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Performance of Manipulated Direct Osmosis in Water Desalination Process

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ABSTRACT

The present work aims to study the factors affecting the performance of novel forward (direct) osmosis (FO) desalination process. Forward osmosis module is made from polyamide spiral-wound membrane type TFC – SSRO50G. Sodium sulphate (Na_2SO_4), magnesium chloride hexahydrate ($MgCl_2.6H_2O$), magnesium sulfate hydrate ($MgSO_4.7H_2O$), glucose and sucrose were used as draw solutions to extract water from sodium chloride solution across a semi-permeable polymeric membrane.The driving force in the FO process is provided by a difference in osmotic pressures (concentrations) across the membrane between the draw and brine solution sides. Process variables studied were draw solutions concentration (10 – 90 g/l), draw solutions flow rate (2.4 – 8.4 l/hr), and feed temperature of draw solution (18 and 36 ^{o}C). It was found that water flux increases with increasing draw solution concentration and feed temperature of draw solution, and decreases with increasing draw solution flow rate. It was found also that the effect of draw solution concentration has the higher effect on the water flux among other variables. Sodium sulphate (Na_2SO_4) has a high water flux than other materials which studied.

Keywords: *Osmosis; Forward Osmosis; Direct Osmosis; Desalination; Reverse Osmosis; Draw Solution.*

1. INTRODUCTION

The use of membrane technology has been growing rapidly during the last few decades. New membrane technologies are being developed and existing processes are also being improved to enhance their physical and chemical performance along with economic competitiveness (Young, 2003). Some of the membrane processes are capable of removing both dissolved and particulate contaminants. The best known and most utilized processes in the field of water and wastewater treatment are those utilizing pressure gradients as the process driving force. These processes include reverse osmosis, nanofiltration, ultrafiltration and microfiltration. Other membrane separation methods are in use or in various stages of development. These methods utilize electrical potential, concentration or temperature gradient as their driving force instead of pressure gradient (Csey, 1997 and Jørgen, 2001).

Freshwater scarcity is a growing problem in many regions in the world. Unchecked population growth and the impairment of existing freshwater sources cause many countries and communities in dry regions to turn to the ocean as a source of freshwater. Current desalination technologies are, however, prohibitively expensive and energy intensive. Reverse osmosis (RO), a commonly used desalination technology, is significantly more expensive than the standard treatment of freshwater for potable use. Less expensive methods of desalination are needed to make desalination technologies more competitive with freshwater treatment (John et al., 2005).

Direct (or forward) osmosis is a process that may be able to desalinate saline water sources at a notably reduced cost. In forward osmosis, like reverse osmosis, water transports across a semi-permeable membrane that is impermeable to salt. However, instead of using hydraulic pressure to create the driving force for water transport through the membrane, the direct osmosis process utilizes an osmotic pressure gradient (Stache, 1989). A draw solution having a significantly higher osmotic pressure than the saline feed water flows along the permeate side of the membrane, and water naturally transports across the membrane by osmosis. Osmotic driving forces in direct osmosis can be significantly greater than hydraulic driving forces in reverse osmosis, potentially leading to higher water fluxes and recoveries (Beaudry and Herron, 1997 and Jones et al., 2003).

Fewer publications on the use of osmosis – also called forward osmosis (FO), or direct osmosis (DO) – for water treatment/ engineering applications appear in the literature. Nevertheless, forward osmosis (FO), has been used to treat industrial wastewaters and to treat liquid foods in the food industry (Beaudry and Lampi, 1990 York at el., 1999). Forward osmosis (FO) is also being evaluated for reclaiming wastewater for potable reuse in life support systems (at demonstration-scale), for desalinating seawater and for purifying water in emergency relief situations (Cath et al., 2005). Recent developments in materials science have also allowed the use of forward osmosis (FO), in controlled drug release in the body. Pressure-retarded osmosis (PRO), a closely related process, has been tested and evaluated since the 1960s as a potential process for power generation (Lee et al., 1981 and Seppala and Lampinen, 1999). Pressure-retarded osmosis (PRO) uses the osmotic pressure difference between seawater, or concentrated brine, and fresh water to pressurize the saline stream, thereby converting the osmotic pressure of seawater into a hydrostatic pressure that can be used to produce electricity.

The main advantages of using forward osmosis (FO) are that it operates at low or no hydraulic pressures, it has high rejection of a wide range of contaminants, and it may have a lower membrane fouling propensity than pressure-driven membrane processes. Because the only pressure involved in the FO process is due to flow resistance in the membrane module (a few bars), the equipment used is very simple and membrane support is less of a problem (Phuoc and Tai-Shung, 2014, and Rana, 2011). Furthermore, for food and pharmaceutical processing, FO has the benefit of concentrating the feed stream without requiring high pressures or temperatures that may be detrimental to the feed solution (Keith et al., 2005 and Yong-Jun et al., 2009). For medical applications, FO can assist in the slow and accurate release of drugs that have low oral bioavailability due to their limited solubility or permeability.

In the process of the present work, the first solution (brine solution) is placed on one side of a selective membrane. A second solution (draw solution) having a higher osmotic potential is placed on the opposite side of the membrane. A osmotic agent solution (draw solution) has a higher solute concentration (and therefore lower solvent concentration) than sodium chloride solution (brine solution), such that solvent (water) from the NaCl solution passes across the membrane to dilute the driving (draw) solution, and extracting solvent from the draw solution, wherein the driving (draw) solution contains solute species that are too large to pass through the pores of the membrane.

