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Periodic Operation of a Reverse Osmosis Water Desalination Unit

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ABSTRACT

An experimental investigation was carried out to study the periodic operation of a reverse osmosis water desalination unit with a spiral-wound membrane. The operating pressure was varied according to a symmetric square wave function around time-average values of 40 and 50 bars. Time periods ranging from 5 to 15 minutes and amplitudes of 5 and 10 bars were investigated. The results of these periodic tests were compared with results obtained from the conventional steady-state mode of operation. It has been found that the cyclic operation leads to higher time average permeate flow rates than that obtained from the corresponding steady-state operating conditions. It has also been found that the permeate rate increases with increasing amplitudes and decreasing time periods of the forcing function. For the considered amplitudes and periods, the improvements in the sweet water production rate ranged from 0.3 to 13%. These enhancements in the permeation flux have been obtained at the expense of marginal increases in the power requirements. As for the product quality, the concentration of salt in the permeate did not exhibit any specific trend. The value of salt rejection ranged from 98 to 99%.

Key Words. Periodic operation; Reverse osmosis; Water desalination

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INTRODUCTION

Periodic or cyclic operation of chemical engineering processes has been the subject of many investigations in the past three decades. It has been shown that in many cases the time-average performance of the process with cyclic operation can be superior to that corresponding to steady-state operation (1). The processes for which periodic operation has been investigated include distillation, liquid extraction, membrane systems, and heat exchangers (2–4). However, much of the recent publications about this subject have concentrated on chemical reactors, particularly for the oxidation of carbon monoxide. Periodic operation of chemical reactors has been shown to increase the rate of reaction compared to steady-state operation, as demonstrated in various experimental works published in the literature (5–13).

Improving the performance of pressure-driven membrane processes by imposing flow instabilities has also been the subject of many studies in recent years. A very good review of the methods used to introduce various types of flow disturbances was provided by Winzeler and Belfort (2). Among these techniques are the use of membranes with rough surfaces, vortices (Taylor and Dean vortices), and flow pulsations. Introducing flow instabilities tends to produce better mixing and to reduce the resistances to separation caused by membrane fouling and concentration polarization. The result is a higher permeate flux. As an example, Kennedy et al. (14) obtained about 70% increase in the permeate flux by oscillating the flow of a sucrose solution to a reverse osmosis unit at a frequency of 1 Hz. An analysis by Ilias and Govind (15) showed that the extra power required to obtain such a gain in transmembrane flux is a minute fraction of the power needed to maintain the corresponding steady flow. Several other studies reported higher gains by using unsteady fluid instabilities to operate microfiltration and ultrafitration experimental setups (2).

For cyclic operation, two types of forcing functions have been employed in published works, namely sinusoidal inputs and square wave variations (4). The latter approach, which is also known as the bang-bang type, has been shown to be the optimal forcing function (16). This is due to the fact that a square wave produces the most abrupt disturbance as shown in Fig. 1, where τ and A are, respectively, the period and amplitude of the wave, and P_0 is the average value of the periodic input which is equal to the value of the input under conventional steady-state operation. The split or pulse width, γ, is the ratio of the duration of the positive peak to that of the total period, τ. For a symmetric wave, $\gamma = 0.5$.

Reverse osmosis is one of the new and important processes widely used for the large-scale desalination of both sea- and groundwaters in areas having a shortage of fresh water, such as Saudi Arabia, Kuwait, Bahrain, and other

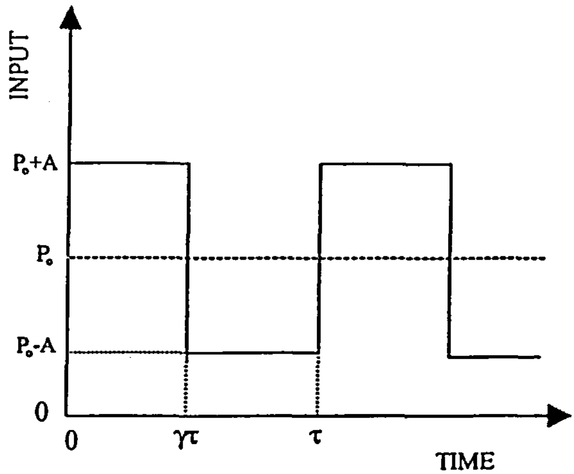

FIG. 1 Bang-bang cyclic strategy.

countries in the Middle East. No attempts appear to have been made to use cyclic operation of the reverse osmosis water desalination process either on commercial units or pilot plants. However, another membrane water desalination process which uses electric potential instead of pressure, namely electrodialysis reversal (EDR), has been using periodic operation in small to relatively large scale commercial units for a number of years. In the case of EDR, the polarity of the electrodes is reversed about every 10 minutes. This technique has led to a reduction of the scaling problems without the need for using any chemical antiscalents (17).

