Reduction of Concentrating Poisonous Metallic Radicals from Industrial Wastewater by Forward and Reverse Osmosis

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Abstract

The research aims to use a new technology for industrial water concentrating that contains poisonous metals and recovery quantities from pure water. Therefore, the technology investigated is the forward osmosis process (FO). It is a new process that use membranes available commercial and this process distinguishes by its low cost compared to other process.

Sodium chloride (NaCl) was used as draw solution to extract water from poisonous metals solution. The driving force in the FO process is provided by a different in osmotic pressure (concentration) across the membrane between the draw and poisonous metals solution sides.

Experimental work was divided into three parts. The first part includes operating the forward osmosis process using TFC membrane as flat sheet for NaCl. The operating parameters studied were: draw solutions concentration (10 – 95 g/l), draw solution flow rate (12-36 I/h), temperature of draw solution (30 and 40°C), feed solution concentration (10 -210 mg/l), feed solution flow rate (10 -50 l/h), temperature of feed solution (30 and 40°C) and Pressure (0.4 bar).

The second part includes operating the forward osmosis process using CTA membrane as flat sheet for NaCl. The operating parameters studied were: draw solution concentration (15 – 95 g/l), feed solution concentration (10-210 mg/l). Constant temperature was maintained at 30°C.

The last part includes operating the reverse osmosis process using TFC membrane as spiral wound module in order to separate NaCl salt from draw solution and obtain on pure water so as to usefully in different uses and also obtain on solution of NaCl concentrate which was recirculated to forward osmosis process. It is then used as draw solution. The operating parameter studied was: feed solution flow rate (15-55 l/h).

The experimental results show that the water flux increases with increasing draw solution concentration, feed solution flow rate, temperature of draw solution and decreases with increasing feed solution concentration, draw solution flow rate and temperature of feed solution. The experiments also show that CTA membrane gives higher water flux than TFC membrane for forward osmosis operation.

Keyword : Forward osmosis; Reverse osmosis; wastewater; membrane; heavy metals; lead; cadmium; nickel.

اختزال تركيز جذور المعادن السامة من مخلفات المياه الصناعية بواسطة التنافذ الأمامي والتنافذ العكسي

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الخلاصة

يهدف البحث لاستخدام تكنولوجيا جديدة لتركيز المياه الصناعية الحاوية على المعادن السامة واسترجاع كميات من المياه النقية . لذلك تمت دراسة عملية التنافذ الأمامي وهي طريقة جديدة تستخدم الأغشية المتوفرة تجارياً وتمتاز هذه العملية بكلفتها القليلة مقارنة بالطرق الأخرى .

تم استخدام كلوريد الصوديوم (NaCl) كمحلول سحب لنزع الماء النقي من محاليل المعادن السامة . القوة الدافعة في عملية التنافذ الأمامي ناتجة من فرق الضغط التنافذي (التركيز) على جانبي الغشاء بين محلول السحب ومحلول المعادن السامة .

تم تقسيم الجزء العملي إلى ثلاث أقسام : يضم القسم الأول تشغيل عملية التنافذ الأمامي باستخدام غشاء TFC على شكل صفيحة مستوية لمحلول سحب كلوريد الصوديوم.

الظروف التشغيلية التي تم دراستها : تركيز محلول السحب (15-95 g/l) ، معدل الجريان لمحلول السحب (12-36 l/h) ، درجـة حرارة محلـول السحب (30 , 40°C) ، تركيز محلول اللقيم (10-210 mg/l) ، معدل الجريان لمحلول اللقيم (10-50 l/h)، ودرجة حرارة محلول اللقيم (30 , 40 °C) . الضغط (0.4 bar).

القسم الثاني يضم تشغيل منظومة التنافذ الأمامي باستخدام غشاء نوع CTA على شكل صفيحة مستوية لمحلول السحب كلوريد الصوديوم . وكان تركيز محلول السحب (15-95 g/l) ، وتركيز محلول اللقيم (10-210 mg/ l) . درجة الحرارة ثابتة عند 30°C .

القسم الثالث تضمن تشغيل منظومة التنافذ العكسي باستخدام غشاء نوع TFC على شكل وحدة حلزونية لفصل ملح الـNaCl من محلول السحب والحصول على مياه نقية يمكن الاستفادة منه في العديد من الاستخدامات وكذلك الحصول على محلول NaCl مركز يتم استرجاعه إلى منظومة التنافذ الأمامي واستخدامه من جديد كمحلول سحب . وكان الظرف التشغيلي الذي تم دراسته : معدل الجريان لمحلول اللقيم (15-55l/h).

أظهرت نتائج البحث ان معدل تدفق الماء يزداد بزيادة تركيز محلول السحب ومعدل الجريان لمحلول اللقيم ودرجة حرارة محلول السحب والقوة الدافعة ويقل بزيادة تركيز محلول اللقيم ومعدل الجريان لمحلول السحب وزيادة درجة حرارة محلول اللقيم . وكذلك أظهرت النتائج ان أغشية CTA تعطي معدل تدفق ماء أعلى من أغشية TFC في عمليات التنافذ الأمامي .

Introduction

Industrial wastewater , which have heavy metals , are an important source of environmental pollution , Pb , Cd , Cu , Hg , Cr , Ni and Zn are the main trace elements that are the most harmful for public health . The optimization of wastewater purification process requires a development of new operation based on low cost raw materials with high pollutant removal efficiency. The complexity of effluents makes the process of heavy metals removal more difficult, as well as strict limitation that have been imposed to wastewater discharge everywhere in aquatic recipients (Achanai et al., 2008).

Several treatment technologies have been adopted to remove heavy metals. The major mode of removing heavy metals from water is by physical – chemical treatment.

Technologies for removing heavy metals include:

- Precipitations, including coagulation/ filtration, direct filtration and other methods.
- Adsorptive processes, including adsorption on to active alumina, activated carbon.
- Ion exchange processes, specifically anion exchange.
- Membrane filtration, including nanofiltration, reverses osmosis and other methods.

Some of these technologies are traditional treatment process (Coagulation / filtration and membrane filtration), which have been tailored to improve removal of heavy metals from water in water treatment plants (Jacks et al., 2001).

Fresh water 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 freshwaters (Mesa et al., 1997).

As a result of water scarcity and increasing demands for freshwater, water desalination is becoming an attractive method to produce water for both industrial and domestic usage. Currently, reverse osmosis (RO) is one of the most commonly used technologies due to the availability of stable and good performance membranes, and its relatively lower overall cost compared to thermal processes. Nevertheless, (RO) process generally requires high applied pressure, which leads to high energy requirement and thus, high operational cost. Recently forward osmosis (FO) process, which is a natural process, has been developed as a possible alternative technology for desalination due to its lower energy requirement.