The selected membrane used a polymeric membrane (thin film composite (TFC) membranes) constructed as a special modification of spiral wound membrane module, which may be used as a dializer or for direct osmosis separations. The basic advantages of this type of membrane are the higher productivity compared with the total volume of the module, and stability of the polymer towards the chemical effect. The study will focus on the effect of different parameters such as draw solution concentration, draw solutions flow rate and feed temperature of draw solution on the water flux through membrane.

2. EXPERIMENTAL WORK

Fig. 1 shows a schematic diagram of experimental rig of direct osmosis process. Draw and brine feed solutions was prepared in the QVF glass vessels by dissolving the solid salt in 25 liter of demineralized water, and then the out let valve of the feed vessel was open to let the solutions fill the whole pipes of the system. The feed brine solution drawn from the feed vessel by means of a centrifugal pump to pass through filters (5 μm) to remove macromolecules, colloids and suspended solids. Then the brine solution is introduced into the permeator (on the feed side) by means of a high pressure pump. The draw solution is fed to the forward osmosis unit (spiral-wound membrane module) on the permeate side. The feed brine and draw solution flow tangent to the membrane in the same direction (co-current flow). Through osmosis, water transports from the brine solution across the salt rejecting membrane and into the draw solution.

The steady - state took between 1 to 1.5 hr to reach. In this time the conductivities and concentrations of the feed brine solution, feed draw solution, reject brine solution concentrate and product dilute draw solution were measured by the conductivity and TDS meters, and the flow rate of the product dilute draw solution for each run was recorded. After recording the results, the solution was drained by means of a drain valve. The whole system was washed by pure demineralized water. Now, the system is ready for the next run.

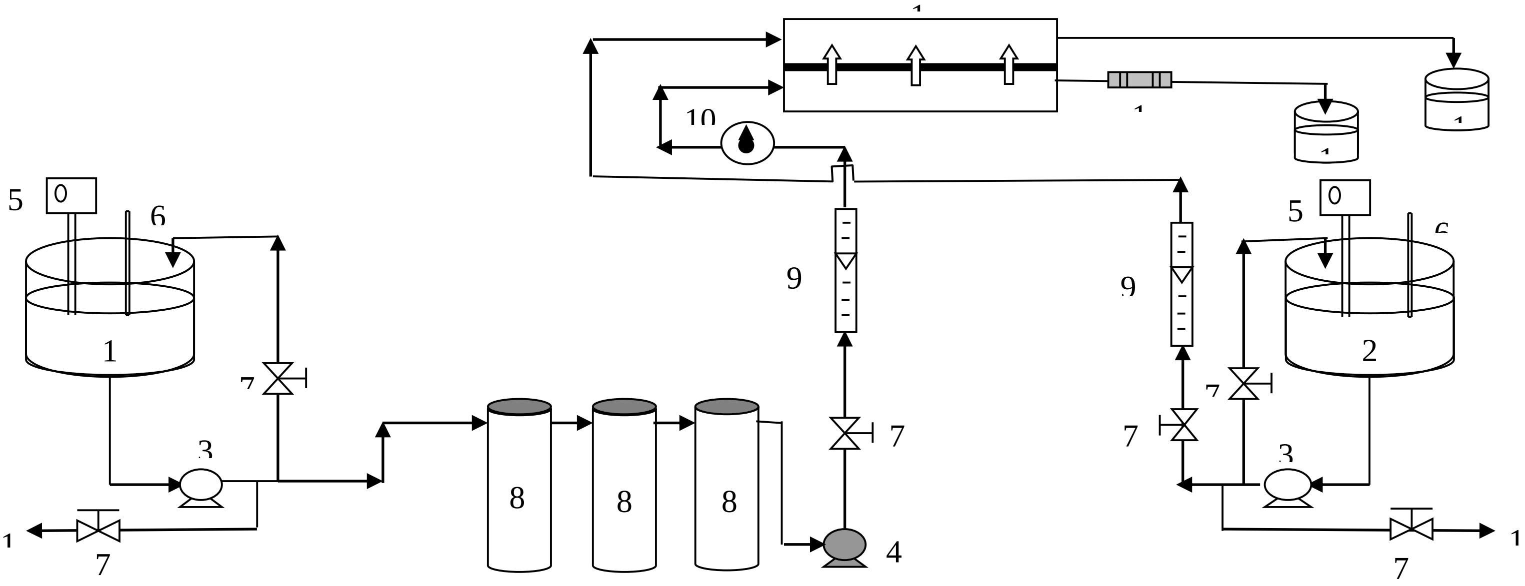

Fig. 1 Schematic Diagram of Direct (Forward) Osmosis Process.

1. Brine Solution Feed	2. Draw Solution Feed	3. Pump	4. High Pressure Pump	5. Heater	6. Thermometer	7. Valve	
8. Filters	9. Rotameters	10. Pressure Gauge	11. Spiral Wound Membrane	12. Brine Flow Control	13. Brine Solution Product	14. Draw Solution Product	15. To Drain

SPIRAL – WOUND MODULE

Commercially marketed spiral-wound membrane elements (e.g., spiral-wound RO elements) are adopted and operated with only one stream (the feed stream) flowing under direct control of its flow velocity tangential to the membrane. The permeate stream flows very slowly in the channel formed by the two glued membranes. The composition and flow velocity are controlled by the properties of the membrane and the operating conditions. Therefore, in its current design, spiral-wound membrane elements cannot be operated in FO mode because the draw solution cannot be forced to flow inside the envelope formed by the membranes.

