Backwash of RO spiral wound membranes

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Abstract

Osmotic backwash experiments were conducted and analytical model was developed in attempt to describe the backwash mechanism. A single unit of a spiral wound RO membrane was used in the experiments. The RO membrane was fed by salted water solution. Permeate flux characteristics of the membrane were determined through steady-state RO experiments. Then the system was shifted immediately to a backwash process by reducing the feed pressure, Δp, either to zero or to a level below the osmotic pressure to allow net backwash driving force. The backwash experiments reveal that the backwash process has two distinct regions. The flow rate drops sharply at the initial backwash process, followed by a prominently slower flow rate continuously slows down until it reaches a constant value (toward zero, for Δp = 0). These results suggest that the first backwash stage acts mainly to dilute the salt concentration at the feed concentration polarization (CP) layer. The second stage of the backwash flow rate exhibits salt dilution of the bulk solution. RO experiments were conducted also with a super-saturated CaCO₃ solution, to cause salt precipitation and partially clogging of the membrane surface followed by flux reduction. The permeate flux was resumed to its original level with osmotic backwash cleaning of the membrane. Effects of three independent RO feed variables; feed concentration, flow rate, and applied pressure, on the accumulated volume of backwash water, v(t) were analyzed experimentally. It was found that feed concentration has the strongest effect on v(t), while the other two parameters has only minor effects on the process. Presence of operational pressure during the backwash process reduces v(t) dramatically, as a consequence of the driving force reduction. A simple analytical model was developed and fits well the experimental data of the second stage without feed flow during the backwash process.

Keywords: Desalination; Backwash; Cleaning; Reverse osmosis; Osmotic backwash

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1. Introduction

Fouling is an inherent phenomenon in RO desalination technique. It may build up on the membrane surface progressively during the desalination process and thereby deteriorates the membrane performance [1–3]. Furthermore, some fouling types, such as biofouling, scaling of silica and others, when detected in an advanced stage may be irremovable [1], causing irreversible damage to the membrane. In the present study it was clearly shown that dissolving of CaCO$_3$ salt from the membranes by osmotic backwash can easily be made immediately after precipitation. As time goes on, the dissolution of the salt may be impossible due to hardening of the scale. To minimize RO plants deterioration due to fouling, periodic cleaning of the membrane is essential. The selection of a cleaning method depends on the type of the foulant.

There are three main cleaning methods: physical, chemical, and physicochemical methods [4]. Chemical cleaning methods are assigned to weaken cohesion forces between the foulant and the membrane surface [3]. The chemical methods are useful in biofouling and scaling of silica [1]. UF membranes, in filtration of wastewater, are cleaned with liquids or gases containing chemical agents [5–7]. Some membranes are vibrated by feeding of gases to accelerate pollutants separation from the membrane surface, in addition to chemical agents [8].

Physical cleaning methods include forward and reverse flushing, backwashing, vibrations, air sparging and CO$_2$ back permeation. Of the physical methods, the backwash method has proved to be an efficient physical cleaning method for flux recovery of membranes not severely fouled [3]. The backwash used in membranes is based on permeate back-flow to the concentrate side [9–11]. Therefore, membranes must have high pressure durability in both directions, which is not the case for RO spiral-wound membranes. An osmotic cleaning of RO membranes is based on flow induced by osmotic pressure as direct osmosis cleaning (DOC) [12]. The cleaning process in DOC is based on negative driving pressure between the operating and the osmotic pressures of the water solution in the feed side of the membrane. This can be done either by reducing operation pressure below the osmotic pressure of the solution or by increasing the permeate pressure to a level that allows backflow. The later possibility is carried out without changing parameters of the feed side of the RO process, yet high pressure piping is required at the permeate side.

Minimizing the backwash time and the amount of water needed are major purposes of the backwash process, as it saves permeate water and production time. The minimization can be done by determining the minimum amount of permeate water necessary to remove the contamination accumulated on the membrane, which is out of the scope of this work.

As a preliminary study, the main purpose is to investigate the backwash mechanism and identifying its main parameters. The present study contains detailed definition of the backwash problem for a single spiral wound membrane, in which the driving force of the backwash water is the osmotic pressure alone, i.e. atmospheric pressures allows on both the permeate and the concentrate sides. A mathematical model was developed and verified by corresponding experiments. Additional experiments were conducted for backwash pressure under lower pressure drops, bellow the osmotic pressure.

