REMOVAL OF HEAVY METALS USING REVERSE OSMOSIS

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ABSTRACT

The aim of this work is to study reverse osmosis characteristics for copper sulfate hexahydrate ($CuSO_4.6H_2O$), nickel sulfate hexahydrate ($NiSO_4.6H_2O$) and zinc sulfate hexahydrate ($ZnSO_4.6H_2O$) removal from aqueous solution which discharge from some Iraqi factories such as Alnasser Company for mechanical industries. The mode of operation of reverse osmosis was permeate is removed and the concentrate of metals solution is recycled back to the feed vessel. Spiral-wound membrane is thin film composite membrane (TFC) was used to conduct this study on reverse osmosis. The variables studied are metals concentrations (50 – 150 ppm) and time (15 – 90 min). It was found that increasing the time results in an increase in concentration of metal in permeate, feed concentration in feed vessel and recovery percent. While, it was found that water flux, rejection percent and mass transfer coefficient is decreasing with increasing operating time. Also, it was found that the permeate concentration and feed concentration in feed vessel increases with increasing feed concentration, on the contrary, water flux, the percentage of recovery, rejection percent and mass transfer coefficient decreases with increasing the concentration of feed solution. The maximum rejection of copper, nickel, and zinc salts are 96.6%, 95.7% and 98.2% respectively. The maximum recovery percentage of copper, nickel, and zinc salts are 40.8%, 41.35% and 38.44% respectively. The pure water permeability constant was calculated for TFC membrane.

Key words: reverse osmosis, heavy metal, copper, nickel, zinc.

ازالة المعادن الثقيلة باستخدام التناضح العكسي

الخلاصة

ان هدف هذا البحث هو دراسة خواص التناضح العكسي عند ازالة المعادن (سلفات النحاس المائية، سلفات النيكل المائية، سلفات الخارصين المائية) من المحاليل المائية التي تطرحها بعض مصانع العراق مثل شركة النصر للصناعات الميكانيكية. ان اسلوب التشغيل للتناضح العكسي هو ازالة الماء النقي والماء المركز بالمعادن الثقيلة ليتم ارجاعه الى خزان اللقيم الرئيسي. تم استعمال غشاء اللف الحلزوني وهو غشاء رقيق لهذا النوع من الدراسة ، وان المتغيرات التي استعملت هي تراكيز المعادن (50-150 جزء بالمليون) و الزمن (15 – 90 دقيقة) . لقد وجد ان زيادة الزمن يؤدي الى زيادة تركيز المعدن في الماء النقي وزيادة التركيز في خزان اللقيم الرئيسي وزيادة نسبة الاسترجاع ، بينما لقد وجد ان معدل جريان الماء ونسبة الرفض ومعامل انتقال الكتلة يقل بزيادة الزمن. كذلك وجد ان تركيز الماء النقي وتركيز المعادن في خزان اللقيم الرئيسي يزداد بزيادة تركيز المعادن ، على العكس من ذلك فان معدل جريان الماء ونسبة الاسترجاع ونسبة الرفض ومعامل انتقال الكتلة تقل بزياده تركيز المعادن في اللقيم. وان اكبر معدل رفض لاملاح النحاس والنيكل زالخارصين هو 96,6%، 95,7% و98,2% على التوالي . ووجد ان اكبر استرجاع للنحاس والنيكل والخارصين هي 40.8%، 41.35% و 38.44% على التوالي.تم ايضا حساب معامل نفاذية الماء النقي للغشاء المستعمل.

INTRODUCTION

Heavy metals are one of the most important sources of environmental pollution. Some of them can form compounds which are toxic even in very low concentration (Srisuwan and Thongchai, 2002). Some of these compounds may suppress the immune system, leading to increase susceptibility to disease while others may be carcinogenic (Crespo et al., 2004).

Membrane technology has become increasingly promising in removing heavy metals from wastewater and improving water recovery rate due to its high efficiency and low cost (Liu et al., 2008). Huge improvements have been made in recent years, and the utilization of membrane technology has dramatically increased in potable water treatment. It is expected that membrane processes will be used more and more in the future as well as more stringent drinking water quality standards will likely become enforced. Therefore, Membrane processes such as microfiltration (MF), ultrafiltration (UF), nanofiltration (NF) and reverse osmosis (RO) are increasingly being applied for treating wastewater (Syed et al.,2000). Microfiltration and ultrafiltration used as pretreatment for nanofiltration and reverse osmosis processes. Membrane separation processes have been found greatly used in industrial applications as an alternative to thermal separation process. Some of the advantages of membrane process are low energy consumption, high product quality, and, flexible design and installation. Seawater desalination, waste reduction, food processing, biotechnology and medical applications are some of the processes where membranes are used (Cheryan., 1998).

Reverse osmosis is a hyperfiltration process which allows the removal of particles such as metals, bacteria, salts, sugars, proteins, particles, dyes, and other constituents that have a molecular weight of greater than 150-250 daltons (Ghulam, 2007). Reverse osmosis (RO) is a pressure driven process similar to conventional filtration processes but using a much tighter filter or membrane. Reverse osmosis (RO) involves separating water from a solution of dissolved solids by forcing water through a semipermeable membrane. As pressure is applied to the solution, water and other molecules with low molecular weights pass through micropores in the membrane (Sourirajan, 1970 and Fazilet, 2000). Larger molecules, such as organic dyes and metal, are retained by the membrane (Patrick, 1976 andNes et al., 2008). This process (RO) found a broad application in the desalination of sea and brackish water. It is applied to purify water for laboratory use and is very promising as a pre-concentration technique in trace and environmental analysis (Belkacem et al., 2008).

