Forward Osmosis for Desalination and Wastewater Treatment

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ABSTRACT

Forward osmosis (FO) is a membrane process in which water moves across a salt-rejecting membrane under a concentration gradient. Instead of applying a hydraulic pressure (as in the case of reverse osmosis (RO)), a concentrated draw solution with high osmotic pressure is utilized to drive the FO process. The lack of high pressure in FO process means that it requires minimum pumping energy. Thus, its energy consumption can be potentially much lower compared to its counterpart RO. In recent years, FO has gained growing interests. Promising applications span over a wide spectrum, including seawater desalination, wastewater treatment and reclamation, resource recovery, and food processing. The objective of the current work is to model FO performance for wastewater treatment and desalination applications, which is essential for assessing the technical and economic feasibility of the technology. A mass transfer model that incorporates internal concentration polarization and reverse solute diffusion is used analyse FO performance. For the case of wastewater treatment, it is found that the available FO water flux is highly dependent on the properties of the rejection layer as well as that of the support layer. In contrast, FO water flux in seawater desalination is far less dependent on membrane separation properties. The modelling results provide useful inputs for accessing the potential of various FO configurations in the context of wastewater treatment, wastewater reclamation, and seawater desalination.

1. INTRODUCTION

Forward osmosis (FO) is an emerging membrane process that has many potential applications for wastewater treatment and desalination [1,2]. In FO, water permeates through a dense salt-rejecting membrane from a low concentration feed solution (FS) to a high concentration draw solution (DS, see Figure 1). Unlike conventional pressure-driven membrane processes such as reverse osmosis (RO), the driving force in FO is the trans-membrane osmotic pressure difference between the FS and DS. Due to the lack of applied hydraulic pressure, energy consumption of FO can be substantially lower compared to that of RO, provided that DS regeneration is not required (e.g., using naturally available seawater as a DS). On the other hand, for applications where DS regeneration is needed, significant amount of energy may be needed to extract water from the diluted DS and to reconcentrate DS for the subsequent FO cycles.

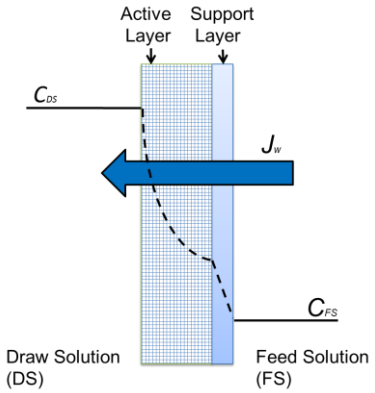


Figure 1: Principle of forward osmosis

A critical issue in FO is internal concentration polarization (ICP). As shown in Figure 1, a typical FO membrane comprises a dense active layer (which is generally placed against the FS for better membrane fouling control [3]) and a porous support layer. As water permeates through the active layer into the porous under the osmotic pressure gradient, the DS inside the support layer is diluted. As a result, the effective osmotic pressure difference across the active layer becomes much lower than the apparent osmotic driving force (i.e., the osmotic pressure of DS π_{DS} – that of the FS π_{FS}), which can severely limit the available FO water flux. Due to the dilutive ICP in the porous support layer, the dependence of FO water flux on membrane properties and operational conditions is generally highly non-linear. There is yet a lack of clear guiding principles for FO membrane optimization for different potential applications.

The objective of the current work is to model FO water flux performance for wastewater treatment and desalination applications, which is essential for assessing the technical and economic feasibility of the technology.

2. MODELLING

A mass transfer model for FO water flux has been previously developed by Tang and co-workers [3]:

$$J_w = \frac{D}{S}\ln\left(\frac{A\pi_{DS} + B}{A\pi_{FS} + J_w + B}\right) \qquad (1)$$

where J_w is the FO water flux, D is the diffusion coefficient of the solutes, S is the structural parameter of the support layer, A is the water permeability of the active layer, and B is the solute permeability of the active layer.

Equation (1) incorporates the effect of ICP by considering the balance of (a) the convective transport of draw solutes away from the support layer due to the FO water flux and (b) the diffusive transport of draw solutes from the bulk DS into the support layer under the concentration gradient (Figure 1). In this model, the structural parameter S represents the length scale of ICP, and its value is determined by the tortuosity (τ), thickness (l), and porosity (ε) of the support layer [3]:

$$S = \frac{\tau l}{\varepsilon} \qquad (2)$$

The effect of membrane active layer on FO water flux is captured in Equation (1) by the A and B values. Here, A indicates how permeable the membrane is to water and B indicates how permeable the membrane is to solutes. As the active layer has finite rejection rate of draw solutes, solutes can diffuse through the active layer from the high-concentration draw solution to the low-concentration feed solution. The effect of this reverse solute diffusion across the active layer is captured in the mass transfer model by the B/A ratio. The simulation conditions are specified in Table 1.

