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Optimization of hybrid system consisting of forward osmosis and reverse osmosis: a Monte Carlo simulation approach

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ABSTRACT

Forward osmosis (FO) is a membrane process that has been studied as novel technology for treatment of a wide variety of aqueous solutions. FO uses a semi-permeable membrane to extract cleaning water from impaired water by an osmotic pressure gradient but it also needs to have a posttreatment so-called "draw solute recovery." The focus of the current study was to investigate a FO–reverse osmosis (RO) hybrid process in which RO is being used to recover draw solutes in product water from FO. A Monte Carlo method was applied to optimize the system. The key parameters affecting the energy efficiency of the hybrid system were also identified. The results indicated that the FO–RO hybrid system has advantages over RO-only system under high fouling conditions. It was found to be essential to minimize the internal concentration polarization to ensure high-energy efficiency and smaller requirements of membrane surface area.

Keywords: Forward osmosis; Reverse osmosis; Hybrid process; Draw solutes; Monte Carlo simulation; Optimization

1. Introduction

Forward osmosis (FO) is a separation process that uses an osmotic pressure gradient, such that a "draw" solution of high concentration (relative to that of the feed solution), to induce a net flow of water through the membrane into the draw solution [1]. Unlike reverse osmosis (RO), FO does not require high pressure, which serves to counteract the osmotic pressure gradient [2]. Moreover, FO membrane has been found to be less sensitive to fouling and scaling [3,4]. This allows FO to have potential of lower energy consumption than RO, especially for energy-intensive water treatments such as desalination and water reuse [5].

However, one of the factors that have been often ignored in considering FO systems is the recovery draw solutes [6]. During FO process, the feed is concentrated while the draw solution becomes dilute. Thus, engineered applications of FO require the continuous reconcentration of the draw solution in a closed loop. One of the prominent methods that have been widely investigated for DSR is the FO–RO

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hybrid system [7]. Synergistically coupling FO with RO produces an exceptionally robust, multi-barrier system for treating water and wastewater [8]. In this FO–RO hybrid system, the FO process may be viewed as a pretreatment for downstream unit processes, especially for water with high scaling or fouling propensity. Recent studies have demonstrated the efficiency of the hybrid FO/RO systems in treating secondary wastewater effluent, landfill leachate, and brackish water brines [9].

Nevertheless, little has been done for in-depth analysis of the energy efficiency of the FO–RO hybrid system. The FO–RO hybrid system may use more energy than the RO-only system depending on its design and operating conditions. In this context, this study compares the FO–RO hybrid system with competing RO-only system by considering energy requirement and practical feasibility. The Monte Carlo method was applied to examine a variety of conditions for the FO–RO hybrid system and the RO-only system. The optimum ranges of parameters for the FO–RO hybrid system were also suggested based on the model calculations.

2. Model development

We have applied the solution-diffusion model modified with the film theory model to analyze the performance of FO and RO systems. The standard flux equation for FO is given as [10]:

$$J_w = L_v\left(\pi_{D,b}\exp\left(-\frac{J_w}{K_D}\right) - \pi_{F,b}\right) = L_v\left(\frac{\pi_{D,b}}{\beta} - \pi_{F,b}\right) \quad (1)$$

where J_w is the permeate flux, L_v is the water transport parameter, $\pi_{F,b}$ is the bulk osmotic pressure on the feed side. $\pi_{D,b}$ is the bulk osmotic pressure on the draw solution side, K_D is the mass transfer coefficient for internal concentration polarization, and β is the internal concentration polarization ratio. Since the external concentration polarization is relatively small compared with the internal concentration polarization, [11], it is ignored in this work.

For an RO-only system, in the absence of salt passage and negligible effect of the external concentration polarization, the generalized flux equation is:

$$J_w = L_v(\Delta P - \pi_{F,b}) \quad (2)$$

where ΔP is the transmembrane pressure.