The FO process utilizes an osmosis pressure gradient generated by a highly concentrated solution (known as "draw" solution) to allow water to diffuse through a semi permeable membrane from a saline feed water, which has a relatively lower concentration. Consequently, a less concentrated draw solution is being produced which may be further treated to extract for freshwater. FO bears some analogy to RO for that in both processes, water transports through a semi permeable membrane while salts are withheld by the membrane. However, the driving force in the FO process is created naturally by the concentration differences between the feed and draw solutions across the membrane, which substitutes the high pressure that is required in the (RO) process. Therefore, lesser energy is required for the (FO) process compared to the (RO) process (Howy et al., 2006). The main advantages of using FO are that operates at low or no hydraulic pressures, it has high rejection of a wide range of contaminates, and it may have a lower membrane fouling propensity than pressure-driven membrane process. 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 problem (Tzahi et al.,2006).The concentrated solution on the permeate side of the membrane is the source of the driving force in the FO process. When selecting a draw solution, the main criterion is that it has a higher osmotic pressure than the feed solution. Also, osmotic agent solution solute must be non toxic and probably the solute is edible in some cases. Ideal draw solution does not interact with the membrane or degrade the membrane. It should be noted, the solute in a draw solution non-edible must be separated easily and economically to be used again (Mustafa, 2009). For these reasons forward osmosis process was used in this search.

The main purpose of this study is use forward osmosis process to reduce heavy metals in wastewater to level acceptable for water reuse or discharge. The first step is to study the effect of various operating condition for Feed (Lead nitrate $Pb(NO_3)_2$, Cadmium nitrate $Cd(NO_3)_2$ and Nickel chloride $NiCl_2$) and draw (NaCl) solution such as concentration, flow rate and temperature for the thin film composite (TFC) membrane which constructed as flat sheet module, and then study the effect of feed and draw solutions concentrations on water flux in the cellulose triacetate (CTA) membrane which is constructed as same module.

The second step is to use reverse osmosis (RO) process in order to separate draw solution (NaCl).

Concentration Polarization

The water flux in osmotic – driven membrane processes is described by equation

$$J_w = A\,(\sigma\,\Delta\pi - \Delta P) \qquad (1)$$

Where J_w is the water Flux, A the water permeability constant of the membrane, σ the reflection coefficient, ΔP is the applied pressure, and Δπ represents the osmotic pressure difference across the active layer of the membrane. In such processes, the osmotic pressure difference across the active layer is much lower than the bulk osmotic pressure difference, which results in much lower water flux than expected (Mehta and Loeb, 1978; Lee et al., 1981; Leop et al., 1997.,Seppala and Lampinen, 2004 and Mccutcheon et al., 2006). The lower than expected water flux is often attributed to several membranes associated transport phenomena.

Specifically, two types of concentration polarization (CP) phenomena external CP and internal CP can take place in osmotic driven membrane processes as discussed below:

External Concentration Polarization

Concentration polarization on the feed side of a membrane is a significant problem in pressure driven membrane desalination processes. This phenomenon inhibits permeate flow due to an increased osmotic pressure at the membrane active layer interface on the feed side of the membrane. In an osmotic process, this phenomenon occurs on both sides of the membrane, with the effect being dilutive on the permeate side. These two phenomena collectively are referred as ECP. Specifically, this phenomenon on the feed and permeate side will be referred to as concentrative and dilutive ECP respectively.

To predict flux in the presence of ECP, the effective osmotic driving force at the membrane solution interface on both the feed and permeate sides of the membrane must be determined.

For a pressure driven membrane process, such as RO in the absence of ECP, the generalized flux equation is

$$J_w = A\,(\Delta P - \pi_{F,b}) \qquad (2)$$

Where A is the pure water permeability coefficient, ΔP is the transmembrane pressure and $\pi_{F,b}$ is the osmotic pressure of the bulk feed solution. Complete rejection of the feed solute (i.e., the reflection coefficient σ = 1) is assumed. Equation 2 is valid only when the flux is low or the feed solution is very dilute. If flux becomes higher, the concentration polarization effect becomes significant. The membrane surface concentration on the feed side becomes larger than that of the bulk as solute is rejected, thus concentrating the feed solute. This phenomenon is referred as concentrative ECP. Equation 2 can be modified to account for concentrative ECP:

$$J_w = A\left(\Delta P - \pi_{F,b}\,\exp\left(\frac{J_w}{k_F}\right)\right) \qquad (3)$$

Here, the exponential term is the concentrative ECP module (Mccutcneon and Elimelech, 2006) which is a function of water flux and mass transfer coefficient.

For osmotically driven membrane processes with a non dilute feed, a similar concentrative ECP will occur. In an osmotically driven membrane process, however, we must also consider the dilutive effect that occurs on the permeate side of the membrane. Dilutive ECP occurs as permeate water flow displaces draw solute at the membrane - draw solution interface, reducing the effective driving force of the draw solution. These two ECP phenomena are coupled for osmotic flow when solute is present on both sides of the membrane.

The standard flux equation for FO is gives as

$$J_w = A\,(\pi_{D,b} - \pi_{F,b}) \qquad (4)$$

Which predicts flux as a function of the difference in bulk osmotic pressure of the draw ($\pi_{D,b}$) and feed solutions ($\pi_{F,b}$). This equation does not account for ECP, which may be valid only if the permeate flux is very low. When flux rates are higher, though, the equation must be modified to include both concentrative and dilutive ECP moduli:

$$J_w = A\left[\pi_{D,b}\exp\left(-\frac{J_w}{k_D}\right) - \pi_{F,b}\exp\left(\frac{J_w}{k_F}\right)\right] \qquad (5)$$

Note that the dilutive effect is indicated by the negative exponential term modifying the draw solution osmotic pressure. Individual mass transfer coefficients on the feed, k_F, and permeate k_D, sides of the membrane must be considered. Equation 5 represents an implicit model for osmotic flux using a dense symmetric membrane. Therefore consider the case where the membrane is a symmetric, for which ICP effects are most significant (Jeffery et al., 2007).

$$k_F = 1.85\,\frac{D}{d_h^{0.67} L^{0.33}}\,(Re\ Sc)^{0.33} \qquad (6)$$

$$k_D = \frac{D\,\varepsilon}{\tau\, l} \qquad (7)$$

Where D is the diffusion coefficient, d_h is the hydraulic diameter, L is the channel length, 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 (Young et al., 2009).

Finally, the flux of combined system using FO and RO is:

$$J_w = A\left[\Delta P + \pi_{D,b}\exp\left(-\frac{J_w}{k_D}\right) - \pi_{F,b}\exp\left(\frac{J_w}{k_F}\right)\right] \qquad (8)$$

Figure 1 (a) shows this phenomenon with a dense symmetric membrane.