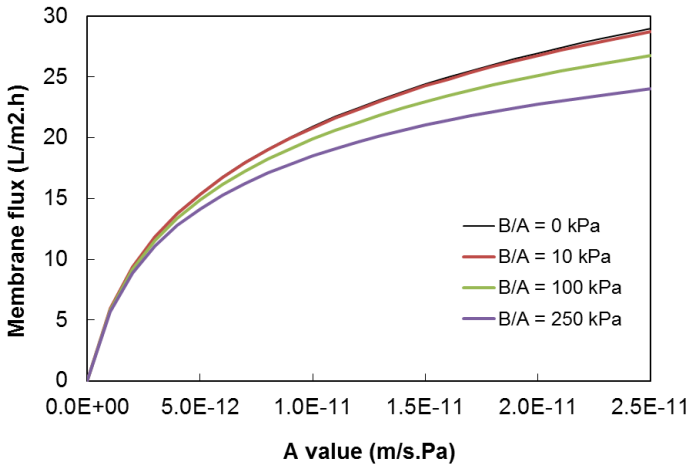
Table 1 Simulation conditions

Parameters used in simulation	Wastewater treatment scenario	Seawater desalination scenario
π_{FS}	50 kPa (corresponding to the osmotic pressure of a 10 mM NaCl solution)	2.5 MPa (corresponding to the osmotic pressure of a typical seawater)
π_{DS}	2.5 MPa (corresponding to the osmotic pressure of a typical seawater)	10 MPa
A value	1×10^{-12} m/s.Pa to 2.5×10^{-11} m/s.Pa	
B/A ratio	0 – 250 kPa	
S value	0.2 mm – 2 mm (typical value 0.4 mm)	
D value	fixed at 1.69×10^{-9} m^2/s	

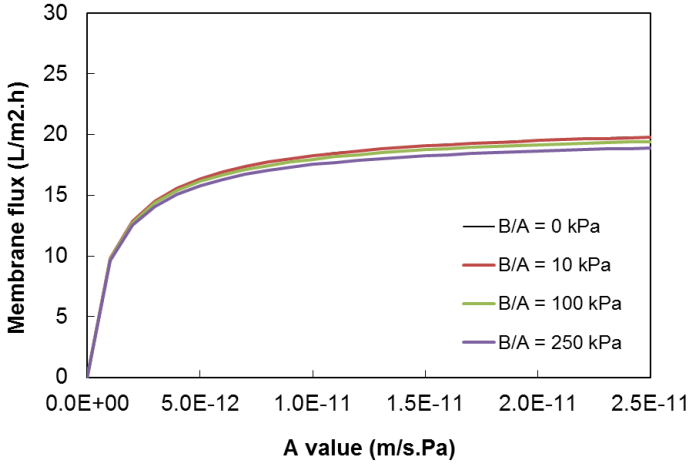
3. RESULTS AND DISCUSSION

Figure 2 shows the effect of membrane active layer properties (*A* and *B* values) on FO water flux. The wastewater treatment scenario (π_{FS} = 50 kPa and π_{DS} = 2.5 MPa) is considered in Figure 2(a). Clearly, higher FO water flux is achieved for membranes with greater water permeability. However, the flux curves appear to be highly non-linear. Increasing *A* value is most effective to promote higher FO water for low permeability membranes ($A < 5 \times 10^{-12}$ m/s.Pa). For membranes with such low permeability, the frictional resistance of the active layer dominates over the ICP effect. Further increasing *A* value beyond this range becomes somewhat less effective in increasing FO water flux, indicating that FO water flux are affected by both frictional resistance and ICP in this region. Nevertheless, reasonably high water flux of > 20 L/m^2.h can be achieved for the highly permeable membranes.

The effect of *B/A* ratio is also considered in Figure 2(a). This ratio represents the effect of reverse solute diffusion (i.e., the leakage of solutes from the DS to the FS). At low *B/A* ratio (0 and 10 kPa), the *B/A* ratio has little effect on FO water flux. However, when *B/A* is greater than the osmotic pressure of the FS (*B/A* at 100 and 250 kPa), reverse solute diffusion starts to play a major role in ICP. A severer leakage of draw solutes to the FS side results in a significant loss of draw solutes in the porous support layer, which leads to lower effective driving force across the active layer and thus lower water flux.



(a)



(b)

Figure 2: Effect of membrane active layer properties (*A* and *B*) on FO water flux. (a) Wastewater treatment scenario and (b) seawater desalination scenario. Other simulation conditions include *S* = 0.4 mm and *D* = 1.69 x 10^{-9} m^2/s.