In the present work designed and successfully test a unique spiral wound element for forward osmosis (FO). Both outside-in and inside-out operation can be used. In Fig. 2, (inside-out operation), the brine solution flows through the spacers and between the rolled membranes, in the same way that a feed stream flows in a spiral-wound element for reverse osmosis (RO). However, unlike RO elements, the central collecting tube is blocked halfway through so that the feed draw solutions cannot flow to the other side. Instead, an additional glue line at the center of the membrane envelope provides a path for the feed draw solutions to flow inside the envelope. In this configuration, the feed draw solutions flows into the first half of the perforated central pipe, is then forced to flow into the envelope, and then flows out through the second half of the perforated central pipe. The brine solution outside of the envelope can be pressurized similar to the way it is done in spiral-wound membrane elements for reverse osmosis (RO).

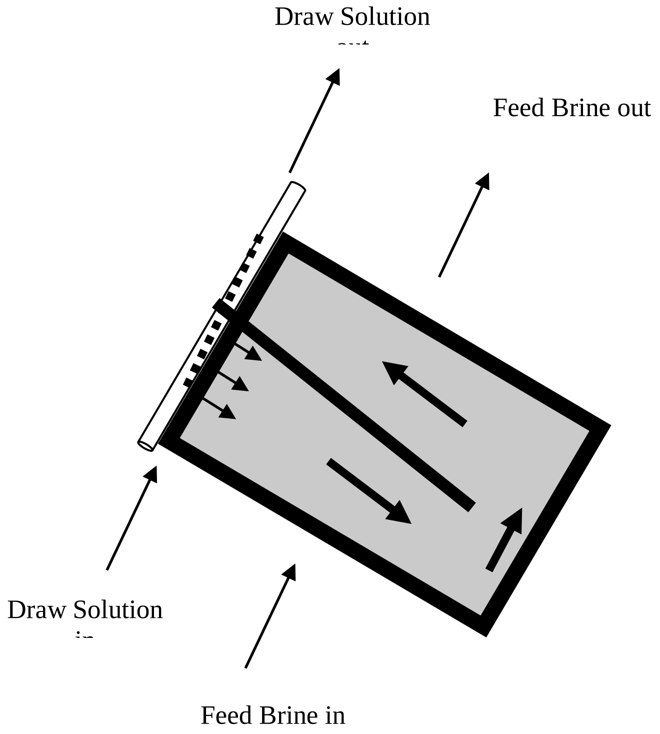

Fig. 2 Flow patterns in a spiral-wound module modified for Forward Osmosis.

3. RESULTS AND DISCUSSION

Draw Solution Feed Concentration Effect

The characteristic water flux equation for flow across a semi-permeable membrane, when osmotic pressure is the driving force, can be written as,

$$J_V = A\,\Delta\pi \qquad , \qquad \Delta P \approx 0 \tag{1}$$

Two parameters can affect the water flux: water permeability constant (A) and driving force ($\Delta\pi$). The driving force is the difference in osmotic pressures across the membrane between the draw and feed solution sides.

The increase of draw solution feed concentration will increase the driving force and vice versa. An increase in the driving force should lead to an increase in water flux, as demonstrated in Figures 3, 4, 5, 6, and 7 for sodium sulphate (Na_2SO_4), magnesium chloride hexahydrate ($MgCl_2.6H_2O$), magnesium sulfate hydrate ($MgSO_4.7H_2O$), glucose, and sucrose as draw solutions respectively, at different feed flow rate. The effect of draw solution feed concentration on product concentration is shown in Figures 8, 9, 10, 11, and 12 for sodium sulphate (Na_2SO_4), magnesium chloride hexahydrate ($MgCl_2.6H_2O$), magnesium sulfate hydrate ($MgSO_4.7H_2O$), glucose, and sucrose respectively, at different draw solution feed flow rate. Figures 13, 14, 15, 16, and 17, show the effect of draw solution feed concentration on brine solution outlet concentration at different draw solution feed flow rate.

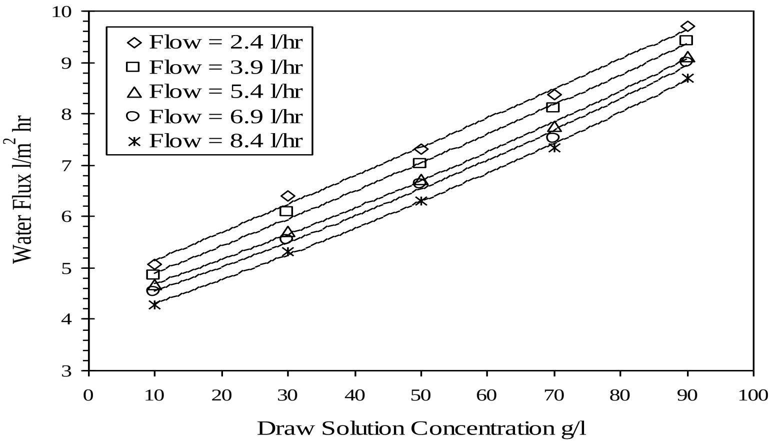

Fig. 3 Water Flux with Feed Concentration of Na_2SO_4 for Different Na_2SO_4 Flow Rate [Temp. (Na_2SO_4 & NaCl) = 18± 1 ^{0}C, Conc. (NaCl) = 2.5 g/l, Flow Rate (NaCl) = 12 l/hr, Pressure = 1.3 bar].

Increasing of draw solution feed concentration will dilute the concentration of draw solution product and concentrated the brine solution out. The reason, pure water flows through the membrane from brine solution into draw solution due to driving force ($\Delta\pi$).

Draw Solution Feed Flow Rate Effect

Figures 3 to 17 show the effect of draw solution flow rate on water flux, product concentration of draw solution, and brine solution outlet concentration respectively.

Increasing the draw solution feed flow rate prevents the concentration buildup in the solution at the vicinity of the membrane surface, and resulting in decreasing the driving force. Thus, water flux decreased with the increase in draw solution feed flow rate. This can explain the increase of concentration of draw solution product and the decrease of brine solution outlet concentration with the increase of draw solution feed flow rate.

