Performance of Reverse Osmosis Units at High Temperatures

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Abstract

There are few parameters which are typically used to describe the performance of reverse osmosis units operation. Product flow rate and salt rejection are the key performance parameters. They are mainly influenced by variable parameters such as pressure, temperature recovery and feed water salt concentration. The effect of temperature on membrane performance is the most important parameter. When temperature of feed water is increased for constant product flow the required applied feed pressure decreases and the product water salinity increases. Energy consumption is decreased as the applied pressure decreases. If the permeate flow is let to increase as the temperature increase fewer membrane elements will be required. This leads to a considerable saving in the water production cost. As a rule of thumb membrane capacity increases about 3% per degree Celsius increase in water temperature.

In this paper, intensive trials will be undertaken to study the performance of reverse osmosis units. Known computer software will be used for this purpose as well as some operating data of Riyadh water treatment plants. It is expected that this work will help in optimizing the operation of reverse osmosis units. The balance between feed pressure, recovery, flux and membrane area will be maintained at the desired product water quality.

Introduction

Well water every where is found at high temperatures. In Riyadh, Saudi Arabia raw water from deep wells is pumped at a temperature in the range of 50-60 ^{o}C. The first step in treatment of this water is cooling. Cooling takes place in cascade chillers (forced draught towers) to bring the temperature down to 30-35 ^{o}C to meet the RO membrane specifications[1]. If high temperature membranes are available cooling of raw water can be eliminated.

The limit of practical operating temperature is established by the characteristics of the membrane polymer. Depending upon the membrane manufacturer guidelines, the maximum allowable temperatures varies from 35 to 45 ^{o}C; e. g. Toyobo 35 ^{o}C, DuPont 40 ^{o}C, Dow/FilmTec, Fluid Systems, Hydranautics and Toray 45 ^{o}C.

Permeate and salt passage increase with increasing the feed water temperature. There is about 3 % increase in water production rate for each degree rise in temperature. However, the increase in feed water temperature accelerates the rate of membrane degradation. High temperature also affects the membrane retention coefficient. Low membrane retention is obtained at high temperature. So optimizing of the operation of reverse osmosis system should be studied in order to maintain the desired product water quality at the optimum operating variables.

Basic Reverse Osmosis Relations

The osmotic pressure, π, of a solution can be related to the concentration of dissolved salts in solution by the following Equation:

$$\pi = 1.19\ (t + 273) * \Sigma\ (mi) \qquad (1)$$

where π = osmotic pressure, psi, t is the temperature, °C, and Σ (mi) is the sum of molal concentration of all constituents in a solution. An approximation for π may be given by:

$$\pi = \frac{0.0385\,C\,(t + 273)}{1000 - \frac{C}{1000}} \qquad (2)$$

where C is the total dissolved solids (TDS), mg/l (ppm). So at 1000 ppm of total dissolved solids the osmotic pressure, π, equals about 11.5 psi (0.79 bar).

The rate of water passage through the reverse osmosis membrane is given by the following relation:

$$F_w = K_w\ (\Delta P - \Delta\pi)\ A / x \qquad (3)$$

where F_w is the rate of water flow through the membrane, ΔP is the hydraulic pressure differential across the membrane, $\Delta\pi$ is the osmotic pressure differential across the membrane, K_w is the membrane permeability coefficient for water, A is the membrane area, and x is the membrane thickness.

The rate of salt flow through the membrane is is given by the following relation:

$$F_s = K_s\ (C_f - C_p) \qquad (4)$$

where F_s is the flow rate of salt through the membrane, K_s is the membrane permeability coefficient for salt, $(C_f - C_p)$ is the salt concentration differential across
the membrane, where C_f is the feed water concentration and C_p is the product (permeate) water concentration.

The salinity of the permeate, C_p, depends on the relative rates of water and salt transport through reverse osmosis membrane. It can be given by:

$$C_p = F_s / F_w \qquad (5)$$

Permeate recovery or conversion rate of feed water is defined by the following Equation:

$$R = 100 * (F_w / F_f) \qquad (6)$$

where R is recovery rate, %, F_w is the product water flow rate, and F_f is the feed water flow rate.