The objective of the present work was to study the effect of cyclic operation on the performance of an industrially important process, particularly for dry regions such as the Middle East; namely, water desalination using reverse osmosis. The considered module is a small-scale commercial spiral-wound membrane system. The unit operating pressure was varied in a symmetric square wave about a time-average value. The effects of the amplitude and period of the wave on the performance of the reverse osmosis plant were investigated.

EXPERIMENTAL SETUP AND PROCEDURE

A schematic diagram of the experimental unit used is shown in Fig. 2. This experimental setup includes feed, permeate, and concentrate PVC storage tanks with sizes of 340, 45, and 340 L, respectively. A 1.3-kW pump draws

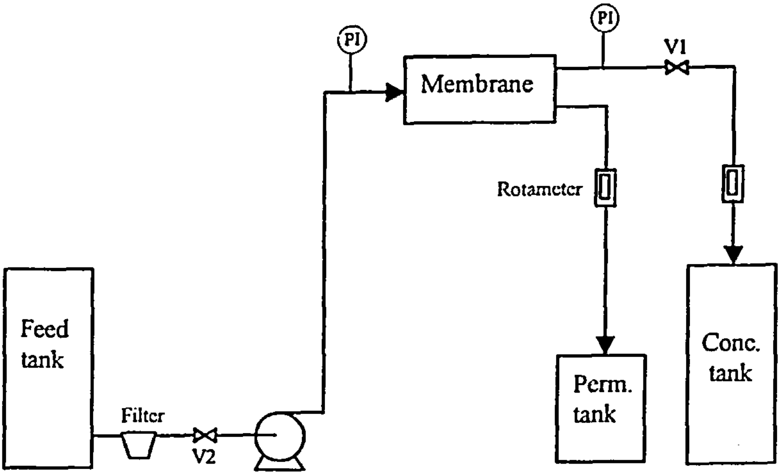

FIG. 2 Schematic diagram of the experimental setup.

the feed solution from the feed tank through a cartridge filter and a manual valve, V2, and delivers it at high pressure to a FilmTec membrane which is a spiral-wound thin film composite type placed in a GRP shell of 61 mm diameter and 457 mm length. The membrane is housed inside a hoop-wound GRP tube with a cylindrical plug inserted at each end. Two streams leave the membrane unit; a permeate and a concentrate solution. Each of these two streams passes through a rotameter to measure its flow rate before it enters its corresponding tank. The flow rates were also calculated from the total amount of each stream collected at the end of each run. The operating pressure was set using valve V1 installed in the concentrate line. The inlet and outlet pressures to the membrane were measured using Bourdon tube gauges. The concentration of salt in each of the two exit streams was measured by taking samples from the permeate and concentrate tanks at the end of each run.

At the beginning of each experimental test, the feed tank was charged with 300 L of a water solution having a concentration of 10,000 mg NaCl/L. For all the operating pressures considered, such a quantity was sufficient for a continuous run of more than 30 minutes. The feed solution was prepared by mixing sodium chloride with distilled water.

Initially, steady-state experiments were performed at two different operating pressures: 40 and 50 bars. The duration of each run was 30 minutes. The results of these steady-state experiments were employed as reference points against which the performances of the periodic tests were compared. Periodic tests were performed using a square wave forcing function by fluctuating the operating pressure around one of the two considered steady states. Two amplitudes (5 and 10 bars) and five different time periods (5, 7, 10, 13, and 15 minutes) were investigated. Small time periods were also considered ($\tau < 5$ minutes). However, due to the time lags of the process, we were unable to generate such relatively high frequency square waves. As mentioned earlier, the pulse width employed was 0.5 for all the tests. The duration of each experimental run was 30 minutes or less, such that an integral number of time periods was obtained. For example, for an amplitude of 5 bars, a time period $\tau = 13$ minutes, and a time-average pressure of 40 bars, the unit was started with an operating pressure of 45 bars. The pressure was maintained at this value for a duration of 6.5 minutes, then dropped to 35 bars for another 6.5 minutes. It was then raised to 45 bars for another 6.5 minutes. This process was continued for a total duration of 26 minutes (two time periods). The permeate production rate was then obtained through division of the amount of product collected by the run duration (26 minutes). The readings obtained from the rotameters were in close agreement with these more accurate manually calculated values. Note that all the rates presented in this study are those obtained from the manual flow measurement technique and not from the rotameters' readings. The duration of the runs corresponding to time periods of 5, 10, and 15 minutes was 30 minutes, whereas that corresponding to a time period of 7 minutes was 28 minutes.

