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Desalination of seawater: an experiment with RO membranes

M.N.A. Hawlader*, J.C. Ho, Chua Kok Teng

Department of Mechanical and Production Engineering, National University of Singapore, 10 Kent Ridge Crescent Singapore 119260
Tel. +65 874-2218; Fax +65 779-1459; e-mail: mpehawla@nus.edu.sg

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Abstract

Effects of feed water concentration, temperature, pressure and flow rate on membrane performance are examined using a reverse osmosis (RO) system with a product capacity of about 5 m^3/d. Performance charac-teristics of Hollow Fibre and Spiral Wound permeators, connected in parallel to the feed water system, are also evaluated. Experiments were conducted using salt (NaCl) solution of known concentration. Flow rates and concentrations of product and reject waters were closely monitored during the experiments. Product recovery is found to increase with feed water temperature and pressure, but decrease with increasing feed water concentration and flow rate. Salt passage increases with feed water temperature and concentration, but decreases with increasing feed water pressure and flow rate. Although hollow fibre and spiral wound permeators have different physical configurations, both react similarly, though with slightly different degrees, to the changes in experimental conditions. Notably different is their respective product recovery and salt passage, which can be qualified by the different morphological characteristics of the two membranes. Under identical feed conditions, product recovery of hollow fibre varies from 12%–30%, while that of spiral wound varies from 6%–18%. Degradation analysis is inconclusive since it is likely that membrane operation has not stabilized after only 100 h of operation.

Keywords: Desalination; Reverse osmosis; Permeators performance; Hollow fibre and spiral wound permeators

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1. Introduction

In general, there is a short supply of water in many parts of the world. This may be attributed, partly, to the growth of population and increased industrial activities. Singapore is no exception, although it is surrounded by water. It has to import a large fraction of its fresh water requirements to meet local industrial and domestic needs. Singapore has seen a steady increase, slightly over 4% per annum, in water usage with 334.7 million m^3 in 1987 to 481.3 million m^3 in 1996. Of the total requirements of 1.53 million m^3/d (340 MGD, 2000 figure), 53% went to domestic applications, and 47% for industrial and

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*Corresponding author.

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other sectors. Singapore has devoted considerable effort to identify reliable alternative sources of fresh water supply. In recent years, desalination has received significant attention considering the use of multi-stage flash (MSF), multi-effect distillation (MED) and reverse osmosis (RO) processes. However, considering the land scarcity of the nation and improvements in cost and durability of membranes, it is likely that the future desalination processes for the production of fresh water will find greater use of membrane modules [1,2].

To play it safe, as the technology is proven, Singapore decided to build its first large desalination plant of 30 mgd capacity based on MSF method. Subsequently, the plan was revised to consist of a 20 mgd MSF and a 10 mgd RO systems. A good deal of activities is slowly building up in the area of MED and RO systems, and private companies have shown great initiatives.

NUS Department of Mechanical and Production Engineering embarked on a research programme to gain a better understanding of the desalination processes and the development of local manpower for the industry. Undergraduate final year research and design projects, and graduate research programme have provided a deeper insight into the desalination technology [3–6]. A test facility has been developed to evaluate performance of different RO permeators under various operating conditions. This also enables us to determine the ageing effect of membranes. The authors have carried out extensive studies on B-10 Permasep HF permeator. These results are compared with a SW composite polyamide permeator. However, it should be highlighted here that no conclusive results regarding the superiority of one membrane over the other could be derived from the present experiment. This is because the two membranes compared have different functional and morphological parameters. Factors such as membrane and pretreatment costs, to name only a few, may complicate matters further. Instead, emphasis is on understanding and appreciation of the membrane operations and drawing of correlation between the experimental results and the intrinsic physical characteristics of the two membranes.