Internal Concentration Polarization

Asymmetric membrane, commonly used in pressure driven membrane processes, use porous layer to mechanically support a thin salt rejecting active layer. In osmotic processes, salt must pervade this porous layer, which do not reject the salt to any appreciable degree, yet still hinder its diffusion, to establish the osmotic driving force across this active layer. When water permeates the membrane, concentration polarization occurs on both sides of this active layer. However, the porous layer provides a protected environment on one side of the active layer where the polarized layer can form without the mitigating effects of cross flow (Mccutcheon and Elimelech, 2006 and Gray et al., 2006). There are two types of ICP depending on the orientation of the membrane. In the PRO mode, the porous layer is against the feed solution and the feed solute will be concentrated within the membrane, Figure (b). In the FO mode, the porous layer is against the permeate side. The draw solute diffuses into this porous layer but becomes diluted as water permeates the membrane, Figure 1(C). These are referred phenomena as concentrative and dilutive ICP, respectively (Gray et al., 2006 and Mccutcheon and Elimelech, 2006).

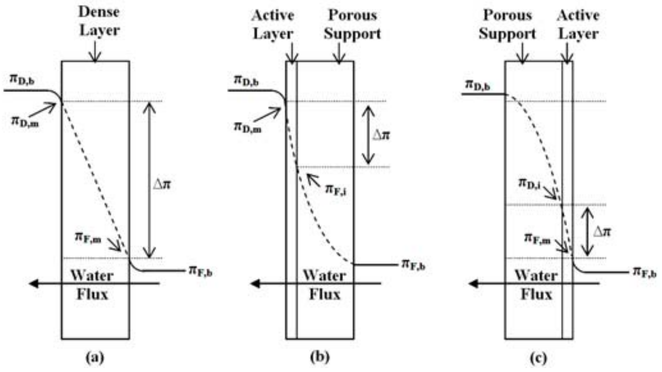

Fig. 1 Illustration of osmotic driving force profiles for osmosis through several membrane types and orientations, incorporating both internal and external concentration polarization. (a) The profile illustrates concentrative and dilutive external CP.

(b) PRO mode; the profile illustrates concentrative internal CP and dilutive external CP.

(c) FO mode; the profile illustrates dilutive internal CP and concentrative external CP.

EXPERIMENTAL

Feed Solution

Three types of feed solution were used for the forward osmosis process. Lead nitrate ($Pb(NO_3)_2$), Cadmium Nitrate ($Cd(NO_3)_2$) and Nickel Chloride ($NiCl_2$). Deionized water, of (3-8) µs/cm conductivity, was used for preparing feed solution with concentration of (10 to 210) mg/l. The chemical analysis of the feeds is given in Table 1.

Table 1 Chemical Specification of Feed Solutions

Lead Nitrate $Pb(NO_3)_2$ = 331.23	Assay > 98.0% Chloride (Cl) < 0.005% Copper(Cu) < 0.005% Iron (Fe) < 0.005% Zinc (Zn) < 0.005% Calcium (Ca) < 0.005%
Cadmium nitrate $Cd(NO_3)_2$ = 236.43	Assay > 98.0% Chloride (Cl) < 0.005% Sulfate (So_4) < 0.005% Copper(Cu) < 0.005% Lead (Pb) < 0.005% Iron (Fe) < 0.005% Zinc (Zn) < 0.005% Calcium (Ca) < 0.005%
Nickel chloride $NiCl_2$ = 129.6	Assay > 98.0% Copper(Cu) < 0.005% Lead (Pb) < 0.005% Iron (Fe) < 0.005% Zinc (Zn) < 0.005% Calcium (Ca) < 0.005%

Draw Solution

Deionized water of (3-8) µs/cm conductivity, was used for preparing sodium chloride with concentration of (15 to 95) g/l. NaCl was selected as osmotic agent because it has high osmotic pressure, high solubility, easily and economically be separated and recycled to high concentration using reverse osmosis process. Table 2 shows (NaCl – H_2O) draw solution concentration and their corresponding conductivities at 30°C temperature. The chemical analysis of the NaCl is given in Table 3.

Table 2 Sodium Chloride Conductivity, at 30 °C

Concentration (g/l)	Conductivity (ms/cm)
5	9.95
15	27.7
25	44.2
35	59.4
45	73.8
55	87.6
65	100.6
75	112.8
85	124.6
95	135.6

Table 3 Chemical Specification of Sodium Chloride Solutions

Sodium chloride (Assay 99.5% min)	
Maximum limits of Impurities	%
Ammonia	0.002
Iron	0.002
Lead	0.0005
Potassium	0.02
Sulphate	0.02
Molecular weight of Nacl	= 58.44

The Forward Osmosis Process

Figure 2 describes the forward osmosis apparatus used in laboratory of chemical engineering department. The feed and draw solutions were pumped by means of a centrifugal pump (11.4 – 54.6 l/min, 3 – 13.7 m. H, 210 Watt, STUART TURNER LTD. HENLEY ON THAMES ENG, England) to pass through channels of osmosis cell. The flow rate of draw and feed solutions was regulated by means of globe valve connected at the discharge of the pumps, and measure with a calibrated rotameters with range flow (12– 120 l/hr) and (6-60 l/h). Both the draw and feed solutions were held at the same temperature and flow rate during the FO tests. Concentration of heavy metals was measured by digital total dissolved solid (TDS) meter(waterproof TDSTestr High+, range(0-1 * 10^4 mg/l), operating temperature (0-50 °C), accuracy is ±1 % , and Oakton instruments), While, the concentration of draw solution was measured by digital laboratory conductivity meter (inoLab Cond 720, range (0 – 2 * 10^6 µS/cm), operating temperature (0 – 55 ^{o}C), accuracy is ± 0.5% full scale, the electrode material is graphite, and made in Germany (WTW)) and a digital balance was used to measure the samples weight in experiments(Sartorius BP 3015 max. 303 g, d= 0-1 mg). The flat sheet module was designed to serve forward osmosis operation it has two symmetric flow channels on both side of the applied membrane. The dimensions of the cross section: width W = 6 Cm, length L = 19.7 Cm and hight H = 10 Cm. The feed solution and the draw solution flow on same side of a flat sheet membrane. In this study used two types of (TFC) and (CTA). Thin film composite membrane is an aromatic polyamide consisting of three layers: polyester support web, microporous polysulphone interlayer, and ultra thin polyamide barrier layer on the top surface. The specifications of the module are: membrane active area (197 cm^2), salt rejection (96-99%), maximum operating pressure (6.9 Mpa), and maximum operating temperature (113 F). The CTA was specifically developed for FO applications and was a required from Hydration Technologies In. (Albany , OR).The thickness of the membrane is less than 50 μm and the structure of cellulose triacetate (CTA) forward osmosis membrane is quite different from standard reverse osmosis membranes. Reverse osmosis membrane typically consist of a very thin active layer (less than 1 µm) and a thick porous support layer. The specification of the module is: membrane active area (197 cm^2), salt rejection (greater than 95%).

The Reverse Osmosis (RO) process

The draw solution from the forward osmosis process is fed into the reverse osmosis process and the product of the reverse osmosis is two streams, the one stream contains pure water and the other stream contains solution of NaCl concentrate that recirculated to the forward osmosis. The devices used in forward osmosis unit itself was used in reverse osmosis unit, except the selected membrane used a TFC membrane constructed as spiral – wound module instead of plate and frame module. An experimental rig of reverse osmosis unit was constructed in the laboratory as shown schematically in figure 3. Also, in RO we need to high pressure pump (Santoprene and Polyproplene materials, maximum pressure = 120 psi, power = 220 – 240 V, and Current = 1.2 A). To overcome on osmotic pressure for salt NaCl in water.

