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Regeneration efficacy of sodium chloride and sucrose binary draw solutions using hollow fine fibre reverse osmosis membrane

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ABSTRACT

In this study, the regeneration performance of sodium chloride and sucrose draw solutions using a forward osmosis (FO) membrane was experimentally investigated in a FO–RO system. This efficiency was examined in terms of water flux (J_w), water recovery percentage ($R\%$) and specific energy consumption (SEC) using a commercial RO membrane. Two sodium chloride feed solution concentrations of 9.3 g/l (osmotic pressure (OP) = 7.31 bars) and 17.9 g/l (osmotic pressure (OP) = 14.05 bars), as well as two sucrose feed solution concentrations of 150 g/l (OP = 11.21 bars) and 200 g/l (OP = 15.13 bars) were tested separately. At each experiment, feed solution is pumped to the RO membrane at different applied feed pressure values, while the flow rate and temperature of the solutions were kept constant throughout the experiments. The experimental results indicated that: water flux and water recovery percentage for sodium chloride and sucrose feed solutions in general are increased with rise in the RO feed pressure applied. Also, the SEC for sodium chloride and sucrose feed solutions decreased as the RO feed applied pressure was raised. The findings exhibit that the hollow fine fibre HR3155P RO membrane is more reliable for the regeneration of sodium chloride draw solution than sucrose draw solution. Moreover, the RO technique is not reliable to use in the regeneration of sucrose draw solution in a FO–RO system.

Keywords: Sodium chloride; Sucrose; FO–RO; Water flux; Water recovery; SEC

1. Introduction

Desalination is an increasingly common solution to produce drinking water in many regions of the world, where this resource is scarce. [1]. Among all the desalination technologies, RO membrane desalination is the primary choice where it dominates up to 44% of the total world's desalination capacity [2]. A wide range of membranes have been developed for the treatment of seawater and production of freshwater

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from feed water of different salinities. Currently, the most popular membrane processes for saline water treatment are reverse osmosis (RO), nanofiltration (NF) and membrane distillation (MD) [2–8]. A dual-stage NF process was proposed for seawater desalination but it required a very complex set of circumstances for optimal membrane operation [5]. Instead, a dual-stage NF-BWRO (Brackish Water Reverse Osmosis) process was proposed for seawater desalination to overcome the operating complexities in the dual-stage NF process. MD is a mass transfer process driven by a potential vapour pressure difference due to a temperature gradient between the hydrophobic porous membranes. A temperature difference of 10–20˚C between warm water and cold water stream can be sufficient to produce distilled water at desirable quality [4]. MD has the potential to reduce the power consumption for seawater desalination as it does not require high pressure conditions for membrane operation [9]. However, low recovery rates and high thermal consumption make the MD process less attractive for seawater treatment in large desalination plants [10].

On the other hand, the RO process offers a number of benefits which make it an attractive technology for seawater desalination. These include its reliability, high water recovery and salt rejection rates, and its ability to treat a wide range of seawater concentrations [1,11]. At present, more than 50% of the desalinated water in the world is produced by the RO process. Moreover, RO membranes have been specifically developed for application in wastewater reuse and production of ultra-pure water [12,13]. In spite of the RO process having a number of advantages, the high power consumption is the main drawback of the process. With the energy recovery instrument (ERI), an average of 3.5 kW h/m^3 is required for seawater desalination (seawater TDS 35,000 mg/L) [14]. In fact, reducing the power consumption in the process of RO has been the objective of many studies [5,9,15].

The forward osmosis (FO) process is a membrane technology which exploits the natural osmotic pressure as a driving force and hence, it does not require a high hydraulic pressure. The potential applications of FO have been widely discussed. The reported applications of FO include wastewater treatment [16,17], brackish groundwater desalination [18], sweater desalination [19–21], power generation [22–24], food processing [25,26] and fertiliser use in irrigation [27,28].

With the emergence of the FO technology, scientists conceived the idea that the cost of desalination could be reduced, if FO was utilised as a pre-treatment process due to the FO membrane working as a barrier for undesirable compounds and elements that can cause fouling or scaling in the RO membrane. Fouling and scaling in RO membrane led to an increase in the energy consumption and the cost accordingly.

