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Performance decline in brackish water FilmTec spiral wound RO membranes

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Abstract

In this paper, long-term operational data from a medium scale RO plant based on brackish water FilmTec spiral wound RO membranes are presented and analysed. It was found that over a period of 500 days of continuous operation, the water permeability coefficient for the overall plant decreased by about 25% and the salt rejection dropped by 1.9%. Simple formulae representing the long-term performance of the plant were developed. These expressions were found to fit the data with very good accuracy.

Keywords: RO; Brackish water desalination; Spiral wound membrane; FilmTec; Long-term performance

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1. Introduction

The reverse osmosis (RO) process has undergone major developments during the past three decades. In the water desalination sector, the recent advances in RO technology have made it possible and economical to construct large-scale plants to treat both brackish and seawater feeds in many parts of the world that complain from shortages of natural fresh water. RO has many advantages when compared to the other widely used technique for water desalination, namely, multi-stage flash (MSF) distillation. They include lower capital cost and energy requirement, smaller plant area and modular design which gives it the flexibility of adding new modules and the simplicity of replacing damaged elements. One major disadvantage of RO and other mem-

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brane separation processes is the requirement of careful monitoring and control of the quality of feed so as to reduce the effects of fouling and to prevent structural damage to the membrane. Feed pre-treatment may include pH adjustment, filtration to remove particulates, use of complexing agents to ionize slightly soluble salts and metals and the addition of disinfectants for control of microbial growth.

In addition to feed pre-treatment, periodic membrane cleaning is another approach used to control membrane fouling. Use of fluid instabilities is a third technique, which can be used to reduce one important cause of membrane fouling, namely, concentration polarization [1–3].

In desalination, the two characteristics, which should be maximized for the most efficient and economical use of the process, are product water quantity and quality. In RO systems these two characteristics are adversely affected by membrane fouling, compaction and hydrolysis [4]. In practice, the operating pressure is increased so as to overcome the reduction in productivity and maintain a constant production rate. This leads to a higher cost of water production. Therefore, analysis and prediction of long-term performance are essential for the successful operation of the plant. Usually, membrane manufacturers present performance decline schemes based on nominal test conditions. However, the factors affecting the performance of the plant are closely linked to the characteristics of the raw water as well as the pre-treatment scheme used. This means that predictions of the long-term performance decline should be based on actual plant data. In this paper, the long-term data of a medium scale industrial brackish water RO process is analysed. Also, simple models, which can be used to predict the future performance of the plant, are developed.

The paper is structured as follows. The theoretical tools required for analysing the data are treated in section 2. The industrial plant, from which the data were collected, is briefly described in section 3. The results and analysis are given in section 4. Section 5 presents the main conclusions.

2. Theory

As mentioned earlier, concentration polarisation (CP) is one factor, which promotes membrane fouling and limits the performance of RO systems. CP refers to a layer next to the membrane surface having a much higher solute concentration than the bulk of the fluid. A material balance within this layer between the solute carried to the membrane by convection and the solute carried away by diffusion yields [5].

$$D\frac{\mathrm{d}C}{\mathrm{d}y} = CJ_w \tag{1}$$

where D is the diffusivity of the solute, C is the solute concentration and y is the distance perpendicular to the membrane wall. J_w is the water flux. Integration of Eq. (1) leads to the following expression

$$\frac{C_m - C_p}{C_b - C_p} = \exp\left(J_w / k\right) \tag{2}$$

where β is the thickness of the layer and k is the mass transfer coefficient given by the ratio of D over β. Subscripts b, m and p refer to bulk, membrane and permeate.

The coefficient k may be estimated using an appropriate empirical mass transfer expression. For fully developed turbulent and laminar flow regimes, Belfort [6] gives the following expressions.

Turbulent flow:

$$\mathrm{Sh} = 0.04\,\mathrm{Re}^{0.75} \cdot \mathrm{Sc}^{0.33} \tag{3}$$

Laminar flow:

$$\mathrm{Sh} = 1.86(\mathrm{Re}\cdot \mathrm{Sc}\cdot d_h / L)^{0.33} \qquad (4)$$

where Sh, Re, and Sc are the Sherwood, Reynolds and Schmidt numbers respectively. L is the length of the membrane and d_h is the hydraulic diameter of the flow channel.