Experimental Procedure

Forward Osmosis Process

Two types of solution were prepared to run the experiments in the present work. The first is the draw solution which is the solution containing NaCl which was prepared in the QVF glass vessels by dissolving the NaCl salt in 20 liter of deionized water . The second solution is the feed solution which is prepared in the QVF glass by dissolving different amounts of either Lead nitrate or Cadmium nitrate or Nickel chloride to obtain different concentration of heavy metals in 20liter of deionized water. NaCl solution was pumped to one side of the membrane and heavy metals solution was pumped to the other side of the membrane by different pump. The apparatus was designed so that both the draw solution flow and feed solution flow tangent to the membrane in the same direction (Co-current flow).

The steady – state took between 0.5 to 1 hr. In this time the conductivities and concentrations of the feed solution, draw solution, feed solution outlet concentration and draw solution outlet concentration were measured by the conductivity and TDS meters, and the water flux through membrane. The water flux was calculated by dividing the permeate volume by the product of effective membrane area and time.

Reverse Osmosis Process

The diluted draw solution (NaCl-H_2O) exterior from forward osmosis process is sent to a reverse osmosis process in order to separate draw solution into two streams; that is one contains pure water and the other contains solution of NaCl concentrate

After recording the conductivity and concentrations, calculations of required mentioned parameters were reported. The solution was drained through a drain valve. The whole system washed by deionized water, so that it can be ready for next run.

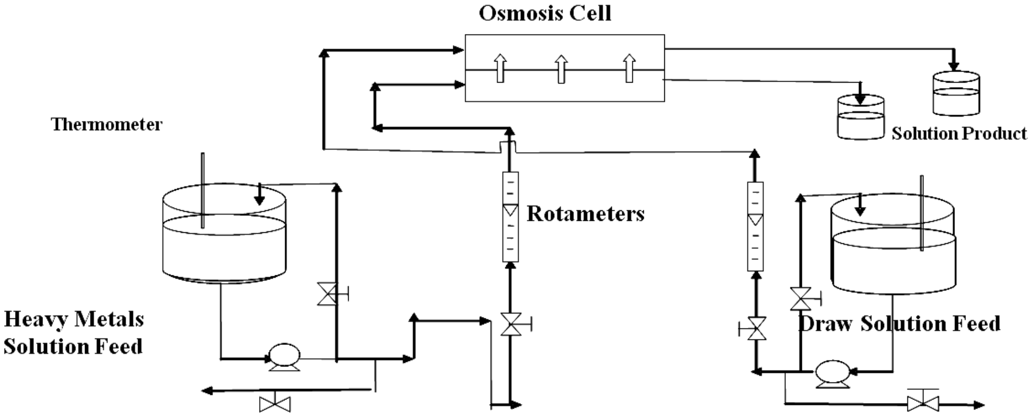

Fig. 2 Schematic Diagram of Forward Osmosis Process

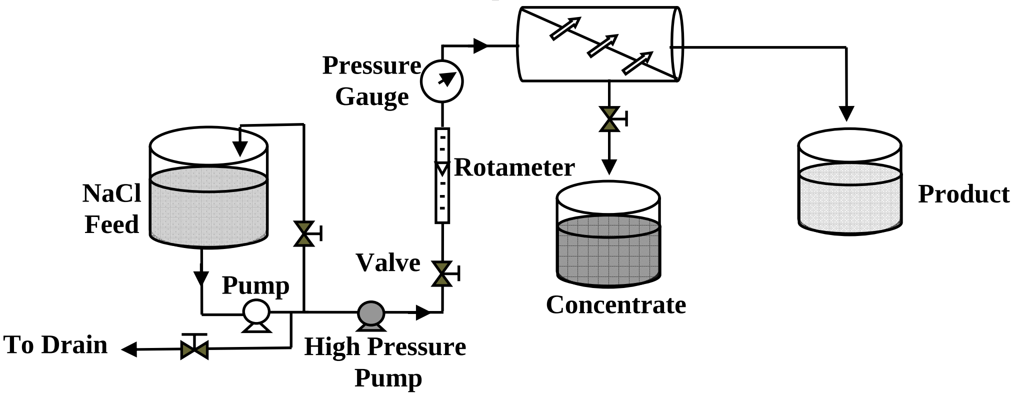

Fig. 3 Schematic Diagram of Reverse Osmosis Process

Results And Discussion

Forward Osmosis Process

Thin Film Composite Membrane

The water flux calculated by dividing the volume of pure water which transfers from feed to draw solution on time and active area of membrane. The water flux increasing with increasing draw solution concentration because the driving force (osmotic pressure of draw solution – osmotic pressure of heavy metals) increased. An increase as demonstrated in Figure 4 for Sodium chloride (NaCl) as draw solution at three types of feed solution. The solution of heavy metals loses quantities of pure water and this leads to increased concentration of heavy metals. The same quantities of pure water transferred across the membrane to the draw solution, as a result, decrease the concentration of draw solution. The effect of draw solution concentration (C_{NaCl} inlet) on draw solution outlet concentration (C_{NaCl} outlet) is shown in Figure 5. Figure 6 show the effect of draw solution concentration (C_{NaCl} inlet) on feed solution outlet concentration (C_{metals} outlet) at three types of feed solution.

By increasing feed solution concentration (C_{metals} inlet), driving force decreases, see figure 7. This appears as a decrease of water flux through the membrane. The water flux decreasing with increasing feed solution concentration because the driving force (osmotic pressure of draw solution – osmotic pressure of heavy metals) decreases for Lead Nitrate ($Pb(NO3)_2$, Cadmium Nitrate ($Cd(NO3)_2$ as feed solution at NaCl draw solution. Osmotic pressure depends on the molecular weight of solute and number of dissociation. The dcrease in water flux resulted from Lead Nitrate ($Pb(NO3)_2$) is larger than Cadmium Nitrate ($Cd(NO3)_2$ and Nickel Chloride ($NiCl_2$) because it has large osmotic pressure (driving force) than (Cd(NO3)2) and ($NiCl_2$). The effect of feed solution concentration on draw solution outlet concentration (C_{NaCl} outlet) is show in figure 8. Figure 9 show the effect of feed solution concentration on feed solution outlet concentration. Increasing the draw solution flow rate (Q_{NaCl}) prevents the concentration buildup in the solution at the vicinity of the membrane surface (support layer), and resulting in decreasing the driving force. Thus, water flux decreased with increasing the flow rate .This is shown in Figures 10.The effect of draw solution flow rate on draw solution outlet concentration (C_{NaCl} outlet) is shown in figure 11. Figure 12 show the effect of draw solution flow rate on feed solution outlet concentration. Increasing the feed solution flow rate prevents the concentration buildup in the solution at the vicinity of the membrane surface (Active layer), leading to increase a driving force($\Delta\pi$).This behavior contradicts the case of increasing the draw solution flow rate. Figures 13 show the effect of feed solution flow rate on water flux for three types of feed solution at NaCl solution. The effect of feed solution flow rate (Qmetals) on draw solution outlet concentration (C_{NaC}l outlet) is shown in figure 14. Figure 15 show the effect of feed solution flow rate on feed solution outlet concentration (C_{metals} outlet).

