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Numerical analysis of spacer impacts on forward osmosis membrane process using concentration polarization index

Minkyu Park [a,b], Joon Ha Kim [a,b,c,*]

[a] School of Environmental Science and Engineering, Gwangju Institute of Science and Technology (GIST), Gwangju 500-712, Republic of Korea
[b] Sustainable Water Resource Technology Center, GIST, Gwangju 500-712, Republic of Korea
[c] Center for Seawater Desalination Plant, GIST, Gwangju 500-712, Republic of Korea

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ABSTRACT

Understanding the mass transfer in membrane separation processes plays a crucial role in improving the process performance. In this study, we numerically scrutinized the impacts of spacers—a structure enhancing the mass transfer in the vicinity of the membrane—on the concentration polarization (CP) in a forward osmosis (FO) process. To quantitatively measure the extent of CP, we introduce a concentration polarization index (CPI), which is proportional to the degree of CP and inversely proportional to the permeate flux. Based on the CPI, we simulated the impact of spacers on FO performance at various concentration conditions and found that the FO spacers generally reduce the extent of the CP; subsequently, this shows that FO spacers are important factors for the advancement of FO technology. In FO processes it was found that the boundary layer compression is more efficient for diminishing the CP than the boundary layer disruption, whereas the disruption mechanism was more successful in alleviating the CP in reverse osmosis (RO) processes. This contradiction was subsequently attributed to the intrinsic characteristics of the boundary layer disruption, which inevitably caused a dead zone near the spacer attachment and thereby boosted the CP in the FO process. Moreover, it was observed that spacers in feed channels increase the CP even when the concentration of the feed solution is zero, unless the membrane completely rejects salt, because any solute penetrating through the active layer of the membrane by a reverse diffusion mechanism accumulates near the spacer attachment. Hence, it is crucial to minimize the adverse impacts of FO spacers to maximize the beneficial effects of spacers to decrease the CP and improve the performance of FO processes.

1. Introduction

Mass transfer in the vicinity of a membrane significantly influences the performance of membrane separation processes since the osmotic pressure difference due to the concentration difference across the membrane is a major contributor determining the driving force [1,2]. In reverse osmosis (RO) processes, the high pressure required to overcome the osmotic pressure difference allows water to penetrate through the membrane and towards a solution having a lower concentration (i.e., permeate side), with rejected salts inevitably accumulating on the membrane surface that faces the solution with the higher concentration (i.e., feed side)—a phenomenon referred to as the concentration polarization (CP). Hence, enhancement of the mass transfer plays an imperative role in diminishing the CP and ultimately improving the performance of RO processes [3]. In a similar vein, alleviating the CP is critical for improving the performance in forward osmosis (FO) process. However, different aspects of the CP in forward osmosis (FO) than found in RO render the understanding of CP in FO more abstruse. As depicted in Fig. 1, the operating pressure for overcoming osmotic pressure due to the concentration difference (chemical potential difference) allows water to penetrate from a higher concentrated feed solution into a lower concentrated solution in the RO process. In this case, rejected salts are accumulated in the vicinity of the membrane of the feed side and provoke a severe concentration polarization (i.e., external concentration polarization, ECP) whereas having a low concentrated permeate (traveling through the support layer) causes a minimal polarization and is relatively negligible. Conversely, in FO, water infiltrates through the membrane from a low concentrated solution (feed solution) to a high concentrated solution (draw solution). Hence, the dilutive and concentrative polarizations of the two solutions occur simultaneously. However, these concurrent phenomena unavoidably lead to severe CP in the support layer (i.e., internal concentration polarization, ICP) as well as ECP, regardless of the

* Corresponding author at: School of Environmental Science and Engineering, Gwangju Institute of Science and Technology (GIST), Gwangju 500-712, Republic of Korea. Tel.: +82 62 715 3277; fax: +82 62 715 2434.
E-mail address: joonkim@gist.ac.kr (J.H. Kim).

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