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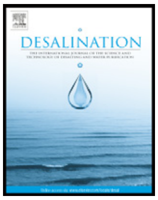


# A novel analysis of reverse draw and feed solute fluxes in forward osmosis membrane process

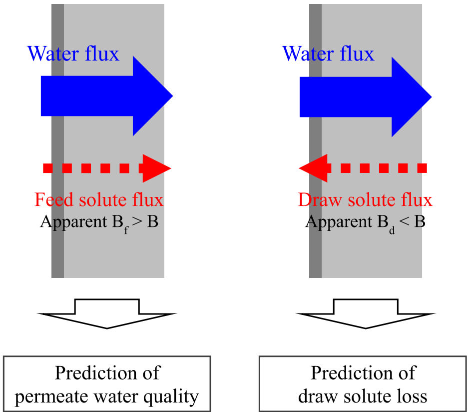
Bongchul Kim, Sangyoup Lee, Seungkwan Hong *

*School of Civil, Environmental & Architectural Engineering, Korea University, 1-5 Ga, Anam-Dong, Seongbuk-Gu, Seoul 136-713, Republic of Korea*

## HIGHLIGHTS

- A novel method to determine draw and feed solute fluxes in FO was developed.
- Draw and feed fluxes were not well predicted with the existing solute permeability.
- Apparent draw ($B_d$) and feed ($B_f$) solute permeability were proposed.
- $B_d$ and $B_f$ were applied to analyze draw solute loss and permeate water quality.

## GRAPHICAL ABSTRACT



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## ABSTRACT

A novel method to determine reverse draw and forward feed solute fluxes in forward osmosis (FO) membrane was developed to analyze FO performance more accurately. Specifically, apparent draw solute permeability ($B_d$) and feed solute permeability ($B_f$) were proposed, instead of relying on single solute permeability (B). Our results clearly demonstrated that both draw and feed fluxes were not well predicted with the solute permeability (B) measured by RO mode experiment, typically employed in FO membrane characterization. In this study, the draw and feed solute permeabilities were evaluated independently by the experimental protocols which simulated actual FO operation more closely. Much better agreement between experimental observations and theoretical predictions was obtained when both $B_d$ and $B_f$ were applied for the analysis of draw and feed solute fluxes, respectively. Thus, the utilization of apparent draw and feed solute permeabilities provides more precise assessment of draw solute loss and permeate water quality, which are very important for FO membrane process design and operation.

## 1. Introduction

Membrane processes represent one of the most feasible options for water shortage alleviation and water supply augmentation [1]. Such examples include microfiltration (MF) and ultrafiltration (UF) for membrane bioreactors in wastewater treatment [2] and for pre-treatments in seawater desalination [3] as well as nanofiltration (NF) and reverse osmosis (RO) in brackish water [4] and seawater desalination [5–7]. The forward osmosis (FO) process has also been attracting great attention for its potential applications in seawater desalination [8,9], wastewater reclamation [10,11], and industrial wastewater treatment such

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* Corresponding author. Tel.: +82 2 3290 3322; fax: +82 2 928 7656.
*E-mail address:* skhong21@korea.ac.kr (S. Hong).

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as shale gas produced wastewater [12–14]. Particularly, in terms of membrane fouling/cleaning, FO process is assumed to be more preferable to RO process [9,10,15–18].

When describing the performance of FO membranes, three parameters are commonly employed: the pure water permeability coefficient (A) and solute permeability coefficient (B), which describe mass transport across the membrane active layer, and the structural parameter (S) which governs the transport phenomena across the membrane support layer. These parameters are typically used to describe the permeate water and solute fluxes of FO process, and thus represent the standard criteria for determining FO membrane characteristics and comparing their performance.

The existing approaches for measuring FO performance parameters involve at least two separate independent experiments. 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 support layer structural parameter (S) is determined by a FO mode experiment which uses osmotic pressure as the driving force [8,16,19]. In addition, the measurements made in pressure retarded osmosis (PRO) mode experiments, with the draw solution facing the active side of the membrane, may be used to complement or substitute those made in FO mode experiments [20,21]. As presented in a recent study [22], by changing the concentration of the draw solution in each FO experiment set, water flux and reverse solute flux are determined, and then membrane performance parameters are estimated through non-linear regression, where A, B, and S are treated as adjustable parameters to fit the FO transport equations to the experimental data.

All of the aforementioned conventional approaches to determine the performance parameters of FO membranes consider only one way transport behavior. Whereas RO mode experiments, for example, evaluate only feed solute flux, PRO and FO mode experiments evaluate only reverse draw solute flux. FO processes, however, intrinsically have simultaneous two-way transport behaviors across the active and support layers of FO membranes. Therefore, to delineate the solute transport behaviors of FO process more accurately, it may be essential to assess both forward feed and reverse draw solute fluxes separately.

