Relating solution physicochemical properties to internal concentration polarization in forward osmosis

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ABSTRACT

Recently forward osmosis (FO) has attracted growing attention on many potential applications such as wastewater treatment, desalination and power generation. FO performance is primarily limited by the presence of internal concentration polarization (ICP), which significantly reduces the permeate flux. This study explores the relationship between the physicochemical properties of the solution against the membrane support layer and ICP by incorporating constrictivity. Four solutions with different diffusivities, ion/molecule sizes and viscosities were systematically investigated using a bench-scale FO system. It is found that ICP in the support layer is strongly dependent on the physicochemical properties of the solution facing the support layer. When the solution against the membrane support layer has a lower aqueous diffusivity but larger ion/molecule size and higher viscosity, The ICP phenomenon will be more severe, resulting in lower water flux. The identical diffusion direction of the feed solute and the water flux may reduce the effective diffusivity of the solute in the support layer when the feed solution facing the membrane support layer, resulting in high concentrative ICP. These findings have significant implications for the development of new draw solutes, the pretreatment of the feed solution and the selection of the membrane orientation.

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1. Introduction

As an emerging technology forward osmosis (FO) has attracted growing interest in wastewater treatment [1–3], seawater/brackish desalination [4–6], food processing [7–10] and power generation [11–14]. FO is an osmotically driven membrane process that takes advantage of the osmotic pressure gradient to drive water across the semipermeable membrane from the feed solution (low osmotic pressure) side to the draw solution (high osmotic pressure) side. Due to low hydraulic pressure is required, FO may bring many advantages such as less energy input [15], lower fouling tendency or easier fouling removal [1,3,16] and higher water recovery [17] over other pressure-driven processes. There is still a long way to go even though FO looks extremely promising due to no extra pressure applied.

To move FO from laboratory research to real practical applications, there is a strong need to achieve breakthroughs in the developments of both novel FO membranes and draw solutes [6]. Recently both flat sheet [18–21] and hollow fiber [22–26] membranes have been novelly prepared to be used in FO applications. At the same time, many novel materials have also been synthesized or designed to be used as the draw solutes [27–30]. Chung's group

has synthesized some hydrophilic magnetic nanoparticles and 2-methylimidazole-based compounds as the draw solutes used in FO [27–29]. Li et al. [30] have designed a type of stimuli-responsive polymer hydrogels to be used as the draw solution. These synthesized novel draw solutions hold great promise in FO applications because the drawn water can be easily released from them.

However, the water flux in FO is much lower than the theoretical value no matter using which kind of membrane or draw solution. It has been proven that the unsatisfying water flux in FO is mainly caused by internal concentration polarization (ICP) in the membrane porous layer [6,31,32]. Therefore, it is necessary to understand the mechanism of minimizing ICP in FO. An ideal FO membrane should be thin, porous for the support layer and highly selective for the active layer [15,33]. While an ideal draw solute should be highly water soluble, be able to generate a high osmotic pressure, non-toxic, and highly diffusive [4,34]. The solution diffusivity determines the ability of the solute to diffuse in and out of the membrane support layer, which reflects ICP in FO. ICP within the FO membrane support layer has been supposed to be related to the solution diffusivity [34,35]. However, there are few studies investigating the relationship between the solution physicochemical properties and ICP systematically.

The objective of this paper is to develop the understanding of the relationship between the physicochemical properties of feed/draw solutions and ICP phenomenon in FO. This finding will help improve FO performance by selecting or designing suitable draw solutes