However, the cost of desalination by FO is affected by a number of factors including the type of FO membrane, type of draw solution, concentration of the draw solution and the regeneration process [28,29]. McGinnis and Elimelech proposed using ammonium carbon dioxide as a draw solution for seawater desalination [30,31]. The MD process was then used for the regeneration of the draw solution because of the lower evaporation temperature of ammonium carbon dioxide compared to water. In the FO process, the impact of the concentration polarisation phenomenon on the efficiency of the FO membrane was investigated and found to be more significant when the draw solution and the feed solution are facing the support layer and the membrane active layer, respectively [32].

Al-Mayahi and Sharif suggested a two-stage seawater desalination process using FO in the first stage and NF in the subsequent stage [33]. In this case, multivalent chemical compounds, such as $MgCl_2$, Na_2SO_4 or $MgSO_4$ were proposed as the draw solutions due to their high rejection by the NF membranes. Chung et al. used magnetic nanoparticles coated with hydrophilic polymers as a draw solution in the FO process. Although the magnetic nanoparticles exhibited high osmotic pressure, regeneration was a problem due to the agglomeration of nanoparticles [34]. Hydrogel polymers were proposed as a draw solution in the FO process because of their high osmotic pressure. Water flux across the FO membrane increased when carbon nanoparticles were added but the excessive addition of carbon nanoparticles resulted in a flux reduction [35].

Regeneration is the most expensive stage in the FO–RO process for seawater desalination, regardless of the draw solution type. Most of the previous studies in this area have focused on the evaluation and optimisation of the FO process through the membrane, while little attention was paid to the performance of the entire desalination system which includes the FO and the regeneration processes. In principle, FO only produces a diluted solution which requires further treatment, before it can be used for human applications. Freshwater is extracted from the diluted draw solution in the regeneration process, which has been identified as the most expensive stage in the FO–RO desalination.

In the current study, RO was chosen for the regeneration of the draw solution due to its high efficiency and suitability to treat different types of draw solutions. Typically, the recovery rate in RO does not exceed 50% for low salinity seawater because of the scaling problems. However, this is not an issue in FO because of the high purity of the draw solution. Thus, the recovery rate of the RO in the FO–RO process can be increased to over 50%.

In the previous work of Al-Aibi et al. [36], the efficiency of sodium chloride and sucrose as draw solutions using a FO membrane in FO–RO system was tested. These draw solutions were both used due to their non-toxicity and high solubility characteristics in water as well as high osmotic pressure yields. The performance evaluation of these two draw solutions is carried out experimentally against deionised and salty feed water (5 gm/l, equivalent to the brackish water) using the DURA-SEP FO membrane. The findings revealed that sodium chloride against deionised and salty feed water exhibited high efficiency compared with sucrose draw solution. At high draw solution concentrations, the sucrose against salty feed water exhibited higher efficiency in terms of water flux, water recovery percentage and specific energy consumption (SEC) than when used against deionised feed water. Moreover, the sucrose draw solution was more effective in desalting brackish water than sea water due to the significant rise in the viscosity of sucrose as its concentration increases, which subsequently maximises the concentration polarisation and restricts water diffusion through the FO membrane (lower water flux). Principally, the RO membrane offers a more effective technique in order to regenerate the sucrose draw solution compared with thermal processes due to lower energy consumption rates and the fact that thermal processes lead to the concentrate having a more viscose solution. Furthermore, in terms of energy consumption, the FO–RO system consumes more energy than RO alone but, using FO as a pretreatment step can reduce the energy consumption in RO stage via reducing the fouling and scaling effect which can occur when using RO alone.

The aim of this study is to evaluate the regeneration efficiency of sodium chloride and sucrose draw solutions using a RO membrane. The regeneration efficiency of these two draw solutions is tested in terms of water flux (J_W), water recovery percentage ($R\%$) and SEC using hollow, fine fibre RO membrane type HR3155P RO supplied by the Toyobo company.

