IJCPE
Iraqi Journal of Chemical and Petroleum Engineering

Iraqi Journal of Chemical and Petroleum Engineering
Vol.14 No.4 (December 2013) 11- 18
ISSN: 1997-4884

University of Baghdad
College of Engineering

A Study of Water Flux through Forward Osmosis Membrane Using Brine\Fresh Water System

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Abstract

The present work aims to improve the flux of forward osmosis with the use of Thin Film Composite membrane by reducing the effect of polarization on draw solution (brine solution) side.This study was conducted in two parts. The first is under the effect of polarization in which the flux and the water permeability coefficient (A) were calculated. In the second part of the study the experiments were repeated using a circulating pump at various speeds to make turbulence and reduce the effect of polarization on the brine solution side.

A model capable of predicting water permeability coefficient has been derived, and this is given by the following equations:

$$z = Z_0 + \frac{C.R.T}{9.8\left(\frac{d^2}{D^2}+1\right)} \left[\text{Exp. } \left[-9.8\left(\frac{d^2}{D^2}+1\right)\frac{A.M}{\rho}.\,t\right]-1\right]$$

Key Word: Osmosis, Forward osmosis, Permeable membrane.

Introduction

Membranes have gained an important place in chemical technology and are used in a broad range of applications. The key property that is exploited is the ability of a membrane to control the permeation rate of a chemical species through the membrane. In controlled drug delivery, the goal is to moderate the permeation rate of a drug from a reservoir to the body. In separation applications, the goal is to allow one component of a mixture to permeate the membrane freely, while hindering permeation of other components. Systematic studies of membrane phenomena can be traced to the eighteenth century philosopher scientists. For example, Abb´e Nolet coined the word ‘osmosis’ to describe permeation of water through a diaphragm in 1748. Through the nineteenth and early twentieth centuries, membranes had no industrial or commercial uses, but were used as laboratory tools to develop physical/chemical theories. For example, the measurements of solution osmotic pressure made with membranes by Traube and Pfeffer were used by van’t Hoff in 1887 to develop his limit law, which explains the behavior of ideal dilute solutions; this work led directly to the van’t Hoff equation. At about the same time, the concept of a perfectly selective semipermeable membrane was used by Maxwell and others in developing the kinetic theory of gases [1]. Following the progress in membrane science in

the last few decades, especially for reverse osmosis applications, the interests in engineered applications of osmosis has been spurred. Osmosis, or as it is currently referred to as forward osmosis, has new applications in separation process for wastewater treatment, food processing, and seawater/brackish water desalination. Other unique areas of forward osmosis research include pressure- retarded osmosis for generation of electricity from saline and fresh water and implantable osmotic pumps for controlled drug release [2].Forward (or direct) osmosis (FO) is a process that may be able to desalinate saline water sources at a notably reduced cost. In forward osmosis, like RO, 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 FO process utilizes an osmotic pressure gradient. 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 FO can be significantly greater than hydraulic driving forces in RO, potentially leading to higher water flux rates and recoveries. The lack of hydraulic pressure may make the process less expensive than RO, while the minimization of brine discharge reduces the environmental impact of the desalination process (Jeffrey et al. [2] and Gordon et al. [3]. However, a major limiting factor of FO system performance is a permeate flux decline due to concentration polarization. The present work aims to reduce the effect of polarization on brine solution side at different concentration to improve the water flux, finding the permeability coefficient for each concentration and compare these results with a mathematical model, derived in this study.

Experimental Work

Materials

1. Natural coarse salt (NaCl), purified in the laboratory to ensure it does not contain any impurities.
2. Distilled water with PH of 7 and TDS 0.001.

Equipment

1. Buchner flask with its funnel.
2. Ten Beakers with 1000 ml capacity.
3. Filter paper with 15 cm diameter.
4. Vacuum pump made by Banant Company.
5. Mixer to dissolve coarse salt in 1 liter of distilled water.
6. Magnetic stirrer for saturation concentration preparation at constant temperature (30^{o}C).
7. A digital balance with 2 decimal points was used to weigh the required quantities of materials used for preparing the samples.