Cellulose Triacetate Membrane

By increasing the concentration of draw solution, osmotic pressure difference increases and then the driving force increases, this leads to an increase in water flux, inversely when increasing the feed solution concentration osmotic pressure difference ($\Delta\pi$) decreases. This appears as a decreasing in water flow through the membrane. This shown in Figures 16and 17.

The effect of feed and draw solution concentrations on the draw solution outlet concentration and feed solution outlet concentration are shown in Figures 18, 19, 20, and 21. Generally, any membrane consists of two layers: active layer and support layer. In RO which operates at high pressure it needs membrane with very thick support layer to withstand this pressure but FO which operates at low or no hydraulic pressure it needs membrane with very thin support layer. Because CTA membrane has thickness less than that of TFC membrane, it is found that for forward osmosis operation CTA membrane is more suitable than TFC membrane. CTA membrane was designed to operate for forward osmosis operation. This can be shown in Figure 22 where the water flux with CTA without using pressure is higher than TFC with using pressure.

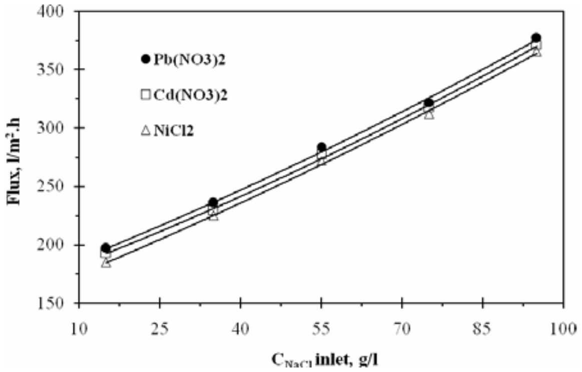

Figure 4 Water flux with draw solution inlet concentration (C_{NaCl} inlet) for different feed solutions (Q_{metals} = 60 l/hr, Q_{NaCl} = 12 l/h, C_{metals} inlet = 150 mg/l, T (feed & draw) = 30 ± 1 °C, P = 0.4 bar).

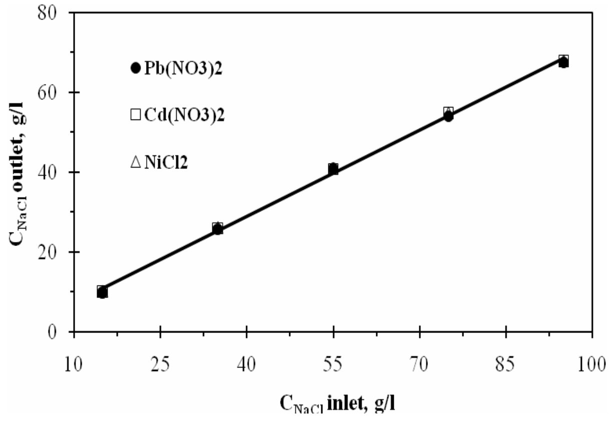

Figure 5 Draw solution outlet concentration (C_{NaCl} outlet) with draw solution inlet concentration (C_{NaCl} inlet) for different feed solutions (Q_{metals} = 60 l/h, Q_{NaCl} = 12 l/h, C_{metals} inlet = 150 mg/l, T (feed & draw) = 30 ± 1 °C, P = 0.4 bar).

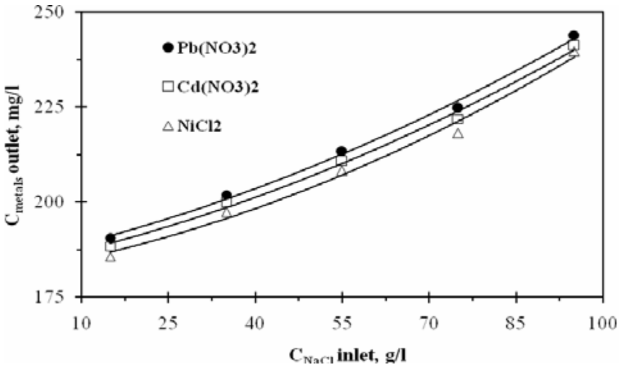

Figure 6 Feed solution outlet concentration (C_{metals} outlet) with draw solution inlet concentration (C_{NaCl} inlet) for different feed solutions (Q_{metals} = 60 l/h, Q_{NaCl} = 12 l/h, C_{metals} inlet = 150 mg/l, T (feed & draw) = 30 ± 1 °C, P = 0.4 bar).

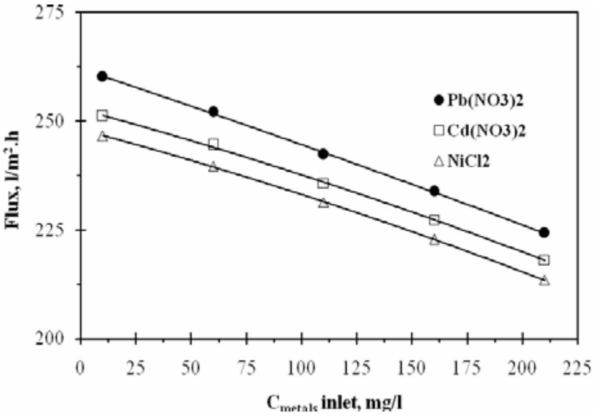

Figure 7 Water flux with feed solution inlet concentration (C_{metals} inlet) for different feed solutions (Q_{metals} = 60 l/h, Q_{NaCl} = 12 l/h, C_{NaCl} inlet = 35 g/l, T (feed & draw) = 30 ± 1 °C, P = 0.4 bar).

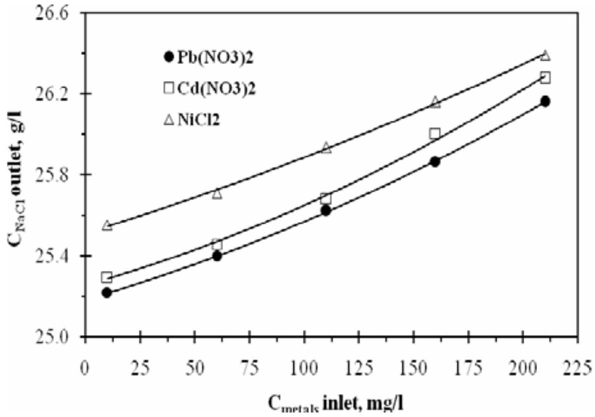

Figure 8 Draw solution outlet concentration (C_{NaCl} outlet) with feed solutions inlet concentration (C_{metals} inlet) for different feed solutions (Q_{metals} = 60 l/h, Q_{NaCl} = 12 l/h, C_{NaCl} inlet = 35 g/l, T (feed & draw) = 30 ± 1 °C, P = 0.4 bar).

