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DRINKING WATER FROM DESALINATION OF SEAWATER: OPTIMIZATION OF REVERSE OSMOSIS SYSTEM OPERATING PARAMETERS

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Abstract

This paper reports on the use of pilot scale membrane separation system coupled with another pilot scale plate heat exchanger to investigate the possibilities of sweetening seawater from Telok Kalong Beach, Terengganu, Malaysia. Reverse osmosis (RO) membrane of a surface area of 0.5 m^2 was used during the experimental runs. Experiments were conducted at different transmembrane pressures (TMP) ranged from 40 to 55 bars, operation temperature ranged from 35 to 45^{o}C, feed concentration (TDS) ranged from 34900 to 52500 ppm and cross flow velocities ranged from 1.4 to 2.1 m/s. The result show that the flux values increased linearly with TMP as well as sodium ion rejection. Permeate flux values increased proportionally with the temperature and the later effect was more significant at high pressures. The temperature changing has also influenced the rejection of sodium ion. The minerals content especially NaCl and total dissolved solid (TDS) in the drinking water produced in this research are conforming to the standards of World Health Organization (WHO).

Keywords: Drinking water, Reverse osmosis, Pilot plant, Seawater.

Nomenclatures

Q_w	Volumetric permeate rate [l/hr]
J_w	Permeate flux [l/hr.m^2]
CFV	Cross flow velocity [m/s]
ppm	Part per million
TDS	Total Dissolved Solid
A_c	Membrane area
P_f, P_r, P_p	Pressure in the feed, retentate and permeate streams

1. Introduction

The concepts of "osmosis" and "reverse osmosis" have been known for many years. Studies on osmosis were carried out as early as 1748 by the French scientist Nollet. Many researches reported on reverse osmosis system and desalination of seawater, Most of them using hollow fiber or spiral wound membrane in their research [1]. Effects of different operating parameters (feed water concentration, temperature, pressure and flow rate) on membrane performance were examined using RO system [2]. Sensitivity of different design parameters (internal diameter, total number of tubes) on the recovery ratio was also studied [3].

Besides predicting the performance of RO membrane, several models for mass transport in membrane have been developed such as solution-diffusion model, models from irreversible thermodynamics, etc. [4 and 5]. Simulation and optimization of various RO membrane, study on concentration polarization in RO system and many case study on existing plant was reported.

Although many studies were conducted on reverse osmosis membrane, tubular membrane was rarely investigated. This study is aimed at investigating the tubular RO module. The performance of this membrane on different operating parameters has been examined and the best operating condition of RO system with the best permeate quality were utilised to produce drinking water from seawater.

2. Chemicals and Methods

The feed stock for reverse osmosis system is the seawater. Seawater from Telok Kalong Beach, Terengganu, Malaysia is chosen because the location is still free from pollution. Thirty bottles of 20 litres each were used to fill seawater by pumping using 5 hp portable petrol engine operated pump. Sand existing in the collected water was separated by settling. The NaCl concentration and TDS content in the collected water was measured in the laboratory.

The RO system is relatively simple to design as shown schematically in Fig. 1. It consists of a feed water tank fitted with a heater, feed pre-treatment (filter 1 & 2) to remove particles using a 5 µm filter, high pressure plunger pump (CAT Triple Plunger

Pump, Model 241, Belgium) which can give a maximum pressure of 130 bar, RO tubular membrane module (PCI, Model B1-AFC99, UK), plate heat exchanger (Alfa Laval, Model M3-FGL), and a permeate tank.