2. Methodology

RO is the process by which an applied pressure greater than the osmotic pressure is exerted on the compartment that once contained the high-concentration solution (Fig. 1). This pressure forces water to pass through the membrane in the direction reverse to that of osmosis. Water now moves from the compartment with the high-concentration solution to that with low-concentration solution; in this manner, pure water passes through the membrane into one compartment, while dissolved solids are retained in the other. Hence, the water in the one compartment is purified or demineralised and the solids in the other compartment are concentrated or dewatered. Due to the additional resistance from membrane, the applied pressures required to achieve RO are significantly higher than the osmotic pressure [37].

Flux is defined as the volumetric flow rate of the fluid through a given area. The flux of water through a RO membrane is proportional to the net pressure driving force applied to the water and it can be calculated using the following equation [37]:

$$J_W = k(\Delta P - \Delta \pi) \tag{1}$$

where J_W = water flux, k = water transport coefficient = permeability/thickness of the membrane active layer, ΔP = pressure difference across the membrane in bar and $\Delta\pi$ = osmotic pressure difference across the membrane in bar.

Recovery is a term used to describe what volume percentage of influent water is recovered as permeate. Generally, RO system recoveries range from about 50–85% with the majority of system designs aiming for 75% recovery. Recovery is calculated using the following equation [37]:

$$\%R = \left(\frac{Q_P}{Q_f}\right) \times 100 \tag{2}$$

where $\%R$ = recovery percentage, Q_P = solution passing through membrane (permeate) flow rate in l/min and Q_f = feed water flow rate in l/min.

Rejection (R_j) is a term used to describe what percentage of an influent species a membrane retains. Rejection of a given species is calculated using the following equation [37]:

$$\%R_j = \lceil (C_f - C_P)/C_f \rceil \times 100 \tag{3}$$

where C_f = feed concentration of a specific component in g/l and C_P = influent concentration of a specific component in g/l.

Note that for exact calculation, the average feed concentration takes into account the concentration of both the feed and concentrate rather than just the feed concentration at a single point in time. Salt passage is essentially the opposite of rejection [37]:

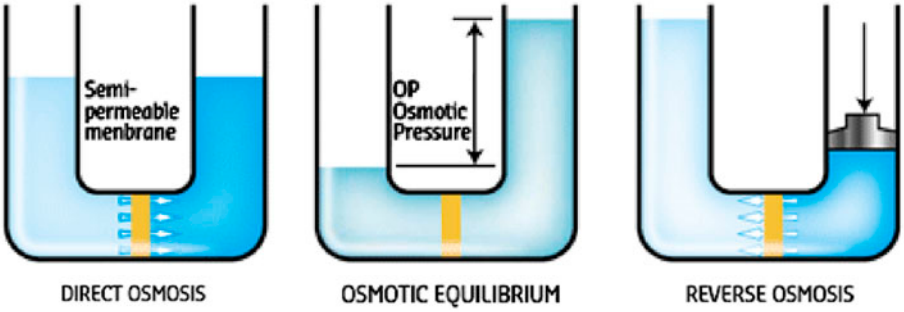

Fig. 1. Schematic diagram of reverse osmosis concept.

$$\%\ \text{Salt Passage} = 100 - \%R_j \tag{4}$$

or:

$$\%\ \text{Salt Passage} = \left(\frac{C_p}{C_F}\right) \times 100 \tag{5}$$

The SEC (kW h/m^3) in RO is calculated using the following equation [38–40]:

$$\text{SEC} = \frac{\Delta P}{R} = \frac{(P_f - P_o)}{R} \tag{6}$$

where P_f = feed applied pressure in bar, P_o = permeate pressure in bar and R = water recovery.

3. Experimental works

3.1. Materials

In this study, 5 kg of food grade sucrose powder with 99.9% purity, supplied by Tate & Lyle of the UK, and 25 kg of sodium chloride salt (sea salt) with up to 90% purity, supplied by a British salt company, were used for preparing the draw solution and salty feed water. All solutions in this study were prepared by dissolving the sucrose and salt in deionised water.