2. The RO system

The desalination system, capable of producing about 5 m^3/d, as shown in Fig. 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 (capacity: 5 gpm at 30 to 50 psi) 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, where the two membranes, HF and SW, are mounted in parallel and controlled by valves located at inlet and outlet of the membranes. The HF and SW permeators used have product flow capacity of 7.57 m^3/d (±15%) and 4.2 m^3/d, respectively, albeit under different operating conditions specified by the manufacturers. Part of the product water is collected in a flush tank for washing 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 to the

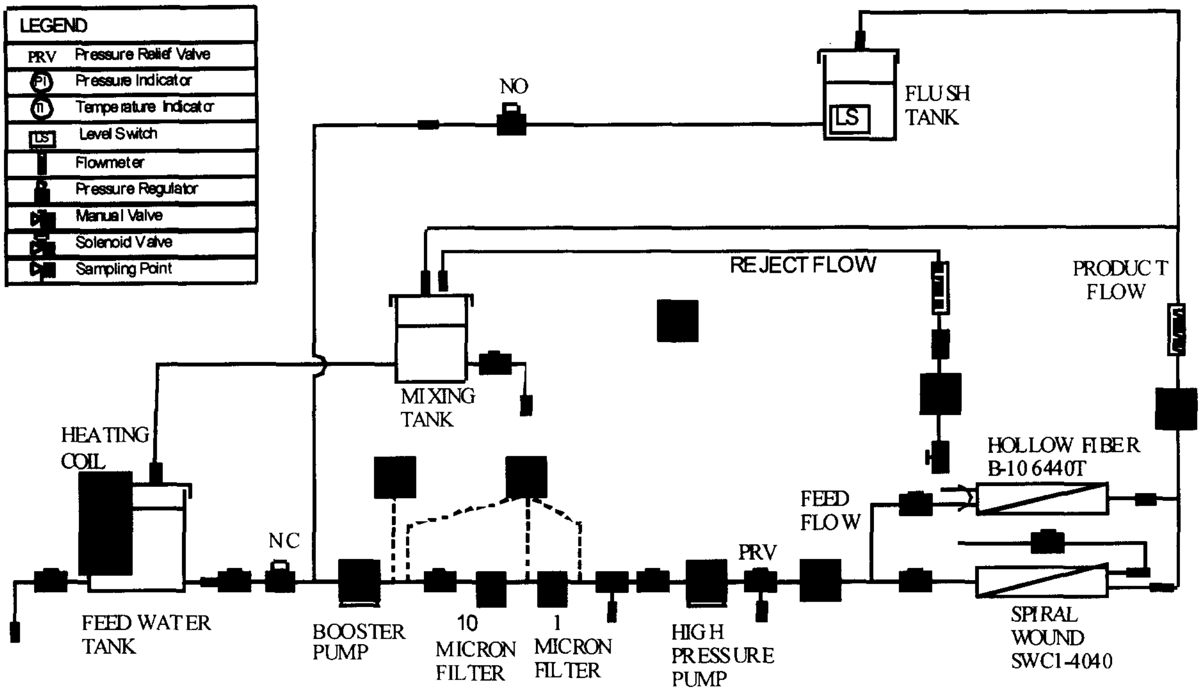

Fig. 1. Schematic diagram of an RO desalination system.

feed tank to ensure uniform feed concentration and temperature.

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 meta-bisufite (Chemkon) before it is delivered to the membranes. The variables considered in the experiment are shown in Table 1.

In the experiments, the feed water to the membranes is prepared by dissolving appropriate amount of NaCl to about 500 litres of tap water to obtain the desired TDS. The solution is cooled to ≈19°C. In order to mix this solution with the liquid trapped in pipelines and in the membrane module, the pump is operated with the RO module for a few minutes. The temperature of the solution is increased steadily to ≈20°C. The flush tank is checked to ensure that it is full before data acquisition begins. Product and reject flow rates, together with their concentrations and pressures, are recorded. Tests are repeated at presures from 700 psi to 1000 psi, keeping temperature and flow rate constant. The temperature is allowed to increase at 2°C intervals and the same steps are performed, until temperature reached 30°C. Then the flow rate is changed and the