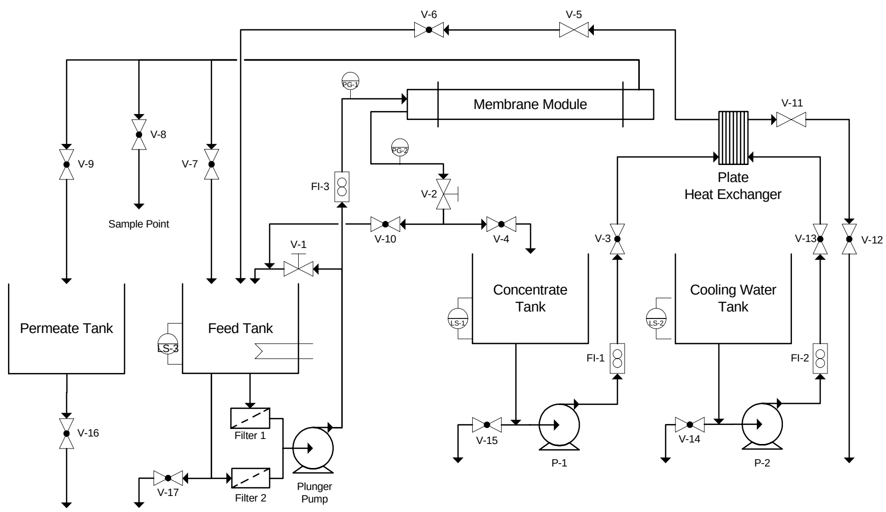

Fig. 1. Schematic diagram of RO system

The membrane module used in this research was a 10 polyamide membranes tubes in 10 perforated stainless steel tubes arranged in a concentric mode. This polyamide membrane has 99% salt rejection with a recommended pH range of 1.5 to 12, and maximum pressure and temperature of 64 bar and 80^{o}C respectively. Cleaning chemical for this membrane is nitric acid (0.2%) at a temperature of 40^{o}C.

The plunger pump receives the water from the feed tank through filter 1 & 2. This pump raises the pressure to the desired value which is monitored by PG-1. The water then flows through FI-3 into membrane module. Retentate flows to the concentrate tank while permeate flows to the feed tank. P-1 will circulate the retentate through FI-1 to the heat exchanger and recycle back to the feed tank.

Prior to each experiment, membrane was chemically cleaned with 0.2% nitric acid in distillate water at temperature of 40^{o}C. The membrane was then rinsed twice using distillate water, for 20 minutes each time to clean up the residue chemical. This is to ensure that the distilled water flux is comparable to the clean membrane distilled water flux. These experiments were performed keeping all the parameters (i.e. temperature and cross flow velocity) constant except the pressure.

The experiments on seawater involved changing the feed flowrate, pressure, temperature and feed concentration. Each set of experiments had a different operating parameter and maintained other parameters constant. The feed tank was filled with seawater, while the cooling water tank was filled with tap water. The flowrate of concentrate from cooling system was adjusted by manipulating V-3. The cooling system was set to keep the temperature of concentrate constant. The first set of experiment was conducted at constant feed flowrate of 0.4 m^3/hr measured from FI-3.

The flowrate and membrane module inlet pressure of 40 bar was set together by manipulating V-1 and V-2 at constant temperature of 35°C. Tests were conducted when the steady state conditions are achieved. The steady state conditions are defined as the constant operating parameters (pressure, temperature and flowrate) for at least 20 minutes. Sample from feed, permeate and retantate was collected. This was followed by recording the permeate flux through measuring the time required for collecting 250 ml of permeate. The calculation of permeate flux is done using Eqns. (1) and (2).

$$Q_w (l/hr) = \frac{250ml}{xs} x \frac{3600s}{1hr} x \frac{1l}{1000ml} \quad (1)$$

Permeate flux, $$J_w (L/hr.m^2) = \frac{Q_w}{0.9m^2} x \frac{18}{10} \quad (2)$$

The total area of membrane for 18 tubes is 0.9 m^2. Since only 10 tubes were used in this study, the area is corrected by a 1.8 factor.

The outlet pressure of the module was recorded to calculate the transmembrane pressure. The pressure was changed by steps of 5 bar increasing from 40 to 55 bar while the flowrate kept constant following the same procedure mentioned earlier. The second set of experiment involved changing the flow rate by steps of 0.1 m^3/hr from 0.4 to 0.6 m^3/hr.