Howard (1973) showed that heavy metal removal increases with increasing temperature of feed solution in the reverse osmosis process. Removal percentage also increases with operation time of the system until reaching steady value. He also proved that the percentage of removal of heavy metals would vary this variation due to the metal's ability or inability to form complex ion structures which would be retained by the membranes. Oh et al., (2000) applied reverse osmosis and nanofiltration membrane processes for the treatment of arsenic contaminated water applying low pressure by using pump, they concluded that low-pressure nanofiltration with pre-oxidation or reverse osmosis with a pump device could be used for the treatment of arsenic contaminated groundwater in rural areas. Myzairah (2007) showed the importance of operating pressure in determining the permeate flux in reverse osmosis process, even for low pH and feed concentration of the feed solutions. The higher the operating pressure, the higher the permeate flux. His results showed that the feed concentration of copper chloride and pH were the most important factors in determining the significant parameters for the percentage of copper removal. It can be summarized that the higher the feed concentration of copper and pH, the higher the percentage of copper removal.

The present study includes application of reverse osmosis process to recovery of water from wastewater by heavy metals. Membrane used in this work was polyamide (thin film composite (TFC)) membrane. The effect of time and feed solution concentration on recovery percentage, water flux, product concentration of metals, rejection percentage and mass transfer coefficient have been determined.

Rejection Percentage

The measure of membrane selectivity is solute rejection, the ratio of solute rejected by a membrane to the solute in the feed. It is the most common method of evaluating a membrane's ability to separate solute, because the determination is simple and can be done as accurately in the field as in the laboratory (Hasan 2008 and Yip et al., 2010).

$$R\% = \left(\frac{C_F - C_P}{C_F} \right) \times 100 \qquad (1)$$

Where C_F is the concentration of a specific component in the feed solution to the membrane process and C_P is the concentration of the same specific component in the product stream leaving the membrane system.

RECOVERY PERCENT

The recovery rate (Y%) is a measure of efficiency of reverse osmosis system and can be calculated by

Y% = (volume of treated water produced/total volume of feed water) *100 (2)

TRANSPORT EQUATION FOR REVERSE OSMOSIS PROCESS

Reverse osmosis models can be divided into three types: irreversible thermodynamics models (such as Kedem-Katchalsky and Spiegler-Kedem models); nonporous or homogeneous membrane models (such as the solution-diffusion, solution-diffusion-imperfection, and extended solution-diffusion models); and pore models (such as the finely-porous, preferential sorption capillary flow, and surface force-pore flow models). The transport models focus on the top thin skin of asymmetric membranes or the top thin skin layer of composite membranes since these determine fluxes and selectivities of most membranes (Bhattacharyya and Williams, 1992). Also, most of the membrane models assume equilibrium (or near equilibrium) or steady state conditions in the membrane.

The transport of solvent water (N_B) through the porous membrane is proportional to the effective pressure, and that of the solute is due to pore diffusion and hence proportional to its concentration difference across the membrane (Taha, 2000).

The solvent flux is calculated according to the following equation

$$N_B = A\left[P - \{\pi(X_{A2}) - \pi(X_{A3})\}\right] \qquad (3)$$

Where N_B is the solvent flux, P is the applied pressure, $\pi(X_{A2})$ and $\pi(X_{A3})$ represent the osmotic pressure corresponding to mole fraction of solute X_{A2} at membrane surface and X_{A3} in permeate respectively. A is defined as a pure water permeability constant which is obtained independently from the pure water permeation data with the use of the following relation

$$A = \frac{N_{BP}}{P} \quad (\Delta\pi=0) \qquad (4)$$

Where N_{BP} is the pure water permeation rate with pure water as the feed as shown in figure 1. Concerning the solute permeation rate N_A, a simple diffusion (solution-diffusion model) equation is assumed as:

$$N_A = \frac{c_m . D_{AM}}{\delta}(X_{AM2} - X_{AM3}) \qquad (5)$$

Where D_{AM}, X_{AM} and c_m are the diffusivity, mole fraction and molar density of solute in the membrane respectively, and δ is the effective thickness of the membrane. If the distribution ratio of solute between the aqueous solution and the membrane is assumed constant, then:

$$c.X_A = K.c_M X_{AM} \qquad (6)$$

Where K is constant. And equation (5) becomes

$$N_A = \frac{c_M . D_{AM}}{K\delta}(X_{A2} - X_{A3}) \qquad (7)$$

We assume that the total molar density of the solution ,c, is constant throughout the module. Further, the linear relations express osmotic pressures

$$\pi(C_{A2}) = bC_{A2} = bcX_{A2} \ ,$$
$$\pi(C_{A3}) = bC_{A3} = bcX_{A3} \qquad (8)$$

Where b is osmotic pressure constant

Since

$$X_{A3} = \frac{N_A}{N_A + N_B} \qquad (9)$$

Substituting equation (9) in equation (7)

$$N_B = \frac{c_M . D_{AM}}{K\delta} . \frac{(1 - X_{A3})}{X_{A3}} .(X_{A2} - X_{A3}) \qquad (10)$$

Now we want to examine the concentration of solute in the near neighborhood of the membrane, on the high-pressure side figure (1).