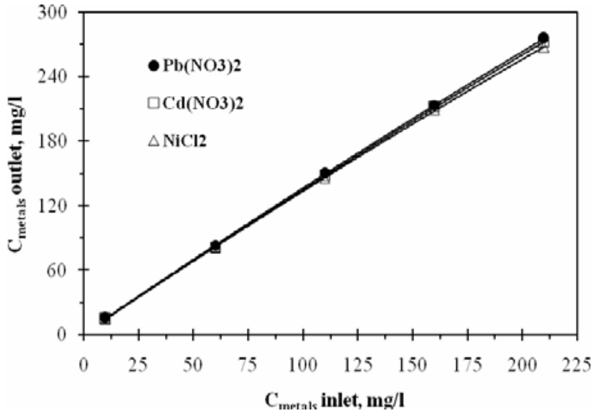

Figure 9 Feed solution outlet concentration (C_{metal} outlet) with feed solution inlet concentration (C_{metals} inlet) for different feed solutions (Q_{metals} = 60 l/h, Q_{NaCl} = 12 l/h, C_{NaCl} inlet = 35 g/l, T (feed & draw) = 30±1 °C, P = 0.4 bar).

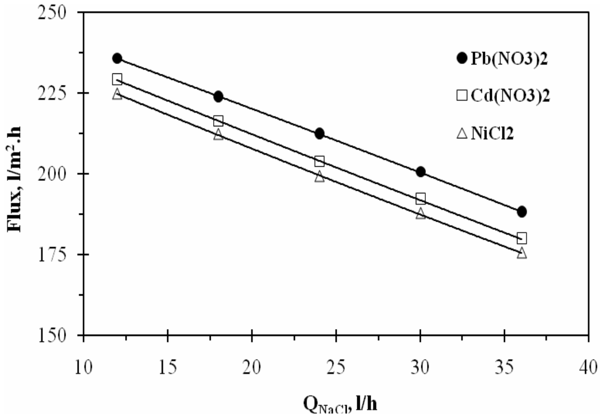

Figure 10 Water flux with draw solution flow rate (Q_{NaCl}) for different feed solution (Q_{metals} = 60 l/hr, C_{metals} inlet = 150 mg/l, C_{NaCl} inlet = 35 g/l, T (feed & draw) = 30 ± 1 °C, P = 0.4 bar).

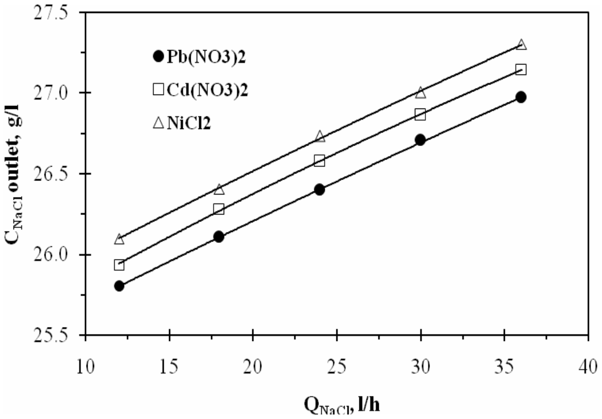

Figure 11 Draw solution outlet concentration (C_{NaCl} outlet) with draw solution flow rate (Q_{NaCl}) for different feed solutions (Q_{metals} = 60 l/h, C_{metals} inlet = 150 mg/l, C_{NaCl} inlet = 35 g/l, T (feed & draw) = 30 ± 1 °C, P = 0.4 bar).

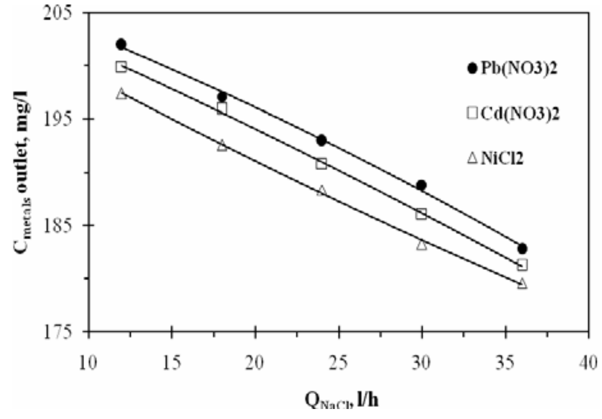

Figure 12 Feed solution outlet concentration (C_{metals} outlet) with draw solution flow rate (Q_{NaCl}) for different feed solutions (Q_{metals} = 60 l/h, C_{metals} inlet = 150 mg/l, C_{NaCl} inlet = 35 g/l, T (feed & draw) = 30 ± 1 °C, P = 0.4 bar).

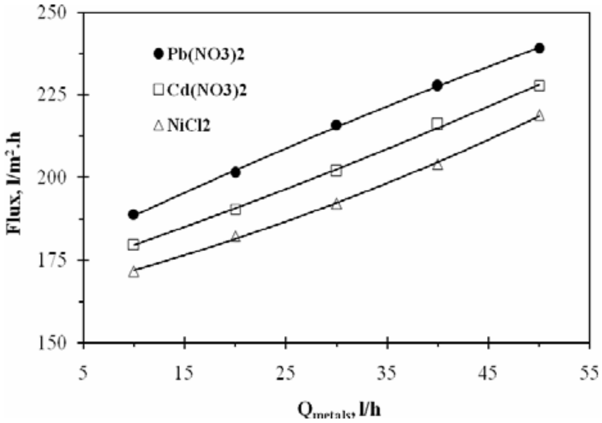

Figure 13 Water flux with feed solution flow rate (Q_{metals}) for different feed solutions (Q_{NaCl} = 12 l/h, C_{metals} inlet = 150 mg/l, C_{NaCl} inlet = 35 g/l, T (feed & draw) = 30 ± 1 °C, P = 0.4 bar)

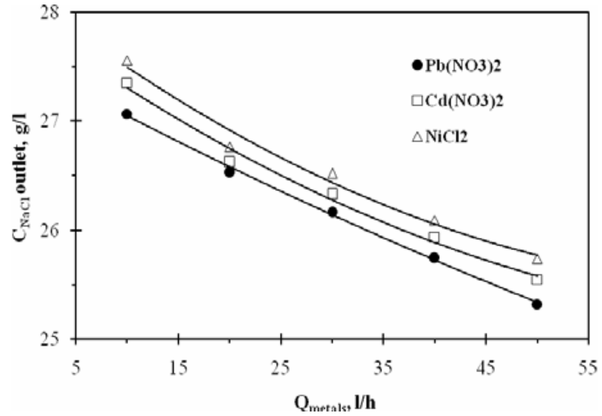

Figure 14 Draw solution outlet concentration (C_{NaCl} outlet) with feed solution flow rate (Q_{metals}) for different feed solutions (Q_{NaCl} = 12 l/h, C_{metals} inlet = 150 mg/l, C_{NaCl} inlet = 35 g/l, T (feed & draw) = 30 ± 1 °C, P = 0.4 bar).