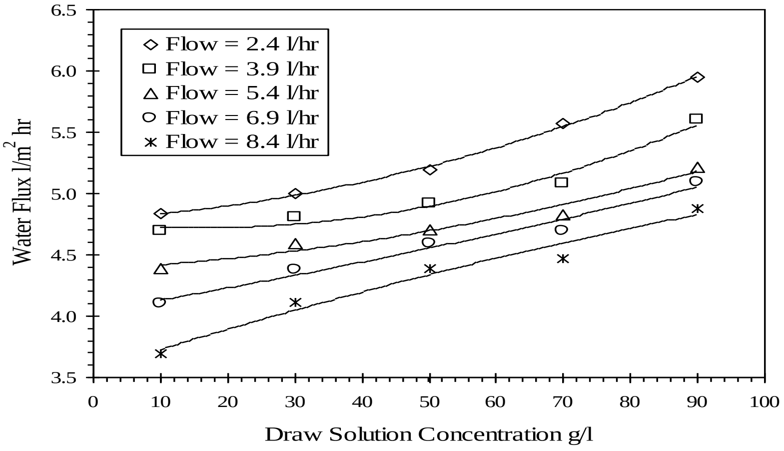

Fig. 4 Water Flux with Feed Concentration of $MgCl_2.6H_2O$ for Different $MgCl_2.6H_2O$ Flow Rate [Temp. ($MgCl_2.6H_2O$ & NaCl) = 18± 1 ^{0}C, Conc. (NaCl) = 2.5 g/l, Flow Rate (NaCl) = 12 l/hr, Pressure = 1.3 bar].

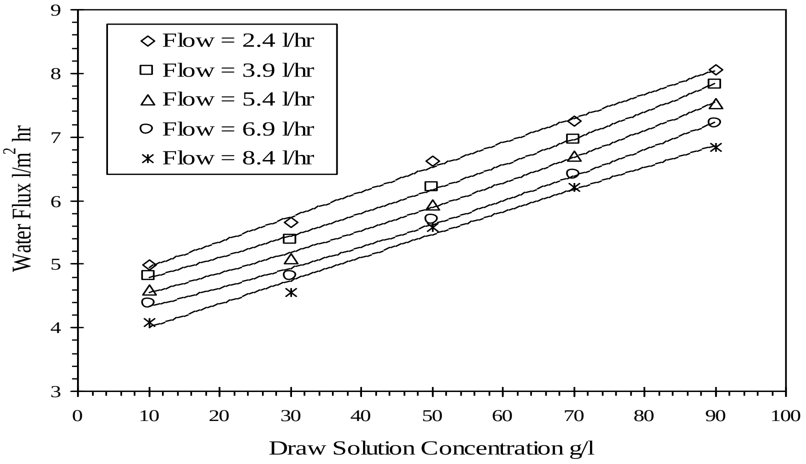

Fig. 5 Water Flux with Feed Concentration of $MgSO_4.7H_2O$ for Different $MgSO_4.7H_2O$ Flow Rate [Temp. ($MgSO_4.7H_2O$ & NaCl) = 18± 1 ^{0}C, Conc. (NaCl) = 2.5 g/l, Flow Rate (NaCl) = 12 l/hr, Pressure = 1.3 bar].

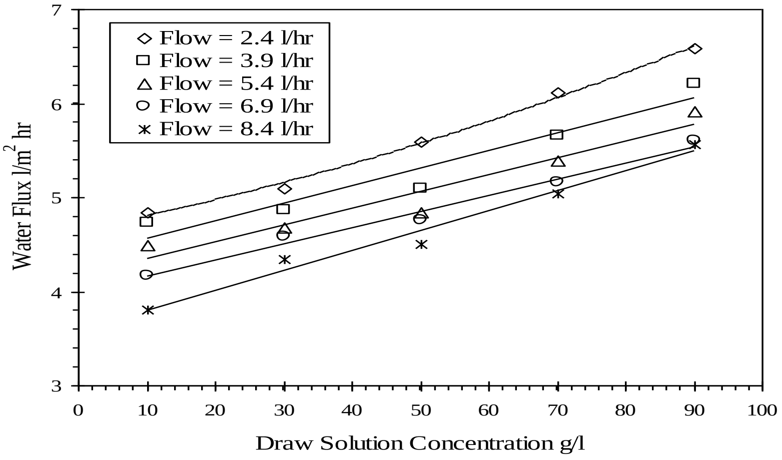

Fig. 6 Water Flux with Feed Concentration of Glucose for Different Glucose Flow Rate [Temp. (Glucose & NaCl) = 18± 1 ^{0}C, Conc. (NaCl) = 2.5 g/l, Flow Rate (NaCl) = 12 l/hr, Pressure = 1.3 bar].

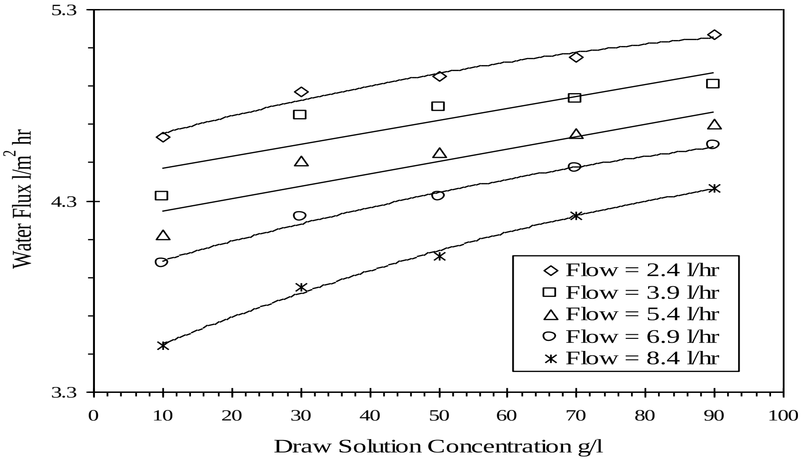

Fig. 7 Water Flux with Feed Concentration of Sucrose for Different Sucrose Flow Rate [Temp. (Sucrose & NaCl) = 18± 1 ^{0}C, Conc. (NaCl) = 2.5 g/l, Flow Rate (NaCl) = 12 l/hr, Pressure = 1.3 bar].

