AN EXPERIMENT WITH SPIRAL WOUND REVERSE OSMOSIS MEMBRANES FOR THE DESALINATION OF SEAWATER

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ABSTRACT

In the research, the performance characteristics of Reverse Osmosis (RO) Spiral Wound (SW) membrane are evaluated. The effects of feed water concentration, temperature, pressure and flow rate on the performance of this membrane are investigated. The product recovery (ϕ) of SW membrane is found to increase with feed water temperature and pressure, but decrease with increasing feed water concentration and flow rate. Salt passage (SP) increases with feed water temperature and concentration, but decreases with increasing feed pressure and flow rate. Under the tested feed water conditions, ϕ of SW varies from 6% – 18% and permeate salinity is approximately 130ppm. In addition, validity of the Complete Mixing Model is verified and successfully extended to the derivation of water and salt transport parameters of SW membrane. Plots of 1/SR' versus $1/J_w$ display linear relationships, as predicted in the model.

1. INTRODUCTION

The emergence of RO, as a promising technology for seawater desalination and many other applications, has made it necessary to understand not only the process, but also its related technologies. Since membrane forms the heart of a RO process, knowledge on how different module configurations may affect its performance becomes an important aspect. Moreover, the wider availability of membranes has made the task of choosing one more difficult. This situation is accentuated by a lack of independent performance data for the various membrane types.

Recognizing this need, the NUS Department of Mechanical Engineering embarks on a research programme to gain a better understanding of the membrane and its process. A test facility has been developed to evaluate performance of different RO permeators under various operating conditions. B-10 Permasep Hollow Fibre membrane has been studied in detail previously and current research will focus on SWC1-4040 Spiral Wound membrane. SW membrane is a plate-and-frame system wrapped around a central collection pipe, in a similar fashion to a sandwich roll. The feed-side spacer separating the top layer of two "membrane pockets" acts as a turbulence promoter, reducing the effect of concentration polarization. Within the module, the feed water flows axially, parallel to the central pipe, whereas the permeate flows radially towards the central pipe. In the study, effects of feed water concentration, temperature, pressure and flow rate on the performance of the SW membrane will be investigated.

2. THE RO SYSTEM

The desalination system, capable of producing about 4.2 m^3/day, as shown in Figure 1, consists of a feed water tank, where the feed water temperature is controlled by circulating cool water through a heat exchanger immersed in the tank. A submersible pump allows flow of water over the heat exchanger and maintains uniform temperature inside the tank. A centrifugal booster pump draws water from the feed water tank, pumps it through the pre-treatment cartridge filters and, subsequently, delivers it to the high pressure positive displacement pump powered by a 4 kW electrical motor. The capacity of the booster pump is enough to overcome pressure drop in the cartridge filters and also provide sufficient pressure head for the high pressure pump to operate. The temperature of the feed stream is measured by a thermocouple inserted into the piping. The high pressure pump delivers pretreated water to the RO membranes. Part of the product water is collected in a flush tank for backflushing the membranes after the system is shut down. Flow rates and concentrations of the product and reject waters are measured by the flow meters and the conductivity meter, respectively. The product and the reject waters are either collected separately or channelled to a mixing tank before it is delivered to the feed tank to ensure uniform feed concentration and temperature.