Eqs. (2) and (3) or (4) may be used together with Eqs. (5) and (6) below to determine the permeabilities A and B of the water and solute respectively.

$$A = J_w / (\Delta P - \Delta\pi) \qquad (5)$$

$$B = J_s / (C_m - C_p) \qquad (6)$$

where ΔP is the pressure difference between the feed side of the membrane and the permeate side. Similarly, $\Delta\pi$ is the osmotic pressure difference across the membrane. For not too high solute concentrations, the relationship between the osmotic pressure and concentration is approximately linear.

$$\pi = \alpha C \qquad (7)$$

For sodium chloride with C in weight per cent and π in bars, $\alpha = 7.79$.

For low to moderate salinity brackish waters, concentration polarisation may be neglected and hence the average bulk concentration is used to calculate the osmotic pressure.

3. Process description

A block diagram of the considered process is shown in Fig. 1. It is a medium scale industrial plant that is used to desalinate brackish water to produce about 40 m³/d. Raw water is pumped from a 74 m deep well to the surface. It is passed through a pre-treatment sequence before entering the production plant. The pre-treatment process consists of chlorination with $Ca(HClO)_2$, sand

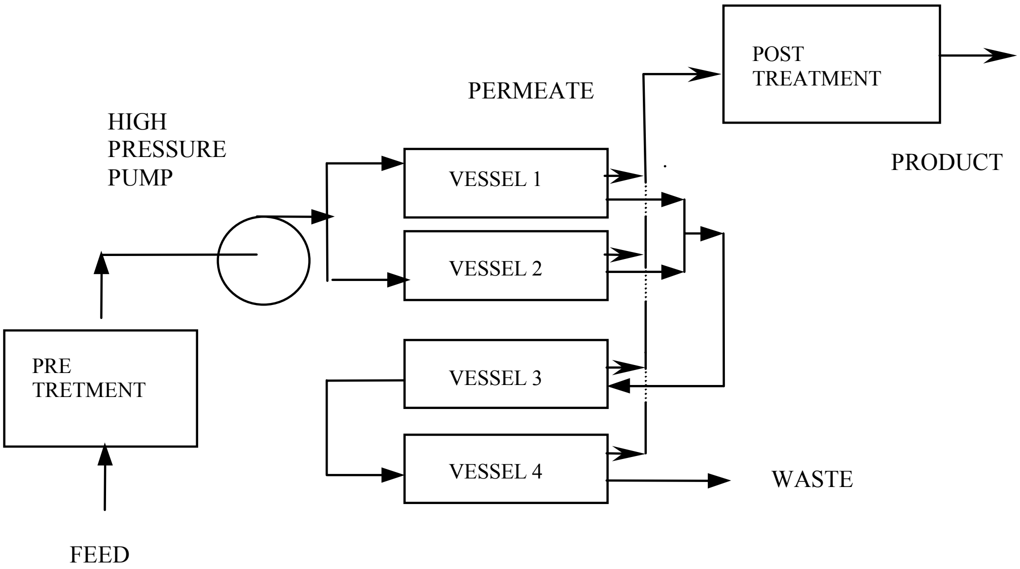

Fig. 1. Schematic diagram of the plant.

filtering, dechlorination using sodium-bimetasulfite, activated carbon filtering and UV treatment. Then, an antiscalant and sulfuric acid are added to the feed water. To complete the pretreatment process the water is passed through a cartridge filter. A pump delivers the pre-treated feed water to the production plant at a pressure of approximately 12 bars.

The production facility is composed of three consecutive stages. The first stage contains two vessels whereas the other two are single-vessel stages.

Each vessel contains three FilmTec BW30-400 elements. The concentrate from the first stage is used as the feed to the second stage with the concentrate of this latter stage being used as the feed to the third and final stage. The permeates from all vessels are combined to form the product which passes through a post-treatment phase. This phase consists of the addition of caustic soda, ozonation, filtering through activated carbon and finally dosing with fluoride.

