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Theoretical investigation of hybrid desalination system combining reverse osmosis and forward osmosis

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ABSTRACT

Forward osmosis (FO) is a membrane-based desalination technique using an osmotic pressure gradient as a driving force. FO enables lower energy consumption to produce water than reverse osmosis (RO) because it does not require high transmembrane pressure. However, FO needs to be combined with other processes such as RO or evaporation because the draw salts in the FO products should be removed. This paper focused on theoretical investigation of combined systems with FO and RO for seawater desalination. A theoretical model to predict the performance of the combined systems was developed based on the solution–diffusion model and the modified film theory. The effect of internal concentration polarization on FO efficiency was also considered in the model. A pilot-scale system of FO and RO was assumed for model calculations. Results showed that the combinations of FO with seawater reverse osmosis (SWRO) have potential for desalination with high recovery (up to 80%). It was also found that FO may be incorporated with brackish reverse osmosis (BWRO) to produce high quality of water with higher flux and recovery than conventional RO-based desalination systems.

Keywords: Desalination; Water reuse; Reverse osmosis; Forward osmosis; Hybrid system

1. Introduction

A seawater desalination process separates saline seawater into two streams: a fresh water stream containing a low concentration of dissolved salts and a concentrated brine stream. This process requires some form of energy to desalinate, and utilizes several different technologies for separation. A variety of desalination technologies has been developed over the years on the basis of thermal distillation, membrane separation, freezing, and electrodialysis. [1].

Forward osmosis (FO), a potential alternative to pressure-driven membrane processes such as RO in certain applications, has been considered a promising technology for seawater desalination [2]. FO uses a concentrated draw solution to generate high osmotic pressure, which pulls water across a semi-permeable membrane from the feed solution. The draw solute is then separated from the diluted draw solution to recycle the solute, as well as to produce clean product water. FO enables lower energy

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consumption to produce water than reverse osmosis (RO) because it does not require high transmembrane pressure. However, FO alone cannot be used for desalination and water treatment because the draw salts should be removed.

Recently, a few works have been done to investigate the feasibility of FO technology for seawater desalination. Energy consumption and fouling have been the main issues for these works. Energy requirement of FO systems using ammonia-carbon dioxide was calculated to be much lower than that of RO systems [3,4]. Flux recovery in the FO mode was found to be much higher than that in the RO mode under similar cleaning conditions because of less compact organic fouling layer formed in FO mode due to the lack of hydraulic pressure [5]. This allowed FO membranes to be cleaned without chemicals. A novel operation mode of FO system was also investigate to achieve high efficiency [6]. Nevertheless, further work is still required to bring FO technologies into practice, including development of new FO membranes, design of new hybrid systems, development of new draw salts and recovery systems [2].

This paper was intended to theoretically investigate combinations of FO and RO processes for seawater desalination. A model to predict the performance of this new hybrid system using FO and RO was developed based on the solution-diffusion model modified with film theory. The effects of external and internal concentration polarization on FO efficiency were also considered in the model.

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. We only give a broad outline of the model here, since details are provided separately [6,7].

2.1. FO model

For an FO system, the water flux equation is:

$$J_w = A\left(\pi_{D,b} - \pi_{F,b}\right) \tag{1}$$

where J_w is the permeate flux, A is the water transport parameter, $\pi_{D,b}$ is the osmotic pressure on the draw side, and $\pi_{F,b}$ is the osmotic pressure on the feed side. The standard flux equation for FO is given as [2]:

$$J_w = A\left(\pi_{D,b}\exp\left(-\frac{J_w}{k_D}\right) - \pi_{F,b}\exp\left(\frac{J_w}{k_F}\right)\right) \tag{2}$$

where k_D is the mass transfer coefficient for internal concentration polarization, and k_F is the mass transfer coefficient for external concentration polarization. Based on the mass transfer correlations, k_F and k_D are given as [3,8]:

$$k_F = 0.5510\,\mathrm{Re}^{0.4}\,\mathrm{Sc}^{0.17}\left(\frac{D}{d_h}\right)\left(\frac{C_b}{\rho}\right)^{-0.77} \tag{3}$$

$$k_D = \frac{D\varepsilon}{\tau l} \tag{4}$$

where D is the diffusion coefficient, d_h is the hydraulic diameter, Re is the Reynolds number, Sc is the Schmidt number, ε is the porosity of support layer, l is the thickness of support layer, and τ is the tortuosity of support layer.