Preparation of the Draw Solution (Brine Solution)

1. Weighing the coarse salt (NaCl) to give a certain concentrations and dissolving in one liter of distilled water using a mixer.
2. Purification of the solution using filter paper, Buchner flask with its funnel and vacuum pump and then introducing the prepared solution into the system that running the experiment.

The Forward Osmosis System

1. The experiment rig is as shown in Fig.(1), consists of a small bore leg (diameter: 0.025m; length: 1m) containing the pure water and a larger bore leg (diameter: 0.15m; length: 0.6m) containing the brine draw solution.

2. The membrane is placed midway on the pipe connecting the two legs alongside a valve.
3. The glassware, valves and connections were all QVF supplied by Corning Limited.
4. For circulating the draw solution a dosing pump supplied by Watson-Marlow Pump Limited was used. The reason for circulation is to increase turbulence and remove the concentrated solution in the neibourhood of the membrane in order to reduce polarization.

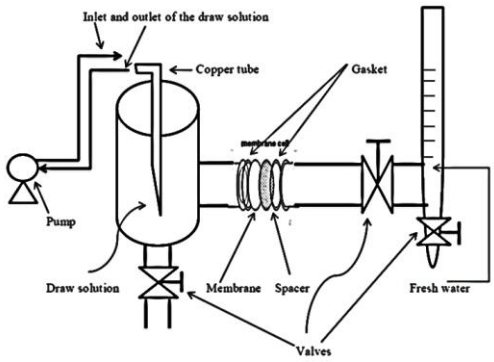


Fig. 1, Schematic diagram of forward osmosis system

The membrane used in the system is thin film composite (TFC), specifically designed for forward osmosis processes without the thick woven fabric support, is provided by Koch membrane.

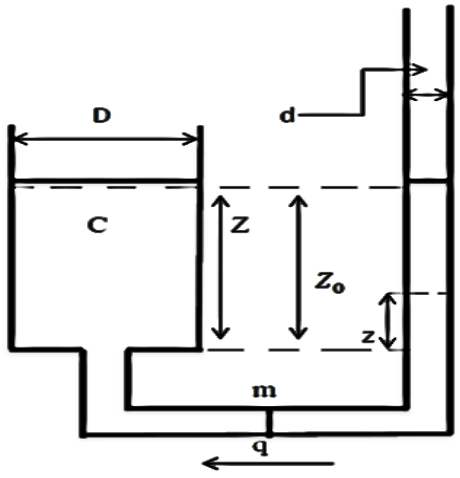
Experimental Procedure

1. 10 liter of draw solution with various concentration of NaCl (35, 98, 161, 224, 287, 350 gm/l) was prepared.
2. With the valve on the connecting pipe closed, the draw solution and distilled (fresh) water were placed in their respective container legs to the same level.
3. When opening the connecting valve, fresh water starts to permeate through the membrane and its level drops. The rise in the level on draw solution side is negligible since the cross section of the large leg is 36 times that of the small one, i.e., there is, hardly, any hydraulic back pressure.
4. The level in the small leg and the concentration of the draw solution are recorded every hour for duration of 5 hours.

The above procedure is repeated using circulation pump flow of 4, 8, and 12 ml/sec.

Mathematical Model

The equipment is as shown in the diagram consists of a small bore leg containing pure water and a large bore leg containing brine solution. The membrane (m) is placed midway as shown. A and a are the cross sectional area of the large and small legs respectively. Z_0 being the initial liquid level and z and Z are the final levels after time t of the pure water and brine solution respectively.