In the FO–RO hybrid system, RO is used to recover draw solutes from the diluted draw solution in FO permeate, as illustrated in Fig. 1(a). Accordingly, the flux equations are given by:

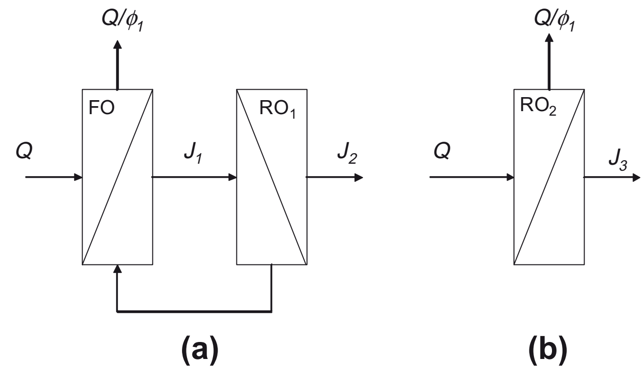

Fig. 1. Schematic diagrams for (a) the FO–RO hybrid system and (b) the RO-only system.

$$\begin{aligned} J_1 &= L_1\left(\frac{\pi_{D,b}}{\beta} - \pi_{F,b}\right) \\ &= L_1\left(\frac{c_{D,b}RT}{\beta} - c_{F,b}\left(\frac{1+\phi}{2}\right)RT\right) \end{aligned} \quad (3)$$

for the FO system

$$J_2 = L_2(\Delta P_2 - \pi_{D,b}) = L_2(\Delta P_2 - c_{D,b}RT) \quad (4)$$

for the RO-only system

where J_1 and L_1 are the permeate flux and water permeability for the FO membrane; J_2 and L_2 are the permeate flux and water permeability for the RO membrane; ϕ is the permeate recovery, which is defined as the ratio of the permeate flow rate to feed flow rate in the RO-only system; ΔP_2 is the transmembrane pressure for the RO membrane in the FO–RO hybrid system; R is the gas constant; and T is the temperature. Combining Eqs. (3) and (4), ΔP_2 is given by:

$$\Delta P_2 = \frac{J_1\beta}{L_1} + \frac{J_2}{L_2} + c_{F,b}\left(\frac{1+\phi}{2}\right)\beta RT \quad (5)$$

If the same feed water is treated only by the RO membrane, the flux equation is given by:

$$J_3 = L_3(\Delta P_3 - \pi_{F,b}) \quad (6)$$

where J_3, L_3, and ΔP_3 are the permeate flux, water permeability, and the transmembrane pressure for the RO membrane in the RO-only system, respectively. If membrane fouling occurs, Eq. (6) is modified as:

$$J_3 = \frac{L_3}{1+R_f}(\Delta P_3 - \pi_{F,b}) \quad (7)$$

where R_f is the dimensionless form of the membrane fouling resistance. The effect of fouling was not considered in the FO membrane because FO membrane fouling has been reported to be less severe than that of RO membrane. This leads to the following equation:

$$\Delta P_3 = \frac{J_3(1+R_f)}{L_3} + \left(\frac{1+\phi}{2}\right) c_{F,b} RT \tag{8}$$

Depending on the conditions, fouling in FO process may be as severe as that in RO process. Even in such cases, it is still reasonable to assume that R_f in FO membrane is much smaller than that in RO membrane because FO fouling is more reversible than RO fouling.