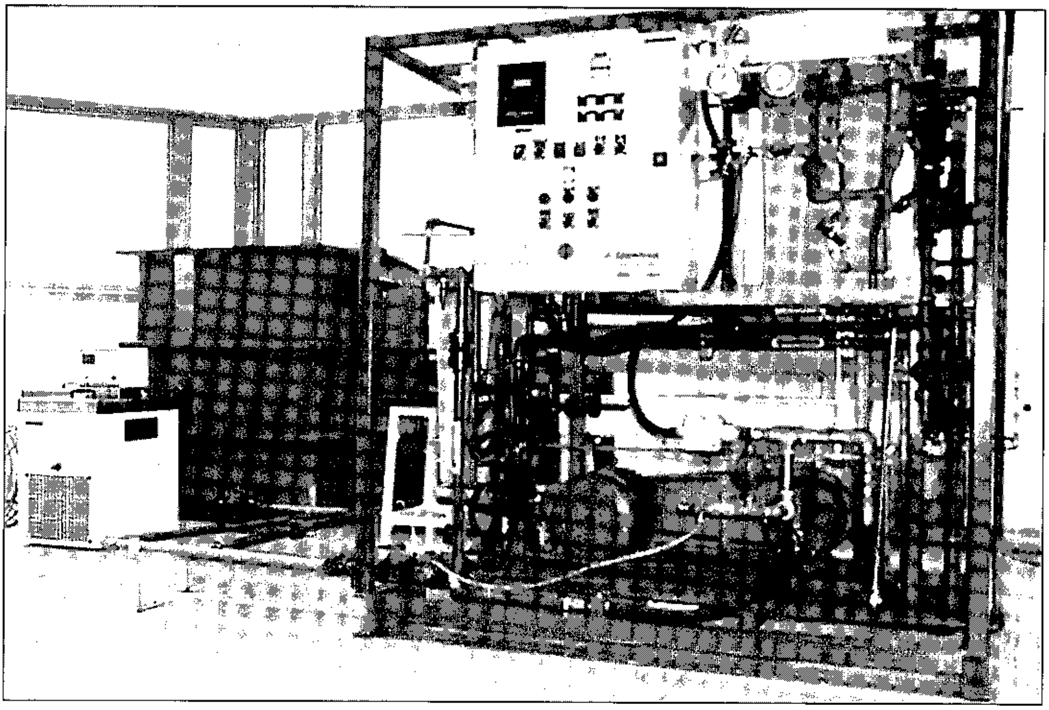

Figure 1: Picture of RO pilot system.

In the existing test facility, currently, there is no provision for pretreatment of seawater and, as such, saline solutions, using NaCl, of similar concentrations as seawater is prepared for use in the experiments. As the membranes are sensitive to chlorine, feed water is dechlorinated using sodium metabisufite before it is delivered to the membranes. The variables considered in the experiment are shown in Table 1.

Table 1: Variables and their ranges considered in the experiments.

Experimental variables	**Range**	**Steps**
Feed concentration (ppm)	20,000 - 35,000	5,000
Pressure (psi)	700 - 1,000	100
Temperature (°C)	20 - 30	2
Flow rate (cm^3/s)	~300 and ~ 250	-

In the experiment, the feed water supplied to the membrane is prepared by dissolving appropriate amount of NaCl to about 500 litres of tap water to obtain the desired TDS. In order to mix this solution with the liquid trapped in pipelines and in the membrane module, the pump is first operated with the RO module for a few minutes. Product and reject flow rates, together with their concentrations and pressures, are recorded. Tests are repeated at pressures from 700 psi to 1000 psi, keeping temperature and flow rate constant. The temperature is then allowed to increase at 2°C intervals and the same steps are performed, until temperature reaches 30°C. Subsequently, the flow rate is changed and the procedure is repeated.

3. THEORY

In 1982, Soltanieh and Gill[1] developed a Complete Mixing Model to describe the behaviour of radial flow HF modules. From the Complete Mixing Model, a plot of the inverse of solute rejection, 1/SR', versus the inverse of product flow rate per unit membrane surface area, $1/J_w$, yields a straight line, the slope of which is equal to the solute/salt permeability coefficient, B. Complex numerical technique is not required, as in the case of other models, in the calculation of the membrane permeability coefficients. In this study, the Complete Mixing Model, initially developed for the radial flow HF membranes, is extended to the axial flowing SW membranes. Such an approach was adopted by Eriksson[2].

Some major assumptions of this model are:
(i) Uniform shell-side concentration which is equal to the reject concentration;
(ii) Small pressure drop in the shell in the radial direction;
(iii) Uniform permeate concentration in the radial direction; and
(iv) Small concentration polarization.

One advantage of the Complete Mixing Model is that it can be solved by adopting a few different transport models to suit the actual permeator performance. In the study, Constant Ratio (CR) model[2] is used.