4. Results and discussion

Operational data, spanning a period of 500 d (12,000 h), were collected from the plant. Data collection started from the first day of production. The data obtained included flow rates, pressures, pH, temperatures and conductivities of the feed, permeate and concentrate. It is interesting to note that measurements of the feed conductivity showed that the feed salinity increased over the data collection period by 13% (from 2540 ppm to 2870 ppm). To avoid the decline in production rate resulting from this increase in feed salinity and deterioration of membrane performance, the operating pressure had to be gradually increased with time. The permeability coefficients A and B were then calculated using the collected data and Eqs. (4) and (5).

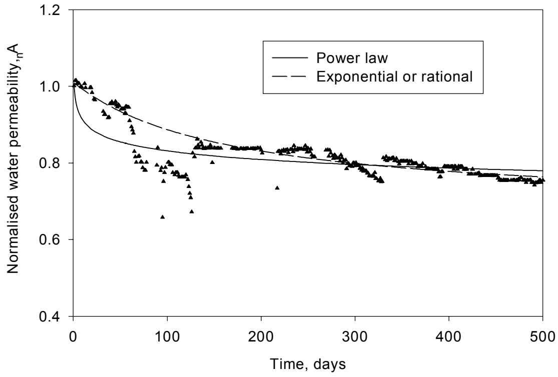

Fig. 2. Evolution of water permeability coefficient with time.

Fig. 2 shows the evolution of the normalised solvent permeability coefficient, $A_n = (A/A_0)$, as a function of the operational time. A_0 is the initial solvent permeability. A continuous decline in the permeability can be noticed. The sharp drop that can be seen after a time period of about 60 d was due to a mechanical failure of two membranes, which were replaced with new ones resulting in restoration of normal permeation rates. During the considered period of operation the permeability decreased by 25% (from $A_n=1$ to $A_n=0.75$). As expected, most of the reduction in permeability occurred in the first few months after start-up. For example, the average reduction in permeability was 7% and 16% two months and six months after start-up, respectively.

It is customary to represent the decline in plant productivity by a power law function, i.e.,

$$A_n = t^{-m} \tag{8}$$

Fitting Eq. (8) to the data lead to a permeability decline coefficient, m, of 0.042. This figure falls well within the range of values reported in the literature. Belfort [6] compiled a table of m-values for various membrane types operating at different conditions. The set of values reported by Belfort range from 0.008 to 0.08.

As illustrated by Fig. 2, the power law function does not fit the data with reasonable accuracy, particularly at the initial period of operation. Two simple expressions have been found to represent the full range of data with very good accuracy. They are:

A rational function

$$A_n = \frac{168.0 + 0.68t}{166.3 + t} \tag{9}$$

And an exponential function

$$A_n = 0.68\exp\left(\frac{79.0}{t + 201.1}\right) \tag{10}$$

One of the factors, which affect the performance of RO membranes, is the feed temperature which can seasonally vary by several degrees. The rate of change of water flux with temperature is approximately 3%/°C [7]. In this study, since the feed is pumped from a 74 m deep well, the temperature variations are not large as shown in Fig. 3; it varies between 28°C and 30°C. The higher values of temperature occurred during the summer months (June to September).

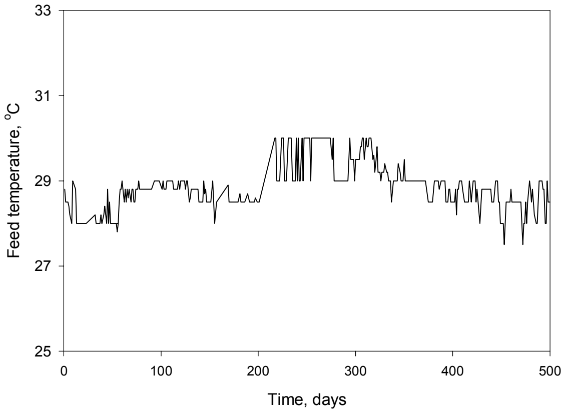

Fig. 3. Variation of feed temperature with time.

