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Quantitative evaluation of concentration polarization under different operating conditions for forward osmosis process

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HIGHLIGHTS

- Both the ICP and the ECP were quantitatively evaluated under different operating conditions for the first time.
- The ICP always occupied a domain role for the origination of the osmotic pressure drop across the FO membrane.
- Typical ways were adopted and discussed to relieve the adverse effects of the CPs.

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ABSTRACT

Concentration polarization (CP) in forward osmosis is one of the main factors that lower the operating performance of the process. This study quantitatively analyzes the influences of different CPs on the osmotic pressure drop across the membrane under different operating conditions. Results of the study showed as the draw solution concentration increased from 0.25 M to 1.5 M, the osmotic pressure drop proportions caused by the internal CP and the external CP rose from 32.63% to 50.88% and 11.86% to 30.13% respectively, indicating that the influence of the internal CP is dominant and that of the external CP can't be ignored as before especially for high salinity solutions. For relieving the adverse effect of the CPs, the unilateral strengthen of flow rate in draw solution is more meaningful than that in feed solution flow rate, or bilateral strengthen for both solutions. Moreover, the optimal configuration of spacers should be a spacer in contact with active layer in feed channel and a spacer 2.7 mm away from support layer in draw channel. The obtained conclusions in this paper would lay a good foundation for quantitatively understanding of the effects for different CPs and provide a guide for the optimization of the forward osmosis system.

1. Introduction

With the rapid development of economy, high concentration of population and serious pollution of water, it's projected that nearly two-thirds of the population in the world will face the threat of water shortage by 2025 [1–3]. In order to solve the water crisis, forward osmosis (FO) as a novel method and an alternative to pressure-driven membrane processes has emerged in the field of desalination and waste water treatment. In forward osmosis process, a synthetic polymeric FO membrane separates a feed solution of low concentration from a draw solution of high concentration. The natural osmotic pressure difference between the draw solution and the feed solution facilitates diffusion of water through the membrane while rejecting almost all dissolved and suspended constituents [4–6].

Potential applications of forward osmosis technology may include water desalination, power generation, food processing and wastewater treatment. While the forward osmosis faces several challenges, including concentration polarization (CP), membrane fouling, reverse solute diffusion and the need for new membrane development and draw solute design, the CP of the FO membrane is the main barrier that seriously reduces the effective osmosis pressure differential and thus the water flux of the process [7–10]. Since most of the membranes used in forward osmosis process are asymmetric, including a dense active layer and a porous support layer, and the solution on either side of the membrane always has concentration, the CP generally appears on both sides of the membrane and can be further classified as internal concentration polarization (ICP) in the membrane support layer and external concentration polarization (ECP) on the membrane surface layer.

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In the paper, a FO mode was adopted, meaning that the membrane active layer faced the feed solution, and the membrane support layer neared the draw solution. During the separation process, the solute accumulates on the active layer and the solution concentration on membrane surface adds in gradient, generating a concentration boundary layer. This phenomenon is called concentrative ECP. Differently, the solute in the porous support layer is transported solely by hindered diffusion in the stagnant zone of the support, and the concentration of draw solution is commonly diluted by the permeating water from the feed solution, this kind of diluted concentration layer is called dilutive ICP. Previous studies have indicated that both the ICP and ECP reduce the effective driving force of the forward osmosis process and it is the ICP that severely hampers the flux performance of the forward osmosis [11–13]. In this paper the influence degree of the ICP and the gap between ECP and ICP was researched through quantitative comparison.

Currently the most common method to mitigate the ICP is to modify the structure of FO membrane or to prepare a new symmetric FO membrane with two active layers. K.Y. Wang et al. [14] mentioned a forward osmosis membrane which comprises a highly porous sub-layer sandwiched between two selective skin layers via phase inversion. This double-skin-layer membrane displayed a high water flux using $MgCl_2$ as the draw solution. It can mitigate the ICP in some extent by preventing the solutes in the draw solution from penetrating into the membrane porous support. J.R. McCutcheon [15] believed a wetted hydrophilic support would reduce concentration polarization by increasing the wetting of small pores within the support layer and it's desirable to develop a membrane combining the hydrophilic polymers. I.L. Alsvik et al. [16] successfully developed a modified interfacial polymerization method by reacting hydrophilic CTA with a linking molecule. The prepared membrane has the fewer charged groups on the support membrane and an increased wetting of the CTA support, displaying stable water flux less dependent upon the change of draw solution concentration.