3.1 Mathematical representation of CR model

In the CR model, water and salt transport through the membrane are a combination of diffusive and convective flows. The diffusive flow is $A(\Delta P - \Delta\pi)$ for the water transport and $B(C_m - C_p)$ for the salt transport. The convective flow is through defects in the membrane, with no salt rejection. In the model, it is assumed that the convective flow is a constant ratio of the total permeate flow, independent of the pressure. Thus the convective flow is XJ_w for water and XJ_wC_m for salt.

Slight modifications are made in the Complete Mixing Model and CR transport model after consideration of the flow dynamics of the SW RO permeators. Average concentration of the feed and reject, instead of reject concentration, is used as an approximation of the uniform shell side concentration (i.e. C_m is replaced by C_{fr}). While the actual flow dynamics within the shell is not fully understood[1], treating the uniform shell-side concentration to be the reject concentration, as in the 1st assumption, will be an over-estimation.

CR Model[2] can be represented as follows:

$$J_w = A(\Delta P - \Delta\pi) + XJ_w \qquad (1)$$

$$J_wC_p = B(C_{fr} - C_p) + XJ_wC_{fr} \qquad (2)$$

Assuming convective permeate flux is negligible compared with diffusive permeate flux, Eq. 1 & Eq. 2 can be simplified to

$$J_w = A(NDP) \qquad (3)$$

$$1/SR' = 1/(1 - X) + B/(1 - X)(1/J_w) \qquad (4)$$

where

$$\Delta P = (P_f + P_r)/2 - P_p \qquad (5)$$

$$\Delta\pi = \pi_{fr} - \pi_p \qquad (6)$$

$$\pi = 0.2654\ C\ (T + 273.15)/(1000 - C/1000) \qquad (7)$$

$$NDP = \Delta P - \Delta\pi \qquad (8)$$

$$SR' = 1 - C_p/C_{fr} \qquad (9)$$

The ASTM method[3] is used to represent the osmotic pressures of the feed-reject and permeate solutions. Variations between this method and others can be considered acceptable[4].

4. RESULTS AND DISCUSSION

As stated earlier, tests are performed under different operating conditions using SW membrane, and the results are presented and discussed in this section. The effects of feed water temperature, pressure, concentration and flow rate on the ϕ and SP of SW membrane are evaluated.

4.1 Effect of temperature

The effect of feed water temperature on ϕ is shown in Figure 2. It is evident that ϕ increases with feed water temperature. For the range of temperature considered in this study, the rate of increase of ϕ averaged around 6% for every 2°C increment. As the temperature of feed water increases, the net driving pressure (NDP) decreases due to an increase in osmotic pressure. However, the increase in water permeability coefficient outweighs the effect of decreasing NDP, leading to an overall increase in ϕ. Al-Bastaki and Al-Qahtani[5] also observed similar phenomena and attributed it to an increase in pore size of the membrane with temperature. Current experimental results show slight increase in SP, when temperature is increased. The solute permeability coefficient of SW membrane, calculated at the temperature range of 20 – 30°C, increases with temperature.

4.2 Effect of pressure

The effect of pressure on ϕ is shown in Figure 3, when operated under two different flow rates. For a particular flow rate, SW membrane shows an increase in ϕ with the increase in pressure. The ϕ increases only slightly as the feed flow rate decreases. The SP through the membrane declines at a decreasing rate as the pressure is increased. In fact, quantity of

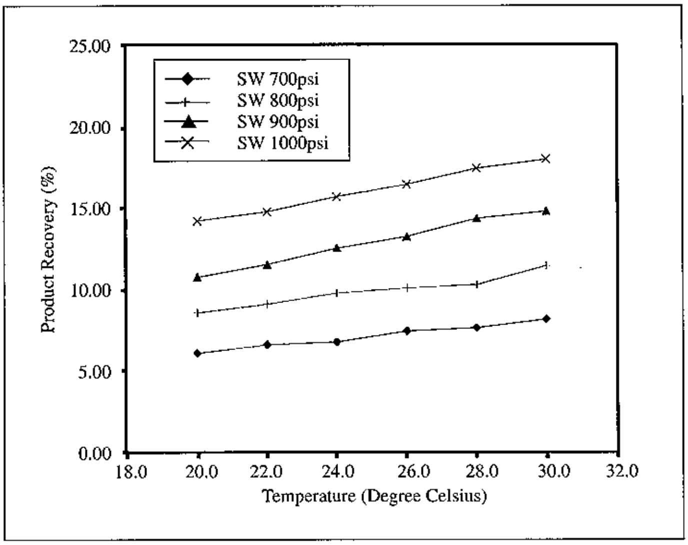

Figure 2: The effect of feed water temperature on product recovery. (Feed water at 35000ppm and flow rate at 300cm^3/s)