3.2. Equipment

RO pilot plant membrane designed and built by Resnova company was used in this study. A Seven Multi Mettler-Toledo Conductivity meter supplied by Mettler-Toledo company in the UK was used to determine the conductivity, total dissolved solute (TDS) and resistivity of sodium chloride. HPLC instrument (Varian 385-LC ELSD with Evaporative Light Scattering Detector Column and with mobile phase 80% acetonitrile, flow rate 3.0 ml/min) was used to measure the sucrose concentrations of samples. OLI analyser stream software was used to determine the osmotic pressure values for all solutions used in this study.

3.3. Experimental work descriptions

Toyobo module in RO configuration, as shown in Fig. 2, consists of one feed stream, flow-in and one concentrate stream, flow-out; both passing through the membrane shell side. The feed solution was pumped by a high pressure pump. The specifications of HR3155P membrane are presented in Table 1, while the dimensions and layout are shown in Table 2 and Fig. 3, respectively.

In the FO membrane test, the sodium chloride and sucrose draw solutions were tested to treat deionised and salty water (5 gm/l: as brackish water). Table 1 specifies the concentrations of feed draw solutions and diluted draw solutions out from the FO membrane with their osmotic pressures.

In the sodium chloride regeneration efficiency tests, two different sodium chloride solutions with concentrations of 9.30 gm/l (OP = 7.31 bars) and 17.90 gm/l (OP = 14.05 bars) were pumped separately at constant pump speed. The first solution was pumped at different applied pressures from 15 to 30 bars, while the second solution from 20 to 35 bars. In

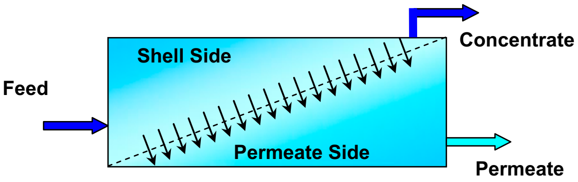

Fig. 2. HR3155P RO membrane configuration.

Table 1
HR3155P membrane specifications (http://www.toyobo-global.com/seihin/ro/spec-HR3155PI.htm)

Product flow rate	Nominal	0.4 m^3/D
	Minimum	0.3 m^3/D
Salt rejection	Normal	99.6%
	Minimum	99.4%
Test conditions	Feed water, NaCl solution	35,000 mg/L
	Pressure	5.39 MPa
	Temperature	25℃
	Recovery	30%
Operating conditions	Maximum pressure	5.9 MPa
	Temperature range	5–40℃
	Brine flow rate	0.7–3.5 m^3/D
Feed water qualities	Maximum fouling index (SDI_{15})	4.0
	pH range	3–8
	Maximum residual chlorine	1.0 mg/L

Table 2
Module dimensions of HR3155P RO membrane

Number of element		1
Module size	Outer Diameter, DO	104 mm
	Length, L	400 mm
Weight (Filled with water)		approx. 5 kg
Connection	Feed	PT 3/8 inch
	Brine	PT 1/4 inch
	Product	PT 3/8 inch

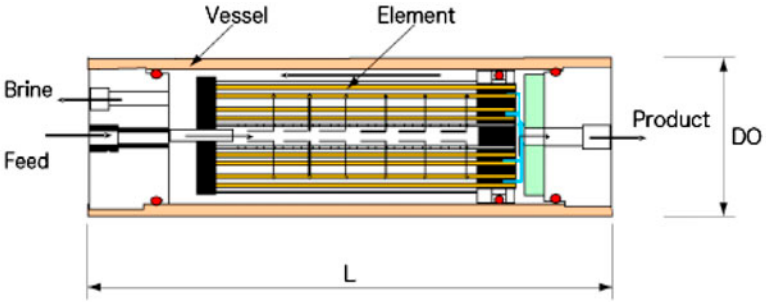

Fig. 3. HR3155P RO membrane model used in this study.

the sucrose regeneration test, two different sucrose solutions with concentrations of 150 gm/l (OP = 11.21 bars) and 200 g/l (OP = 15.13 bars) were pumped separately at a constant pump speed. The first solution was pumped at different applied pressures, from 15 to 30 bars, while the second solution from 20 to 40 bars. For each applied pressure, the flow rates, concentrations of permeate and concentrate streams were measured as well as the membrane pressure drops. The experimental results of this study are presented in Figs. 4–9.