The objective of this study is to demonstrate new experimental ways of determining membrane performance parameters and apply them for a better understanding of the FO process in terms of permeate water quality and draw solute loss. For the first time in the literature, the solute permeability coefficient (B), typically measured by single RO and/or FO mode experiments, was separated into apparent draw ($B_d$) and feed ($B_f$) solute permeabilities. These parameters were then employed to describe draw and feed solute transport in FO membrane process. The method and analysis presented in this study are expected to provide a useful tool to predict permeate water quality and draw solute loss in various FO applications.

## 2. Materials and methods

### 2.1. FO membrane

The cartridge type FO membrane used in this study was provided by Hydration Technologies Innovations (Albany, OR) and contained a woven polyester mesh embedded in thin film of cellulose acetate. A detailed description regarding structure and properties of this membrane is available in a previous study [9].

### 2.2. RO and FO systems

Typical bench-scale crossflow RO and FO systems were used in this study, and their schematic diagrams can be found elsewhere [8–10]. The membrane cells in both systems had the same geometry, except that the FO cell had two symmetric channels on both sides of the membrane for co-current flows of the feed and draw solutions. More specifically, the crossflow FO cell was custom-built with a channel 77 mm long, 26 mm wide and 3 mm deep, creating an effective membrane area of 20.02 $cm^2$. No feed spacers were used in the feed or draw solution channels of the FO cell. Variable speed gear pumps (Micropump, Vancouver, WA) were used to deliver the liquids in a closed loop. The cross-flows of feed and draw solutions were fixed at 21.4 cm/s (Reynolds number of this system is 1141). We assumed a constant diffusion coefficient of NaCl solution for the range of concentrations of the solution considered in this work, namely 0.05–1.5 M. Over this range, diffusion coefficients of NaCl solutions varied by less than 3% in a previous study [22]. A constant temperature water bath was used to maintain both feed and draw solution temperatures at 25 ± 1.0 °C. After the initial flux was stabilized, which took about 30 min, the weight of draw solution tank was measured over time to determine the permeate water flux by computer and digital scale (CAS, Korea). The conductivity of feed and draw sides was measured with a calibrated conductivity meter (model 30, YSI Incorporated, Yellow Springs, OH) to determine solute flux.

### 2.3. Water flux measurements in FO membrane process

Typical FO experiment was performed to measure water flux through the FO membrane. In this mode (i.e., active layer facing feed solution, AL-FS mode), water flowed from the active layer to the support layer, while draw solutes diffused from the support layer to the active layer. Concentrated stock solution (3 M NaCl or dextrose) was added to the draw side to establish the desired osmotic driving force, and the resulting permeate water flux was measured. Osmotic pressure was calculated using software from OLI (Morris Plains, NJ).

### 2.4. Determination of FO membrane performance parameters

#### 2.4.1. Solute permeability measured by RO system

The feed solute permeability of the FO membrane was determined using a laboratory scale cross-flow RO test unit. A diagram depicting this method with a FO membrane is given in Fig. 1(a). Initially, the membrane was equilibrated with DI water at the applied hydraulic pressure ($\Delta P$) of 17.25 bar until the permeate flux reached a steady value. After equilibration, NaCl rejection (R) was determined at the same applied pressure. Using 50 mM NaCl feed solution, the rejection was determined from the difference in bulk feed ($C_f$) and permeate ($C_p$) solute concentrations, using the equation, $R = 1 - C_p / C_f$. The

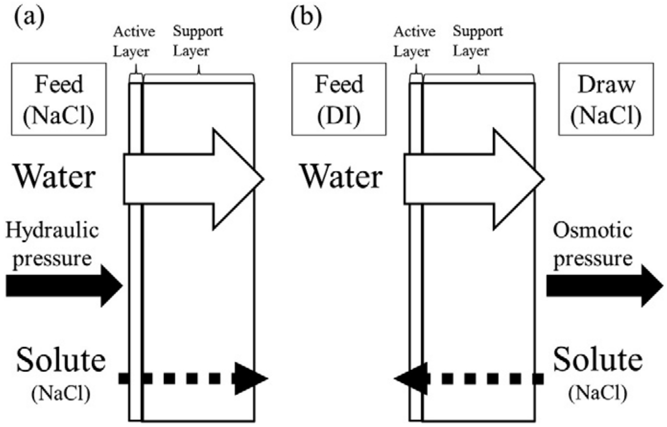

**Fig. 1.** Determination of solute permeability (B) by (a) RO mode experiment and (b) FO mode experiment. The direction of water and solute fluxes is schematically illustrated with driving force of each system. Experimental procedures are described in Sections 2.4.1 and 2.4.2.