Water Material Balance on Large Leg

In = Out + Accumulation

$$q = 0 + \frac{\rho}{M} \cdot \left(\frac{\pi}{4} \cdot D^2\right) \frac{dz}{dt} \qquad \ldots(1)$$

The permeate flow across the membrane, q, is also given by:

$$q = A \left(\frac{\pi}{4} \cdot d^2\right) [\pi - 9.8 (Z - z)] \qquad \ldots(2)$$

Where π is the osmotic pressure, M is the molecular weight, A is the permeability coefficient and 9.8 is the conversion of meters of water to Kpa
From equations (3) and (4):

$$\frac{dz}{dt} = \frac{A.M.d^2}{\rho.D^2} [\pi - 9.8 (Z - z)] \quad \ldots(3)$$

Water into large leg = Water out of small leg

$$(Z - Z_0) . \frac{\pi}{4} . D^2 = \frac{\pi}{4} . d^2(Z_0 - z)$$

$$\therefore Z = (\frac{d^2}{D^2} + 1) . Z_0 - \frac{d^2}{D^2} . z \quad \ldots(4)$$

Differentiate wrt t:

$$\frac{dZ}{dt} = - \frac{d^2}{D^2} . \frac{dz}{dt} \quad \ldots(5)$$

Substituting equations (6) and (7) in equation (5):

$$\frac{dz}{dt} = - \frac{A.M}{\rho} [\pi - 9.8 (\frac{d^2}{D^2} + 1) Z_0 + 9.8 (\frac{d^2}{D^2} + 1) z] \quad \ldots(6)$$

$$\frac{1}{9.8 (\frac{d^2}{D^2}+1)} \int_{Z_0}^{z} \frac{9.8 (\frac{d^2}{D^2}+1) dz}{[\pi - 9.8 (\frac{d^2}{D^2}+1) Z_0 + 9.8 (\frac{d^2}{D^2}+1) z]} = - \frac{A.M}{\rho} \int_0^t dt \quad \ldots(7)$$

$$\frac{1}{9.8 (\frac{d^2}{D^2}+1)} \ln[\frac{[\pi - 9.8 (\frac{d^2}{D^2}+1) Z_0 + 9.8 (\frac{d^2}{D^2}+1) z]}{[\pi - 9.8 (\frac{d^2}{D^2}+1) Z_0 + 9.8 (\frac{d^2}{D^2}+1) Z_0]}] = - \frac{A.M}{\rho} . t \quad \ldots(8)$$

$$\ln [\frac{[\pi - 9.8 (\frac{d^2}{D^2}+1) Z_0 + 9.8 (\frac{d^2}{D^2}+1) z]}{[\pi]}] = - 9.8 (\frac{d^2}{D^2} + 1) \frac{A.M}{\rho} . t \quad \ldots(9)$$

$$\pi - 9.8 (\frac{d^2}{D^2} + 1) Z_0 + 9.8 (\frac{d^2}{D^2} + 1) z = \pi . \text{Exp.} [- 9.8 (\frac{d^2}{D^2} + 1) \frac{A.M}{\rho} . t] \quad \ldots(10)$$

$$\therefore z = Z_0 + \frac{\pi}{9.8 (\frac{d^2}{D^2}+1)} [\text{Exp.} [-9.8 (\frac{d^2}{D^2} + 1) \frac{A.M}{\rho} . t] -1] \quad \ldots(11)$$

Vant Hoff equation for NaCl:

$$\pi = C R T \quad \ldots(12)$$

Substituting for π in equation (11):

$$\therefore z = Z_0 + \frac{C.R.T}{9.8 (\frac{d^2}{D^2}+1)} [\text{Exp.} [- 9.8 (\frac{d^2}{D^2} + 1) \frac{A.M}{\rho} . t] -1] \quad \ldots(13)$$

Results and Discussion

Effect of Velocity on Water Permeability

Figures (2) to (7) show the comparison between effect of brine concentration on water permeability and the influence of the pump velocities 12, 8, 4 ml/sec. These have been examined on the measured height of fresh water per hour for brine solution concentrations as shown in figures.

It must be mentioned that the above results are to be expected when considering Vant Hoff model and the model derived in this study.