Since the energy consumption in RO-only system is proportional to the applied pressure, the ratio of pressure requirements was estimated to compare the energy efficiency of FO–RO hybrid system with that of competing RO-only system, which is given as:

$$cf = \frac{\Delta P_3 - \Delta P_0}{\Delta P_2 - \Delta P_0} = \frac{\frac{J_3(1+R_f)}{L_3} + \left(\frac{1+\phi}{2}\right) c_{F,b} RT - \left(\frac{J_2}{L_2} + \left(\frac{1+\phi}{2}\right) c_{F,b} RT\right)}{\frac{J_1\beta}{L_1} + \frac{J_2}{L_2} + c_{F,b}\left(\frac{1+\phi}{2}\right)\beta RT - \left(\frac{J_2}{L_2} + \left(\frac{1+\phi}{2}\right) c_{F,b} RT\right)} = \frac{\frac{J_3(1+R_f)}{L_3} - \frac{J_2}{L_2}}{\frac{J_1\beta}{L_1} + c_{F,b}\left(\frac{1+\phi}{2}\right)(\beta-1)RT} \tag{9}$$

$$f = \Delta P_0 = \frac{J_2}{L_2} + \left(\frac{1+\phi}{2}\right) c_{F,b} RT \tag{10}$$

where ΔP_0 is the transmembrane pressure required to treat feed solution by the RO membrane in FO–RO hybrid system (RO1 in Fig. 1(a)). If the RO membrane in RO-only system (RO2 in Fig. 1(b)) has larger water permeability than RO1, f becomes negative, implying that the FO–RO hybrid system uses more energy than the RO-only system. Only if f is over 1, the FO–RO hybrid system uses smaller energy than the RO-only system does.

To explore the optimum conditions for the FO–RO hybrid system, the Monte Carlo method was applied. The Monte Carlo methods (or Monte Carlo experiments) are a class of computational algorithms that rely on repeated random sampling to compute their results [12]. Here, it was used to examine the effect of key parameters for FO–RO hybrid system on the energy efficiency or f. The ranges of these parameters were determined based on literature survey and laboratory-scale experimental tests. Over 20,000 runs of the calculation were implemented while changing 12 parameters simultaneously.

In addition to the energy efficiency, the required surface area of the membranes was compared for the two systems. The capital costs of FO or RO units are best expressed in terms of membrane surface area. For the RO-only system, the membrane area per unit water production is simply J_3^{-1}, while that for the FO–RO hybrid system is $J_1^{-1} + J_2^{-1}$.

3. Results and discussion

3.1. Monte Carlo simulation for FO–RO system

The f values, which imply the energy efficiency of the FO–RO hybrid system, were estimated by the Monte Carlo method. The results are shown in Fig. 2 as a frequency diagram. Only 3.2% of total calculations results in f value over 1. This suggests

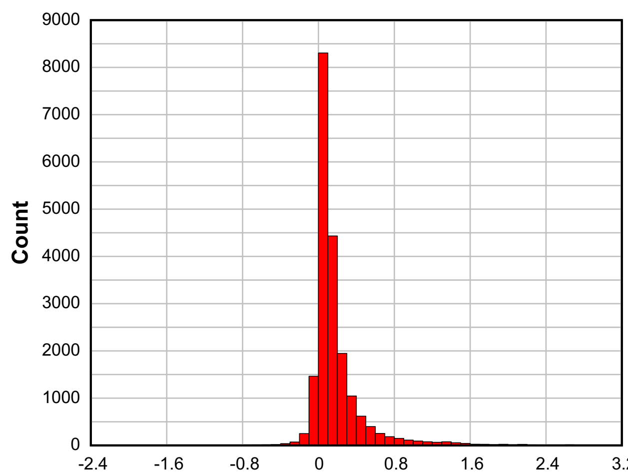

Fig. 2. Histogram for f value in Monte Carlo simulation on FO–RO hybrid system.