The flux of solute (species A) in the region $0<z<\ell$ may be written as the sum of the convective and diffusive fluxes.

$$N_A = X_A(N_A + N_B) - D_{AB} c \frac{dX_A}{dZ} \qquad (11)$$

Where D_{AB} is the diffusivity of solute in the aqueous feed solution. Using equation (9), and in integrated equation (11) with a boundary conditions

When $z=0$, $X_A=X_{A1}$

And $z=\ell$, $X_A=X_{A2}$

Solving the simple differential equation (11) with the above boundary conditions

$$\ln\frac{X_{A2}-X_{A3}}{X_{A1}-X_{A3}}=\frac{N_A+N_B}{c}\cdot\frac{\ell}{D_{AB}} \qquad (12)$$

Defining the mass transfer coefficient k_1 , on the high pressure side of the membrane.

$$k_1=\frac{D_{AB}}{\ell} \qquad (13)$$

Equation (12) can be written as

$$\ln\frac{X_{A2}-X_{A3}}{X_{A1}-X_{A3}}=\frac{N_A+N_B}{k_1 c} \qquad (14)$$

Equation (3) , (10) and (14) are combined to give the following relations

$$N_B=k_1 c(1-X_{A3})\ln\frac{X_{A2}-X_{A3}}{X_{A1}-X_{A3}} \qquad (15)$$

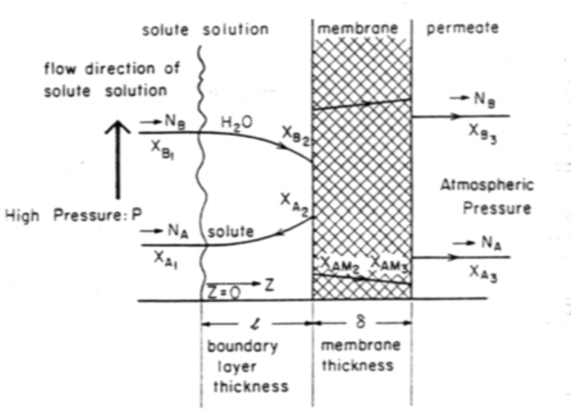

Fig.1 Concentration distribution in the boundary layer and the membrane (Ahmed ,2000)

EXPERMEMTALS

Materials

The salt solution of Copper sulfide hexahydrate, Nickel sulfide hexahydrate, and Zinc sulfide hexahydrate were used as heavy metals solution in this study. The chemical analysis of the solutions are given in Table 1.

Table 1 Chemical Specification of Feed Solutions

Substance	Properties
Copper sulfide hexahydrate, $CuSO_4.6H_2O$, M.W: 267.68 fluka,Switzerland.	Assay 96% min. Max. limits of impurities (%) Free acid: 0.2% As: 0.0005% Pb: 0.001% Fe: 0.005% CD: 0.005% Chloride: 0.001% Cu: 24.96% Zn: 0.001% Ni: 0.0005%
Nickel sulfide hexahydrate, $NiSO_4.6H_2O$, M.W:262.86 fluka,Switzerland.	Assay 99.7% min. Max. limits of impurities (%) Mg 0.005% Ca 0.005 % Zn 0.0005% Pb 0.0005% Fe 0.0005% Cu 0.0005%
Zinc sulfide hexahydrate, $ZnSO_4.6H_2O$,269.54 fluka,Switzerland.	Assay 99% min. Max. limits of impurities (%) Arsenic 0.008% Cu 0.013% Cl 0.02%

Reverse Osmosis Membrane

Commercially marketed spiral-wound membrane elements are adopted in this research. The membrane used in spiral wound module is a thin film composite membrane consisting of three layers: a polyester support web (120 µm), a microporous polysulfone interlayer (40 µm), and an ultra thin polyamide barrier layer (0.2 µm) on the top surface. Each layer is tailored to specific requirements.

Table 2 The specifications of the module

Type	SSRO50G
Membrane Type	Thin film composite (TFC)
Membrane length	115 cm
Membrane width	21cm
No. of membrane	2
Membrane active area	4830 cm^2
Metals rejection	=96 – 99 %

Experimental Procedure

Feed solution was prepared in the QVF glass vessels by dissolving each metal in 25 liter of demineralized water (2 – 3 mg/l), and then the outlet valve of the feed vessel was opened to let the solutions fill the whole pipes of the system. The feed solution drawn from the feed vessel 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 reverse osmosis pump. Then the solution is introduced into the spiral-wound RO elements by means of a high pressure pump (santoprene and polypropylene materials, maximum pressure = 120 psi, power = 220 – 240 V, and current = 1.2 A). Through reverse osmosis, water transports from the solution across the metals rejecting membrane and into the product solution as shown in figure 2.