Salt passage and salt rejection is the opposite to each other. Salt passage is defined as the ratio of concentration of salt on the permeate side of the membrane relative to the average feed concentration. It can be expressed by the following relation:

$$SP = 100 * (C_p / C_{fm}) \qquad (7)$$

where SP is the salt passage, %, C_p is the salt concentration in the permeate, and C_{fm} is the mean salt concentration in feed stream. So the salt rejection, SR, is defined by the following Equation:

$$SR = 100 - SP \qquad (8), \text{ or}$$

$= 100 * (C_{fm} - C_p)/ C_{fm}$

Performance of Reverse Osmosis Units

Upon solving the previous basic RO Equations, the applied feed pressure as a function of feed salinity is shown on Figure 1. As the feed salt concentration increases the required feed pressure increases too. If the feed pressure is kept constant, an increase in the feed concentration will cause the water flux to drop. The increasing osmatic pressure due to the increase in salt concentration offsets the feed driving pressure.

Also from the basic RO Equations, it is obvious that the rate of water flow through a membrane is proportional to net driving pressure differential, NDP, ($\Delta P- \Delta\pi$) across the membrane. Water flux increases in direct proportion to an increase in the applied pressure. However, the membrane permeability coefficient for water, K_w, is not constant anymore if the pressure increased. It is rather decreased as the feed pressure increased, as show in Figure 2[2]. This phenomena is known as membrane compaction. It imposes a limitation on the feed pressure.

Compaction will yield an increase in the density of membrane material which will decreases the rate of diffusion of water and dissolved constituents through the membrane. As a result of compaction, higher pressure has to be applied to maintained the design permeate flow. The effect of compaction is more significant in asymmetric cellulose membranes than in composite polyamide membranes. In seawater RO, where the feed pressure is much higher than in brackish applications, the compaction process will be more significant. Usually membrane compaction results in few percent flux decline, and has strongest effect during the initial operating period[3].

The rate of salt flow is mainly proportional to the concentration differential across the membrane. The concentration gradient across the membrane acts as a driving force for the flow of salt through the membrane. This is reflected by Equations 3 and 4. As feed concentration increases membrane water flux decreases and salt flux increases. An increase in operating pressure will affect both the water flux and the salt rejection. However, there is an upper limit to the amount of salt that can be excluded by increasing the feed pressure. Above that limit some salt will coupled with water flowing through the membrane. Salt passage is an inverse function of pressure; that is, the salt passage increases as applied pressure decreases. This is because reduced pressure decreases permeate flow rate and cause a dilution of salt.

The recovery rate affects salt passage and product flow. As the recovery rate increases, the salt concentration on the feed-brine side of the membrane increases, which causes an increase in salt flow rate across the membrane as indicated by Equation 4. Also, a higher salt concentration in the feed-brine solution increases the osmotic pressure, reducing the NDP and consequently reducing the product water flow rate according to Equation 1. The maximum recovery possible in any RO system usually depends not on the limiting osmotic pressure, but on the concentration of the salt present in the feed water and their tendency to precipitate on the membrane surface[4]. Chemical treatment of feed water can help in preventing salt precipitation and cause significant increase in recovery.

Effect of Temperature on RO Performance

The rate of water permeation through the membrane increase as the feed water temperature increases since the viscosity of the solution is reduced and higher diffusion rate of water through the membrane is obtained[5]. Increasing feed water temperature will yield lower salt rejection or higher salt passage due to higher diffusion rate for salt through the membrane. Figure 3 shows the variation of water flux and salt rejection as function of temperature[6].

The change in the permeate flux with temperature can be described by the following Equation:

$$TCF = \exp(K*(1/(273+t) - 1/298)) \qquad (9)$$

Where TCF is temperature correction factor, K is a constant characteristic for a given membrane material, and t is feed water temperature in degrees Celsius. In this Equation, a temperature of 25 ^oC is used as a reference point, with TCF = 1. The rate of change in permeate flux is about 3 % per degree. Alternatively, the temperature correction factor, TCF, can be expressed as follows:

$$TCF = a^{(t-25)} = \text{flux at } t\ ^oC / \text{flux at } 25\ ^oC \qquad (10)$$

Where a is constant between 1.024 and 1.03. Table 1 shows the expected increase in the flux due to temperature rise with reference to 25 ^oC.

