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Evaluation of draw solution effectiveness in a forward osmosis process

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ABSTRACT

This work investigates the effectiveness of sodium chloride and sucrose binary draw solutions in a forward osmosis pilot plant unit with either deionised or salt water feeds. Specifically, the effects of draw solution concentration on water flux through the membrane, the overall water recovery and the specific energy consumption of the unit are considered. For both feed types, sodium chloride draw solution exhibited a relatively high effectiveness in terms of all the measured performance indicators. Further, improvements in flux and recovery were also achievable with an increase in the sodium chloride (draw solution) concentration. In contrast, a sucrose-based draw solution led to a severe deterioration of the membrane performance that could not be effectively overcome by an increase in the draw solution concentration. This observation was attributed to the relatively large increase in the viscosity of the draw solution with increase in sucrose concentration. Interestingly, in the case of a salt water feed, an increase in the sucrose draw solution concentration led to a relatively small increase in flux and recovery, suggesting some complex but favourable interaction between the salt and sucrose due to the reverse diffusion of the salt into the draw solution.

Keywords: Draw solution agent; FO; SEC; Sucrose; Sodium chloride

1. Introduction

In many countries, the availability of clean water is a serious concern that is being further exacerbated in arid and semi-arid areas due to population growth. Given that 97% of the global water resource is seawater, the desalination of brackish water and seawater remains an attractive prospect. For decades, researchers have been looking for low energy and high efficiency desalination techniques [1–8]. However, amongst the various desalination technologies, such as reverse osmosis (RO) and thermal-based separations [1–7,9,10], the forward osmosis (FO) process, also called direct osmosis, has emerged as particularly attractive.

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In FO desalination a draw solution with high osmotic pressure, on the permeate side of a semi-permeable membrane, serves to draw water from an aqueous solution (usually a saline solution) of lower osmotic pressure on the feed side of the membrane. According to the specific application, the feed solution may include seawater, brackish water [1], treated wastewater [11] or polluted water [12]. In all cases, the selection of an effective draw solution is a significant challenge [13]; see the discussions below. Nevertheless, the specific process advantages of the FO process include: a relatively low operating pressure, high product recovery, a low discharge rate of brine to the environment and, when compared to RO, low membrane fouling.

Various draw solutes have been used in FO processes such as: KCl, $NaNO_3$, KNO_3 and NH_4HCO_3 [13,14]. The control of solute flux is an important consideration in membrane selection. For example, concentration differences across the membrane can also result in solute cross-migration [15,16], thus a deterioration in separation performance, and indeed a loss of draw solute into the concentrate stream. In a similar way, salt ions from the feed water may diffuse into the permeate stream. Irrespective of this solute cross-migration, the permeate will contain draw solute that may require removal through an additional separation step (see below). Furthermore, given the nature of the separation, and the asymmetric nature of currently available membranes, both internal and external concentration polarisation effects will exist. The latter cannot be mitigated by adjustments to process operation, as its impact is inherent to the membrane itself.

As mentioned above, FO has been evaluated for seawater and brackish water desalination [1,17–19] and wastewater concentration and reclamation [20–23]. It can also be used in combination with biological processes as in the case of Osmotic Membrane Bioreactors in wastewater treatment [24,25]. The selection of an optimal draw solution is a key component for the successful development of FO technologies. The first criterion is that the draw solution should have a higher osmotic pressure than the feed solution to produce high water flux. Another important criterion in some FO applications is the availability of a suitable process for effective regeneration (reconcentration) of the draw solution after it has been diluted in FO. The regeneration process should achieve a high recovery of the draw solution to minimise losses, be able to produce a high-quality water product and be affordable. For example, when using FO for the production of potable water, it is important that draw solutes should not be present in the final potable water product. Should trace concentrations be present, they must be below the maximum legal limit of drinking water contaminants. Other important considerations for the selection of proper draw solutions are that the solute is water soluble, is solid at ambient temperature and pressure that it can be handled safely, and its cost is low enough to ensure the economic reliability of the process. Often, a sodium chloride draw solution is used because it is highly soluble, non-toxic at low concentrations and relatively easy to reconcentrate using conventional desalination processes (e.g. RO or distillation) without risk of scaling [20–24,26,27]. The aim of present paper is to investigate the effectiveness of sodium chloride and sucrose-based draw solutions for deionised and salt water feeds. Specifically, water flux and recovery, salt rejection and energy consumption considerations (see below) were given to a commercially available cellulose triacetate-based membrane type (DURASAP-FO-AC membrane) which has been supplied by Toyobo Company Ltd.