The conductivities of the product and concentrate were measured using a Metrohm-type conductivity meter. At the end of each test a sample was taken from each of the product and concentrate tanks for conductivity measurements. The concentration of the solute was then read from available conductivity–concentration calibration curves. The concentrations of some of the samples were also checked by taking samples of known volumes, evaporating the water, and measuring the weight of the dry salt. It was found that the differences between the concentration values obtained using these two techniques were very small. This indicates that the concentration values inferred from measurement of the conductivity are fairly accurate.

RESULTS AND DISCUSSION

Figure 3 shows the permeate flow rate results corresponding to cyclic operation around 40 bars. All flow rates have been normalized by dividing them by the rate obtained through steady-state operation, which is 30 L/h. For example, at $\tau = 5$ minutes and $A = 10$ bars, the production rate was 33.9 L/h and hence the normalized value, Q_N, is $33.9/30 = 1.13$. All of the experimental values given in Fig. 4 were obtained by averaging the results of three repeated runs. In addition, all repeated runs led to permeate fluxes which were in close agreement.

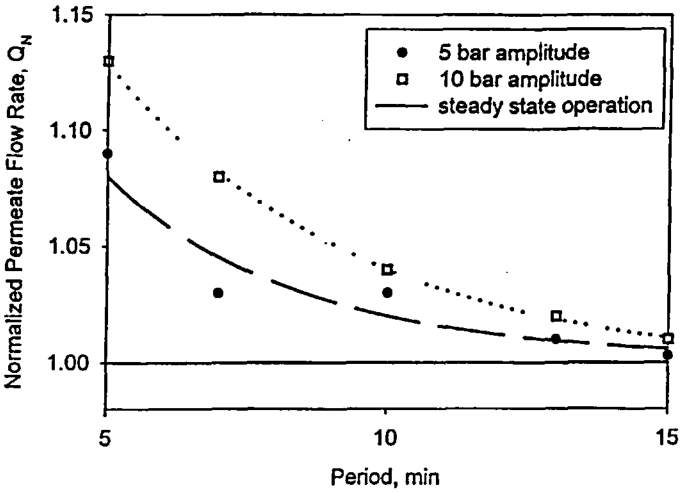

FIG. 3 Normalized permeate flow rate corresponding to periodic operation around a time average pressure of 40 bars. The dotted and broken lines are regression trends.

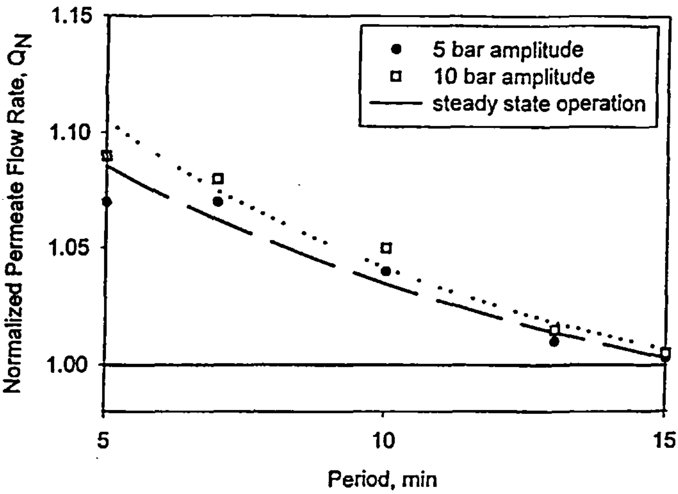

FIG. 4 Normalized permeate flow rate corresponding to periodic operation around a time average pressure of 50 bars. The dotted and broken lines are regression trends.

From Fig. 3 it can be seen that the quantity of permeate produced increases as the period of the fluctuations is decreased and the amplitude is increased. For example, cyclic operation with a time period of 10 minutes and an amplitude of 5 bars leads to a permeate production rate of $Q_N = 1.03$, which is 3% higher than the rate obtained from steady-state operation, whereas the production rate corresponding to $\tau = 5$ minutes and $A = 10$ bars is 13% higher. Periodic operation of the plant around the time-average pressure of 50 bars yielded similar trends as shown in Fig. 4. Note that operation of the desalination unit at a steady-state pressure of 50 bars resulted in a permeate flow rate of 36.8 L/h.