4. Results and discussion

Fig. 4 demonstrates that the water flux increased steadily from 6.66 to 10.33 L/h m^2 with raising the RO feed pressure from 15 to 30 bars when using a 9.3 gm/l sodium chloride feed solution concentration. A moderate increase from 4.98 to 8.66 L/h m^2 was also observed with the applied feed pressure rising from 20 to 35 bars using a 17.9 gm/l sodium chloride feed solution concentration. However, when using a 150 gm/l sucrose feed solution concentration, the water flux

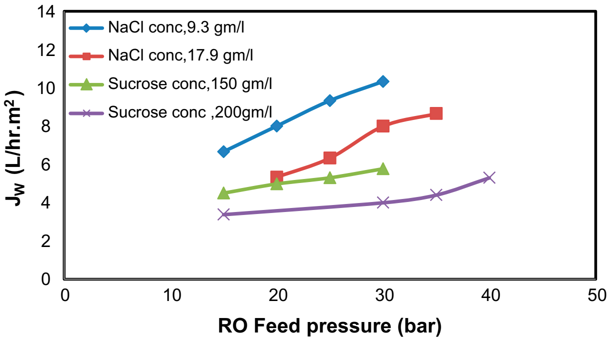

Fig. 4. RO applied feed pressure effects on water flux using HR3155P RO membrane.

increased moderately from 4.5 to 5.77 L/h m^2 with applied feed pressure rising from 15 to 40 bars, and it also increased from 3.8 to 5.3 l/h m^2 when applied feed pressure values rose from 15 to 30 bars. This provided an indication that the water flux increases moderately as the RO feed pressure was raised. For both feed solution types, it was also observed that the water flux is reduced when the feed solution concentration increases.

From Fig. 5, it is evident that when using a 9.3 gm/l sodium chloride feed solution, the water flux increased moderately from 6.66 to 10.33 L/h m^2, when the net driving pressure (NDP) rises from 7.440 to 22.333 bars. However, when using a 17.9 gm/l sodium chloride feed solution, the water flux also increased moderately from 5.33 to 8.66 L/h m^2, as the NDP rose from 5.779 to 20.728 bars. Similarly, when using a 150 gm/l sucrose feed solution, the water flux increased steadily from 4.5 to 5.77 L/h m^2 when the NDP rose from 4.215 to 16.939 bars. However, the water flux rose slightly from 3.38 to 5.3 L/h m^2 when the NDP increased from 3.5 to 21.449 bars. This phenomenon demonstrates that the water flux increases moderately when the NDP values rose.

Fig. 6 illustrates that the water recovery percentage increased steadily from 13.7 to 19.75% when the RO feed pressure applied was raised from 15 to 30 bars using a 9.3 gm/l feed solution concentration. However, the percentage rose from 11.11 to 16.88% when the RO applied feed pressure was increased using a 17.9 gm/l feed solution. When using a 150 gm/l sucrose feed solution, the recovery percentage increased only moderately from 8.5 to 12.5% when the RO feed applied pressure was increased from 15 to 30 bars. In addition, this percentage rose slightly further from 8 to 11% when the RO feed applied pressure was increased from 15 to 40 bars. Consequently, the water flux decreases corresponding to an increase in feed solution concentration. This provided an indication that the water recovery percentage increased with the RO feed applied pressure values and decreased when the feed solution concentration increased. The aforementioned results demonstrate that the RO membrane cannot be used to regenerate sucrose draw solution due to the low recovery percentage obtained in this study.