2. Theory and background

In the current study, the performance of the FO process was evaluated from measurements of the water and draw solute (sodium chloride and sucrose) flux through the membrane (J_w and J_s, respectively), the overall recovery percentage of water from the feed stream ($R\%$) and the specific energy consumption of the unit (SEC). Equations describing flux and recovery are summarised below [28]:

$$J_{\mathrm{w}} = A_{\mathrm{w}}(\pi_{\text{DS-ave}} - \pi_{\text{FW-ave}}) \tag{1}$$

$$J_{\mathrm{s}} = B(C_{\text{FW-ave}} - C_{\mathrm{p}}) \tag{2}$$

$$R\% = \frac{Q_{\mathrm{P}}}{Q_{\mathrm{FW}}} \times 100 \tag{3}$$

The permeate concentration can be calculated from the following equation [28]:

$$C_{\mathrm{p}} = \frac{BC_{\text{FW-ave}}}{JW + B} \tag{4}$$

The specific power consumption in an RO membrane SEC_{RO} (kWh/m^3) is given by

$$\mathrm{SEC}_{\mathrm{RO}} = \frac{P_{\mathrm{f}} \times Q_{\text{FW-in}}}{36 \times \eta \times Q_{\mathrm{P}}} \tag{5}$$

where P_f is the feed pressure (bar) and η is the pump efficiency. In the FO process, the SEC_{FO} is calculated from the following equation [28]:

$$SEC_{FO} = \frac{1}{(36 \times \eta \times Q_P)} (P_f Q_{FW\text{-in}} + P_{DS} Q_{DS\text{-in}}) \tag{6}$$

where P_{DS} is the draw solution feed hydraulic pressure (bar), and $Q_{FW\text{-in}}$ and $Q_{DS\text{-in}}$ are feed water and draw solution flow rates, respectively.

As mentioned earlier, two solutes were evaluated in this study as draw solution, sodium chloride and sucrose, because of their: (i) wide availability; (ii) high osmotic pressure; (iii) high rejection by typical (RO) membranes; and (iv) high solubility.

3. Experimental

3.1. Materials

Food-grade sucrose powder with 99% (w/w) purity was supplied by the Tate & Lyle Company. Sodium chloride (in the form of sea salt) with 99% purity (w/w) was supplied by the British Salt Company. All solutions in this study were prepared by dissolving the sucrose and sodium chloride salt in deionised water (DW); see below for further information on the concentrations of reagents used in this study.

3.2. Equipment

Fig. 1 shows the schematic diagram of the FO pilot plant unit, which has been designed in the Centre of Osmosis Research and Applications (CORA) at the University of Surrey, UK, and constructed by Resnova Ltd. This unit consists of a hollow fine-fibre membrane, DURASEP-FO-AC, supplied by Toyobo Company Ltd; see the specifications presented in Table 1.

Four stainless steel tanks are used in this unit. The first tank (TK-1, 30 l capacity) is used as the draw solution feed tank, while the second (TK-2, 60 l capacity) is used to collect the diluted draw solution leaving the membrane unit. The third tank (TK-3, 100 l capacity) is used as the feed water supply tank, while the fourth tank (TK-4, 60 l capacity) is used to collect the concentrated water leaving the membrane unit. The agitation of draw and feed water solutions is achieved by circulation around TK-1 and TK-3 via centrifugal pumps (Flojet and Totton Pump Companies). The tanks are equipped with liquid level indicators (LG) to determine the volume of the solutions.