In reverse osmosis a certain fraction of the feed passes across the membrane to produce permeate. The feed is gradually concentrated and leaves the system at a higher concentration; the concentrate stream out of the module is directed back to the feed vessel of the module (or stage) and mixed with the feed stream. Every 15 minutes the concentrations of the feed solution, reject solution (concentrate) and product solution were measured by TDS meters (Type Waterproof TDS Test r High+, Range (0 – 1 * 10^4 p.p.m), operating temperature (0 – 50^oC), Accuracy (± 1%) power supply (6 Volt), Oakton instruments), and the flow rate of the product (permeate) solution for each run was recorded. The water flux was calculated by dividing the permeate volume by the product of effective membrane area and time. After recording the results, the solution (remaining in feed vessel), was drained by means of a drain valve. The whole system was washed by distilled water.

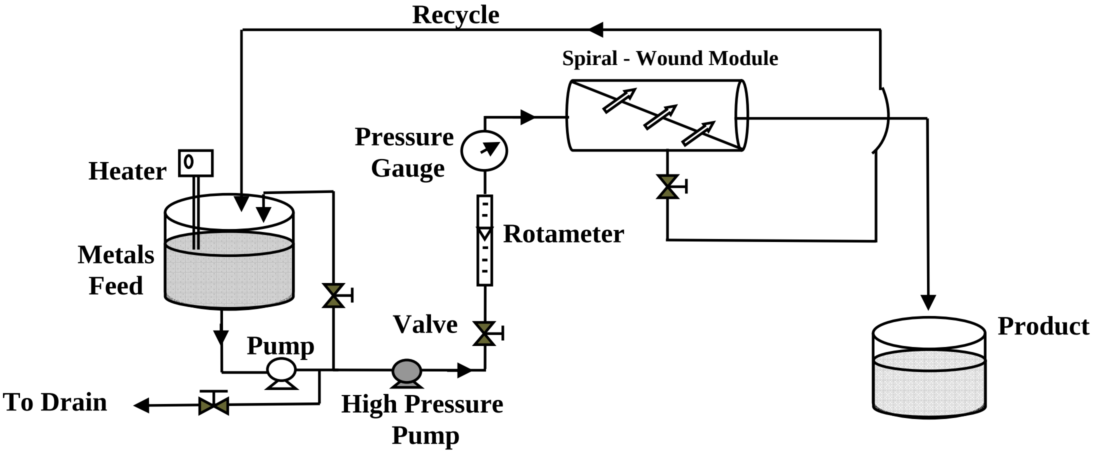

Fig .2 Schematic Diagram of Reverse Osmosis Process

RESULTS AND DISCUSSION

MEMBRANE HYDRAULIC PERMEABILITY

The pure water permeability constant (A) is a fundamental quantity; it is a measure of the overall porosity of the film. Water permeability was experimentally determined using a hydraulically pressurized reverse osmosis (RO) process. The flux of pure water through each membrane was determined under a range of pressures, according to the following equation:

$$N_{BP} = A\,\Delta P \quad , \quad (\Delta\pi = 0) \qquad (4)$$

Where N_{BP} is the pure water permeation rate with pure water as the feed, the result of this hydraulic permeability test is shown in figure (3). As expected, the data show a linear relationship between driving force and water flux. Membrane hydraulic permeability is determined from the slope of this curve, the value of A was obtained 2.713 $l.bar^{-1}\,m^{-2}.hr^{-1}$ and this value is very closely approximate the result of Ahmed (2000).

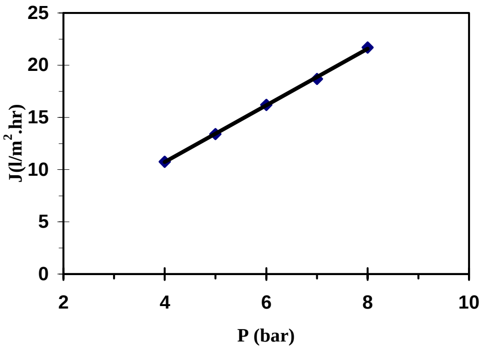

Fig.3 Water Flux vs. Operating Pressure

Effect of Operating Time

Effect of Operating Time and Feed Concentration on Product Rate

The water flux rate from reverse osmosis unit are plotted vs. time, as shown in figure (4 - 6). It can be easily observed that the flow rate from reverse osmosis unit decrease with increase in operating time.

The product rate of a reverse osmosis system decrease as fouling occurs, because the foulants on the membrane surface retard the back diffusion of the salt into the bulk solution to cause concentration polarization at the membrane surface. The increase in concentration polarization causes a decrease in the product rate. This can be explaining the decreasing of product rate with increase operating time, this observation is well agreed with the results of Mohammed and Salaheddin (2007). It can easily observed that the product rate decreases while the feed concentration is increasing and this is due to the possibility of fouling inside the pores of membrane would be larger in case of the concentrated solution flowing, this fouling could be acting in two ways. First, blockage a number of bores completely or partly, so the flow would be decreased, and the second decrease the voidage which increased the osmotic pressure across the membrane and that also would be decreased the product rate, this observation is well agreed with the results of Ahmed (2000) .