Figure 2(b) shows the seawater desalination scenario (π_{FS} = 2.5 MPa and π_{DS} = 10 MPa). Except for very low *A* values (*A* < 5 x 10^{-12} m/s.Pa), increasing *A* value does not appear to be beneficial in enhancing the FO water flux in this case. It can be explained by the much higher osmotic pressure of the feed, which means ICP effect is very severe and it dominates over the frictional resistance effect. Consider the development of polyamide (PA) salt-rejecting membranes, one can easily achieve a water permeability of 1 x 10^{-11} m/s.Pa (corresponding to 3.6 L/m^2.h.bar) with decent salt rejection. Thus, further increasing *A* value beyond the current state-of-the-art seems to be of little help in improving FO water flux. Changing *B/A* ratio also has little effect on the FO water flux for the seawater desalination scenario. For the entire range of *B/A* ratios investigated (0 to 250 kPa), we have *B/A* << π_{FS}, which means that the reverse solute diffusion is relatively insignificant compared to the effect of the feed solutes and the degree of ICP is governed by the feed osmotic pressure. Indeed, for very large π_{DS} and π_{FS} values (π_{DS} > π_{FS} >> *B/A* and J_w/A), Equation (1) can be simplified to:

$$J_w = \frac{D}{S}\ln\left(\frac{\pi_{DS}}{\pi_{FS}}\right) \qquad (3)$$

Equation (3) suggests that, for the seawater desalination scenario, the FO water flux is largely governed by the ICP inside the porous support layer, such that the membrane actively layer properties are not directly relevant. The only membrane parameter appears in Equation (3) is the structural parameter *S*, with J_w inversely proportional to *S*. The dependence of FO water flux on *S* value is shown in Figure 3. The discrete symbols are simulation results based on Equation (1) for membranes with different *A* values, and the continuous line is obtained from Equation (3). For all cases, Equation (3) appears to be an upper bound to the achievable FO water. Once again, the FO water flux is not significantly affected by membrane permeability, especially at higher *S* values where ICP tends to be more severe and where membrane frictional resistance plays little importance.

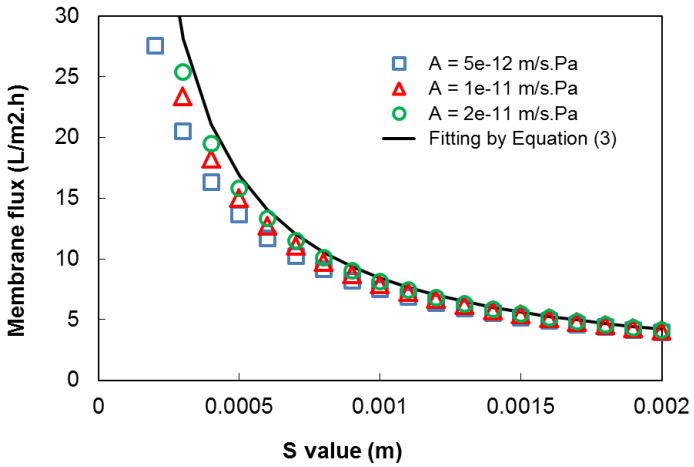


Figure 3: Effect of structural parameter (*S* value) on FO water flux for the seawater desalination scenario. Other simulation conditions include *B/A* = 10 kPa and *D* = 1.69 x 10^{-9} m^2/s.

3. CONCLUSION

A mass transfer model that incorporates ICP and reverse solute diffusion is used analyse FO performance. For the case of wastewater treatment, FO water flux is affected by both the frictional resistance of the active layer and ICP inside the porous support layer. Thus, FO water flux is highly dependent on the properties of both the active layer (*A* and *B* values) and the support layer (*S*

value). On the other hand, the FO water flux in seawater desalination is largely independent of A value and the B/A ratio, as long as $A > 5 \times 10^{-12}$ m/s.Pa and $B/A << \pi_{FS}$. Under these conditions, the FO water flux is dictated by ICP effect and its value is inversely proportional to S.

REFERENCES

[1] Cath, T. Y., Childress, A. E., & Elimelech, M. (2006). Forward osmosis: Principles, applications, and recent developments. Journal of Membrane Science, 281(1-2), 70-87.

[2] Tang, C. Y., She, Q., Lay, W. C. L., Wang, R., & Fane, A. G. (2010). Coupled effects of internal concentration polarization and fouling on flux behavior of forward osmosis membranes during humic acid filtration. Journal of Membrane Science, 354, 123-133.

[3] Zhao, S., Zou, L., Tang, C. Y., & Mulcahy, D. (2012). Recent developments in forward osmosis: Opportunities and challenges. Journal of Membrane Science, 396, 1-21.