The circulation pumps mentioned above are also used to deliver the feed water and draw solutions to the membrane unit. Both pumps operate with a maximum flow capacity of 4 l/min. To measure the flow rates of the solutions, the input and output FO membrane streams are fitted with rotameter-type flow meters (Elettrotec Ltd). The pumps, fittings and valves in this

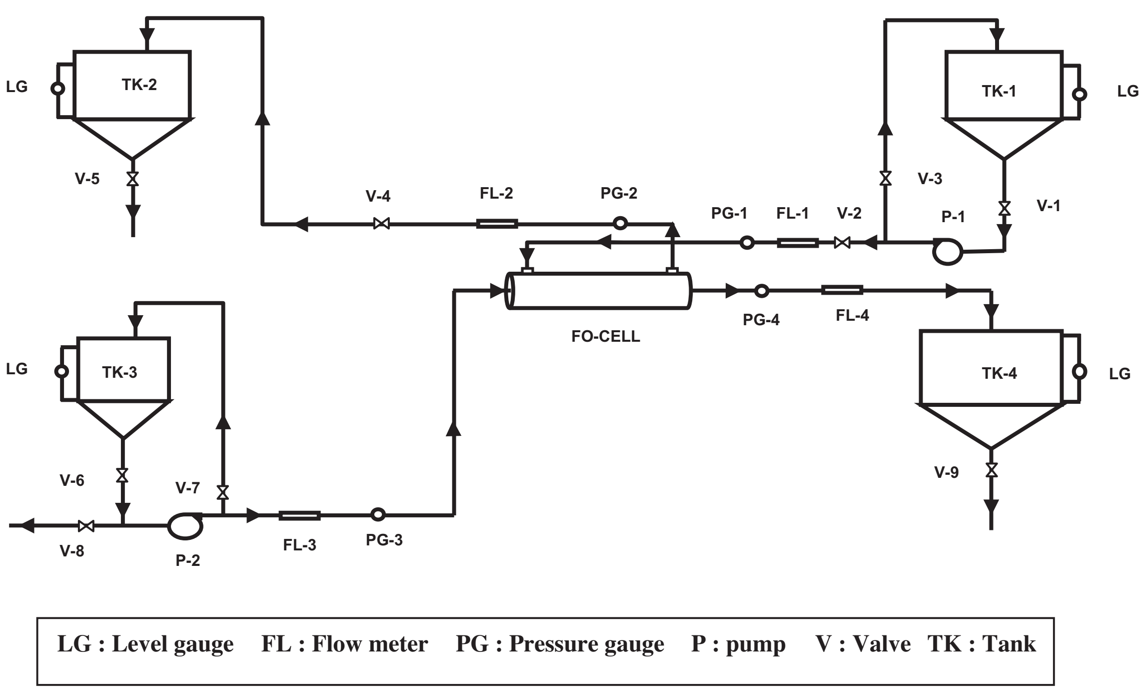

Fig. 1. Schematic diagram of forward osmosis pilot plant unit used in this study.

Table 1
Specifications of the DURASEP-FO-AC membrane (Toyobo Ltd)

Item	Specification
Membrane area	4.0 m^2
Number of fibres	72 000
Membrane material	Cellulose triacetate
Housing materials	Polysulphide
Operating pressure (inside hollow fibre)	<6 bar <1 bar
Operating temperature	<35°C
pH range	3–8
Chlorine resistance	Yes
Hollow fibre diameter	ID 175/OD 85 μm
Hollow fibre performance	Salt rejection 96–98% (1,500 ppm, 15 bar)

unit are manufactured from PVC. Additionally, all the FO membrane input and output streams are equipped with pressure and temperature gauges (Caleffi Ltd).

A conductivity meter (Mettler-Tolledo Ltd) and HPLC equipment (Varian 385-LC ELSD with an Evaporative Light Scattering Detector) were used to determine the sodium chloride and sucrose concentrations of samples, respectively. Finally, osmotic pressure values for all solutions in this study were determined from OLI software.

3.3. Experiment methodology

Fig. 2 shows a schematic diagram of the mode of flow in the membrane module in the FO process. The DURASEP-FO-AC membrane module has two sides; the shell side and the hollow fine-fibre side. Both the draw solution and the feed water are pumped into the membrane module using the centrifugal pumps. The concentrated draw solution is fed into the fibre side and discharged from the other end as a diluted solution. The feed water is fed into the shell side and discharged as concentrated solution from the other end. The two main streams, DS_{in} and FW_{in}, pass through the membrane in a counter current flow mode. The pure water flux in the present FO process is directed from the shell side towards the fibre side, which is matched with the membrane's original design.