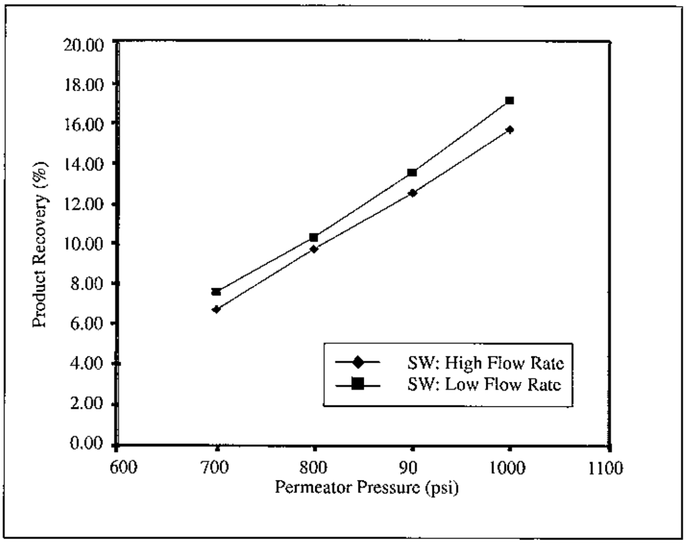

Figure 3: Effects of feed water pressure on product recovery. (Feed water at 35000ppm and 24°C)

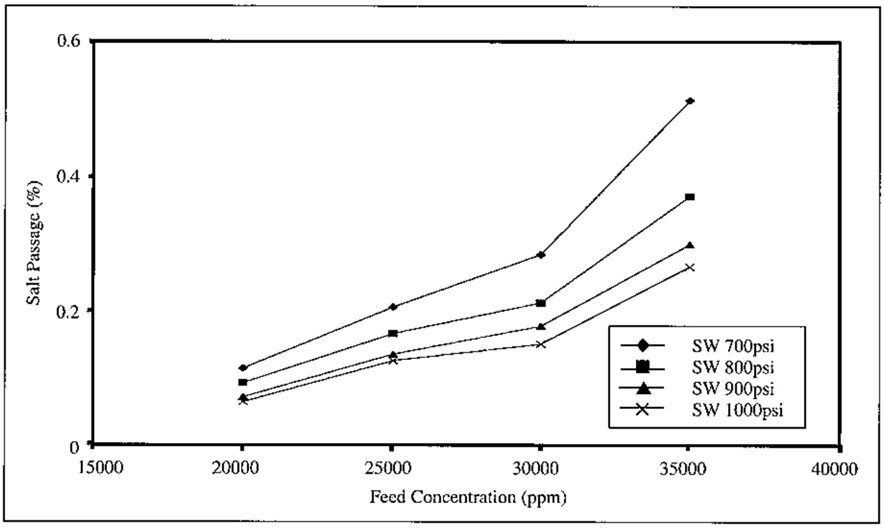

Figure 4: Graph showing the effect of feed concentration on salt passage. (Feed water at 24°C and high flow rate)