2. Theory

The present mathematical model together with experimental data were assigned to point at two backwash stages comprise the backwash mechanism. The experimental situation underlined the present model is as follows: The backwash process starts as soon as the RO stops. Physically, the start moment of the backwash process is when the net applied pressure drops below the osmotic pressure, $\Delta \pi$. This is the moment at which the permeate
water start to diffuse through the RO membrane and through the CP layer into the feed region, and then drained away. The water, when transfers through this path, dilute the salt concentration subject to diffusion and flow laws while possibly removing the fouled layer.

The first backwash stage is characterized by high transient water flow rates due to high osmotic pressure of the CP layer. This stage ends when the salt concentration in the CP layer becomes lower than the salt bulk concentration.

In the second stage, water keeps diffusing into the feed space against the salt concentration. At this stage, when no water fed to the membrane, it is reasonable to assume that time dependent water concentration in the feed side of the membrane is continuously reduced towards asymptotically pure water level. At the same time, transient process of salt concentration dilution continues at the feed side.

The simplest mathematical model accounting for the backwash phenomenon developed in this section, describes part of the second backwash stage at which a simple bulk (spatial independent feed concentrations) dilution process of the salt-solution takes place in the feed side.

2.1. Main assumptions underlying the present model

2.1.1. Water concentration profile, $C_m$, along the membrane wall, may be approximated as linear during the backwash process. This assumption is based on the assumed steady linear concentration profile during the RO process. So is the case at the assumed end of the backwash process, which is also a steady state. Between the two stages, maximal change of the $C_m$, $\Delta C_m/\rho = CM/\rho \approx 0.05 \ll 1$ occurs (where, the water density $\rho = 1000 \text{ kg/m}^3$, and $CM$ is the salt concentration at the membrane surface on the feed side, during the RO process). The effective RO membrane thickness is significantly thinner than the membrane thickness; therefore, linearization effects of possible curved water profiles within the membrane are assumed negligible. This assumption is justified especially for dilute salt concentrations.

2.1.2. Water concentration at feed side end of the membrane ($z = L$), $C_o(t)$ depends on water concentration in the feed space, according to diffusion laws ($L$ is the membrane thickness, $L_i$ is the effective thickness of the RO membrane and $z$ is the spatial coordinate in the main flow direction along the membrane, Fig. 1).

Assumptions 2.1.1 and 2.1.2, determine the linear water concentration distribution within the membrane,

$$C_m(z,t) = C_w - \frac{z}{L} \left[ C_w - C_o(t) \right]$$

where $C_w = \rho - C_p$, $C_p$ is the salt concentration in the permeate space and $C_o(0) = CM$.

2.1.3. Mass diffusion from the permeate space to the feed space is of water only.

2.1.4. At low water density changes, water volume, $\nu(t)$, enters the feed space at time, $t$, [$\delta(t) - \delta(0)$]$\sigma$, dilutes the solution and at the same time same solution volume discharges out of it. $\delta(0) = 0.7 \text{ mm}$, is the distance between the two membranes of the feed space [13], $\delta(t)$ is an intermediate variable, enables calculations of the water volume [$\delta(t) - \delta(0)$]$\sigma$ enters the feed space at time $t$, and $\sigma$ is the surface area of one of the two membranes.

Salt conservation in the feed space together
with assumptions 2.1.3 and 2.1.4, yields,

\[ \delta_o \cdot (\rho - C_{bo}) = \delta(t) \cdot [\rho - C_b(t)] \]  

(2)

where \( \delta_o = \delta(0) \), \( C_{bo} \) is the initial average water concentration in the feed space and \( C_b(t) \) is the water concentration in the feed space. \( C_{bo} \) may be calculated from RO data preceded the backwash process.

\[
C_{bo} = \frac{2}{\delta_o} \int_0^L \left[ C_w - (CM - C_p) \cdot \exp \left( -J_v \cdot \frac{z}{D_s} \right) \right] dz + (\rho - C_f) \cdot \left( 1 - \frac{\delta'}{\delta_o} \right)
\]