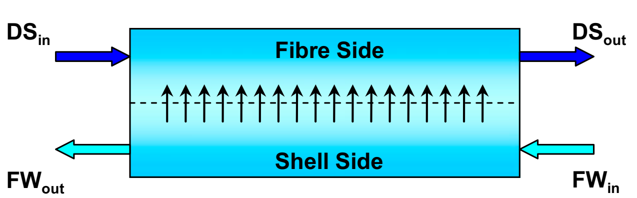

Fig. 2. DURASEP- FO-AC membrane configuration.

As mentioned above, sucrose and sodium chloride have been used as draw solutions in this study. To test the sodium chloride draw solution effectiveness, two experiments were carried out. In the first one, pure DW was used as feed, and membrane performance measured for different concentrations of sodium chloride draw solution (in the range of 20–50 g/l). In the second experiment, salty water (5 g/l salt to simulate brackish water, i.e. ~3 bar osmotic pressure) was used as feed; the same range of draw solution concentrations as experiment one was used.

To test the sucrose draw solution effectiveness, similar experiments were carried out to the above. In this case, sucrose draw solution concentrations in the range of 150–300 g/l were investigated in order to establish comparable osmotic pressures. The concentrations of draw solution used in this study, with their osmotic pressures values, are summarised in Table 2.

For all experiments, the draw solution and feed water flow rates were kept constant at 0.4 l/min and 1.5 l/min, respectively, and the operating temperature at 25°C. The volume of the solutions in the tanks, pressures and flow rates were measured at regular intervals. Outlet stream samples were collected at the start of a run and again after 40 min of operation (when the experiment was terminated), and the salinity and sucrose concentrations of the collected samples were analysed.

4. Results and discussion

Water flux (J_w) and water recovery ($R\%$) as a function of osmotic pressure difference are shown in Figs. 3 and 4, respectively. It can be seen that when using sodium chloride draw solution J_w and $R\%$ increased with an increasing osmotic pressure difference. However, in the case of sucrose as draw solution, the effect of osmotic pressure difference on J_w and $R\%$

Table 2
Draw solution concentrations with their osmotic pressure values used in this study

Sodium chloride draw solution			Sucrose draw solution		
Concentration in g/l	Concentration in Molar	Osmotic pressure value in bar	Concentration in g/l	Concentration in Molar	Osmotic pressure value in bar
20.10	0.343	15.44	150.00	0.438	12.19
29.49	0.504	23.37	200.00	0.584	16.45
36.50	0.624	28.97	250.00	0.730	20.80
50.00	0.841	39.51	300.00	0.876	25.24

was small. The difference in trends for the sodium chloride and sucrose draw solutions may be attributed to the effects of viscosity on permeation rate, i.e. a reduction in the coefficient of membrane permeability with increasing viscosity. Specifically, high increases in the viscosity of the sucrose draw solution for a given increase in the osmotic pressure of the solution. Interestingly, in the case of salty feed water with sucrose draw solution, a small increase in J_w and $R\%$ could be achieved with increasing osmotic pressure difference. A possible explanation for this is the reverse diffusion of salt into the draw solution, thus leading to a reduction in the viscosity of the sugar-only system. Nevertheless, as shown in Figs. 3 and 4, the use of a sodium chloride draw solution produces much higher water flux rates and recoveries then a comparable system using sucrose draw solution.

With reference to Fig. 5, it is evident that SEC decreased with an increase in the osmotic pressure difference between the draw and feed water solutions, except for the case of sucrose draw solution with DW feed. Generally, such decreases in SEC are associated with water flux obtained. From Fig. 6, the SEC increased with increases in recovery percentage when using: the sodium chloride draw solution vs. deionised and salty feed water and sucrose draw solution vs. salty feed water. However, it increased from 0.2 to 0.228 kW hr/m^3 with a decreasing recovery percentage from 4.75 to 3.93%. This could be a result of the reducing water flux when using sucrose draw solution vs. deionised feed water.