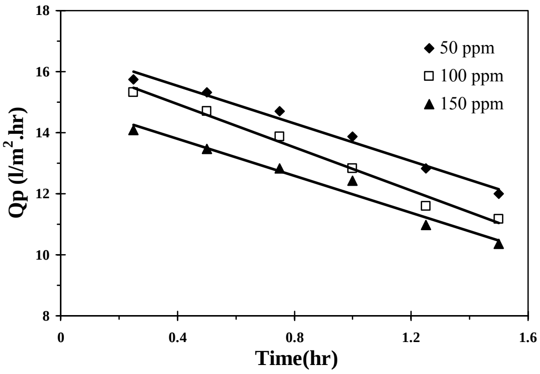

Fig. 4 Product Rate of Cu vs. Time for Reverse Osmosis Unit.

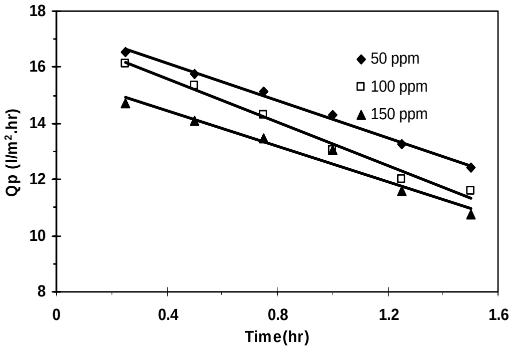

Fig. 5 Product Rate of Ni vs. Time for Reverse Osmosis Unit.

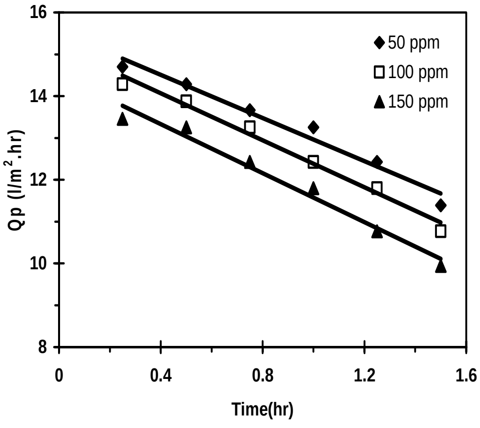

Fig. 6 Product rate of Cu vs. Time for Reverse Osmosis Unit.

Effect of Operating Time on Product Metal Concentration

Figure (7 - 9) shows the effect of operating time on product metal concentration for reverse osmosis industrial unit.

The increase in concentration polarization causes an increase in the salt passage. This reason can be explain the increase metal concentration with increase in operating time and this observation is well agreed with the result of

Kavitskaya et al. (2000). The minimum product concentration at 50 ppm , for copper, nickel and zinc were 2,2.5 and 1 mg/l respectively. While, at 100 ppm for copper, nickel and zinc were 5.3,5.5 and 4.2 mg/l respectively. At the concentration150 ppm, for copper, nickel and zinc were 8.4,8.7 and 7.4 mg/l respectively.

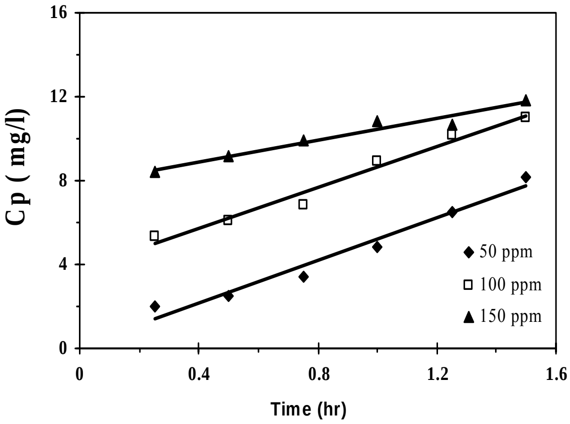

Fig. 7 Product concentration of copper vs. Time for Reverse Osmosis Unit

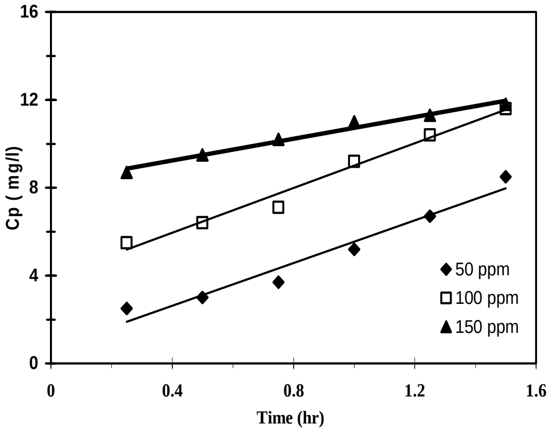

Fig.8 Product concentration of Nickel vs. Time for Reverse Osmosis Unit

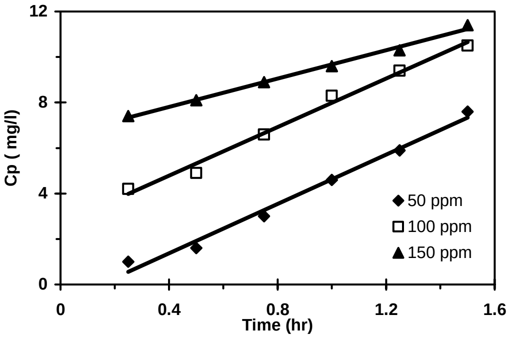

Fig.9 Product concentration of Zinc vs. Time for Reverse Osmosis Unit

Effect of Operating Time on Feed Solute Concentration

As shown in figures (10 - 12) during feed passage across the membrane to produce permeate, the feed concentrated gradually. The concentrate stream is directed back to the feed this cause an increase in feed concentration, the maximum feed solute concentration at 50 ppm, for copper, nickel and zinc were 89.2, 89.4 and 88.1 mg/L respectively. While, at 100 ppm, for copper, nickel and zinc were 139.7, 140.1 and 138.5 mg/L respectively. At the concentration150 ppm, for copper, nickel and zinc were 182.8, 183, and 181.4 mg/L respectively.