An interpretation for this increase in permeate flow rate with cyclic operation may be given in terms of the effect of such an operation mode on polarization. It is known that polarization is caused by a higher salt concentration in the region near the membrane compared to the bulk of the feed. This leads to a lower driving force for the water flux caused by a higher osmotic pressure in the vicinity of the membrane. In the case of periodic operation, the high concentration boundary layer near the membrane is disturbed, thus leading to a lower polarization effect and hence a higher permeate flux. The following equation for the water flux, N_w, which is based on the diffusion mechanism, can be used to understand the effect of polarization:

$$N_w = P_w[(\Delta p - \Delta\pi)]/l \tag{1}$$

where P_w is the specific diffusivity, Δp is the pressure drop across the membrane, $\Delta\pi$ is the osmotic pressure difference of the two solutions across the membrane (i.e., feed and permeate solutions), and l is the membrane thickness. The osmotic pressure difference, $\Delta\pi$, can be calculated from the feed and product concentrations, C_1 and C_2, respectively, using the following formula for dilute solutions:

$$\Delta\pi = (C_1 - C_2)RT \tag{2}$$

where R and T are the ideal gas constant and the absolute temperature, respectively. This equation shows that when the actual solute concentration, C_1, near the membrane wall is higher than that in the bulk of the feed, then the osmotic pressure difference will be higher. This in turn leads to a lower water flux as given by Eq. (1). Cyclic operation disturbs the onset of the thin boundary layer with high solute concentration near the membrane surface. This results in a reduction of the solute concentration buildup near the membrane. Such a reasoning is supported in part by the observation that the further the operation is away from the steady-state condition, the higher the normalized flow rate, as can be seen in Figs. 3 and 4; a low period and a high amplitude lead to a significant departure from steady state.

In addition to concentration polarization, a second factor which limits the transmembrane flux is fouling. Pulsatile flow is known to disturb both of these factors. Therefore, it is expected that if periodic operation is applied to the reverse osmosis of an unclean water solution such as ground- and seawaters, then the improvement in performance will be higher than the 13% obtained in this investigation.

As mentioned earlier, other studies showed that flow instabilities can lead to significant enhancements in the performance of ultrafiltration, microfiltration, and reverse osmosis membrane systems. Using completely different processes (different feed solutions and experimental setups), several other investigations have reported higher improvements in the permeate flux than that obtained in this study. For example, in filtration of whole blood and whey, Bauser et al. (18) reported a 40% increase in permeate flux at 0.5 and 1 Hz for whole blood and whey, respectively. Kennedy et al. (14) showed that improvements in reverse osmosis of sucrose solution can be obtained by pulsing the feed flow over a tubular cellulose acetate membrane according to a harmonic function. At high frequencies (1 Hz), they reported an increase in the permeation flux of 70%. Colman and Mitchell (19) used flow pulsations with baffles to improve permeation rates for a 1 wt% dextran T500 solution. They obtained an average permeation flux which is about 1.5 to 2 times higher than that with unbaffled steady axial flow. By using Dean vortices, Winzeler and Belfort (2) showed that the performance of a commercial ultrafiltration membrane system can be increased by about 5 times.

To investigate the effect of cyclic operation on power requirements, a digital energy meter was used to measure the energy (kW·h) consumed by the pump during each experimental run. The obtained energy was then divided by the duration of the run to yield the average power consumption. It was found that the extra power required to operate the pump in a cyclic manner was marginal. For example, the power consumed by the pump at a steady pressure of 40 bars was found to be 1080 W whereas those corresponding to periodic pressure fluctuations about an average value of 40 bars at an amplitude of 10 bars were 1080.2, 1080.6, 1081, 1081.2, and 1081.5 W for time periods of 15, 13, 10, 7, and 5 minutes, respectively. These results confirm the findings of Ilias and Govind (15) who, using a theoretical analysis, reported that the excess power requirement for periodic operation is a minute fraction of the power required to maintain steady-state flow.

The solute concentration in the permeate did not exhibit any specific trend. Intuitively, due to depolarization of the membrane, one expects that the solute rejection (the difference between the feed and permeate concentrations divided by the feed concentration) would improve with periodic operation. This was not the case; the salt rejection was virtually unaffected by cyclic operation. It varied randomly within a narrow range (from 98 to 99%). These small variations may be attributed mainly to measurement errors. Again, this result agrees with that obtained by Kennedy et al. (14). They found that flow oscillations did not affect the concentration of solute in the permeate for the reverse osmosis of a 10% (w/w) sucrose solution; in all of the considered cases (various periods and amplitudes), the permeating fluid contained 0.2% (w/w) sucrose.

CONCLUDING REMARKS

Cyclic variation of the operating pressure of a reverse osmosis water desalination unit led to improvements in the permeate flow rate. This flow rate increases with increasing amplitude and decreasing period of the forcing symmetric square wave function. In other words, the further away from steady-state operation, the higher the permeate flow rate. As for the product quality, the salt concentration in the produced sweet water was not affected by such a mode of operation. Finally, the results obtained in this work are encouraging and hence suggest that further work will be worthwhile. One future possible use would be to apply periodic operation to the reverse osmosis of unclean water solutions such as ground- and seawaters.

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