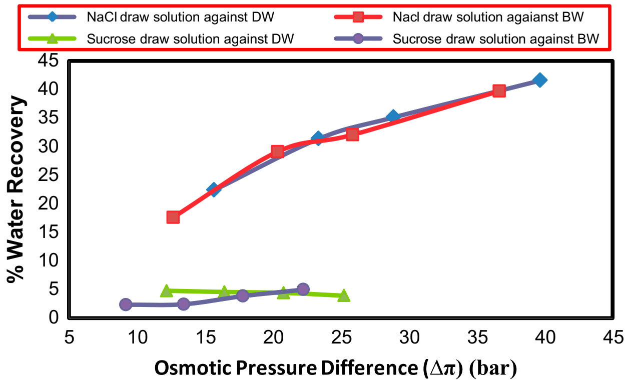

Fig. 4. Osmotic pressure difference effects on water recovery (%) using sodium chloride and sucrose draw solutions against DW and BW feed.

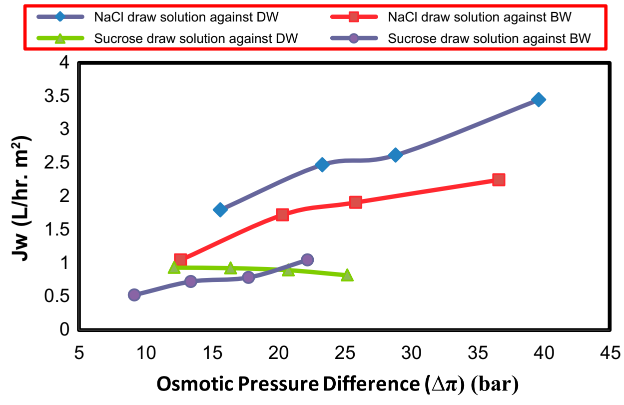

Fig. 3. Osmotic pressure difference effects on water flux using sodium chloride and sucrose draw solutions against DW and BW feed.

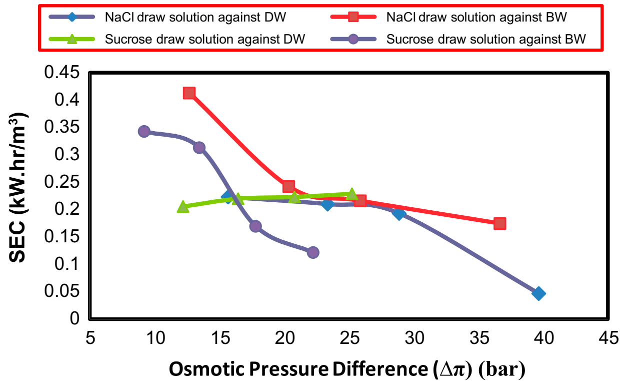

Fig. 5. Osmotic pressure difference effects on SEC using sodium chloride and sucrose draw solutions against DW and BW feed.

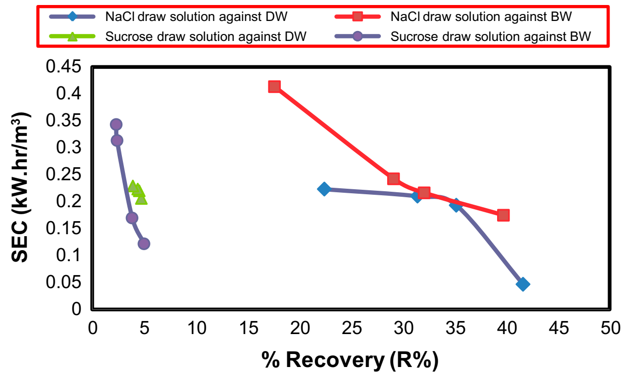

Fig. 6. Water recovery effects on SEC using sodium chloride and sucrose solutions against DW and BW feed.