(3)

where \( C_f \) is salt concentration in the feed at RO process, \( CM, D_s \) and \( \delta' \) are calculated by the following equations of [14]. Eqs. (6), (16) of [15] and Eq. (13) of [14].

\[ D_s = 6.725 \cdot 10^{-8} \]
\[ \cdot \exp \left( 0.1546 \cdot 10^{-3} \cdot C_f - \frac{2513}{273.15 + T} \right) \]

(4)

\[ k_s = 1.63 \cdot 10^{-3} \cdot C_f^{0.4053} \]

\[ CM = C_p + (C_f - C_p) \cdot \exp \left( \frac{J_v \cdot \delta_o}{D_s} \right) \]

2.1.5. Water flux from the membrane to the feed space is subject to the boundary condition,

\[ -D_m \cdot \frac{\partial C_m(L, t)}{\partial z} = h \cdot [C_o(t) - C_h(t)] \]

(5)

where \( D_m \) is water diffusion coefficient in the membrane, and \( h \) is the convective mass transfer coefficient in the feed solution.

Combining Eqs. (1)-(5) yields the following differential equation for \( \delta(t) \).

\[
\frac{d\delta(t)}{dt} = \frac{D_m \cdot S}{\rho \cdot L \cdot (1 + S)} \left[ \frac{\delta_o \cdot (\rho - C_{bo}) - C_p}{\delta(t)} \right]
\]

(6)

where the Sherwood number is given by \( S = hL/D_m \).

The solution of Eq. (6) yields the following \( \delta(t) \) function,

\[ t = a \cdot \alpha \cdot \ln \left( \frac{\alpha - \delta_0}{\alpha - \delta(t)} \right) + \delta_0 - \delta(t) \]

(7)

where

\[ a = \frac{\rho \cdot L \cdot (1 + S)}{S \cdot D_m \cdot C_p} \]

and

\[ \alpha = \frac{\delta_o \cdot (\rho - C_{bo})}{C_p} \]

Water flux \( dv/dt \) enters the backwash system is a measurable variable. It is derived from Eqs. (1), (2), (5), (7)

\[
\left( \frac{dv}{dt} \right) = \frac{D_m \cdot \sigma \cdot S}{\rho \cdot L \cdot (1 + S)} \left[ (\rho - C_{bo}) \cdot \frac{\delta_o}{\delta(t)} - C_p \right]
\]

(8)

The total water volume, \( v(t) \), enters the BW system at time, \( t \), is derived analytically from Eqs. (6), (8)

\[
v(t) = \frac{\sigma \cdot \delta_0 \cdot (\rho - C_{bo})}{C_p} \cdot \ln \left[ \frac{\alpha - \delta_0}{\alpha - \delta(t)} \right] - \frac{\sigma \cdot C_p \cdot S \cdot D_m \cdot t}{\rho \cdot L \cdot (1 + S)}
\]

(9)

Backwash water volume \( v(t) \) in Eq. (9), is compared with experimental data to determine the end point, \( t_e \), of the backwash first stage.
As the present analytical model is based on a bulk concentration assumption (spatial independent), it should fit experimental \( v(t) \) profiles, far enough of the first stage.

3. RO backwash experiments

Experiments, in the present study, were assigned to investigate effects of RO feed salt concentration, \( C_p \), applied pressure, \( \Delta p \), and feed flow-rate, \( Q_f \), on the amount of permeate water used during the backwash process, \( v(t) \) and to validate the analytical model.

3.1. Experimental system

Fig. 2 depicts a schematic diagram of the experimental system. It is equipped with a single laboratory spiral wound module (Filmtec SW30 2521-A). RO data of the membrane includes: membrane length, \( L = 0.4 \) m, width, \( W = 1.2 \) m, the effective membrane thickness, \( L_1 = 3 \times 10^{-8} \) m, and the gap between two membranes, \( d \), is given as \( 7 \times 10^{-4} \) m [13].