Table 1

Expected Increase in Flux Due to Temperature Rise

Temperature, ^oC	TCF	% Increase in Flux
30	1.16	16
35	1.344	34.4
40	1.55	55

When temperature of feed water is increased for constant product flow the required applied pressure decreases and the product water salinity increases. The reduction in the required feed pressure can be displayed on the Table 2 where 25 ^oC was taken as a basis[7]. Energy consumption is decreased as the applied feed pressure decreases. Operating at higher temperature will allow an increase in the productivity. If the permeate flow is let to increase as the temperature increase fewer membrane elements will be required. This leads to a considerable saving in the water production cost.

Table 2

Reduction in Required Pressure as Function of Feed Temperature

Temperature, ^oC	% of Rated Pressure
20	116
21	113
25	100
32	79
35	73

Water permeability of the membrane increases with the increase in feed water temperature. About 1.5% per degree is expected to increase in water permeability of the membrane. Effect of feed temperature on the membrane permeability coefficient for water is reflected on Figure 4. The graph data was collected from Manfouha-I Water Treatment in Riyadh[2].

An analysis of some operating data of Riyadh water treatment plants and computer codes provided by manufacturer were conducted. The variations of product concentration and feed pressure with temperature while holding a constant permeation rate at 378 m^3 /day and recover at 75% are displayed on Table 3 and Figure 5. These data were generated the FilmTech software[8].

Table 4
Values of Product Concentration and Feed Pressure at Various Temperatures

Temperature, °C	TDS, mg/l	Pressure, bar
5	12	27.3
10	13	23.1
15	14	19.7
20	16	17.0
25	17	14.8
30	19	14.8
35	21	11.9
40	23	10.8
45	26	9.8
50	28	9.0
55	31	8.3
60	35	7.7
65	38	7.2
70	43	6.8

Conclusions

The performance of reverse osmosis system was studied and analysis theoretically and by running some known computer software. Operating data of Riyadh water treatment plants were also used. The effect of temperature on membrane performance is the most important parameter. It was found that higher feed water temperature will result in a better RO operation.

When temperature of feed water is increased for constant product flow the required applied feed pressure decreases and the product water salinity increases. Energy consumption is decreased as the applied pressure decreases. If the permeate flow is let to increase as the temperature increase fewer membrane elements will be required. This leads to a considerable saving in the water production cost. The rate of change in permeate flux is about 3 % per degree Celsius increase in water temperature.

References

1- I.S. Al-Mutaz,, M. A. Al-Ghunaimi and S. A. Al-Busaili, "pH Increase In Water Distribution Pipes", IDA World Congress on Desalination and Water Re-Use, San Diego, USA, Aug 29 to Sept 3, 1999.

2- I.S. Al-Mutaz, and B. Al-Sultan, "Prediction of Performance of RO Desalination Plants", The Third Gulf Water Conference, Muscat, Oman, March 8-13, 1997.

3- I.S. Al-Mutaz, and B. Al-Sultan, “Operation Characteristics of Manfouha Reverse Osmosis Plants” The IDA World Congress on Desalination and Water Reuse, Madrid, Spain, October 6-9,1997.

4- Hydranautics, www.membranes.com , Technical Information.

5- S. Sourirajan, Pure and Applied Chemistry 50, 593, 1979.

6- J.E. Cadotte, R.J. Petersen, R.E. Larson and E.E. Erickson, “A new thin-film composite seawater reverse osmosis membrane”, Desalination 32, 25, 1980.

7- H.W. Pohland, “Seawater Desalination and Reverse Osmosis Plant Design“ Desalination 32, 157, 1980.