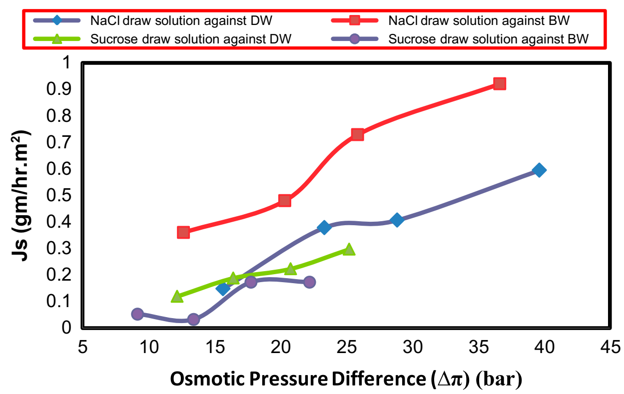

Fig. 7. Osmotic pressure difference effects on the reverse solute flux (J_s) using sodium chloride and sucrose draw solutions against DW and BW feed.

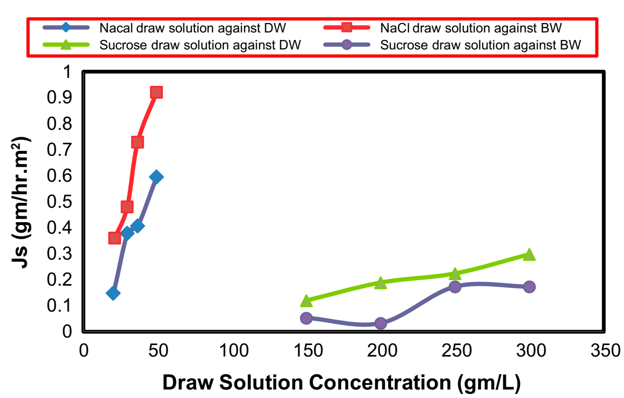

Fig. 8. Draw solution concentration effects on the reverse solute flux (J_s) for sodium chloride and sucrose draw solutions against DW and BW feed.

With reference to Fig. 7, it can be seen that the flux of sodium chloride / sucrose solute due to reverse diffusion (J_s) increased with an increase in the osmotic pressure difference (i.e. an increase in the sodium chloride/sucrose draw solution concentration). This effect was especially pronounced when using sodium chloride as the draw solution, although the concentrations of such solutions were much lower than that for the sucrose system; see the plots of J_s against the actual sodium chloride/sucrose solution concentration in Fig. 8.

5. Conclusions

The current study evaluated the effectiveness of sodium chloride and sucrose draw solutions for FO-based water desalination using a DURA-SAP–FO-AC. Salient points from this study are summarised below:

(1) Water flux and water recovery percentage increased with an increasing osmotic pressure when using sodium chloride draw solution against both DW and BW feeds. However, the effectiveness of sucrose draw solution was relatively poor.
(2) Correspondingly, the SEC decreased with an increasing osmotic pressure, especially when using sodium chloride draw solution.
(3) Reverse solute flux was a particularly pronounced when using sodium chloride draw solution.
(4) Generally, sodium chloride exhibited as high a draw solution efficiency compared with sucrose in terms of water flux, water recovery percentage and reduction in SEC. However, the use of sucrose draw solution with salty feed water emerged to be more effective than using it with a DW feed. This may be due to the reverse diffusion of a certain amount of sodium chloride from the feed to the draw solution, thus partially counteracting the negative effects of high viscosity associated with the sucrose draw solution. This interesting observation suggests scope for the study of sucrose and sodium chloride ternary mixtures as draw solution.

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Symbols

A_w	—	coefficient of membrane permeability (L/m^2 h bar)
B	—	coefficient of salt permeability (L/m^2 h bar)
$C_{FW\text{-}ave}$	—	average concentration of salty feed water (mg/L)
C_P	—	concentration of permeate (mg/L)
J_s	—	solute reverse flux (L/m^2 h)
J_w	—	water flux through membrane (L/m^2 h)
P_f	—	hydraulic pressure of feed (bar)
P_{DS}	—	hydraulic pressure of draw solution feed (bar)
R	—	overall water recovery
$Q_{FW\text{-}in}$	—	flow rate of feed (L/min)
$Q_{DS\text{-}in}$	—	flow rate of draw solution (L/min)
Q_P	—	flow rate of permeate (L/min)
SEC	—	specific energy consumption (kW hr/m^3)

Greek Symbols

η	—	efficiency of pump
$\pi_{FW\text{-}ave}$	—	average osmotic pressure of feed (bar)
$\pi_{DS\text{-}ave}$	—	average osmotic pressure of draw solution feed (bar)

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