Consequently, after three set of experiments, the temperature of feed was step changed to 40 and 45°C by setting the heater in feed tank to the required value. For the last parameter, different feed concentration was performed keeping other parameters constant (temperature = 40°C and feed flowrate = 0.5 m^3/hr).

It is important to mention that after each experiment, the chemical cleaning procedure was performed and all the samples were analysed to get the concentration of minerals and TDS.

The concentrations of cations such as Na^+, Mg^{2+} and Ca^{2+} were measured using atomic absorption spectroscopy (AAnalyst 400, Perkin Elmer) using WinLab32 for Atomic Absorption Ver. 5.80 software to control the instrument. On the other hand, the concentration of anions (Cl^-) was calculated while standard method for TDS was followed.

3. Results and Discussion

Tests were performed under different operating condition using tubular membrane. The best transmembrane, cross flow velocity, feed temperature and feed concentration producing permeate quality were chosen to produce drinking water from desalination of seawater. Each set of data was recorded and presented in form of figure to illustrate the effect different operating parameters.

Cross flow velocity (CFV) was calculated using Eq. (3):

$$CFV = \frac{\text{Flowrate, Q}}{\text{Cross Sectional Area of Membrane, } A_c \text{ x } 3600} \quad (3)$$

$$A_c\,(m^2) = \frac{\pi \text{ x } d^2}{4} \quad (4)$$

Transmembrane pressure (TMP) was calculated by Eq. (5),

$$TMP(\Delta P) = \frac{P_f + P_r}{2} - P_p \quad (5)$$

Because P_p is atmosphere pressure (P_p = 0 gauge pressure), the TMP is the arithmetic average of the feed and retentate pressure. The data for permeate flux before and after chemical cleaning at 4 different transmembrane pressures are shown in Fig. 2 which shows that after the membrane was cleaned with 0.2% nitric acid at 40^oC for 30 minutes, the flux increased and reached the clean membrane flux.

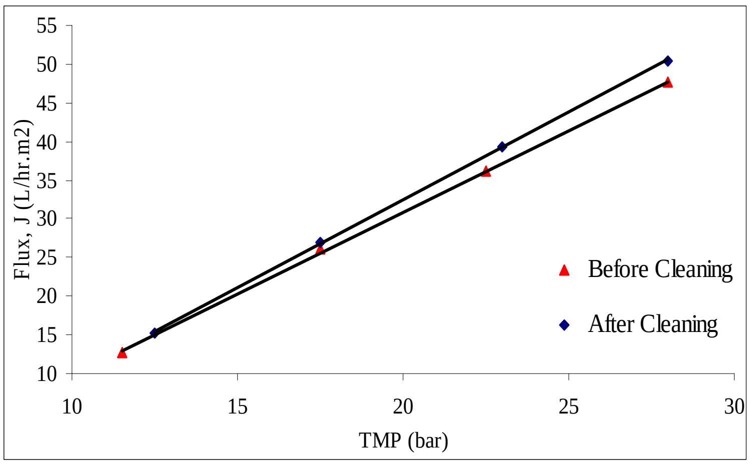

Fig. 2. Permeate flux before and after chemical cleaning.

3.1 Effect of CFV on permeate flux

The effect of CFV at constant feed temperature of 35^oC on permeate flux is depicted in Fig. 3 with the y-axis as the permeate flux and the x-axis is the TMP. It is clear that increasing cross flow velocity leads to the increase of turbulence and mass transfer coefficient. This weakens the effect of concentration polarization and increases the permeate flux. Therefore, the solution residence time, to pass through the membrane channel, will be less hence increasing the flux [6].