Fig. 7 indicates that the sodium chloride rejection percentage increased slightly from 99.363 to 99.464% when the RO feed applied pressure was raised from 15 to 39 bars using a 9.3 gm/l feed solution concentration. It also increased slightly from 99.236 to 99.537% when the RO feed applied pressure was raised from 20 to 35 bars when using a 17.9 gm/l sodium chloride solution concentration. However, a sucrose feed solution of 150 gm/l resulted in this percentage increasing moderately from 87 to 92% when the RO feed applied pressure was raised from 15 to 30 bars. Finally, when using a 200 gm/l sucrose feed solution, the rejection percentage increased slightly from 86.66 to 89% when the RO feed applied pressure was raised from 15 to 40 bars. This indicated that the membrane exhibited

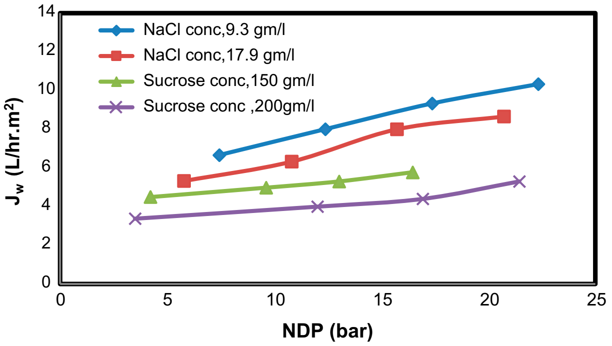

Fig. 5. NDP effects on water recovery percentage using HR3155P RO membrane.

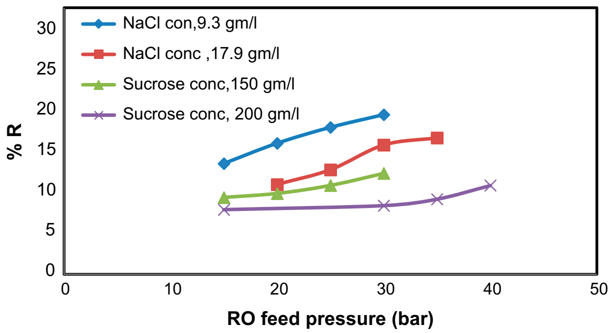

Fig. 6. RO applied feed pressure effects on water recovery percentage using HR3155P RO membrane.

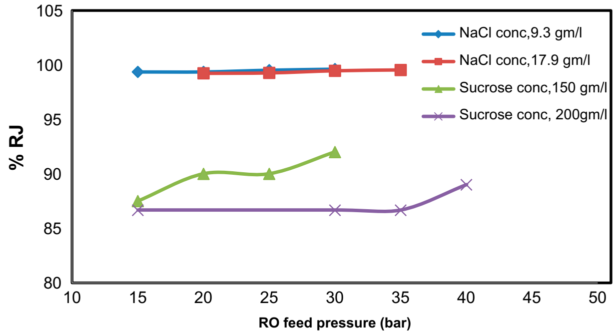

Fig. 7. RO applied feed pressure effects on solute rejection percentage using HR3155P RO membrane.

better reliability in terms of R_j% (up to 99%) when a sodium chloride draw solution was used, rather than sucrose. In addition, it was observed that the solute rejection percentage of both solutions increased when the RO applied feed pressure value was raised and it also decreased when the feed solution concentration was raised.

Fig. 8 exhibits that the SEC using a 9.3 gm/l sodium chloride concentration solution decreased steadily from 4.22 to 3.04 kW h/m^3 with increased RO applied feed pressure from 15 to 30 bars. Also, it decreased from 5.88 to 5 kW h/m^3 when the RO feed applied pressure increased from 20 to 35 using a 17.9 gm/l feed solution concentration. However, the SEC decreased slightly from 6 to 4.95 kW h/m^3 when applied feed pressure increased from 15 to 30 bars using a 150 gm/l sucrose feed solution concentration. When using a 200 gm/l sucrose feed solution concentration, the SEC decreased slightly from 7 to 6.88 kW h/m^3 when feed applied pressure increases from 15 to 30 bars and then decreased moderately to reach 5 kW h/m^3 at a feed applied pressure of 40 bars. This indicates that the SEC decreased when the RO applied feed pressure increases at constant feed solution concentration due to the rise in water flux. In addition, the SEC was reduced when using the sodium chloride solution compared to the sucrose solution owing to differences in the water fluxes which were obtained using these two solutions. Fig. 8 illustrates that the SEC decreased when the RO feed applied pressure increased for both feed solutions and when the feed solution concentration was raised.