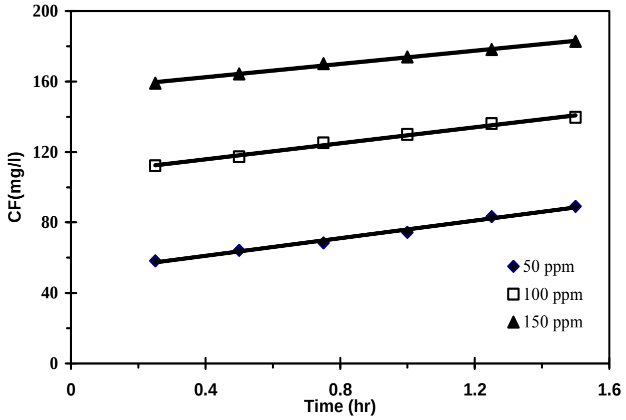

Fig. 10 Feed Concentration of Cu vs. Time for Reverse Osmosis Unit.

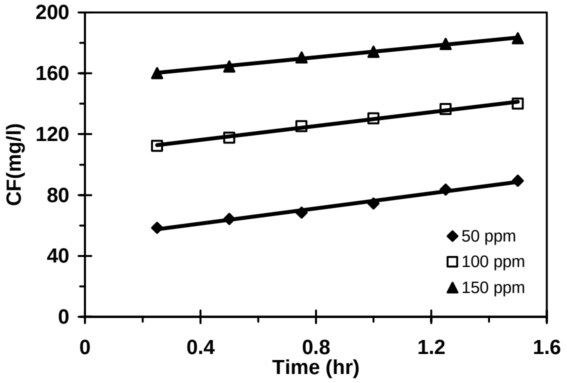

Fig. 11 Feed Concentration of Ni vs. Time for Reverse Osmosis Unit.

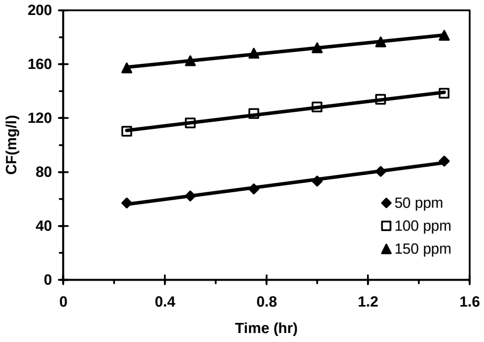

Fig. 12 Feed Concentration of Zn vs. Time for Reverse Osmosis Unit.

Effect of Operating Time on water recovery

As shown in figures (13 –15) the recovery at 50 ppm, for copper, nickel and zinc were 7.6-40.8 ,7.7-41.4 and 7.1-38.4 % respectively. While, at 100 ppm, for copper, nickel and zinc were 7.4-38.4, 7.5-38.9 and 6.8-35.1%respectively. At the concentration150 ppm, for copper, nickel and zinc were 6.8-35.8, 7.1-37.2, 6.5-34.6 % respectively. According to equation (2) the increase in percentage recovery with increase in time is due to an increase in the volume of pure water transfer from feed solution across the membrane to the permeate and this observation is well agreed with the result of Bruce., et al (2008).

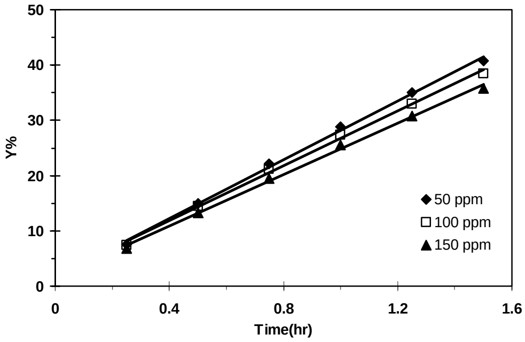

Fig. 13 Recovery percent vs. Time for Reverse Osmosis Unit for Cu.

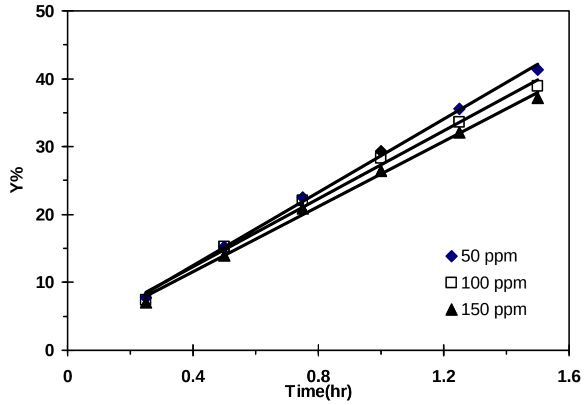

Fig. 14 Recovery percent vs. Time for Reverse Osmosis Unit for Ni.