Finally, J_s and C_p can be calculated using the solution–diffusion model

$$J_s = J_w C_p = B\left(C_b\exp\left(\frac{J_w}{k_F}\right) - C_p\right) \tag{5}$$

From a mass balance of water and solutes (NaCl and draw salts), an FO system using multiple elements was simulated. For this calculation, a linear concentration profile inside an element was assumed. This assumption is commonly used for simplifying the simulation for RO systems [9] and seems to be also applicable for FO systems.

2.2. RO model

For an RO system, the water flux equation is [10]:

$$J_w = A\left(\Delta P - \Delta\pi\right) \tag{6}$$

where ΔP is the transmembrane pressure; π is the osmotic pressure between feed and permeate sides. The solute flux is calculated using Eq. (5). A mass balance was also used to simulate a RO system. Details on the RO model are provided in our previous work [7].

3. Results and discussion

3.1. Characteristics of FO system

The values of model parameters used in this study are listed in Table 1, which were obtained from our previous research [6,7] and literature [8,11]. FO and RO membrane have similar permeability to water but FO has 2.5 times larger permeability to NaCl than RO. This implies that FO membrane may require another process to attain sufficient rejection to salts. The rejection of ammonia carbon dioxide was assumed to be 1.0 (complete rejection).

The geometry of the FO membrane element was assumed to be same as that of the RO element. Although there are few available in such a configuration for FO, it is expected that a commercially available FO module in the future should be spiral wound for compatibility issues. A plate-and-frame configuration for FO has limitations including lack of adequate membrane support and low packing density. A tubular or hollow fiber configuration is advantageous in terms of hydrodynamics, but few membrane materials are available for this module. A

Table 1
Process parameters and operating conditions [6,7,11]

Parameter	Value
FO	
A, m²-s/kg	4×10^{-12}
B, m/s	5×10^{-8}
k_D, m/s	1.73×10^{5}
Geometry	Same as 8040 element
SWRO	
A, m²-s/kg	3.6×10^{-12}
B, m/s	1.96×10^{-8}
k_F, m/s	$4.3\times10^{-12}\times Q_{\text{Feed}}^{0.5}$
Geometry	Same as 8040 element
BWRO	
A, m²-s/kg	8.0×10^{-12}
B, m/s	5.00×10^{-7}
k_F, m/s	$4.3\times10^{-12}\times Q_{\text{Feed}}^{0.5}$
Geometry	Same as 8040 element
Other conditions	
NaCl concentration, mg/L	35,000
Draw solution	Ammonium carbon dioxide (2–6 M)
Temperature, °C	25

spiral wound module configuration cannot be used for FO in its current design because the draw solution cannot be forced to flow inside the envelope formed by the membranes. A modification of the current spiral wound module, however, allow it to be used for FO application, as demonstrated in a previous work [12]. Accordingly, the spiral wound FO module in this work was assumed to have two flow streams including feed and draw flows. A higher flow rate of draw solution results in a high flux but the amount of draw solution to be recovered also increases. Thus, the flow rate of draw solution affects the system performance and water production cost.

Fig.1 also shows a simulation result for a FO system using the parameters in Table 1. In this calculation, the flow rate of new draw solution was set to 50 m³/d, which is 25% of feed flow rate. Using the model, the flux from each element was calculated to compare local characteristics with overall performance. The first element showed the highest flux (37 L/m²-h) but the flux was significantly reduced in elements near the outlet. This is attributed to an increased NaCl concentration and decreased draw salt concentrations, resulting in a decrease in net driving force. After FO, the flow rate of product was 163 m³/d, which should be further treated by a draw salt recovery process. The concentration of NaCl and draw salt in this product water were 432 mg/L and 1.8 M, respectively. The recovery of product water was 0.55.

To compare RO with FO, an RO system, which has a similar feed flow rate condition as the FO system in Fig. 1, was simulated in Fig. 2. Under 50 bar, the recovery of product water in the RO system was lower than that of the FO system (0.375 vs. 0.55) because the average flux of FO was higher than that of RO. A significant decrease in flux from each element was also observed in the RO system. Since the FO system did not require high pressure, its energy consumption may be lower than that of RO systems [3,4]. Nevertheless, the energy efficiency of FO systems largely depends on the efficiency of draw salt recovery systems.