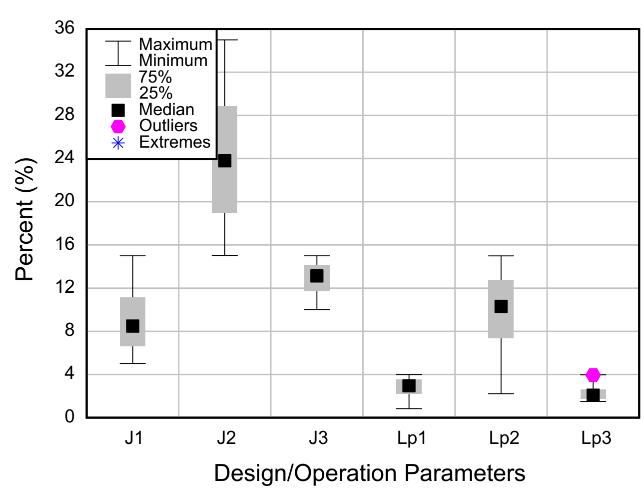

Fig. 3. Ranges of parameters resulting in f values larger than 1 in Monte Carlo simulation on FO–RO hybrid system.

that FO–RO hybrid system may use more energy than RO-only system without the optimization.

Fig. 3 shows the ranges of parameters for the FO–RO hybrid systems with $f > 1$. The Y-axis of the graph indicates the frequency (in percent) of the parameters. The average values of flux for FO, RO for draw solute recovery, and RO for RO-only system were 8.2 L/m^2-h, 24 L/m^2-h, and 13 L/m^2-h, respectively. In this case, the average L_p values for FO, RO for draw solute recovery, and RO for RO-only system were 3 L/m^2-h-bar, 10.2 L/m^2-h-bar, and 2 L/m^2-h-bar, respectively. This implies that the FO membrane with high permeability should be used under relatively low flux to ensure low energy consumption.

Among many parameters, the ratio of internal concentration polarization (β) seems to be one of the most important ones. The impact of internal concentration polarization on the energy efficiency is illustrated in Fig. 4(a). As β increases, f value tends to decrease due to the reduction of FO efficiency. When β is over 4.5, f value cannot be higher than one under any condition.

In addition to the internal concentration polarization, the effect of RO fouling on the f value is also examined in Fig. 4(b). It appears that the f value increases with increasing RO fouling, or R_f. Under high fouling conditions, the f value is even higher than five. This suggests that RO fouling is another key

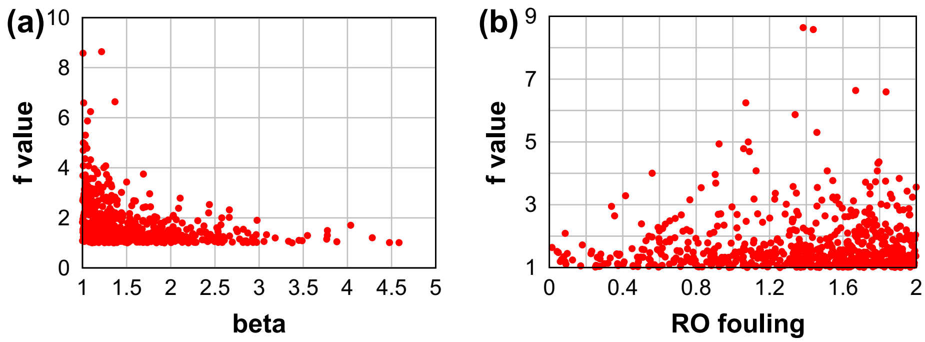

Fig. 4. Monte Carlo simulation on FO–RO hybrid system. (a) Dependence of f on β and (b) dependence on f on R_f.