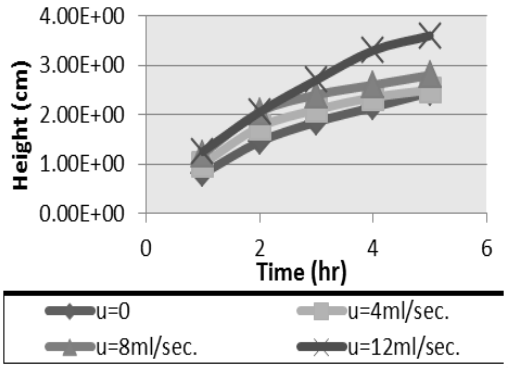


Fig. 2, Height of fresh water versus time for concentration 35 gm/l, at 29± 2 ◦ C

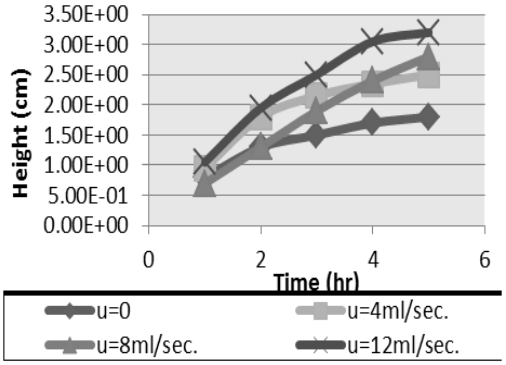


Fig. 3, Height of fresh water versus time for concentration 98 gm/l, at 29± 2 ◦ C

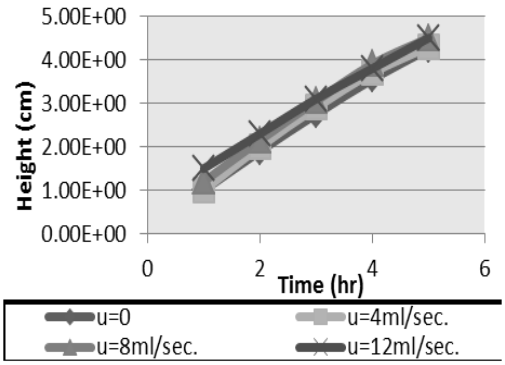


Fig. 4, Height of fresh water versus time for concentration 161 gm/l, at 29± 2 ◦ C

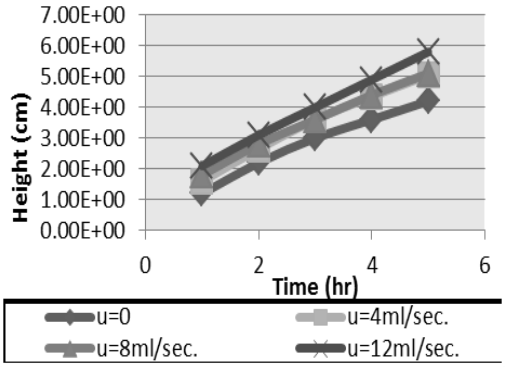


Fig. 5, Height of fresh water versus time for concentration 224 gm/l, at 29± 2 ◦ C

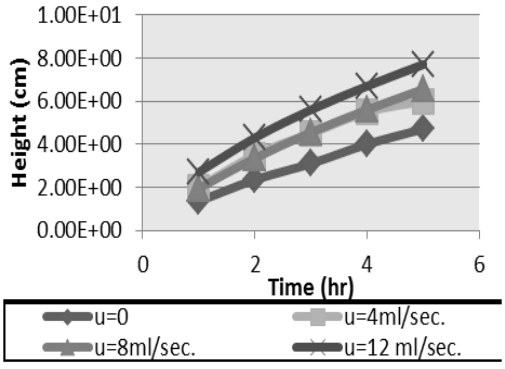


Fig. 6, Height of fresh water versus time for concentration 287 gm/l, at 29± 2 ◦ C