On the other hand, the permeate TDS in the RO system was 225 mg/L, which is significantly lower than that in FO system (432 mg/L). This is attributed to a smaller B value for the RO membrane than for the FO membrane. Since FO membranes are made of cellulose triacetate, its salt rejection is smaller than that of polyamide RO membranes.

To reduce the treatment cost (and energy consumption) by the draw salt recovery system, the concentration of draw salts should be maintained to a proper value. A high concentration of draw salt requires high energy consumption but a low concentration of draw salt leads

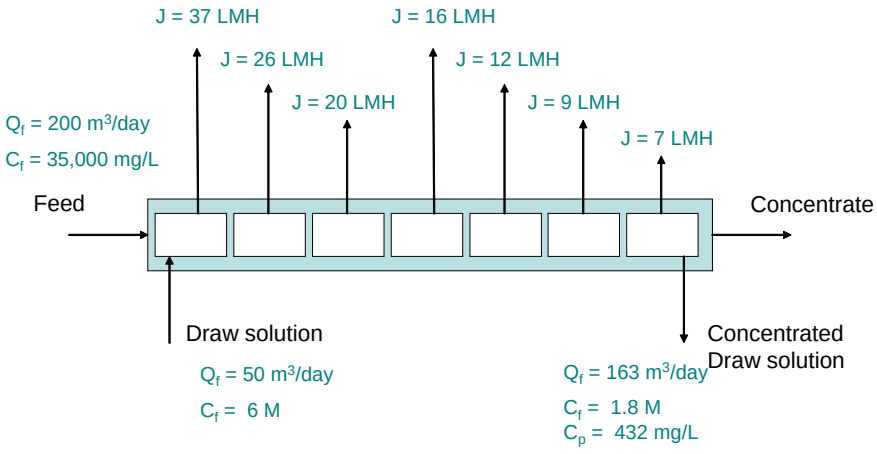

Fig. 1. A simulation result for an FO system in a spiral wound module.

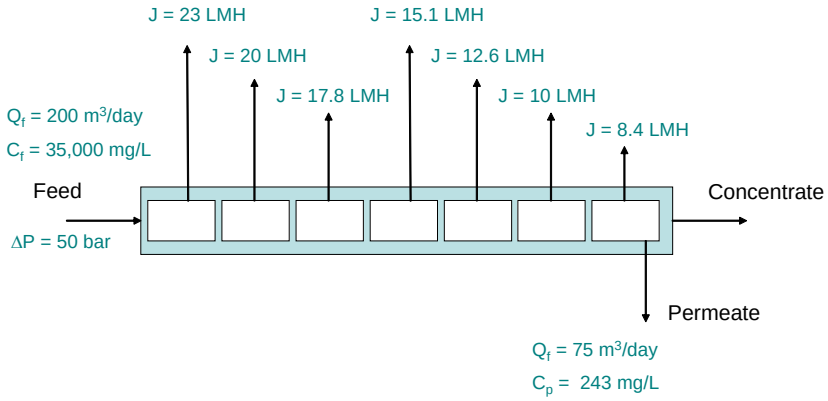

Fig. 2. A simulation result for an RO system under the same conditions as in Fig. 1.

to a low flux and recovery. As shown in Fig. 3, the average flux increased with increasing draw salt concentration. Since most RO systems have average flux of 12–15 L/m^2-h for seawater desalination, the draw salt concentration should be higher than 4 M to make FO systems higher flux than RO systems.

The flow rate of draw solution is another important parameter affecting the efficiency of FO operation. The flux is proportional to the flow rate of draw solution as illustrated in Fig. 4. However, an increased flow rate of draw solution results in an increased cost (or energy consumption) for draw salt recovery after FO treatment.

In FO systems, both internal and external concentration polarizations occur [2]. While external concentration polarization depends on the operating conditions such as feed flow rate and flux, internal concentration polarization is determined by the structure of the membrane and cannot be changed by adjusting operating conditions. Fig. 5 shows the flux of the FO system as a function of external mass transfer coefficient related to external concentration polarization. Although the mass transfer coefficient increases by 5 times, the flux does not increase. This is probably because the relative importance of internal concentration polarization is much higher than that of external concentration polarization.