The flow system enabled either partial recycle (concentrate recycled but permeate withdrawn from the system) or full recycle (both concentrate and permeate recycled to the feed vessel). An auxiliary tank was added, equipped with two valves, so the permeate could accumulate in the tank for a short period or withdrawn to the feed tank. This tank supplies permeate for the backwash experiment. In all experiments, flow through the membrane was at the rate of 450–600 L/h and transmembrane pressure was changed up to 6 MPa. Permeate flow rates were in the range of up to 50 L/h. Pump heat energy was removed from the recycling concentrate by using a water-cooled heat exchanger. Concentrate temperature was typically 30°C±2°C.

After setting the operational conditions, the system was allowed to operate for some time in order to gain stable state. Then the permeate valve was closed and the valve connected to the permeate auxiliary tank was opened, allowing the permeate to accumulate there. Then the operating pressure was changed to the chosen new value and the water level in the tank was recorded, using a video camera.

3.2. Experimental method

Each backwash experiment was conducted after running the experimental system for about 15 min to assure steady state RO operation. Backwash time starts at the stop moment of the RO process, by stopping the applied pressure as quickly as possible, to minimize the shift time between RO and backwash processes.

Applied pressure and the feed flowrate were online monitored and controlled. Feed concentration and permeate concentration were measured.

![Fig. 2. Experimental system.](image-url)
by sampling of the respective solutions before stopping the RO process. Salt concentrations in both permeate and concentrate spaces, were measured by a conductivity device (Consort Conductometer K610) and converted to salt concentration. Each experiment yields data points of a permeate water volume, v, withdrawn from the permeate auxiliary vessel to the RO membrane at time t.

4. Results and discussion

Results of the present study are based on the following RO parameters: the solution permeability, \( L_p = 4.269 \cdot 10^{-12} \text{ m/(s \cdot Pa)} \) derived by preliminary experiments, \( CM, \delta' \), and \( D_\gamma \) are calculated from RO equations presented in [15]. Backwash effects on water production using the RO technology, is illustrated in Fig. 3.

In this figure, preliminary results of controlled osmotic backwash and cleaning of CaCO\(_3\) salt precipitation are depicted. The experiment has been conducted with 0.5% NaCl solution with supersaturated CaCO\(_3\) salt. The super-saturation was high enough to allow salt precipitation on membrane walls. The precipitation was followed, as can be seen by partially clogging the membrane, resulted with low flux decline, of the order of 5%. The operation halted for a short time, stopping the pumps and allowing short osmotic backwash of about 20 s duration. Then the regular operation restarted. It can be seen that apart of the first backwash cycle, other three successive backwash cycles are presenting flux recovery to the highest original level of no salt precipitation. The results should further be repeated and checked more carefully. Also, it is clear that removing of CaCO\(_3\) salt from the membranes can easily be made only immediately after precipitation. As time goes on, the removal may be impossible due to hardening of the scale. However, the experiment shows the capability of the technique for cleaning the membrane after clogging.

Fig. 4 shows a typical backwash experiment. The backwash process starts with high water flux enters the feed channel between the membranes due to the concentration polarization layer. At the beginning of the second stage it is assumed that the concentration reaches the \( C_f \) level, and the backwash water creates a concentration drop in the feed space.

The theoretical curve, calculated by Eq. (8), fits well the experimental data, as expected for low salt concentrations. The two stages of the process are shown in Fig. 4a. The second stage appears to coincide with the predicted model. The two stages can also be seen very clearly in the experimental flux curve presented in Fig. 4b. The first stage is characterized by rapid flux decline, while the flux in second stage is slowly reduced.

Three independent RO variables govern Eq. (8) and therefore the backwash process: \( C_f, \Delta p \), and \( Q_f \). It is interesting to find out quantitatively their effects on the profiles of water permeation during the backwash process.

The most obvious effect on the backwash profile is the initial feed concentration, \( C_f \), as it attracts the water from the permeate channel by direct osmosis. As expected, according to diffusion laws, Fig. 5 shows that at any time the permeated

![Fig. 3. Backwash of CaCO\(_3\) precipitation on a reverse osmosis membrane.](image-url)
Fig. 4. Typical presentation of the penetrating volume of water (a) and water flux (b) as a function of time enter the backwash system at zero pressure. RO data: Δp = 4 Mpa, C_f = 10.6 kg/m^3, C_p = 0.0595 kg/m^3, Q_f = 400 L/h, CM = 21.9 kg/m^3, transport data: D = 1.47×10^{-9} m^2/s, D_m = 1.10×10^{-11} m^2/s, δ' = 3.62×10^{-5} m, S = 5.1.