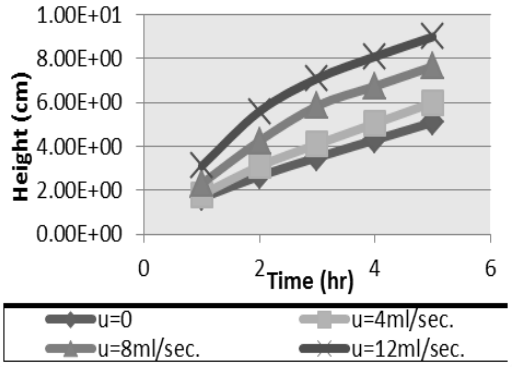


Fig. 7, Height of fresh water versus time for concentration 350 gm/l, at 29± 2 ◦ C

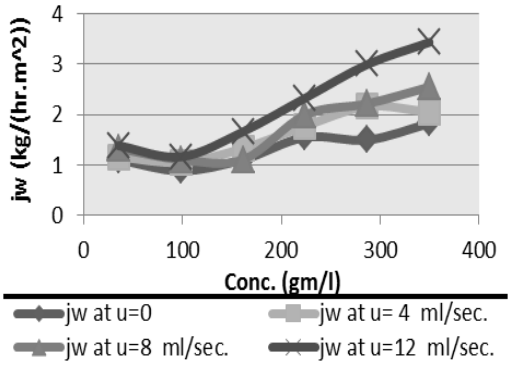


Fig. (8). Flux of fresh water versus NaCl concentrations, at 29± 2 ◦ C

Also in Figs. 2 - 7, it can be seen that increasing the velocity of pump leads to further decrease in the height of the fresh water column and this leads to an increase in water flux as shown in Fig. (8) and this increase is relatively greater at higher brine solution concentrations. The increase in the measured water flux with increasing pump velocity is ascribed to the reduced impact of the ECP and ICP in brine solution side. A similar observation was noticed in the experimental study of Loeb [4].

Effect of Velocity on Membrane Permeability Coefficient (A)

The permeability coefficient (A) was calculated from equation (14) for each concentration used in experiments as shown in Table (1).

$$J_w = A\,\Delta\pi \qquad \ldots(14)$$

We notice from Table (1) that the Permeability Coefficient (A) is almost constant for all concentrations in FO processes and the Permeability Coefficient (A) is more stable when increasing velocity, as a result of reducing the impact of ECP.

Experimenting with DuPont B-9 (flat sheet) and B-10 (hollow fiber) Permasep RO membranes, Mehta and Loeb [5] pointed out that A is not constant in FO; it declines with increasing osmotic pressure (i.e., increasing concentration) of the draw

solution. The decline of A was explained by partial drying or osmotic dehydration of the membrane at high osmotic pressures.

This is not entirely, true because the membrane permeability coefficient is a fixed
property for each membrane and not affected by concentration change.

Table 1, Effect of velocity on Permeability Coefficient (A) at brine concentrations of 98, 161, 224, 287 and 350 gm/l respectively using equation (14)

	(Kg/(hr. m^2.Kpa))			
Concentration gm/l	A at u=0 ml/sec.	A at u=4 ml/sec.	A at u=8 ml/sec.	A at u=12 ml/sec.
98	1.70E-04	2.63E-04	2.10E-04	2.5E-04
161	1.60E-04	1.93E-04	1.62E-04	2.43E-04
224	1.60E-04	1.84E-04	2.10E-04	2.42E-04
287	1.20E-04	1.75E-04	1.78E-04	2.43E-04
350	1.22E-04	1.36E-04	1.71E-04	2.30E-04

Comparison of Membrane Permeability Coefficient (A) Between Experimental Work and Mathematical Model

The present mathematical treatment is subjected to comparison with the experimental work as shown below,

Figures (9) to (16) show comparison between the mathematical model and experimental results.