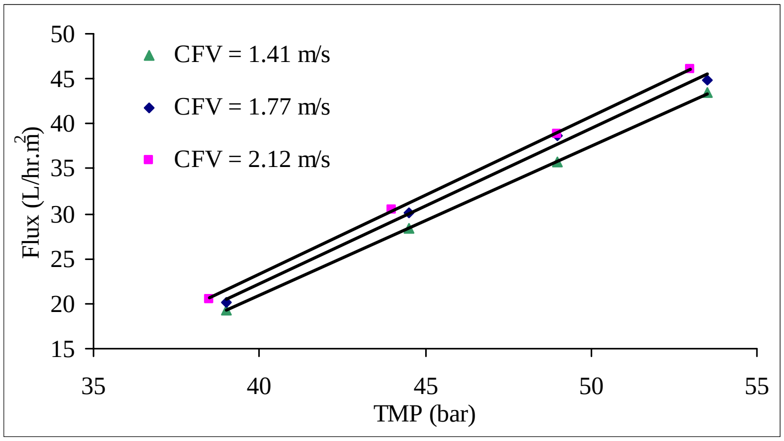

Fig. 3. Effect of CFV at constant temperature of 35^{0}C on permeate flux.

At the same time for constant CFV, the permeate flux increases with increasing transmembrane pressure. This is due to increase in driving force (difference between feed pressure and osmotic pressure).

3.2 Effect of feed temperature on permeate flux

Temperature of the feed sweater has a great impact on the permeate flux. The temperature rises due to circulating of the feed through the membrane module at relatively high cross flow velocity. To study that effect, the feed temperature was changed from 35 to 45^{o}C. Figure 4 illustrates the effect of feed temperature on the permeate flux at a constant CFV and feed concentration.

Increasing the feed temperature increases the permeate flux. This is attributed to the effect of the temperature of the feed water. As this temperature increases, on one hand, this will decrease the net driving pressure due to an increase in osmotic pressure and, on the other hand, will lead to increasing in water permeability coefficient due to the decrease in both viscosity and density. The later one, will overcomes the effect of net driving pressure thus the permeate flux is increased.

3.3 Effect of feed concentration on permeate flux

The profiles of permeate flux change when the feed concentration change are shown in Fig. 5. Increasing TDS or salt concentrations will decrease permeates flux and increase salt passage. This is because the osmotic pressure difference across the membrane increases. Much higher driving force, for the same applied pressure to the feed, is due to the osmotic pressure which is directly related to the salt concentration. The higher feed concentration also leads to surface coating or fouling by salt.

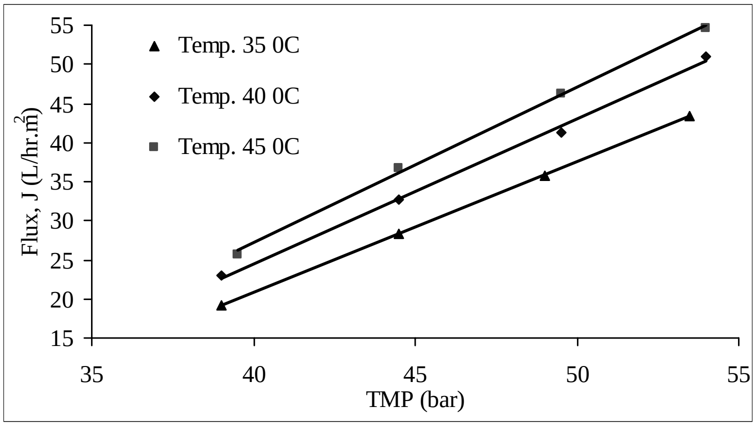

Fig. 4. Effect of feed temperature at constant CFV of 1.41 m/s on permeate flux.

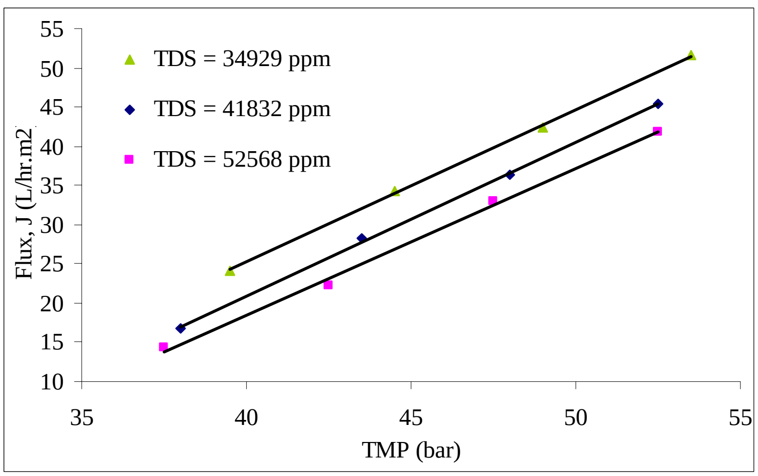

Fig. 5. Effect of feed concentration on the permeate flux.