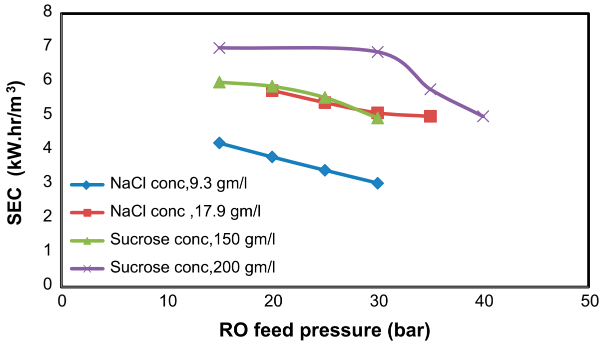

Fig. 8. RO applied feed pressure effects on SEC using HR3155P RO membrane.

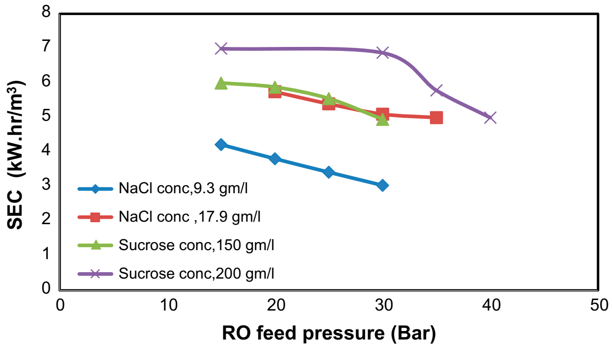

Fig. 9. NDP effects on SEC using HR3155P RO membrane.

Fig. 9 shows that the SEC decreased from 4.22 to 3.04 kW h/m^3 as the NDP rises from 7.433 to 4.22 bars when using a 9.3 gm/l sodium chloride feed solution concentration. Also, it decreased from 5.88 to5 kW h/m^3 with increasing the NDP from 7.3 to 20.728 bars. However, the SEC is reduced moderately from 6 to 4.95 kW h/m^3 with increasing the NDP from 4.215 to 16.466 bars when using a 150 gm/l sucrose concentration feed solution. While for a 200 gm/l sucrose feed solution concentration, the SEC decreased slightly from 7 to 6.88 kW h/m^3 when the NDP rises from 3.5 to 12.02 bars, and then decreased moderately to reach 5 kW h/m^3 at the NDP value of 21.449 bars. Thus, it is validated that the SEC is reduced as the NDP increases for both feed solutions, while it increases with raising the feed solution concentration.

5. Conclusions

The following key points were concluded from this study:

(1) Water flux and water recovery percentage for sodium chloride and sucrose feed solutions are increased moderately with rise in the RO feed applied pressure.
(2) The water flux and recovery percentage are reduced with sodium chloride and sucrose

feed concentration solution increases at the same applied feed pressure value.

(3) HR3155P RO membrane exhibited more reliability to regenerate sodium chloride draw solution in terms of rejection percentage (up to 99%) than sucrose solution. The solute rejection percentage of both solutions is increased with raising the RO feed applied pressure.
(4) The water recovery percentage and water flux increase with rise in the NDP, while they decrease with rise in sodium chloride and sucrose feed solution concentrations at the same NDP values.
(5) The SEC is reduced when RO feed applied pressure is raised at a constant feed solution concentration when using sodium chloride and sucrose as feed solutions.
(6) The SEC is reduced with increasing the NDP values for both feed solutions, while it increased as the feed solution concentration is raised.
(7) Due to the low water recovery percentages obtained, as a result of high concentration polarisation effect, the RO membrane is not reliable to be used in the regeneration of diluted sucrose draw solution from the FO membrane in a FO–RO system.
(8) In the next study, it is recommended to test different commercial RO and NF membrane types in the regeneration of sodium chloride and sucrose so as to identify the most reliable membrane type that can be used in the regeneration stage of a FO–RO desalination system.
(9) It is also recommended to study different regeneration techniques that can be applied to the diluted sucrose draw solution.

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