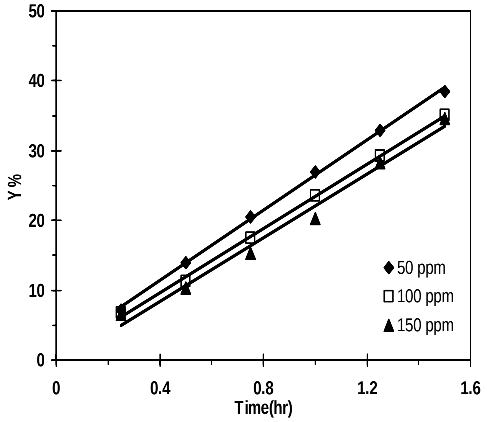

Fig. 15 Recovery percent vs. Time for Reverse Osmosis Unit for Zn.

Membrane metals rejection

Figures (16 – 18) show the influence of operating time on rejection percentage, that was studied by increasing operating time from 15, 30, 45, 60, 75 to 90 minutes with operating pressure fixed at 5.5 bar. According to equation(1) the increase in metals concentration will decrease the rejection percentage, this is due to the layer formed on the membrane surface hinders the back diffusion of the metals from the membrane surface back to the bulk solution. Consequently, created a larger concentration prepared for its diffusion across the RO membrane and this observation is well agreed with the results by How and Menachem (2004).

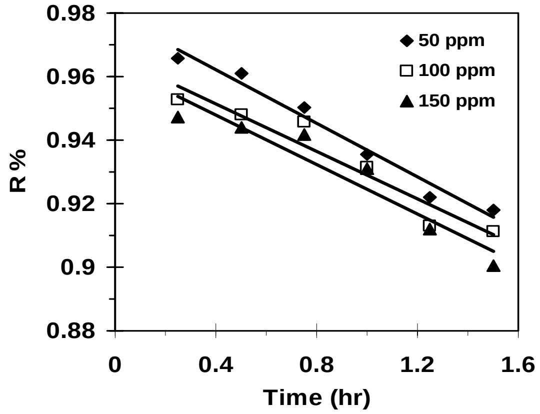

Fig. 16 Cu rejection percent vs. Time for Reverse Osmosis Unit.

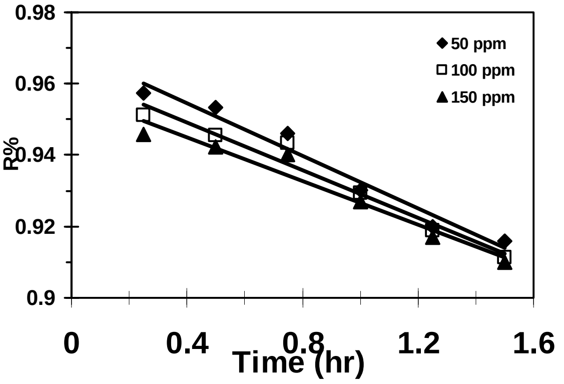

Fig. 17 Ni rejection percent vs. Time for Reverse Osmosis Unit .

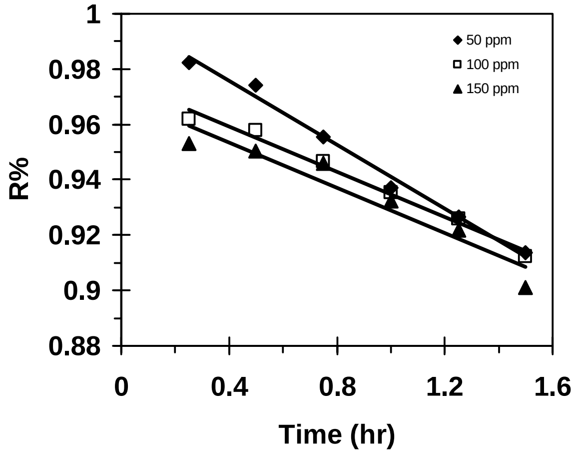

Fig. 18 Zn rejection percent vs. Time for Reverse Osmosis Unit for Zn.

Effect of Time and Feed Concentration on Mass Transfer Coefficient

The value of k1 can be obtained as function of operating pressure and feed concentration. It is calculated according to the following equations:

$$N_B = A\left[P - \{\pi(X_{A2}) - \pi(X_{A3})\}\right] \qquad (3)$$

And

$$N_B = k_1 c(1 - X_{A3}) \ln \frac{X_{A2} - X_{A3}}{X_{A1} - X_{A3}} \qquad (15)$$

As shown in figures (19 – 21) the metal permeability decreases with increasing the metal concentration according to the above equations, as time is increasing the feed concentration increases and this will lead to decreases in metal permeability. The mass transfer coefficient for the metals are very closely related because of their approximate molecular weight, the mass transfer coefficient at 50 ppm for copper, nickel and zinc were (11.4-4.3, 10.9-5.3 and 11-5) $*10^{-7}$ m/s respectively. While, at 100 ppm, for copper, nickel and zinc were (9.3-4, 9.1-4.1 and 9-3.9) $*10^{-7}$ m/s respectively. At the concentration 150 ppm, for copper, nickel and zinc were (8.7-3.7, 8.5-3.4 and 8.5-3.4) $*10^{-7}$ m/s. Water flux decreases with increasing feed solute concentration since the higher concentrations result in larger osmotic pressures (and so a smaller driving force across the membrane). This behavior is also predicted by most of the transport models and this observation agreed with results by Michael (2003).