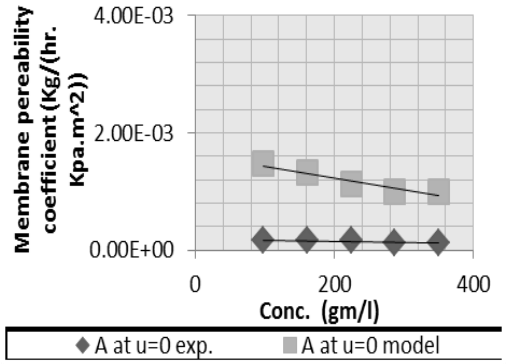


Fig. 9, Membrane permeability coefficient (A) verses brine solutions concentrations

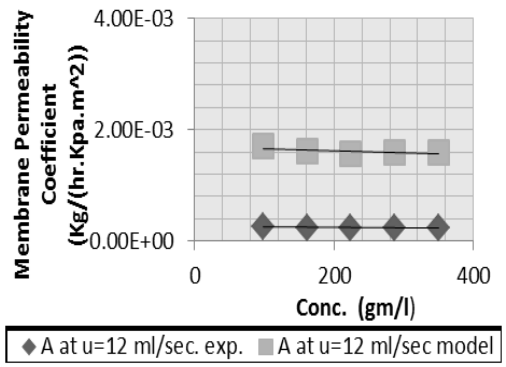


Fig. 10, Membrane permeability coefficient (A) verses brine solutions concentrations

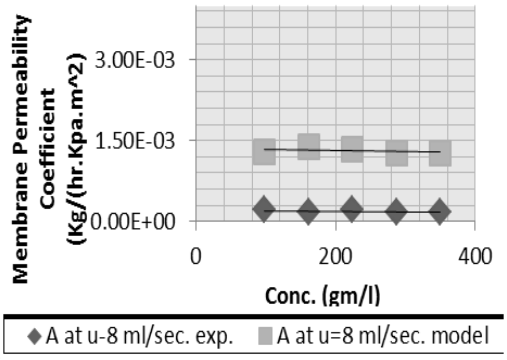


Fig. 11, Membrane permeability coefficient (A) verses brine solutions concentrations

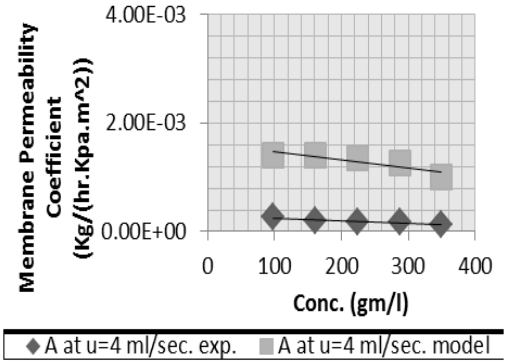


Fig. 12, Membrane permeability coefficient (A) verses brine solutions concentrations

In Figs. (9) to (12) we note the difference between the mathematical model and experimental work, the reason is that the Mathematical Model did not take into account the effect of polarization and assumed perfect conditions.

The values of A obtained from the model is, on average, about 7 times

greater than those obtained from experimentation.

In order to include the effect of polarization in the model, a correction factor is introduced into the model.

This correction factor was found by calculating the average of the ratio $\frac{A_{model}}{A\ exp.}$ for all runs.

The resulting modified model is given by equation (15) below,

$$z = Z_0 + \frac{C.R.T}{9.8\left(\frac{d^2}{D^2}+1\right)}\left[Exp.\ \left[-9.8\left(\frac{d^2}{D^2}+1\right)\frac{7.A.M}{\rho}.\ t\right]-1\right] \quad ...(15)$$

Figures (13) to (16) show the comparison between the mathematical and experimental work after adding the correction factor.