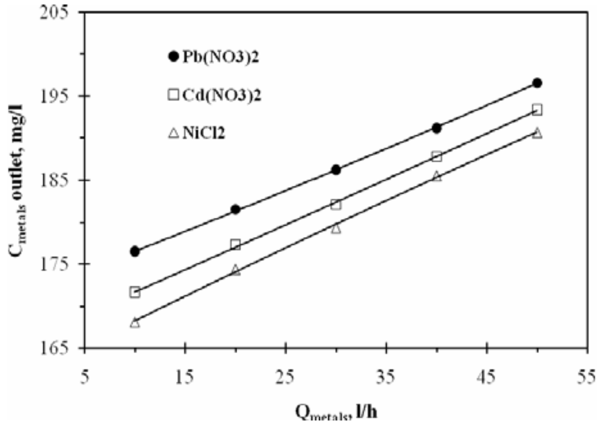

Figure 15 Feed solution outlet concentration (C_{metal} outlet) with feed solution flow rate (Q_{metals}) for different feed solutions (Q_{NaCl} = 12 l/h, C $_{metals}$ inlet = 150 mg/l, C_{NaCl} inlet = 35 g/l, T (feed & draw) = 30 ± 1 °C, P = 0.4 bar).

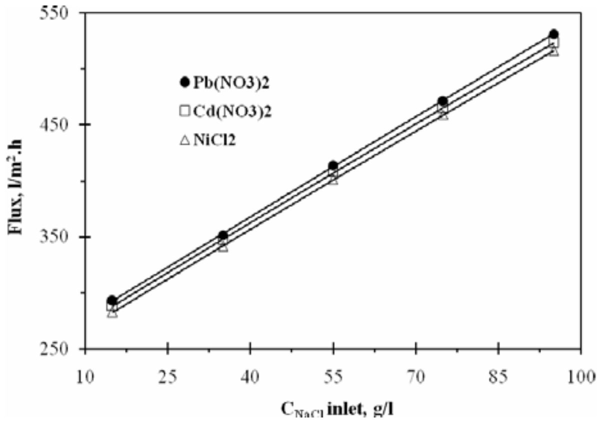

Figure 16 Water flux with draw solution inlet concentration (C_{NaCl} inlet) for different feed solutions (Q_{metals} = 60 l/h, Q_{NaCl} = 12 l/hr, C_{metals} inlet = 150 mg/l, T (feed & draw) = 30 ± 1 °C).

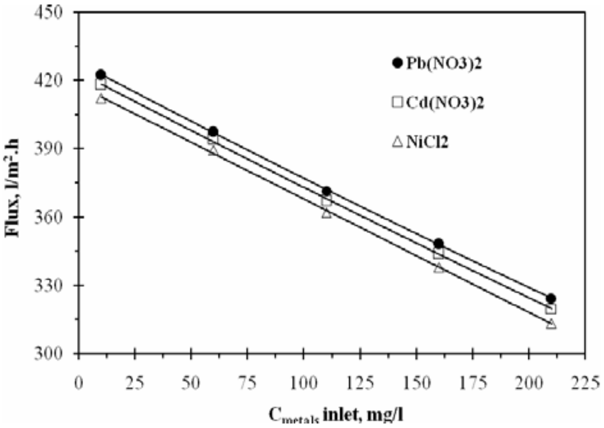

Figure 17 Water flux with feed solution inlet concentration (C_{metals} inlet) for different feed solutions (Q_{metals} = 60 l/h, Q_{NaCl} = 12 l/h, C_{NaCl} inlet = 35 g/l, T (feed and draw) = 30 ± 1 °C).

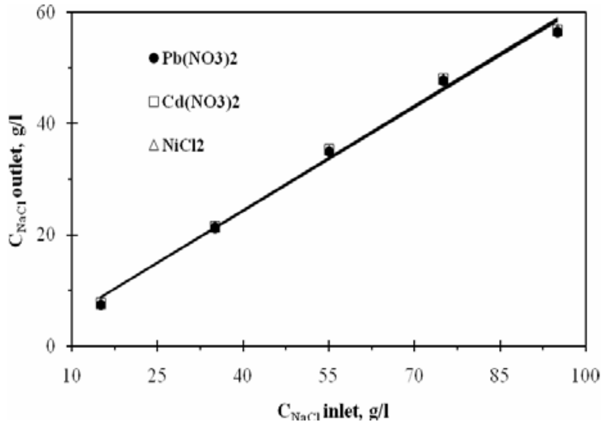

Figure 18 draw solution outlet concentration (C_{NaCl} outlet) with draw solution inlet concentration (C_{NaCl} inlet) for different feed solutions (Q_{metals} = 60 l/h, Q_{NaCl} = 12 l/h, C_{metals} inlet = 150 mg/l, T (feed & draw) = 30°C ± 1).

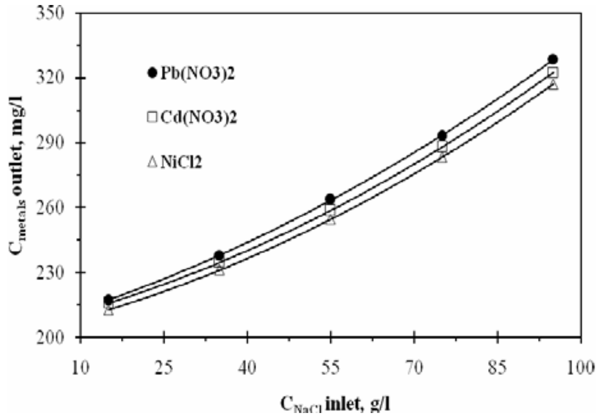

Figure 19 Feed solution outlet concentration (C_{metal} outlet) with draw solution inlet concentration (C_{NaCl} inlet) for different feed solutions (Q_{metals} = 60 l/h, Q_{NaCl} = 12 l/h, C_{metals} inlet = 150 mg/l, T (feed & draw) = 30 ± 1 C).

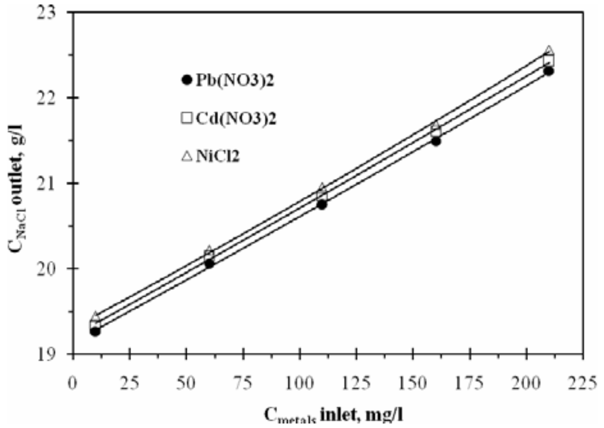

Figure 20 Draw solution outlet concentration (C_{NaCl} outlet) with feed solution inlet concentration (C_{metals} inlet) for different feed solutions (Q_{metals} = 60 l/h, Q_{NaCl} = 12 l/h, C_{NaCl} inlet = 35 g/l, T (feed & draw) = 30 ± 1 °C).