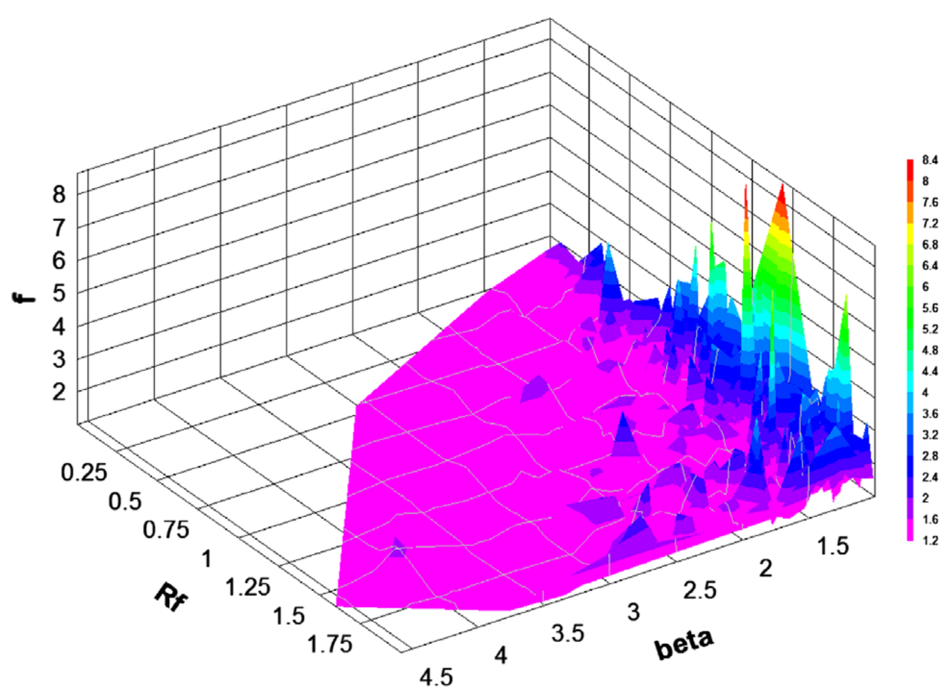

Fig. 5. Effect of the internal concentration polarization and fouling on the energy efficiency for the FO–RO hybrid system.

factor affecting the energy efficiency of the FO–RO hybrid system.

Fig. 5 shows how β and R_f affect the f value, indicating that the f value is high at low β and high R_f conditions. It appears that β should be less than 1.5 and R_f should be more than 0.5 to ensure high f values. This implies that the FO–RO system is appropriate for treating feed water with high fouling potential. It is also clear that the internal concentration polarization should be effectively controlled even under such severe conditions.

3.2. *Effect of operating flux on the energy efficiency and required membrane area*

To further investigate the effect of operating conditions on the FO–RO hybrid system, contours of constant f value and the ratio of membrane area for the FO–RO hybrid and RO-only systems ($g = (J_1^{-1} + J_2^{-1})/J_3^{-1}$) are shown as functions of FO and RO flux in Fig. 6. Here, f is related to energy cost (or operational cost) and g is related to the requirement of membrane area (or capital cost). The flux for the RO-only system is fixed to 15 L/m^2-h, which is a common value. The results are presented for $R_f = 0$ and $K_D = 10$ L/m^2-h. With this K_D, the β ranges from 1.6 to 4.5, depending on the FO flux. It is evident from the figure that the f value increases with decreasing the FO and RO fluxes, suggesting that the operating cost and energy consumption are smaller for smaller flux values of FO and RO. On the other hand, the g value decreases as increasing the FO and RO fluxes. Accordingly, the capital cost for the hybrid system may increase in order to decrease the operating cost by reducing the fluxes.

Fig. 7 shows the contour of constant f value for the FO–RO hybrid and RO-only at $R_f = 1$. It is evident that the f values in this figure were greater than those in