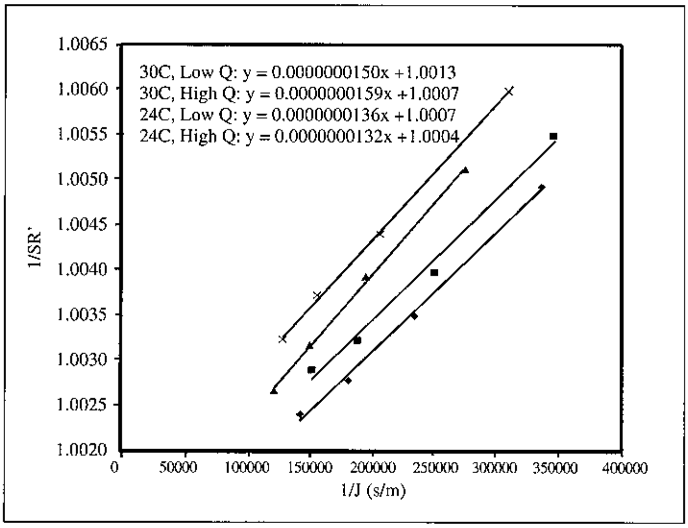

Figure 5: Variation of 1/SR' with $1/J_w$ (s/m). (Feed water concentration at 35000ppm)

salt passing through a membrane is hardly affected by increasing pressure[6]. However, the increase in ϕ leads to the dilution of salt passing through the membrane. Consequently, there is an overall dilution of salt passing through the membrane. Decreasing feed flow rate has the effect of increasing SP.

4.3 Effect of feed concentration

Increasing feed water concentration leads to a decrease in ϕ. This can be explained by the increasing osmotic pressure difference across the membrane, which leads to an overall reduction in NDP. Figure 4 shows the effect of feed water concentration on SP. It is seen from the figure that SP increases at an increasing rate when the feed water concentration is increased from 20,000 ppm to 35,000 ppm.

4.4 Degradation of membrane

To check for degradation of SW membrane, current experimental data, collated after the SW membrane has undergone 100 hrs of discontinuous usage over a period of 9 months, is compared against the manufacturer's specifications. It is noted that the SP values are of no significant difference. This also applies to ϕ. However, the specified performance data is obtained under a feed flow rate that is 3 times higher than that used in the current research. As demonstrated experimentally, lower feed flow rate will result in a higher ϕ. This may explain why the current ϕ is higher than that specified by the manufacturer. As such, this comparison is inconclusive and is not a true reflection of any membrane degradation.

4.5 Validity of complete mixing model and CR transport model

The complete-mixing model predicts that a linear relationship exists between 1/SR' and $1/J_w$, and this is observed at all levels of feed water temperatures, pressures, concentrations and flow rates tested in the experiment. Referring to Figure 5, which shows the plots of 1/SR' versus $1/J_w$ at two different flow rates and temperatures, linear relationships can be derived and all plots are observed to converge to intercepts that are close to unity. According to Eq. 4, intercept of the plot is represented by 1/(1-X), where X is a constant depicting the ratio of convective flow to the overall permeate flow by the diffusive mechanism. Since the main solute transport mechanism is through the diffusive mechanism, constant X is expected to be small in value. Mathematically, this will lead to the intercept, 1/(1-X), of the 1/SR' versus $1/J_w$ plot to be close to unity.

In addition to predicting the existence of a linear relationship between 1/SR' and $1/J_w$, the CR model also predicts the linearity between permeate flux, J_w, and the net driving pressure, NDP. This relationship is also verified experimentally, as illustrated in Figure 6.

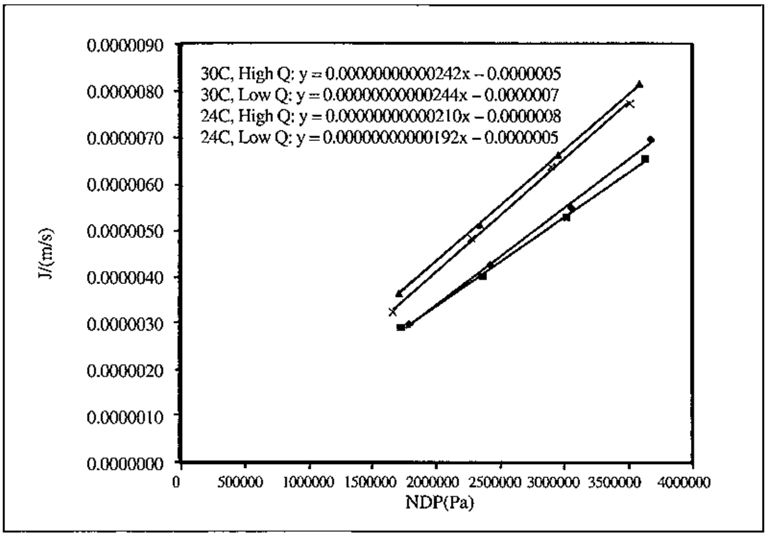

Figure 6: Variation of J_w (m/s) with NDP (Pa). (Feed water concentration at 35000ppm)

5. CONCLUSIONS

In the study of SW membrane, product recovery, ϕ, is found to increase with feed water temperature and pressure, but decreases with increasing feed water concentration and flow rate. Salt passage, SP, is found to increase with feed water temperature and concentration, but decreases with increasing feed water pressure and flow rate.