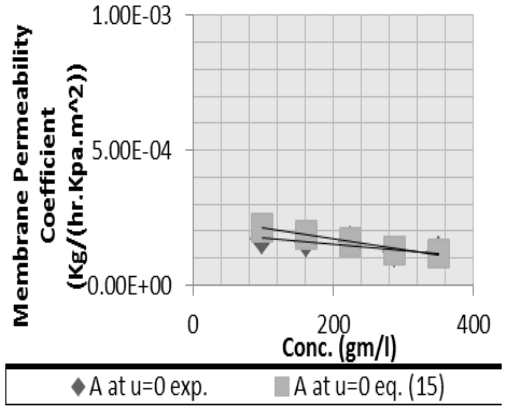


Fig. 13, Membrane permeability coefficient (A) verses brine solutions concentrations

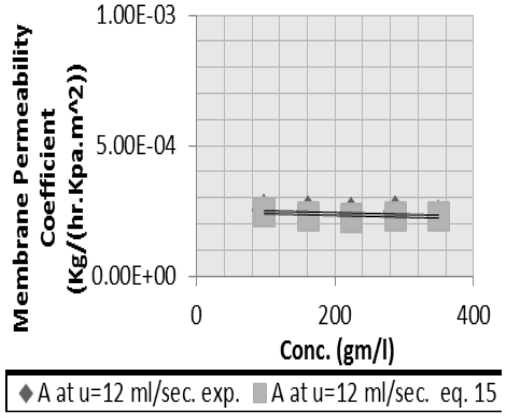


Fig. 14, Membrane permeability coefficient (A) verses brine solutions concentrations

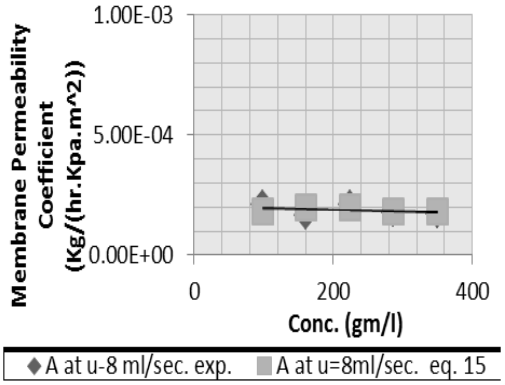


Fig. 15, Membrane permeability coefficient (A) verses brine solutions concentrations

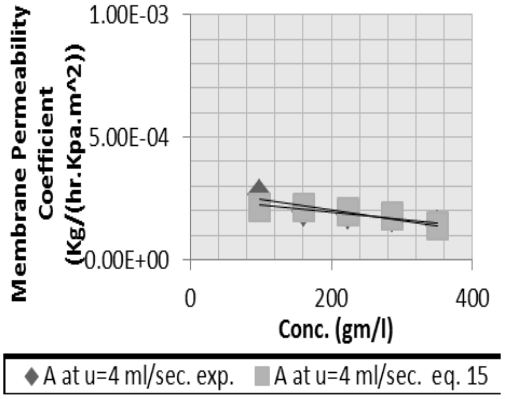


Fig. 16, Membrane permeability coefficient (A) verses brine solutions concentrations

Conclusions

After studying the experimentally detected performance of the TFC Koch membrane one may conclude the followings:

1. The effect of polarization can be reduced by providing sufficient circulation.
2. The high value of water flux can be obtained by using high concentration of draw solutions.
3. The membrane permeability coefficient is constant, not affected by change in concentration of draw solution but it is affected by change in circulation velocity.
4. The present mathematical model has been tested using the present experimental results under FO conditions and shown to be 90% confident.

Nomenclature

A(Kg/m².hr.Kpa)	Membrane permeability coefficient
J_w(Kg/hr.m^2)	Water flux across membrane
u (ml/sec)	Velocity
M (Kg/Kgmole)	Molecular weight
t (sec)	Time
R(Kpa.l/K.mole)	Gas constant
T (C)	Temperature
C (Kmole)	Concentration

Greek Letters

Δπ(pa)	Difference of osmotic pressure of the bulk solutions
ρ (Kg/m^3)	Density

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