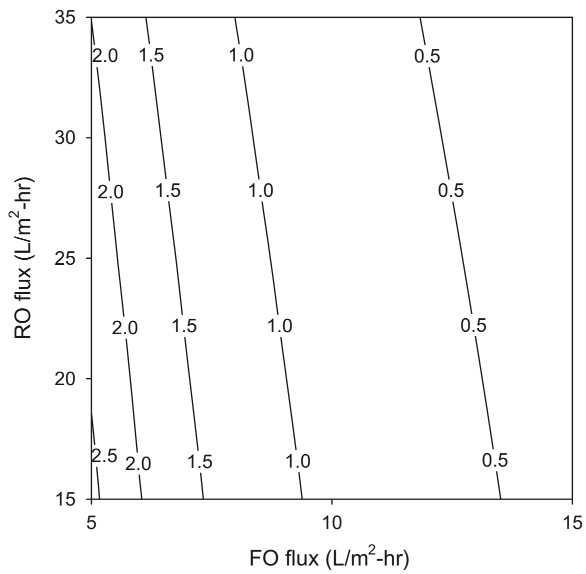

Fig. 7. Contour diagram of f values under high fouling conditions ($R_f = 1$) at different FO and RO fluxes of the FO–RO hybrid system. Conditions: $J_3 = 15$ L/m_2-h; $R_f = 1$; $K_D = 10$ L/m^2-h; $L_1 = 3$ L/m^2-h-bar; $L_2 = 5$ L/m^2-h-bar; $L_3 = 1.5$ L/m^2-h-bar.

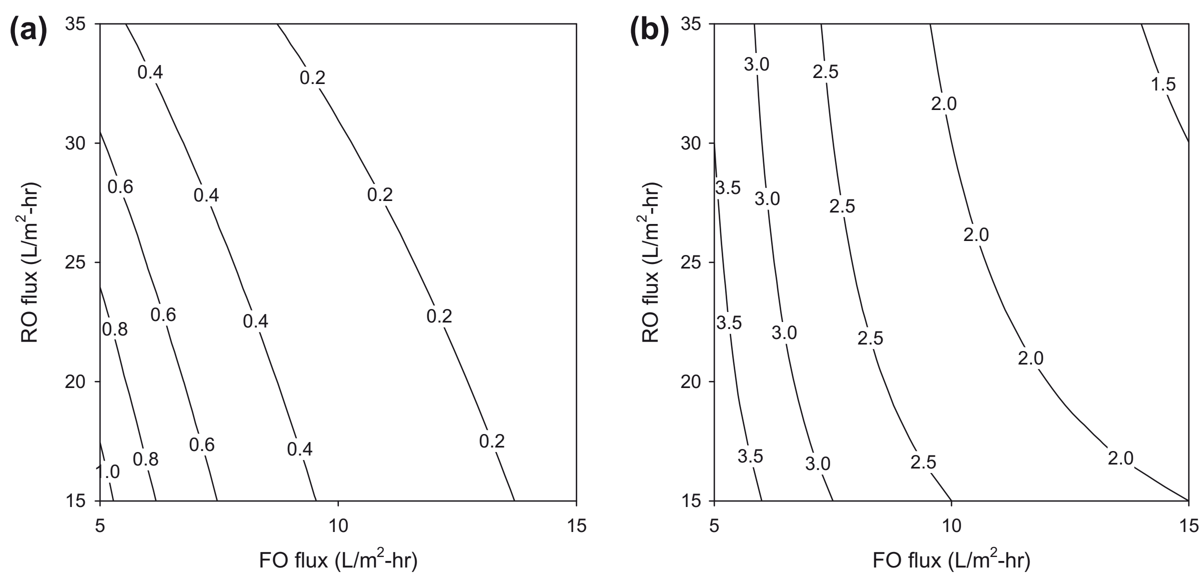

Fig. 6. Contour diagrams of f and g values under no fouling conditions ($R_f = 0$) at different FO and RO fluxes of the FO–RO hybrid system. (a) f value (b) g value. Conditions: $J_3 = 15$ L/m_2-h; $R_f = 0$; $K_D = 10$ L/m^2-h; $L_1 = 3$ L/m^2-h-bar; $L_2 = 5$ L/m^2-h-bar; $L_3 = 1.5$ L/m^2-h-bar.