At feed concentration of 35000ppm and feed flow rate of ≈ 300cm^3/s, ϕ varies from 6% to 18%, depending on the temperature and pressure. In addition, product water salinity varies from 100ppm – 170ppm.

The result of the degradation analyses is inconclusive due to dissimilar feed water test conditions. Moreover, more meaningful results can be derived if the tests are carried out continuously over longer period of time.

Validity of the Complete Mixing Model is verified and successfully extended to the derivation of the solvent and solute transport parameters of SW membrane.

6. FUTURE WORK

New RO membranes with better mechanical properties and salt rejection capabilities are constantly being developed by membrane manufacturers. For example, the use of polymeric material, such as polyamide, in the making of RO membrane has resulted in better mechanical properties and alleviated to a great extent the problem of chemical degradation experienced earlier by cellulose acetate membranes. However, despite these advances and improvements in membrane technology, solving the problem of membrane fouling has somewhat met with limited success. Fouling of membrane will lead to a decrease in product recovery and an increase in salt passage. At the same time, filtrate quality may also degrade. Consequently, the replacement rate of the membranes will increase, leading to an increase in downtime and maintenance costs of the desalination plant. All these will make RO less attractive as a desalination process. While membrane fouling can be attributed largely to the seawater and RO process chemistry, inadequate pretreatment and improper operating parameters, which exceed design conditions, may also precipitate fouling. Different fouling mechanisms include scale precipitation, colloidal fouling, biological fouling and organic fouling.

Eliminating and reducing fouling to a permissible level is never easy. Nature of membrane fouling is not only site specific (i.e. varies with geographical location, industrial pollution, seasonal influences etc.), but is also dependent on the quality of feed pretreatment and strict adherence to design operating conditions. With proper feed pretreatment, suspended and colloidal particles of the feed water can be reduced to a permissible level, putting less strain on the RO membrane. Consequently, the frequency of membrane maintenance and replacement can be reduced substantially.

In view of the instrumental role that pretreatment plays in the success of a RO plant, NUS Department of Mechanical Engineering intends to explore different pretreatment techniques. In particular, effectiveness of conventional pretreatment techniques, such as coagulation and media filtration, will be assessed and compared against the more recent and unconventional pretreatment technique using membranes, such as microfiltration, ultrafiltration and nanofiltration membranes. Membrane pretreatment technique, introduced in the 1980s, presents as an alternative to the traditional coagulation/sedimentation-filtration techniques in seawater pretreatment.

7. NOTATION

A	water permeability coefficient, m/s-Pa (m^3/m^2-s-Pa)
B	salt permeability coefficient, m/s (m^3/m^2-s)
C	concentration, ppm
C_p	product/permeate concentration, ppm
C_{fr}	average concentration of feed and reject streams, ppm
CR	constant ratio
HF	hollow fibre
J_w	permeate flux, m/s (m^3/m^2-s)
NDP	net driving pressure, Pa
P	pressure, Pa
P_f	feed pressure, Pa
P_p	product/permeate pressure, Pa
P_r	reject pressure, Pa
Q	volumetric flow rate, m^3/s
RO	reverse osmosis
SP	salt passage, %
SR	salt rejection, %

SR'	revised salt rejection ratio
SW	spiral wound
T	temperature, °C
X	ratio of convective permeate flux over total permeate flux

Greek letters

π	osmotic pressure, Pa
π_{fr}	average osmotic pressure of feed and reject stream, Pa
π_p	osmotic pressure of product stream, Pa
Δ	difference
ϕ	recovery ratio, %

8. REFERENCES

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