With the development of FO membrane, process studies especially the impact of operating conditions on water flux become a more and more hot research in recent years [17–19]. D.H. Jun. et al. [20] investigated the forward osmosis water flux performance of a forward osmosis module that consists of three channels (one draw solution channel between two feed channels) and two pieces of membrane via a numerical simulation based on mass conservation theorem. In the case of membrane orientation, all-inside case, in which the draw solution faces the active layer, displayed a relatively higher flux performance than all-outside and all-up cases. S.M. Shim et al. [21] used a one-dimensional model to simulate the effect of various operating conditions, such as the flow pattern, the concentration of the draw solution, the membrane module length, and the pathway of the feed and draw solution. Results of this study showed the water flux of counter-current flow is about 10% higher than that of co-current flow. Forming feed solution into series and draw solution into rows are effective in increasing water flux. S. Phuntsho et al. [10] evaluated the influence of some major factors, including membrane type, the properties of draw solution and feed solution, on the performances and assessed their potential implications on the overall process. It was found that the performances of TFC membrane were significantly higher than the CTA membrane and the influence of cross flow velocity was effective only to a certain extent beyond which it was no longer significant. In order to improve the water flux, researchers adopted various methods to optimize the operating conditions. But the influence degree of different CPs causing by the changing conditions and which influence is the greatest need further research.

In recent years, in order to find a simple and effective way to mitigate the adverse effect of CP on forward osmosis performance, a spacer was adopted in the fluid channels to increase turbulent mixing on the membrane surface [22–24]. M. Park et al. [25] numerically analyzed the impacts of various types of spacers on the CP in a forward osmosis process. It was found that spacers in the forward osmosis process were more effective for the separation of highly concentrated solutions. Among the configurations, submerged-type spacers showed the best performance and the cavity-type spacers had the worst permeate flux. Spacers can change the CPs by altering liquid's flow state, thereby improving the water flux in an energy-saving way. So research of spacer effect on CPs should be considered a requisite for future advances in forward osmosis technology. And currently the effect of spacer with different size and location on CPs in the real forward osmosis process still remains an open issue.

The main purpose of this paper was to quantitatively evaluate the influence of ICP and ECP on osmotic pressure differential and thus the water flux of FO membrane under different operating conditions. Firstly, under different concentration of draw solution, the water flux was studied and the proportions of osmotic pressure drop arisen from different kinds of CPs was quantified by a mathematical model formula [26], thereby understanding what extent the conditions affect the flow regime and CPs. Based on this, the operating conditions including flow pattern and velocity were discussed to relieve the adverse effect of concentration polarization. Finally a variety of spacer configurations to reduce the effect of CP was advanced and optimized.

2. Materials and methods

2.1. FO membrane

The FO membrane used in this experiment is a commercial polyester composite membrane TFC film (Hydration Technology Innovations), which possesses a good quality of large water permeability coefficient, small solute permeability coefficient and small structural parameter [15]. The FO membrane is kept in glycerol before the experiment to avoid the irreversible shrinking upon drying.

2.2. Experimental setup and method

The experiments were performed using a custom-made flat organic glass cell with symmetric channels circulating the feed solution and draw solution independently. Dimension of each channel was 80 mm long, 40 mm wide and 3 mm deep, and the effective area was about 0.0032 m^2. Fig. 1 shows the schematic representation of forward osmosis system. Feed solution and draw solution were separately circulated through the corresponding channels in a close loop using two identical peristaltic pumps (Longer Pump BT600-2 J). Temperatures of both solutions were kept constant at 25 ± 1 °C by immersing the flow pipes into a same thermostatic water bath (HH-W420). The water flux and the proportions of osmotic pressure drop arisen from different CPs were calculated through the detected data of the balance (ES5000) and two electrical conductivity meters (DDSJ-308 A). After each experiment, the whole system should be rinsed by de-ionized water for 30 min.

2.3. Analytical method

2.3.1. Water flux

The mass changes of the draw solution are instantly monitored by the balance and a computer, and the water flux of the FO membrane is calculated by the following equation:

$$J_W = \frac{\Delta \mathrm{m}}{\rho S \Delta \mathrm{t}} \tag{1}$$

where J_W ($L/m^2 \cdot h$) is the water flux, Δm (g) is the mass change of the draw solution, Δt (h) is the interval time, S is the effective area of the membrane and is about 0.0032 m^2, and ρ (kg/m^3) is the density of the draw solution.