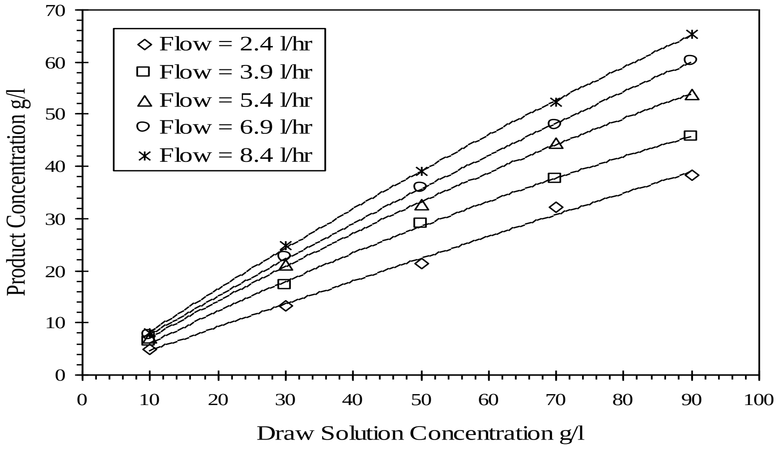

Fig. 8 Product Concentration of Na_2SO_4 with Feed Concentration of Na_2SO_4 for Different Na_2SO_4 Flow Rate [Temp. (Na_2SO_4 & NaCl) = 18± 1 ^{0}C, Conc. (NaCl) = 2.5 g/l, Flow Rate (NaCl) = 12 l/hr, Pressure = 1.3 bar].

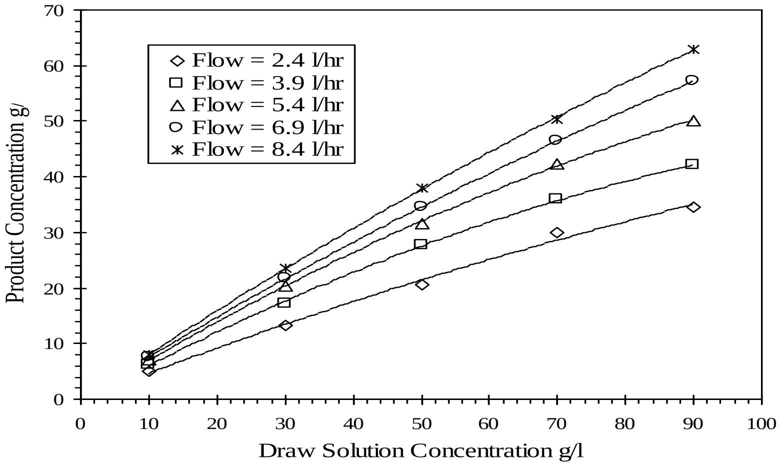

Fig. 9 Product Concentration of $MgCl_2.6H_2O$ with Feed Concentration of $MgCl_2.6H_2O$ for Different $MgCl_2.6H_2O$ Flow Rate [Temp. ($MgCl_2.6H_2O$ & NaCl) = 18± 1 ^{0}C, Conc. (NaCl) = 2.5 g/l, Flow Rate (NaCl) = 12 l/hr, Pressure = 1.3 bar].

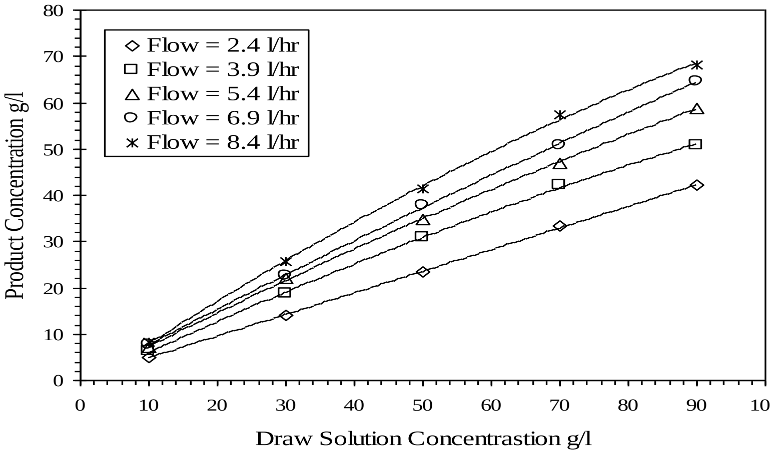

Fig. 10 Product Concentration of $MgSO_4.7H_2O$ with Feed Concentration of $MgSO_4.7H_2O$ for Different $MgSO_4.7H_2O$ Flow Rate [Temp. ($MgSO_4.7H_2O$ & NaCl) = 18± 1 ^{0}C, Conc. (NaCl) = 2.5 g/l, Flow Rate (NaCl) = 12 l/hr, Pressure = 1.3 bar].

