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Alleviation of water flux decline in osmotic dilution by concentration-dependent hydraulic pressurization

Qun Wang[a,b], *Xueli Gao*[a,b,*], *Yushan Zhang*[c], *Jian Wang*[c], *Yuan Xu*[a,b], *Zhiyong Ji*[d], *Xinyan Wang*[e], *Congjie Gao*[a,b,*]

[a] *Key Laboratory of Marine Chemistry Theory and Technology, Ministry of Education, Ocean University of China, Qingdao 266100, China*
[b] *College of Chemistry and Chemical Engineering, Ocean University of China, Qingdao 266100, China*
[c] *Institute of Tianjin Seawater Desalination and Multipurpose Utilization, State Oceanic Administration, Tianjin 300192, China*
[d] *School of Marine Science and Engineering, Hebei University of Technology, Tianjin 300130, China*
[e] *Shandong Zhaojin Motian Co., Ltd., Zhaoyuan 265400, China*

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ABSTRACT

Forward osmosis has motivated practical applications in seawater desalination and agricultural irrigation due to its potential advantage of osmotic dilution. However, water flux decline accompanies with continuous dilution of the DS, which will cause extra membrane expenditure, until final osmotic equilibrium. Without the help of additional driving force, it is impossible to reduce driving force loss in OD. In this study, concentration-dependent hydraulic pressure is exactly introduced as an auxiliary driving force. Investigations on water flux decline behavior in OD showed that water fluxes at lower initial concentration difference, lower initial solution volume and AL-DS orientation suffered more severe decline; furthermore, it implied that additional hydraulic pressure could alleviate adverse effects of greater concentration difference variation generated by pressure-induced water flux increment on water flux. For given dilution of the DS, minimized change in bulk FS concentration was conducive to ensure the effectiveness of constant hydraulic pressure on reducing water flux decline. Validation experiments demonstrated that current model equations were more appropriate under lower hydraulic pressures, and stable water flux also relied on concentration difference variation corresponding to applied hydraulic pressure. Potential implications were highlighted in the context of technical progress of membrane preparation and application potential of OD.

Abbreviations: AL-DS, active layer facing draw solution; AL-FS, active layer facing feed solution; CDHP, concentration-dependent hydraulic pressure; CICP, concentrative internal concentration polarization; CP, concentration polarization; CTA, cellulose triacetate membrane; DICP, dilutive internal concentration polarization; DS, draw solution; FO, forward osmosis; FS, feed solution; HP, hydraulic pressurization; ICP, internal concentration polarization; OD, osmotic dilution; PAFO, pressure-assisted forward osmosis; PAFDO, pressure-assisted fertilizer drawn osmosis; PRO, pressure retarded osmosis; RO, reverse osmosis; RSF, reverse solute flux; SD, solution-diffusion; SHP, staged hydraulic pressure; SWRO, seawater reverse osmosis; TFC, thin film composite membrane.

[*] *Corresponding authors at:* Key Laboratory of Marine Chemistry Theory and Technology, Ministry of Education, Ocean University of China, Qingdao 266100, China. Fax: +86 532 66782017.

E-mail addresses: gxl_ouc@126.com, ouc_wangqun@163.com, gxl_ouc@163.com (X. Gao), gaocjie@ouc.edu.cn (C. Gao).

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1. Introduction

Compared to pressure-driven membrane processes (i.e., reverse osmosis), forward osmosis (FO) has drawn a widespread attention due to lower energy input (Klaysom et al., 2013; Lutchmiah et al., 2014; Shaffer et al., 2015), less fouling propensity (Lee et al., 2010; Li et al., 2012; Coday et al., 2014; Chuna et al., 2015), and simpler membrane cleaning (Chuna et al., 2015; Mi and Elimelech, 2010). Consequently, the essential advantages have recently motivated academic researches in some potential applications including pre-treatment for RO desalination (Cath et al., 2010; Blandin et al., 2015; Yangali-Quintanilla et al., 2011) and desalination for irrigation purpose (Sahebi et al., 2015; Phuntsho et al., 2012; Phuntsho et al., 2011). In these cases, FO played a role to dilute seawater or fertilizer draw solution with wastewater effluent or brackish water with purpose of osmotic dilution (OD), as a result, without regeneration of draw solution (DS).

However, FO is in fact a concentration-based membrane separation process and thereby the water flux decline occurs along with concentration difference variation between the feed solution (FS) and DS. If the primary purpose is to dilute the DS in terms of direct use or energy saving consumption for the post-treatment process, the water permeation from the FS side to the DS side will result in continuous dilution of the DS and simultaneous concentration of the FS until concentration-driven water flux becomes negligible (Phuntsho et al., 2014). At this point, the final concentration of the DS produces equivalent osmotic pressure with that of the FS. Although the final concentration of the DS is attained as expected, the water flux decline tendency is inevitable during the whole process because of one intrinsic limitation of FO—positive correlation between water flux and concentration difference. In addition, lower water flux in the final stage of OD is incline to cause extra expenditure of FO membranes with the aim of given concentration of diluted DS. Therefore, the driving force decline (i.e., concentration difference variation) and osmotic equilibrium limitation determine the dilution efficiency for the DS in FO.