8. FilemTech Membrane Elements, Technical Manual, April 1995.

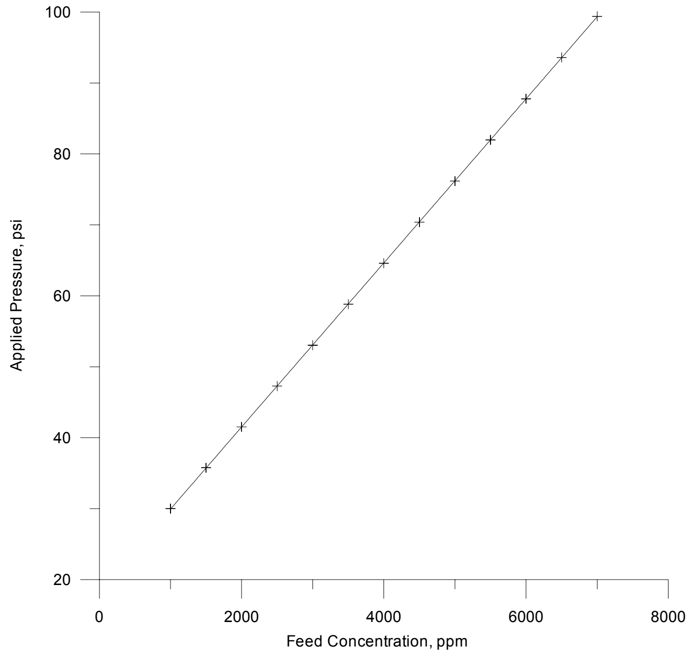

Figure 1 Effect of Feed Concentration on the Applied Pressure.

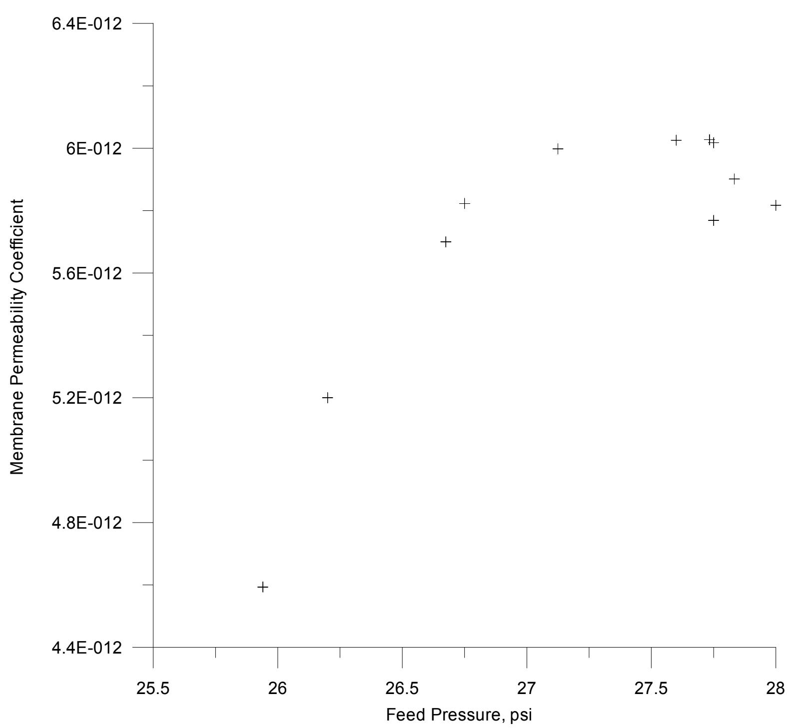

Figure 2 Effect of Feed Pressure on the membrane permeability coefficient for water.
(Graph Data is Collected From Manfouha-I Water Treatment in Riyadh, calculations were given else where [2,3])