Table 1
Variables and their ranges considered in the experiments

Expermental 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	—

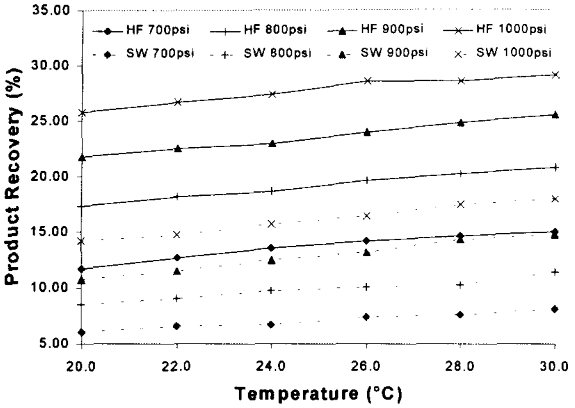

Fig. 2. Graph showing the effect of feed water temperature on product recovery (feed water at 35000ppm and high flow rate).

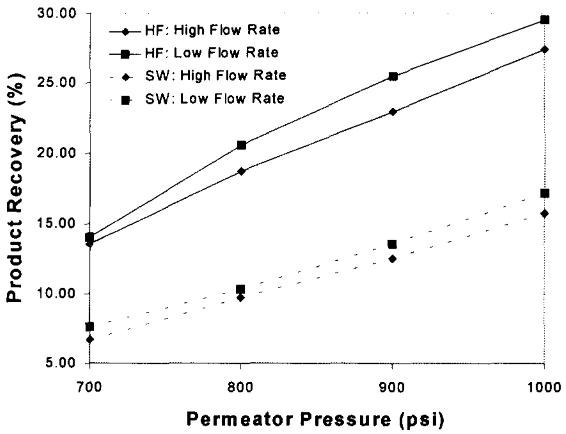

Fig. 3. Graph showing the effect of feed water pressure on product recovery (feed water at 35000ppm and 24°C).

procedure is repeated. The experiments are conducted with both HF and SW membranes.

3. Results and discussion

As stated earlier, tests were performed under different operating conditions using both HF and SW membranes, 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 HF and SW membranes are evaluated.

3.1. Effect of temperature

The effect of feed water temperature on ϕ is shown in Fig. 2 for the two membranes considered in this study. It is evident that ϕ increases with feed water temperature for both HF and SW. For the range of temperature considered in this study, the rate of increase of ϕ averaged around ≈4% for the case of HF and ≈6% for the case of SW 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 coefficients outweighs the effect of decreasing NDP, leading to an overall increase in ϕ. Al-Bastaki and Al-Qahtani [7] also observed similar phenomena and attributed them to an increase in pore size with temperature. The water permeability co-efficient of SW is one order of magnitude higher than that of HF. However, it is seen from Fig. 2 that ϕ of HF is much higher than that of SW, and this is due to a much larger effective membrane area in the case of HF. For both HF and SW, experimental results show slight increase in SP when temperature is increased. The solute permeability coefficients of HF and SW membranes, calculated at the temperature range of 20–30°C, increase with temperature, with the rate of increase higher in the case of HF.

3.2. Effect of pressure

For the two membranes, the effect of pressure on ϕ is shown in Fig. 3, when operated under two different flow rates. For a particular flow rate, both membranes show an increase in ϕ with

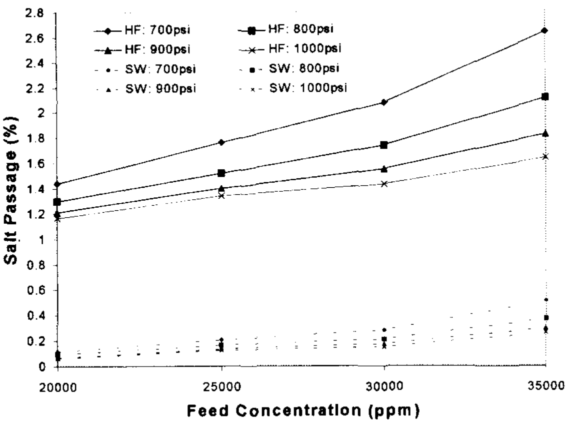

Fig. 4. Graph showing the effect of feed concentration on salt passage (feed water at 24°C and high flow rate).