Recent studies have indicated that additional hydraulic pressure exerting onto the FS side can act as an auxiliary driving force to enhance water flux (Coday et al., 2013; Lutchmiah et al., 2015; Oh et al., 2014; Shibuya et al., 2015; Blandin et al., 2013; Duan et al., 2014a) and final dilution of the DS beyond osmotic equilibrium (Sahebi et al., 2015). Besides, hydraulic pressure is required in industrial FO applications to overcome hydraulic resistance in both flow channels of the FS and DS (Cath et al., 2006; Kim and Park, 2011). Combining with both aspects, pressure-assisted forward osmosis termed as PAFO is an indispensable process in practical application of FO. Nowadays, most of related studies preferred continuous and constant hydraulic pressure, and ignored investigations of hydraulic pressure on water flux decline. Some researchers had made use of pulsation techniques to realize discontinuous hydraulic pressure control with the purpose of lower energy input, instead of stable water flux (Lutchmiah et al., 2015). Furthermore, discontinuous hydraulic pressure had adverse impact on process performance, owing to that the pressure release resulted in a more significant increase of reverse solute flux compared to water flux. For factor-dependent hydraulic pressure specific to concentration difference variation, it is very likely to pointedly compensate driving force loss and thus maintain stable water flux in OD. However, to the best of our knowledge related studies have been rarely involved until now.

The objective of this work is exactly to introduce and validate concentration-dependent hydraulic pressure to compensate driving force loss resulting from concentration difference variation in OD. We first investigated the water flux decline behavior under different operation conditions (i.e., initial solution volume, membrane orientation, and initial concentration difference). Next, we compared effects of constant hydraulic pressure on reducing water flux decline under different concentration controls (such as constant and variational bulk FS concentrations). Through modeling concentration-dependent hydraulic pressure, we validated its positive effects on maintaining stable water flux. Based on experimental results and theoretical analyses, we gained some insights into potential implications of concentration-dependent hydraulic pressure in OD.

Table 1 – Transport parameters for applied TFC FO membrane.

Label	Model	A (L/m^2 h bar)	B (L/m^2 h)	K (m^2 h/L)
TFC	SD	6.90	3.00	0.14

2. Materials and methods

2.1. *Feed and draw solutions*

Feed solution: ultrapure water with a resistivity of 18.2 MΩ cm, provided by a Millipore water purification system (Milli-Q, Academic, Millipore Corporation, Billerica, MA).

Draw solution: 0.5 M or 1.0 M sodium chloride (NaCl), representing osmosis pressure comparable to that of the seawater or seawater RO brine.

2.2. *FO membrane and transport parameters*

A newly commercial flat-sheet forward osmosis membrane dissembled from a 4040 membrane element (Toray Chemical Korea Company Limited, Jung-gu, Seoul, South Korea) was used in our current work. The FO membrane is a thin-film composite (TFC) membrane, which consists of three layers: the dense polyamide active layer, the porous support layer, and the ultrathin support backing.

Membrane pure water permeability (A), salt permeability (B), and solute resistance to diffusion within the porous support (K) in solution-diffusion (SD) model were determined using three tests including (1) pure water permeability tests, (2) low pressure PRO/RO tests, and (3) FO tests. Detailed methods can be found in several references (Duan et al., 2014a; Hancok et al., 2011; McCucheon and Elimelech, 2007). For reference, transport parameters determined by SD model were listed in Table 1.

2.3. *Modeling of concentration-dependent hydraulic pressure*

According to SD model, water fluxes together with concentration polarization (CP) and reverse solute flux (RSF) can be expressed as shown below (Duan et al., 2014b):

$$J_w = AiRT\left\{\frac{\exp\left(-\frac{J_w}{\kappa}\right)C_{D,b}-\exp\left(J_wK\right)\exp\left(\frac{J_w}{\kappa}\right)C_{F,b}}{\exp\left(J_wK\right)+\frac{B}{J_w}\left[\exp\left(J_wK\right)-1\right]}\right\}+A\Delta p(\text{AL-FS}) \quad (1)$$

$$J_w = AiRT\left\{\frac{\exp\left(-\frac{J_w}{\kappa}\right)C_{D,b}-\exp\left(J_wK\right)\exp\left(\frac{J_w}{\kappa}\right)C_{F,b}}{1+\frac{B}{J_w}\left[\exp\left(J_wK\right)-1\right]}\right\}+A\Delta p(\text{AL-DS}) \quad (2)$$

In these equations,$C_{F,b}$ and $C_{D,b}$ are solute concentrations in bulk feed and draw solutions, κ is the mass transfer coefficient ($\kappa = 2.7 \times 10^{-5}$ m/s, detailed calculation method can be found in Ref. (She et al., 2013)), i is the dimensionless van't Hoff factor, R is the universal gas constant, and T is the absolute temperature, respectively. K is the solute resistance to diffusion within the membrane support layer defined by:

$$K = \frac{t_S\tau}{D_s\varepsilon} \quad (3)$$