Fig. 6 illustrates how permeate recovery affects the flux of the FO system. Although FO can have higher recovery than RO, it should not be too high. Increasing the recovery as high as 0.8 (80%) results in a low flux because the osmotic pressure of feed solution flowing inside the module is very high. It is likely that the recovery needs be lower than 0.6 (60%) to maintain flux higher than 12 L/m^2-h.

3.2. Combination of FO with RO

In this work, we consider two kinds of combined system of FO and RO:

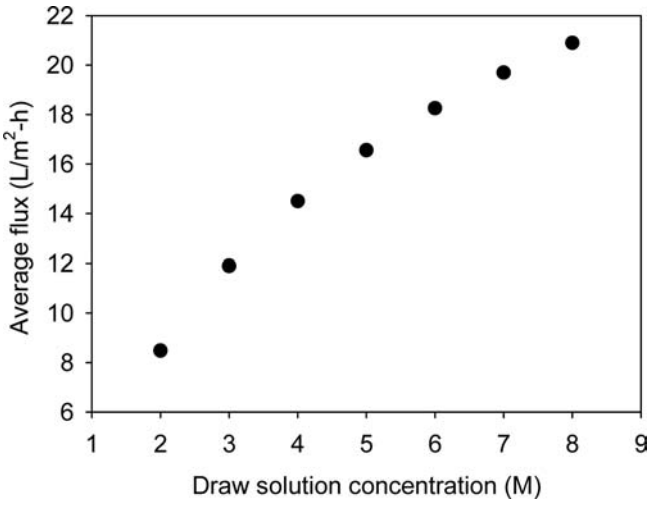

Fig. 3. Effect of draw solution concentration on average flux of a FO system (Simulation conditions: Feed flow rate = 200 m^3/d; Draw solution flow rate = 50 m^3/d).

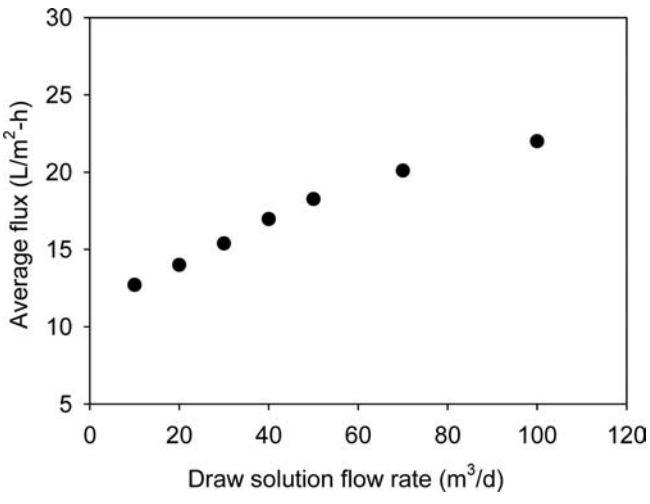

Fig. 4. Effect of draw solution flow rate on average flux of a FO system (Simulation conditions: Feed flow rate = 200 m^3/d; Draw solution concentration = 6 M).

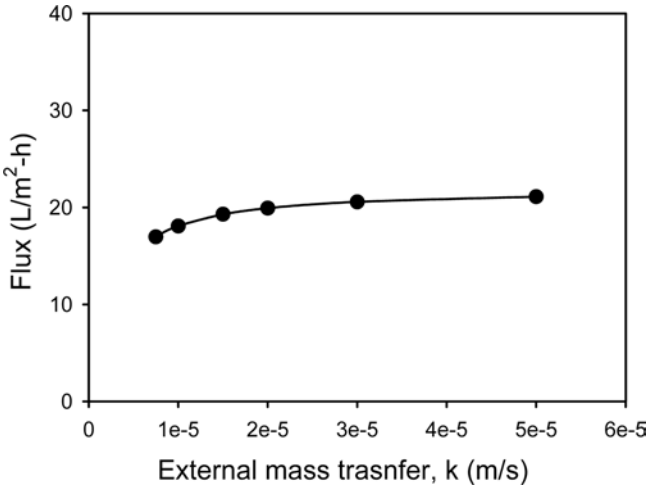

Fig. 5. Effect of external mass transfer coefficient on average flux of a FO system (Simulation conditions: Draw solution flow rate = 50 m^3/d; Draw solution concentration = 6 M).