Fig. 4 shows the evolution of the salt rejection (SR) with time. SR is defined as:

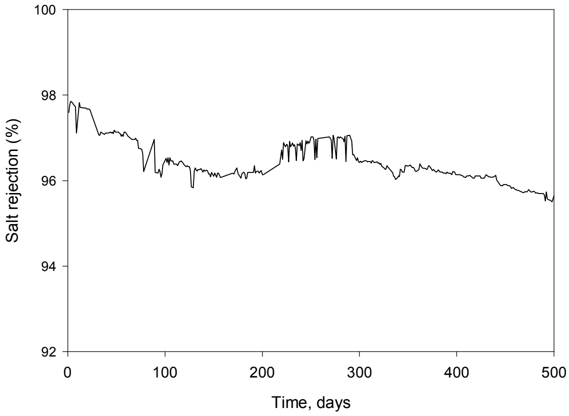

Fig. 4. Evolution of salt rejection with time.

$$SR = 1 - C_p / C_f \tag{11}$$

The salt rejection decreases with time from a value of 97.6% at start-up to a value of 95.7% after 500 d of continuous operation. Note that the SR values given in this work refer to the performance of the plant as a whole and not to a single membrane element. Under nominal test conditions the manufacturer quotes a value of 99% rejection for BW30-400 elements.

For design and performance studies, it is more useful to express the salt rejection in terms of the salt permeability coefficient, B, which is calculated from Eq. (5). The normalised salt transport coefficient $B_n = B/B_0$) is shown in Fig. 5. As B is a measure of the salt passage through the membranes, it is highly influenced by the frequency of cleaning and this is, in turn, is reflected in the level of fluctuation in the data. Examination of Fig. 5 shows that over a period of 500 d the salt permeability coefficient increased by about 85%. As mentioned earlier, the sharp increase that can be seen after a time period of about 60 d was due to mechanical failures of two membranes which were later replaced. It has to be stressed, however, that during this period of quasi-abnormal operation, the quality of the product was maintained well within specifications. The

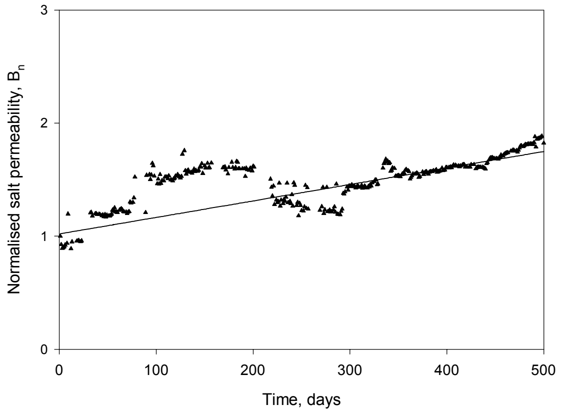

Fig. 5. Evolution of salt permeation coefficient with time.

variation of the salt permeability with time can be approximated by a linear relationship as illustrated by the regression line.

5. Conclusions

Using a low salinity ground water, the performance of spiral wound FilmTec RO membranes exhibited typical declines in water permeability and salt rejection. Over a period of 500 d, the apparent water permeability declined by 25% while the salt rejection dropped by only 1.9%. Based on the collected operational data, simple models for predicting the long-term performance of the plant were developed. These models may be used by the plant managers as additional tools in deciding when to replace some or all membrane elements.

6. Symbols

A — Solvent (water) permeability, m.s^{-1}.bar^{-1}
B — Solute (salt) permeability, kg/(m^2.s.bar)
C — Salt concentration, kg/m^3
D — Salt diffusivity, m^2/s
d_h — Hydraulic diameter of flow channel, m
J — Flux, m^3 water/(m^2.s) or kg salt/(m^2.s)
k — Mass transfer coefficient, m/s
L — Length of the membrane (element), m
ΔP — Pressure drop across membrane, bar
$\Delta\pi$ — Osmotic pressure difference across membrane, bar
Re — Reynolds number
Sh — Sherwood number
Sc — Schmidt number
t — Time, s
y — Distance perpendicular to the membrane wall, m

Greek

α — Proportionality constant, Eq. (7)
β — Thickness of the boundary layer, m

Subscripts

b — Bulk
f — Feed
m — Membrane
n — Normalised
0 — Initial
w — Water
s — Salt

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