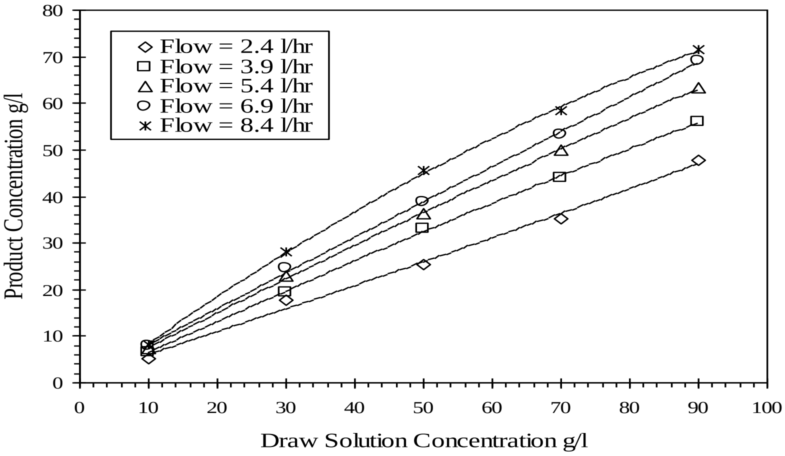

Fig. 11 Product Concentration of Glucose with Feed Concentration of Glucose for Different Glucose Flow Rate [Temp. (Glucose & NaCl) = 18± 1 ^{0}C, Conc. (NaCl) = 2.5 g/l, Flow Rate (NaCl) = 12 l/hr, Pressure = 1.3 bar].

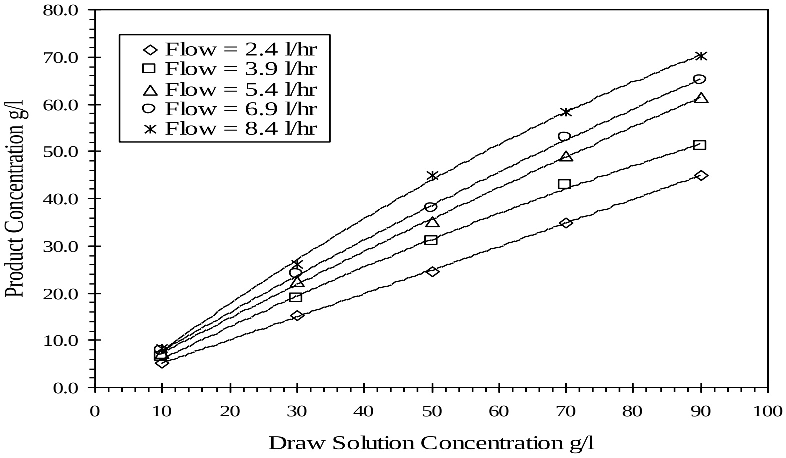

Fig. 12 Product Concentration of Sucrose with Feed Concentration of Sucrose for Different Sucrose Flow Rate [Temp. (Sucrose & NaCl) = 18± 1 ^{0}C, Conc. (NaCl) = 2.5 g/l, Flow Rate (NaCl) = 12 l/hr, Pressure = 1.3 bar].

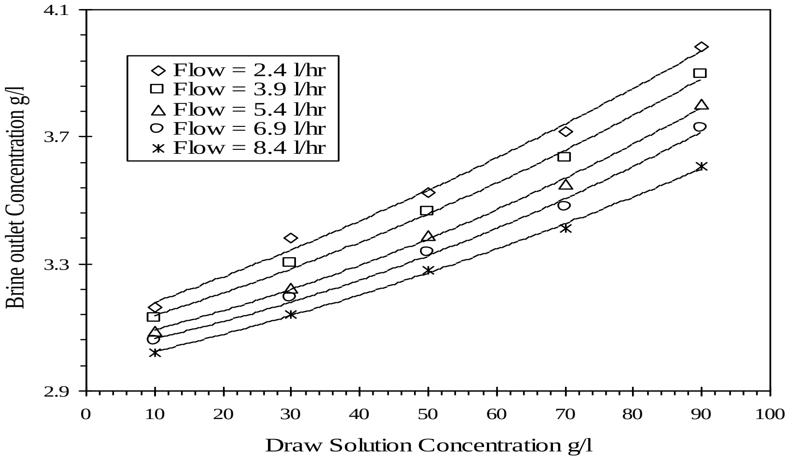

Fig. 13 Brine Concentration (NaCl) out with Feed Concentration of Na_2SO_4 for Different Na_2SO_4 Flow Rate [Temp. (Na_2SO_4 & NaCl) = 18± 1 ^{0}C, Conc. (NaCl) = 2.5 g/l, Flow Rate (NaCl) = 12 l/hr, Pressure = 1.3 bar].

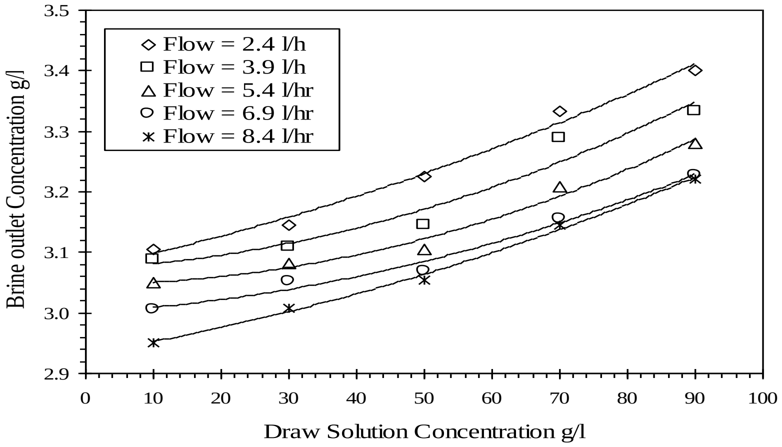

Fig. 14 Brine Concentration (NaCl) out with Feed Concentration of $MgCl_2.6H_2O$ for Different $MgCl_2.6H_2O$ Flow Rate [Temp. ($MgCl_2.6H_2O$ & NaCl) = 18± 1 ^{0}C, Conc. (NaCl) = 2.5 g/l, Flow Rate (NaCl) = 12 l/hr, Pressure = 1.3 bar].