Fig. 5. Effect of the RO feed concentration on the permeation accumulated volume of water, v(t), backwashes the membrane at time, t. RO data: Δp = 4 Mpa, Q_f = 400 L/h. The thickness of the RO concentration polarization layer is proportional to the inverse of the RO feed flow rate, Q_f [14]. Keeping the same feed salt concentration, C_f, and the same applied pressure, Δp, the salt mass in the CP layer increases with the decrease of the flow rate. Effects of the feed flow rates on v(t) were tested. Results in imply that v(t) is practically independent of the prior RO applied pressure for the tested range.

amount of backwash water increases with C_f. For similar reasons, the time needed to backwash with the same amount of water increases with the decrease of C_f.

The RO applied pressure affect the concentration polarization layer. Effects of the applied pressure on v(t) were tested for Δp = 4, 5 and 6 Mpa. The results in Fig. 6 exhibit small and inconstistence differences, explained within the measurement errors. These preliminary results

Fig. 6. Effect of the RO applied pressure on the accumulated volume of water, v(t), backwashes the membrane at time, t. RO data: C_f = 31.1, 31.7, and 31.9 kg/m^3, for Δp = 4, 5, and 6 Mpa, respectively, Q_f = 400 L/h.
Fig. 7. Effect of the feed flow rate on the accumulated volume of water, $v(t)$ backwashes the membrane at time, $t$. RO data: $C_f = 31.8, 31.1,$ and $30.6$ kg/m$^3$, for $Q_f = 200, 400$ and $600$ L/h, respectively, $\Delta p = 4$ Mpa.

Fig. 7 show small differences between the three graphs.

Keeping RO operational conditions constant during the backwash process has a practical importance, in order to prevent unwanted fluctuations in the system [12]. The feed pressure during the backwash process opposes the osmotic pressure, so the net force for suction the permeate water through the membrane into the feed space decreases with the increase of the feed pressure. This net backwash driving pressure diminishes when the feed pressure difference equals the osmotic pressure. The effect of pressure difference on $v(t)$ is illustrated in Fig. 8. The strong relations between operational pressure and $v(t)$ shown in Fig. 8 stem from the osmotic pressure balance. Looking in the figure, it can be seen that with high pressure difference, $\left(\Delta p = 0\right)$, more water penetrate in the first stage than with lower driving pressure. The osmotic pressure for the water concentration in Fig. 8, is equal to 13.7 bar, therefore, operating at 10 bar allows very low driving pressure for the wash process and the accumulated volume is low, reaching rather quickly the final stage.

5. Summary and conclusions

The backwash mechanism and parameters affecting the volume of permeate water, $v(t)$, are discussed in the present study. RO experiments were conducted with a super-saturated CaCO$\text{\textsubscript{3}}$ salt, resulted in salt precipitation and its clogging on the membrane surface. The salt layer reduces the permeate flux by about 5%. The permeate flux has been resumed to its original level due to a backwash cleaning of the membrane. The process was repeated periodically for several times without significant changes.

Backwash experiments reveal the existence of two main stages. The first stage is characterized by a high backwash flux $\frac{dv(t)}{dt}$ for a relatively short time. This stage is attributed to the CP layer dilution. In the second stage the backwash flux is much slower than in the first stage. It continuously reduces with time in the case no feed flow along the membrane. In this case, at a certain point of the second stage the proposed analytical model starts to fit well the data. This point is determined by comparing experiments with the current analytical model, developed in the present study, and based on the assumption of spatial independent concentration in the feed channel.

Effects of the three independent RO variables, $C_f$, $Q_f$, and $\Delta p$, on $v(t)$ were analyzed through experimental data. As expected, $C_f$ has the
strongest effect on $v(t)$. The $\Delta p$ at the RO stage has no practical effect on $v(t)$. The $Q_s$ has small effect on $v(t)$ which needs further investigation. Strong relations of the net osmotic pressure on the $v(t)$, presented experimentally, has a practical application in backwash automation, keeping the RO conditions undisturbed.

References