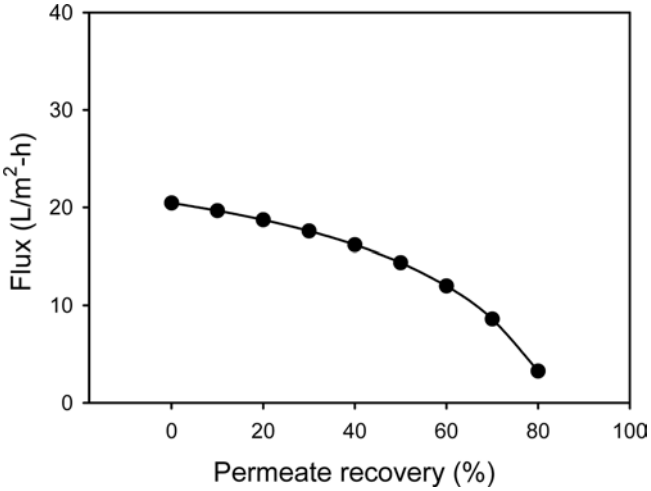

Fig. 6. Effect of permeate recovery on average flux of a FO system (Simulation conditions: Draw solution flow rate = 50 m^3/d; Draw solution concentration = 6 M).

(1) A system with high recovery: FO is applied to treat concentrate from SWRO (as shown in Fig. 7)
(2) A system with high quality of product water: BWRO is applied to treat permeate from FO (as shown in Fig. 8)

Fig. 7 shows the schematic diagram of the high recovery system using FO and RO. A recovery system for draw salt was assumed to be used. Table 2 summarizes the simulation results for this system. It is likely that the combined system can achieve a high recovery (0.69) with reasonable flux (~14.75 L/m^2-h) and permeate concentration (397 mg/L). This may be a unique advantage of FO–RO hybrid systems over RO systems because such a high recovery is hard to be attained in RO desalination systems. Of course, working with such high recoveries

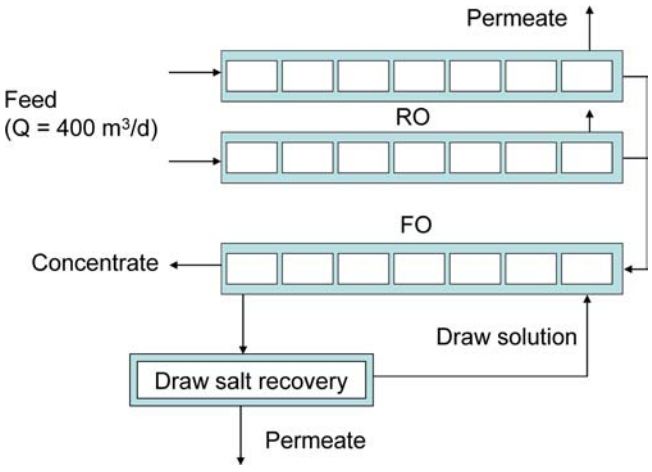

Fig. 7. A combination of FO and RO for high recovery desalination.

Table 2
Simulation results for a high recovery system using FO and RO

SWRO (1st stage)	
Applied pressure, bar	60
Recovery	0.48
Flux, LMH	15.5
TDS in permeate, mg/L	212.54
TDS in concentrate, mg/L	67466.79
FO (2nd stage)	
Draw salt, M	6
Recovery	0.4
Flux, LMH	13.33
Salt in permeate, mg/L	824
Overall recovery	0.69
Overall permeate TDS, mg/L	397
Overall permeate flux, LMH	14.75

will result in scaling problems. Although the effect of scale formation on the performance of FO–RO systems was not considered in this model, it is an important issue to be considered in future works.