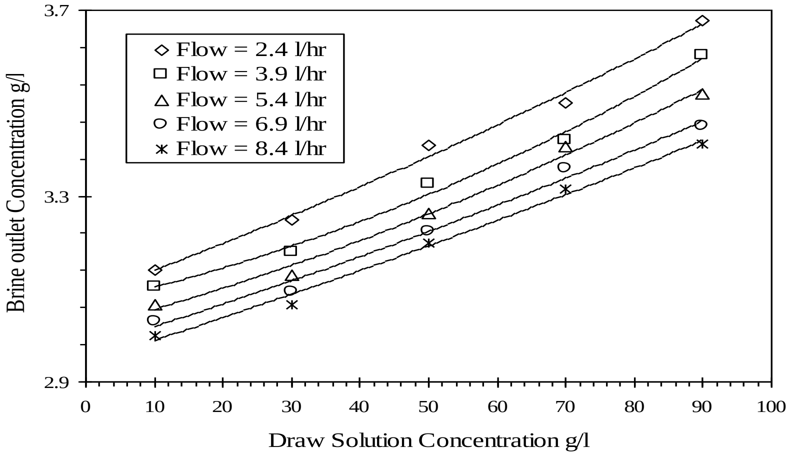

Fig. 15 Brine Concentration (NaCl) out with Feed Concentration of $MgSO_4.7H_2O$ for Different $MgSO_4.7H_2O$ Flow Rate [Temp. ($MgSO_4.7H_2O$ & NaCl) = 18± 1 ^{0}C, Conc. (NaCl) = 2.5 g/l, Flow Rate (NaCl) = 12 l/hr, Pressure = 1.3 bar].

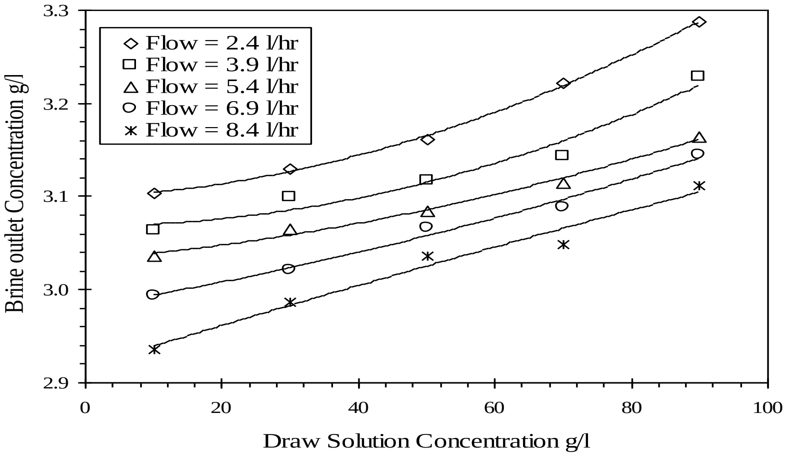

Fig. 16 Brine Concentration (NaCl) out with Feed Concentration of Glucose for Different Glucose Flow Rate [Temp. (Glucose & NaCl) = 18± 1 ^{0}C, Conc. (NaCl) = 2.5 g/l, Flow Rate (NaCl) = 12 l/hr, Pressure = 1.3 bar].

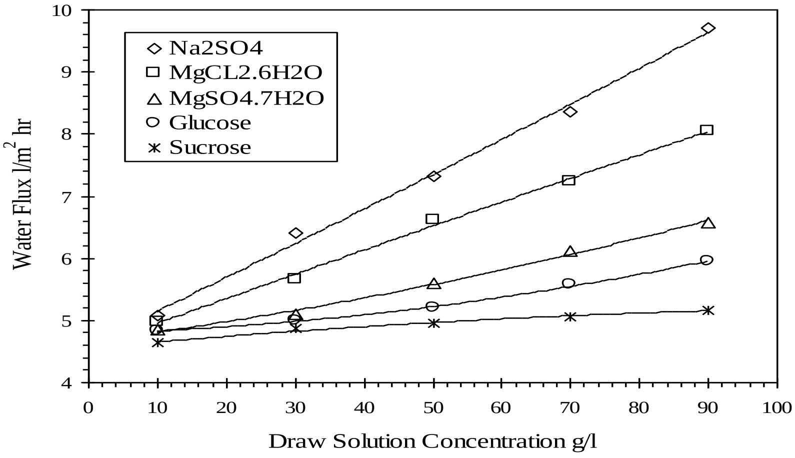

Fig. 17 Brine Concentration (NaCl) out with Feed Concentration of Sucrose for Different Sucrose Flow Rate [Temp. (Sucrose & NaCl) = 18± 1 ^{0}C, Conc. (NaCl) = 2.5 g/l, Flow Rate (NaCl) = 12 l/hr, Pressure = 1.3 bar].