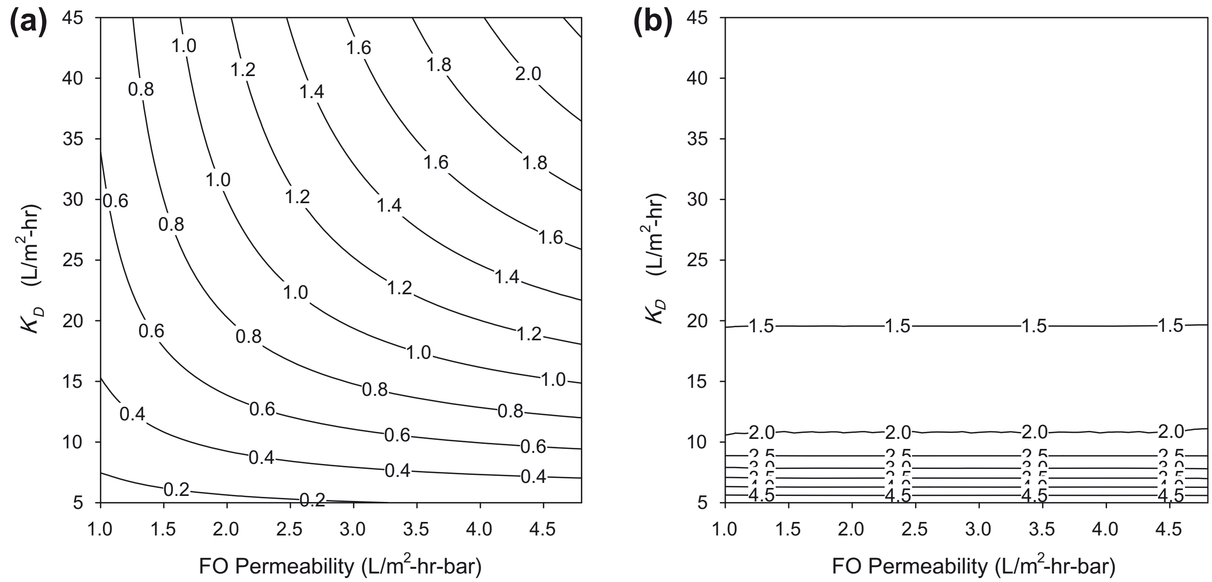

Fig. 8. Contour diagram of f and g values under high fouling conditions ($R_f = 1$) at different FO membrane permeability and K_D values. (a) f value and (b) g value. Conditions: $J_1 = 8\,L/m_2$-h; $J_3 = 15\,L/m_2$-h; $J_3 = 15\,L/m_2$-h; $R_f = 1$; $L_1 = 3\,L/m^2$-h-bar; $L_2 = 5\,L/m^2$-h-bar.

Fig. 6(a) under the same FO–RO flux conditions. Again, the FO–RO hybrid system appears to have advantages over the RO-only system where severe fouling is expected.

3.3. Effect of FO membrane properties on the energy efficiency and required membrane area

The effectiveness of the hybrid system also depends on the characteristics of FO membranes. Fig. 8 shows contours of constant f and g values at different L_1 and K_D values. It is evident that the FO membranes with high L_1 and K_D values result in high f and g values. This implies that the development of new FO membrane will allow higher efficiency of the hybrid system than the currently available FO membranes, which have relatively low L_1 (less than $2\,L/m^2$-h-bar) and K_D values (approximately less than 10–20 L/m^2-h).

4. Conclusions

In this study, FO–RO hybrid systems were theoretically investigated using the Monte Carlo method. The following conclusions were withdrawn:

(1) The optimization of design and operating parameters seems to be critical for energy-efficient FO–RO hybrid system. Without optimizing the design and operating parameters, the FO–RO hybrid system uses higher energy than the RO-only system.

(2) The internal concentration polarization and RO membrane fouling were identified as the most important factors affecting the efficiency of the hybrid system. The FO–RO hybrid system is advantageous than the RO-only system when RO membrane experiences high fouling. The β should be less than 1.5 and the R_f should be more than 0.5 for efficient application of the hybrid system.

(3) Development of new FO membranes with high permeability and low internal concentration polarization was found to be important to improve the efficiency of the hybrid system.

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