In Fig. 8, the recovery was changed by adjusting the concentration of draw solution. The overall recovery of the FO–RO system increases to 0.79 as increasing the draw solution concentration up to 12 M. However, FO system with high recovery results in a deterioration of permeate TDS. Moreover, a substantial amount of energy is required to recover draw salts in FO systems if the concentration of draw solution is high.

Another possible combination of FO with RO is a desalination system for high quality of permeate. Since FO membranes generally have poorer rejection than RO

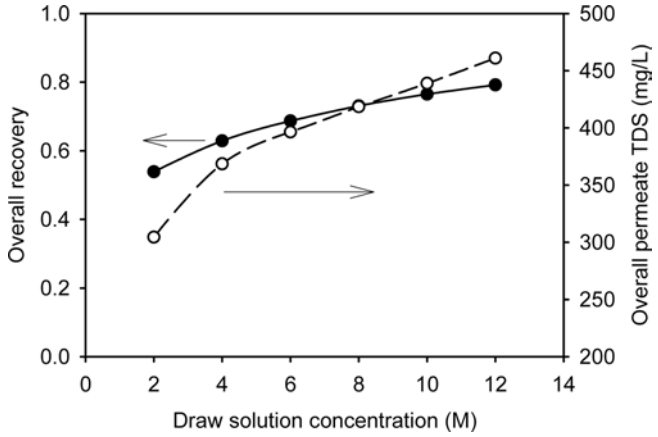

Fig. 8. Effect of draw solution concentration on overall recovery and permeate TDS in the FO-RO hybrid system for high recovery (Simulation conditions: Feed flow rate = 192 m^3/d; Draw solution flow rate = 50 m^3/d).

Table 3
Simulation results for a combined system using FO and RO for high permeate quality

FO (1st pass)	
Draw salt, M	6
Recovery	0.567
Flux, LMH	18.25
Salt in permeate, mg/L	622
RO (2nd pass)	
Applied pressure, bar	12
Recovery	0.73
Flux, LMH	15.9
TDS in permeate, mg/L	110
Overall recovery	0.45
Overall permeate TDS, mg/L	110
Overall permeate flux, LMH	12.8

membranes, the permeate from FO membranes may need a further treatment using an additional RO membrane. Fig. 9 shows the schematic diagram of the FO–RO system for high permeate quality. The characteristics of BWRO membrane are listed in Table 1. As shown in Table 3, the permeate TDS was only 110 mg/L and the recovery is still 0.45.

4. Conclusions

In this work, combinations of FO and RO processes were theoretically investigated for seawater desalination. Under similar conditions, it was calculated that FO has higher flux and recovery than RO. In FO systems, operating parameters such as flow rates (feed/draw side), draw salt concentration, and recovery seem to be important factors affecting their performance. On the other hand, the effect of external concentration polarization may be neglected. Two possible systems combining FO with RO were considered and found to be feasible as continuous systems. The combined systems have superior performance to conventional RO-based systems. Further works are required to find optimum configurations of FO and RO for various applications.

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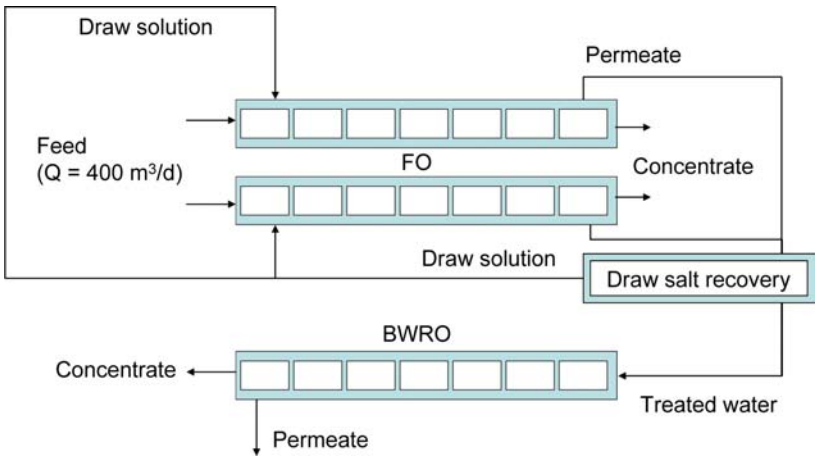

Fig. 9. A combination of FO and RO for high quality of product water.

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