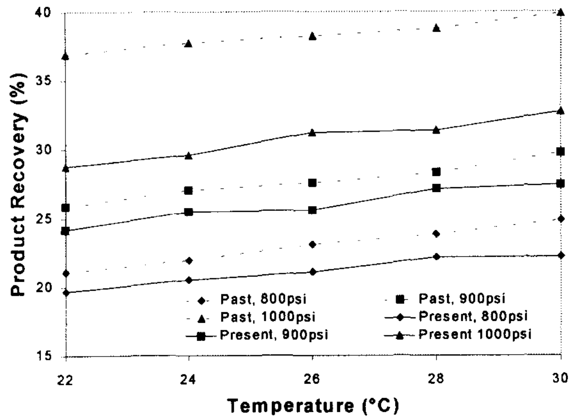

Fig. 5. Comparison of past and present product recovery of HF (feed water conditions at 35000ppm and low flow rate).

an increase in pressure. The ϕ increases only slightly as the feed flow rate decreases. The SP through the membranes declines at a decreasing rate as the pressure is increased. Compared to HF, the effect of pressure on SP for the case of SW is negligible. Decreasing feed flow rate has the effect of increasing SP.

3.3. 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 the NDP. Fig. 4 shows the effect of feed water concentration on SP. HF and SW display similar characteristics in the rejection of salt. 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.

3.4. Degradation of membranes

Fig. 5 shows a comparison of ϕ, before and after the HF membrane has undergone 100 hrs of usage. The "past" result is collated when the membrane is new. It should however be mentioned here that the 100 h is clocked over a period of 9 months of discontinuous operation.

At 800 psi, the present ϕ is almost 8% lower than that of the past. Inlet pressure needs to be increased by about 40 psi to restore the ϕ back to the former level. At the same pressure, SP is ≈ 47% higher than that of the past. The reductions in ϕ are ≈6% at 900 psi and ≈20% at 1000 psi. The corresponding increase in SP are ≈24% at 900 psi and ≈32 % at 1000 psi. At this stage, it is noted that the reduction in ϕ and the increment in SP may be either due to actual degradation of the membrane or just normal workings of the membrane before it enters into the stabilisation phase, or both. After all, the 100 h of degradation analysis conducted here is little compared to the 7500 h of pilot plant trial conducted by Butt, Rahman and Baduruthamal [8]. In their research, SW membrane produced better quality water at 86 ppm, using half the electricity cost compared with the HF membrane, which produced 468 ppm of product water.

For the case of SW membrane, an attempt is made to compare the manufacturer's specification against the current experimental data collated after the SW membrane has undergone 100 h of discontinuous usage over a period of

9 months. It is noted that the SP values are of no significance difference. This also applies to ϕ. However, the specified performance data are obtained under a feed flow rate that is 3 times higher than that used in the present experiment. 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. Conclusions

- In general, changes in feed water temperature, pressure, concentration and flow rate trigger similar responses on the performance of HF and SW membranes. 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.
- While HF and SW membranes react similarly to changes in experimental parameters, they have significantly different ϕ and SP values. At feed concentration of 35,000 ppm and feed flow rate of ≈300cm^3/s, ϕ of HF varies from 12%–30%, depending on the temperature and pressure. Under identical feed conditions, ϕ of SW varies from 6% to 18%. In addition, product water salinity of HF varies from 620 ppm–850 ppm, while that of SW varies from 100 ppm–170 ppm.
- Current experimental data indicates lower ϕ and higher SP after 100 h of usage. At 800 psi, ϕ of HF is almost 8% lower than its initial value. The reduction in ϕ is 6% at 900 psi and 20% at 1000 psi. In addition, SP is significantly higher than that prior to 100 h of usage. However, even such is not indicative of any true degradation as the membrane may merely be in a transition stage before its operation stabilises. In the case of SW, the result of the degradation analysis is inconclusive due to dissimilar feed water test conditions, besides the reason already mentioned earlier.
- Overall, HF and SW membranes have responded in a similar fashion to changes in experimental conditions. In the case of degradation analysis, more meaningful results could perhaps be derived if the tests are carried out continuously over a longer period of time.

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