3.4 Cations analysis

In order to know the concentration of minerals in the produced drinking water, all samples were tested using atomic absorption spectroscopy (AAS) for measuring the concentration of Na, Mg, Ca cations. Concentration of Cl anion is calculated whereas TDS was conducted following a standard method that measures the increase in weight of the dish that evaporated and dried in an oven at 180° C, until the weight of the dish no longer changes.

Table 1 shows five major minerals contained in the studied seawater; Sodium, Chloride, Magnesium, Calcium and Total Dissolved Solid (TDS)

Table 1. Mineral content in studied seawater.

Element	Concentration (ppm)
Sodium (Na)	4783.3
Chloride (Cl)	7695.9
Magnesium (Mg)	1191.7
Calcium (Ca)	8622.9
TDS	34929.0

The minerals content (Sodium, Chloride, Magnesium, Calcium and TDS) in four different TMP permeate for a constant feed temperature, CFV, concentration of 40^{o}C, 1.77 m/s and 34929 ppm, respectively are show in Fig. 6. It is clear that at higher TMP, the quality of the permeate is better. When the TMP increases, the water flux across the membrane is higher but the salt flux remains constant [3].

This shows that reverse osmosis process is suitable to produce drinking water by desalination of seawater. All the minerals (Na, Cl, Mg, Ca and TDS) concentration are below the World Health Organization (WHO) guide-line for drinking water [7].

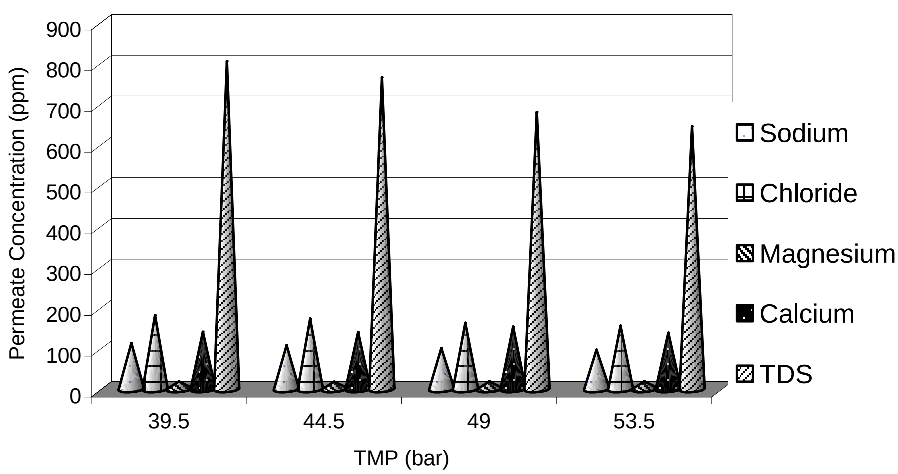

Fig. 6. Permeate quality.

4. Conclusions

In this study, experiments were conducted to get the optimum operating parameters to produce drinking water from desalination of seawater using reverse osmosis system. The best operating conditions to produce drinking water with the Na^+ concentration of 97 ppm which is below the WHO were identified for feed TDS concentration of 34929 ppm (which is the fresh seawater from the source). For a production rate of 413 l/m^2.day with 8 operating hours per day, these optimum operating conditions are found to be: feed temperature of 40^oC, cross flow velocity of 1.77 m/s, transmembrane pressure of 53.5 bar. If higher production is required, the system can be scaled up adding more modules

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