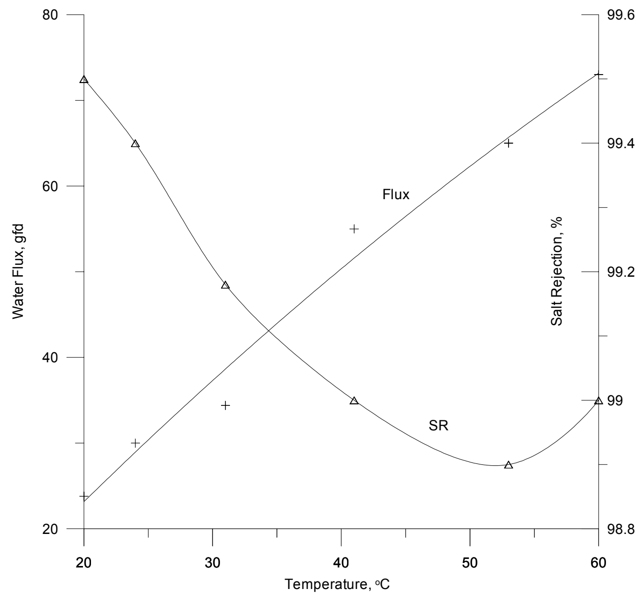

Figure 3 Water Flux and Salt Rejection as Function of Temperature[6].

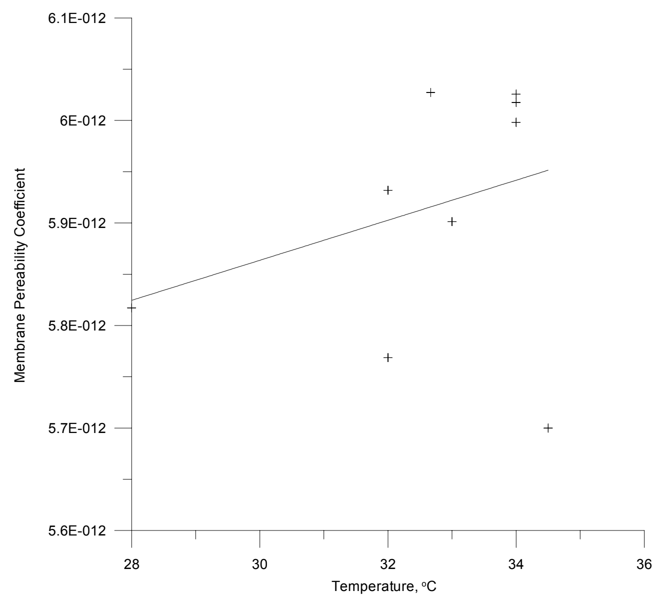

Figure 4 Effect of Feed Temperature on the Membrane Permeability Coefficient for Water. (Graph Data is Collected From Manfouha-I Water Treatment in Riyadh, calculations were given else where [2,3])

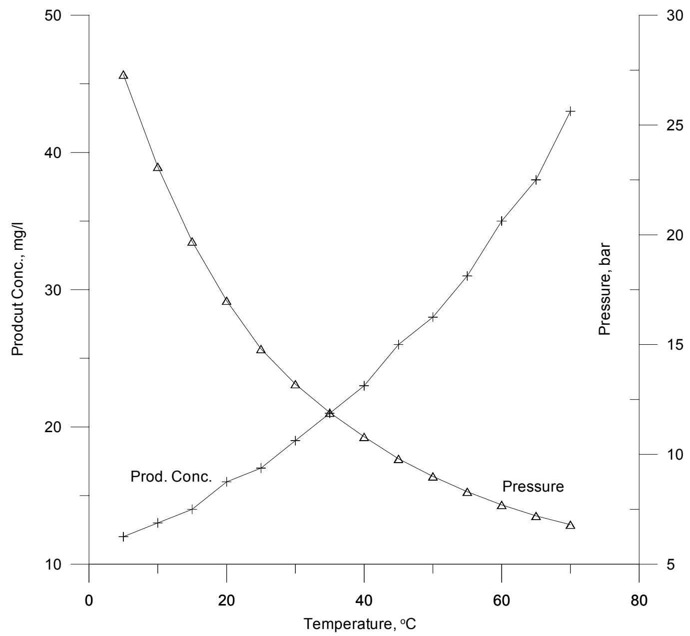

Figure 5 Variations of Product Concentration and Feed Pressure with Temperature at a Constant Permeation Rate of 378 m^3 /day and Recovery of 75%.