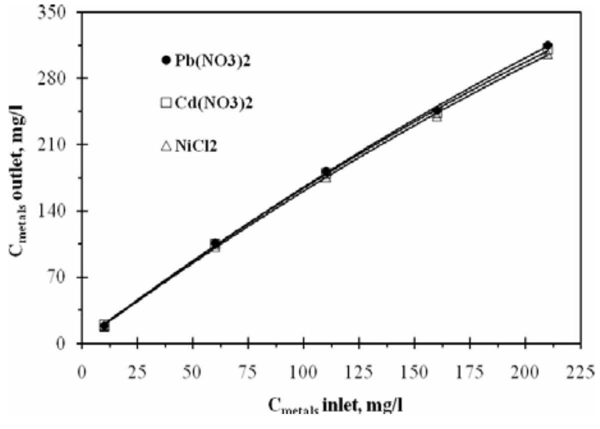

Figure 21 Feed solution outlet concentration (C_{metals} outlet) with feed solution inlet concentration (C_{metals} inlet) for different feed solutions (Q $_{metals}$ = 60 l/h, Q $_{NaCl}$ = 12 l/h, C_{NaCl} inlet = 35 g/l, T (feed & draw) = 30 ± 1 °C).

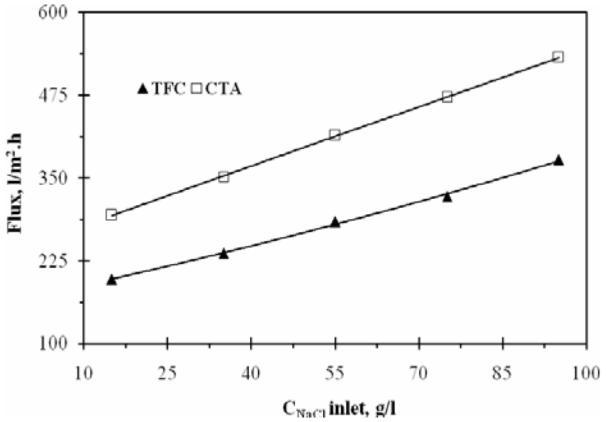

Figure 22 Water flux with draw solution inlet concentration (C_{NaCl} inlet) for $Pb(NO_3)_2$ feed solution and different types of membrane (Q_{metals} = 60 l/h , Q_{NaCl} = 12 l/h , C_{metals} inlet = 150 mg/l, T (feed & draw) = 30 ± 1°C) .

Reverse Osmosis process

Figure 23 illustrates the effect of sodium chloride feed flow rate on water flux. Increasing the brine feed flow rate prevents the concentration build up in the solution at the vicinity of the membrane surface, and result in increasing of driving force (ΔP - $\Delta\pi$). Thus water flux increased with the increase in feed flow rate.

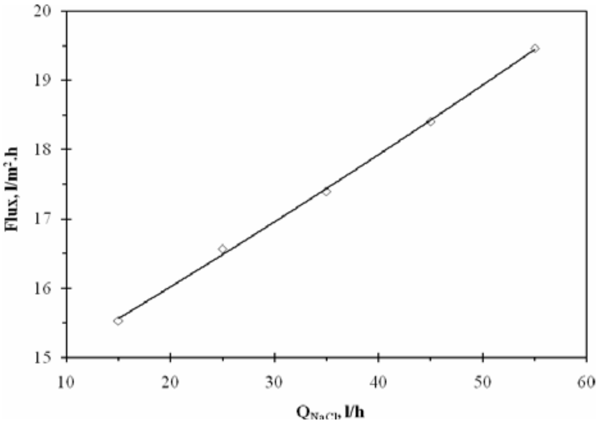

Figure 23 water flux with feed solution flow rate (Q_{NaCl}) (C_{NaCl} inlet = 9000 mg/l, T = 30 ± 1 °C, P = 9.5 bar, pH = 6.5)

Conclusions

The following conclusions could be drawn from the present study:

1- Forward osmosis process is a convenient method and economic for recovery of water from waste water with heavy metals.

2- Different types of heavy metals ($Pb(NO_3)_2$, $Cd(NO_3)_2$ and $NiCl_2$) used as a feed solution and it was found that the order of water flux for this heavy metals was :

$Pb(NO_3)_2 > Cd(NO_3)_2 > NiCl_2$

3- The water flux production from the osmosis cell for TFC and CTA is mainly affected by the increase of concentration of draw solution. The water flux decreases with the increase in flow rate of draw solution and increase when increase in temperature of draw solution.

4- The water flux production from the osmosis cell for TFC and CTA decrease with the increase in concentration of feed solution and increase with the increase in flow rate of feed solution and decrease with increase in temperature of feed solution.

5- Cellulose triacetate (CTA) membrane gave better results than the thin film composite (TFC) membrane. Therefore, CTA membrane prefers more in the forward osmosis process.

6- Reverse osmosis process is a good method to treatment of draw solution to be used again.

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Nomenclature

Symbol	Definition	Units
A	Water Permeability Coefficient	l/bar.m^2.h
B	Solute Permeability Coefficient	m /s
C	Concentration of Solute	g mole/l
C_{Metals}	Feed Solution Concentration	mg /l
C_{NaCl}	Draw Solution Concentration	g /l
D	Diffusivity	m^2/s
d_h	Hydraulic Diameter	m
ECP	External Concentration Polarization	
ICP	Internal Concentration Polarization	
J_W	Water Flux	l/h.m^2
K	Resistance to salt transport in the Porous Support	m/h
k	Mass Transfer Coefficient	m/s
L	Length of the Membrane Channel	m
l	Membrane Thickness	m
P	Pressure	bar
pH	Hydrogen Ion Concentration	
PRO	Pressure – Retarded Osmosis	
Q_{Metals}	Feed Solution Flow rate	l /h
Q_{NaCl}	Draw Solution Flow rate	l/h
Re	Reynolds number	
R_g	Universal Gas Constant	bar.m^3/mol. k
Sc	Schmidt number	
T	Temperature	^{o}C

Greek symbols

Symbol	Definition	Units
Δ	Difference Operator	
ε	Membrane Porosity	
π	Osmotic Pressure	bar
σ	Reflection Coefficient	
τ	Pore Tortuosity	
Φ	Osmotic Coefficient	

Subscript

Symbol	Definition
b	bulk
D	Draw Solution
F	Feed Solution
R	Reject
S	Solute
W	Water