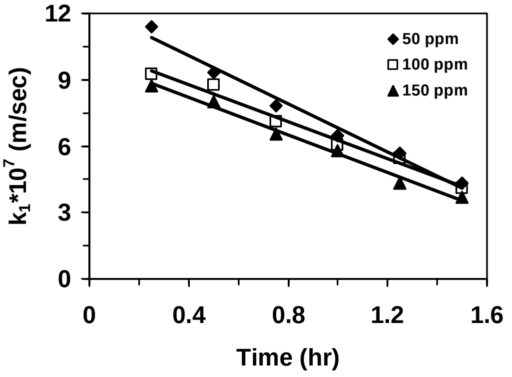

Fig.19 Mass transfer coefficient for Copper vs. time

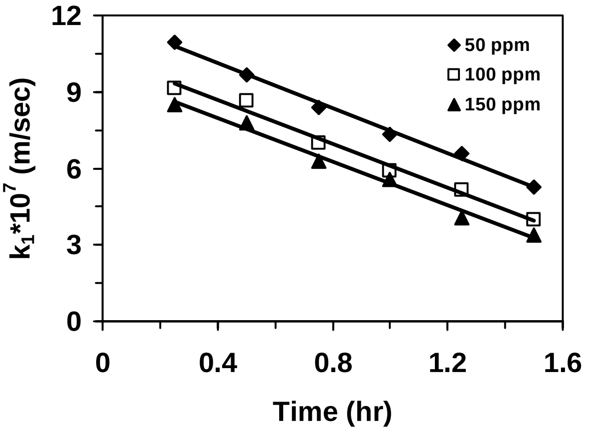

Fig.20 Mass transfer coefficient for Nickel vs. time

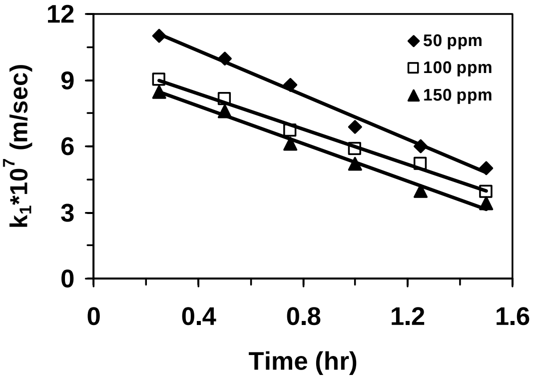

Fig.21 Mass transfer coefficient for Zinc vs. time

CONCLUSION

- The reverse osmosis process gives a high efficiency in separating metals.
- The increases in time cause an increase in metal passage.
- Flow rate of permeate from reverse osmosis unit decreases with increasing in operating time.
- The rejection of metals decreases with increasing time and also the increase in feed metals concentration will decrease the rejection percentage.
- The maximum recovery of copper, nickel, and zinc are 40.8%, 41.35% and 38.44 respectively.
- The maximum Rejection of copper, nickel, and zinc are 96.6%, 95.7% and 98.2% respectively.
- The difference in molecular weight for metals affects the water flux in RO process. Therefore, the results are closely related due to the nearest molecular weight for each metal.
- The pure water permeability constant for TFC membrane is 2.713 gmol $H_2O.bar^{-1}$ $m^{-2}.sec^{-1}$
- Mass transfer of permeate decreases with the time operation.

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NOMENCLATURE

Symbol	Definition	Units
ℓ	Boundary layer thickness	M
ΔP	Transmembrane pressure	Bar
A	Pure water permeability constant	l/(m^2.hr.bar)
B	Osmotic pressure constant	
C	Molar density of solution	gmol .Cm^{-3}
CA_1	Solute concentration inlet	p.p.m
$CA_2=C_m$	Solute concentration in the membrane	p.p.m
CA_3	Solute concentration in the product solution	p.p.m
C_f	Feed concentration	Ppm
C_P	Product concentration	Ppm
D_{AB}	Diffusivity of solute in the aqueous feed solution	M^2. Sec^{-1}
D_{AM}	Diffusivity of solute in membrane	m^2. Sec^{-1}
J	Permeation flux	l/m^2.h
K	Constant	
k_1	Mass transfer coefficient	m.sec^{-1}
N_A	Solute flux through membrane	gmol.m^2. sec^{-1}
N_B	Solvent flux through membrane	gmol.m^2. sec^{-1}
N_B	Solvent flux through membrane	gmol.m^2. sec^{-1}
N_{Bp}	Solvent Flux using pure water as feed	gmol.m^2. sec^{-1}
P	Applied pressure	Bar
Q_p	Product flow rate	l/h
R	Rejection	
t	Time	H
X_{A1}	Solute mole fraction in the bulk solution.	
X_{A2}	Solute mole fraction in the membrane.	
X_{A3}	Solute mole fraction in the product solution.	
X_{AM}	Mole fraction of solute on the membrane	
Y	Recovery percent	

Greek symbols

Symbol		Units
δ	Membrane Thickness.	M
π	Osmotic Pressure	Bar