Effect of the Type of Draw Solution

Fig. 18 illustrates the effect of draw solution feed concentration on water flux at different types of draw solution. For all five draw solutions, the order of pure water flux is:

$$J_{V(Na_2SO_4)} > J_{V(MgCl_2.6H_2O)} > J_{V(MgSO_4.7H_2O)} > J_{V(Glucose)} > J_{V(Sucrose)}$$

Sodium sulphate (Na_2SO_4) has a high water flux because it has high osmotic pressure (driving force) than other material studied. This can be explained by the osmotic pressure equation:

$$\pi_i = \Phi_i m_i RTc_i \qquad (2)$$

Increasing of osmotic pressure of draw solution will increase the driving force ($\Delta\pi$) for water flux. At the same concentration of draw solutions, osmotic pressure depends on the molecular weight of solute, solute that dissociates, also have an additive effect on osmotic pressure (for instance, addition of 1 mole of $MgSO_4.7H_2O$ produces 2 moles of ions in solution, doubling the osmotic pressure compared to a solute that does not dissociate such as glucose and sucrose).

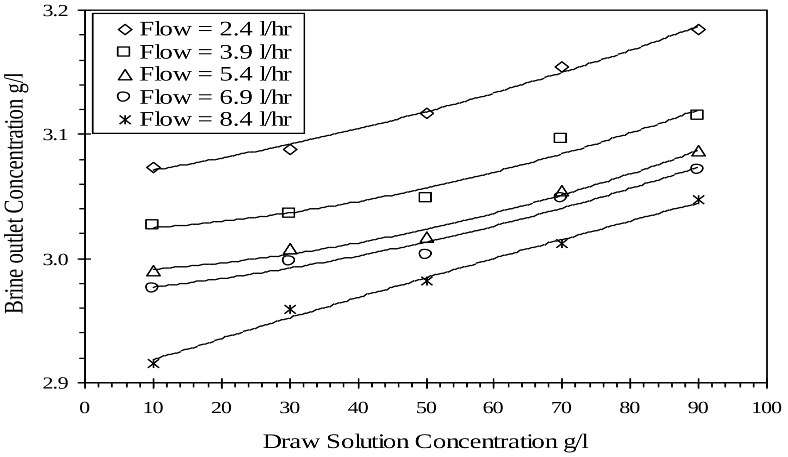

Fig. 18 Water Flux with Feed Concentration of Draw Solution for Different Draw Solutions [Temp. = 18± 1 ^{0}C, Conc. (NaCl) = 2.5 g/l, Flow Rate (Draw Solutions) = 2.4 l/hr, Flow Rate (NaCl) = 12 l/hr, Pressure = 1.3 bar]

Effect of Operating Temperature

The water flux increased with the increase in operating temperature for magnesium sulfate hydrate ($MgSO_4.7H_2O$) draw solution. This is shown in Fig. 19.

Increasing of operating temperature will slightly increase the osmotic pressure (driving force), and cause increase in water flux. This can be explained with the aid of osmotic pressure eq. (2)

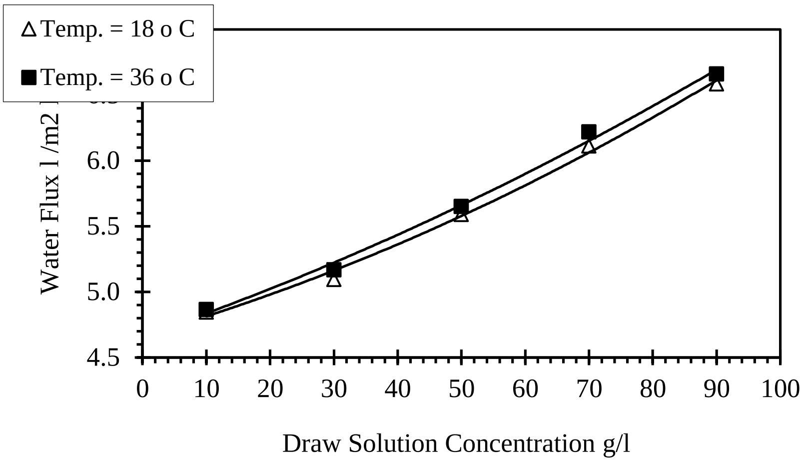

Fig. 19 Water Flux with Feed Concentration of $MgSO_4.7H_2O$ for Different $MgSO_4.7H_2O$ Feed Temperature [Flow Rate ($MgSO_4.7H_2O$) = 2.4 l/hr, Temp. (NaCl) = 18± 1 ^{0}C, Conc. (NaCl) = 2.5 g/l, Flow Rate (NaCl) = 12 l/hr, Pressure = 1.3 bar).

4. CONCLUSIONS

1. Forward (direct) osmosis process using semi-permeable polymeric membranes constructed as a special modification of spiral wound membrane module, which may be used a suitable alternative to reverse osmosis process as lower cost and more environmentally friendly desalination technology.

2. Within the range Variables studied, the water flux in the forward osmosis process increased with
   - Increasing feed concentration of draw solutions.
   - Increasing feed temperature of draw solution.
   - Decreasing feed flow rate of draw solutions.

3. The effect of draw solution concentration is higher than that of the other variables and the effect of these variables on the water flux within the range studied can be represented by:
   Feed Concentration > Feed Flow Rate > Feed Temperature

4. For different types of draw solutions with the same concentration, the water flux is limited by the

molecular weight and solute dissociated. Thus, the order of water flux was given by:

$Na_2SO_4 > MgCl_2.6H_2O > MgSO_4.7H_2O >$ Glucose > Sucrose

NOMENCLATURE

Symbol	Definition	Units
A	Water Permeability Constant	$l/m^2.hr.bar$
c	Salt Concentration in the Feed	g/l
J_V	Solvent Flux	l/m^2 hr
m	Number of Dissociated Ion per Molecule	
P	Operating Pressure	bar
R	Gas Constant	J/gmol. K
T	Temperature	K

Greek Symbols

Symbol	Definition	Units
π	Osmotic Pressure	bar
Φ	Osmotic Coefficient	

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