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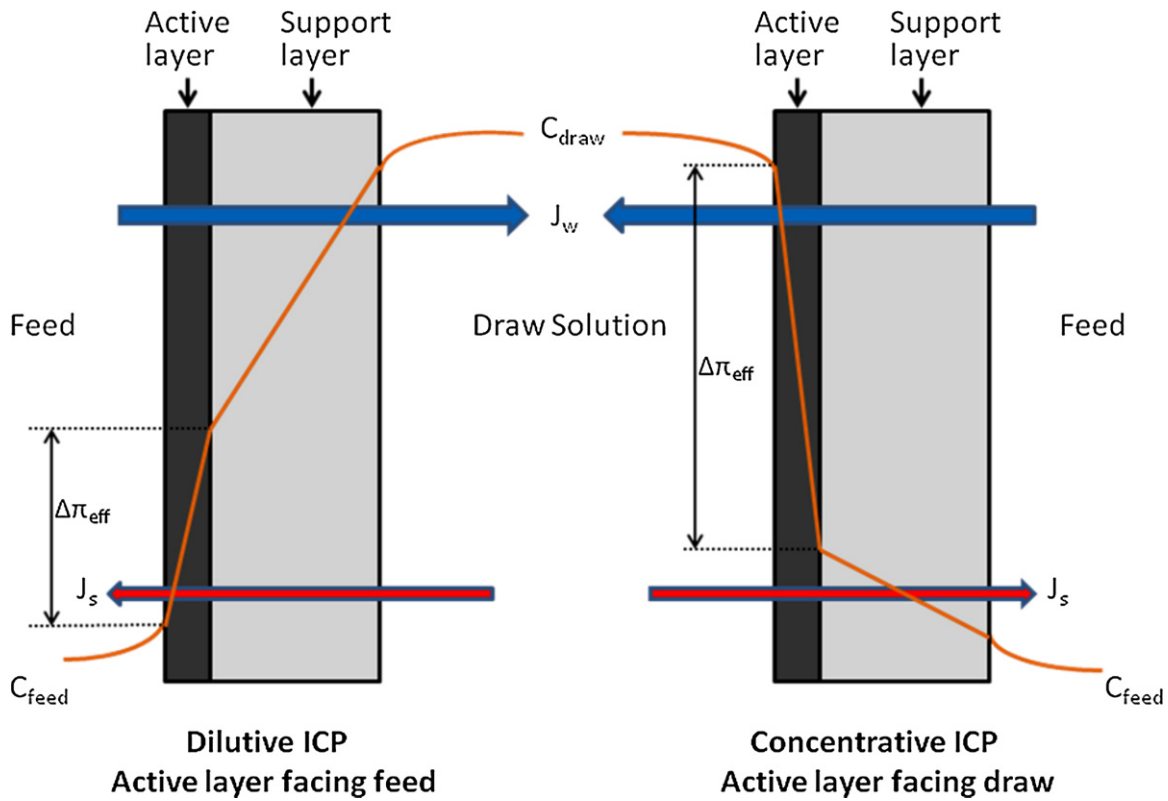E-mail address: linda.zou@unisa.edu.au (L. Zou).

Fig. 1. Illustration of dilutive ICP and concentrative ICP across an asymmetric FO membrane.

with favourable physicochemical properties to reduce ICP in the porous layer of the FO membrane. This study also has significant implications for feed solution pretreatment in order to enhance the water flux by minimizing concentrative ICP in the support layer of the membrane.

2. Theory

2.1. Mass transport in FO

Based on the classical solution-diffusion model, water flux (J_w) in FO can be expressed by the same general equation used in RO:

$$J_w = A(\Delta P - \Delta \pi) \tag{1}$$

In FO the driving force comes from the osmotic pressure difference between the draw solution and feed solution, and the water flux can be specifically expressed by

$$J_w = A(\pi_{draw} - \pi_{feed}) \tag{2}$$

where A is the pure water permeability coefficient of the membrane, ΔP is the applied hydraulic pressure, $\Delta \pi$ is osmotic pressure difference across the membrane, and π_{draw} and π_{feed} are the osmotic pressures of the draw and feed solutions, respectively.

Similarly, solute flux (J_s) in FO can be expressed as

$$J_s = B(C_{draw} - C_{feed}) \tag{3}$$

where B is the solute permeability coefficient, C_{draw} and C_{feed} represent the solute concentrations at the membrane-solution interface on the draw solution side and feed solution side, respectively.

The solute permeability coefficient reflects the selectivity of a membrane and they are closely related to each other. The solute permeability coefficient can be expressed [36,37] as

$$B \frac{A(1 - R)(\Delta P - \Delta \pi)}{R} \tag{4}$$

where R is the solute rejection of the membrane. It is important to note that Eqs. (2) and (3) do not consider the concentration polarization effect in FO. But internal concentration polarization is very important in FO.

2.2. Internal concentration polarization in FO

Both internal concentration polarization (ICP) and external concentration polarization (ECP) may occur in FO. In this study, we focus on ICP only. It has been recognized that water flux decline in FO is dominantly caused by ICP as illustrated in Fig. 1 [6,31,32]. The effect of ICP can be modelled by adopting the classical solution-diffusion theory [11,36]. In FO mode (active layer facing the feed), dilutive ICP is in the dominant place. The water flux (J_w) can be expressed as

$$J_w = \frac{1}{K} \ln \frac{A\pi_{draw} + B}{A\pi_{feed} + B + J_w} \tag{5}$$

where K is called solute resistivity, a measure of salt transport in the porous substrate (support layer). In other words, K is used to measure the solute's ability to diffuse into or out of the membrane support layer, and it can reflect the degree of ICP in the support layer. Smaller K value means less ICP, resulting in higher pure water flux (J_w). K is defined [6,33] as

$$K = \frac{t\tau}{\varepsilon D} = \frac{S}{D} \tag{6}$$