larger membrane area in the module.

In this study, we evaluated the performance of three types of HF membranes with diameters of less than 200 μm. The effect of operating conditions such as the salt concentration of the DS, inlet flow rates of DS and FS, membrane orientation, and temperature on the osmotically driven membrane performance was investigated. Furthermore, the experimentally determined membrane performance was theoretically analyzed.

2. Theory

The osmotically driven membrane performance generally depends on membrane orientation; asymmetric membranes are usually used. The reverse diffusion of the permeate water and salt leakage results in an internal concentration polarization (ICP) in the porous support layer as shown in Fig. 1. When the active layer is facing the DS (AL-DS), the solute concentration at the interface between the active layer and support layer becomes higher than the bulk feed concentration because of the leaked salt accumulation (concentrative ICP). In contrast, when the active layer is facing the FS (AL-FS), the solute concentration at the interface becomes lower owing to the DS dilution by permeated water (dilutive ICP). In both cases, the available osmotic driving force becomes smaller than that based on the apparent concentration difference between the bulk DS and bulk FS. The permeate FO flux (J_w^{FO}) can be expressed by using the classical solution diffusion theory involving ICP effect in support layer as follows [45–52]:

$$J_w{}^{FO} = \frac{D}{S} ln\left(\frac{B + A\pi_{DS,am} - J_w{}^{FO}}{A\pi_{FS,sm} + B}\right) \quad \text{for AL-DS}, \tag{1}$$

$$J_w{}^{FO} = \frac{D}{S} ln\left(\frac{B + A\pi_{DS,S}}{A\pi_{FS,am} + B + J_w{}^{FO}}\right) \quad \text{for AL-FS}, \tag{2}$$

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

where D is the bulk solution diffusivity of DS; π_{DS} and π_{FS} are the osmotic pressures of DS and FS, respectively; A and B are the water permeability and salt permeability, respectively. S, in Eq. (3), is the structural parameter expressed using thickness (t), tortuosity (τ), and porosity (ε) of the support membrane. As shown in Fig. 1, the subscripts of "*sm*" and "*am*" refer to support layer edge and active layer surface, respectively. The subscript of "*s*" refers to the support layer edge contacted with active layer. The relationship between the osmotic pressures at the bulk and membrane interfaces that represent the external concentration polarization (ECP) in the case of AL-DS can be expressed as follows [1,45,47,53]:

$$\frac{\pi_{DS,am}}{\pi_{DS,b}} = \exp\left(\frac{-J_w{}^{FO}}{k_{FO1}}\right) \quad \text{for dilutive ECP}, \tag{4}$$

$$\frac{\pi_{FS,sm}}{\pi_{FS,b}} = \exp\left(\frac{J_w{}^{FO}}{k_{FO2}}\right) \quad \text{for concentrative ECP}, \tag{5}$$

where $\pi_{DS,b}$ and $\pi_{FS,b}$ are the osmotic pressures of DS and FS in the bulk solution, respectively; k_{FO1} and k_{FO2} are the mass transfer coefficients of salt at the outer and the inner side of the HF membrane. In the AL-DS mode, the ECP effect at inner side of the HF membrane is ignored in our calculations because deionized water is used as the FS and the inner side flow rate is sufficient for flashing of concentrated FS. Herein, we theoretically predict the experimental FO flux from Eqs. (1) and (4) in the AL-DS mode.

In contrast, in the AL-FS mode, J_w^{FO} can be calculated from Eq. (2); we assumed that the concentrations of DS and FS are constant. However, in the case of small hollow fiber membranes, DS dilution at the lumen side of the hollow fiber membrane should be considered owing to the lower DS volumetric flow rate. The total permeate (Q_{Jw}) and average FO flux ($J_w{}^{FO}{}_{average}$) *are expressed as follows [54]:*

$$Q_{Jw} = \int J_w{}^{FO} \pi D_{out} N dL, \tag{6}$$

$$J_w{}^{FO}{}_{average} = \frac{Q_{Jw}}{\pi D_{out} NL}, \tag{7}$$