Experimental Investigation of Reverse Osmosis Desalination System Performance
Part two: At Different Feed Temperatures

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Abstract

In the present work, the performance of a small reverse osmosis RO (house scale) desalination unit is experimentally investigated. The parameters such as salinity of the feed water (2000-3000 ppm), and feed water temperature (29^{o}C - 41^{o}C), at feed flow rate of (1.5 L/min) are considered. The results demonstrate that, increase in feed temperature from 29^{o}C to 41^{o}C leads to an increase in the permeate salinity while feed pressure and salt rejection ratio percent decrease by about 4% and 6%, respectively. However, there is an insignificant change in the recovery ratio percent and permeate flow rate with the increase of feed temperature. Also the results illustrate that the increase in feed water salinity leads to an increase of permeate salinity while permeate flow rate and recovery ratio percent decreases.

Keywords: Reverse Osmosis, RO; Flow Rate; Temperature; Salinity; Recovery Ratio; Salt Rejection

1. Introduction

Water shortage became a critical problem in a lot of countries due to excessive usage and increasing pollution to the natural water resources. Therefore, desalination techniques especially membrane filtration techniques are having much attention to produce clean water from various water sources such as waste water, seawater, and brackish water. It is reported that about fifty percent of the industrial plants around the world uses reverse osmosis (RO) membrane because of their high efficiency for space and energy [1]. Some reviewers [2-7] investigated the large-scale desalination plants with reverse osmosis networks. Also, they studied the effect of the feed pressure, pressure drop in the membrane channel, osmotic pressures and a feed concentration on a permeate concentration and productivity. Djebedjian et al. [8] studied the effect of the inlet potential of hydrogen, feed water temperature, the feed water salinity and the feed pressure operating on the performance of a small-scale RO desalination using brackish water. The results showed that both feed water temperature and pressure increase resulted in an increase of the recovery ratio, but the increase of feed water salinity or feed water pH led to a decrease in the recovery ratio.

Goosen et al. [9] analyzed and modeled the accumulation of salt in spiral-wound seawater membrane elements. The effect of operating conditions such as feed flow rate, feed salinity and feed water temperature on permeate production and salinity were evaluated. The life time of the membrane and permeate production were affected by accumulation of solute on the membrane and the fouling resulted from microbial adhesion, gel layer creation and solute adhesion on the membrane surface. The results reported that permeate flux went through a minimum at feed temperature in the range of 20 to 40°C. The permeate flux enlarged by about 60% while the feed temperature increased from range at 20 to 40°C while there was a great difference in the permeate flux between feed temperature of 30ºC and 40ºC.

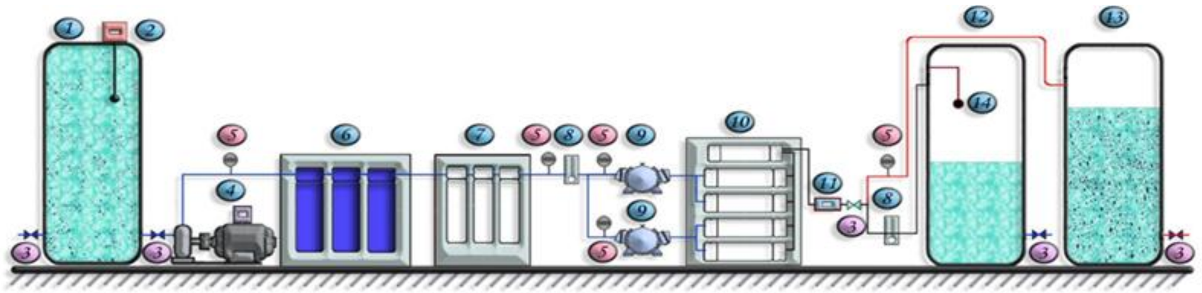
Garcia and Nuez [10] suggested a model dependent on operating time and empirical parameters to predict the average water permeability coefficient decline or permeate flux. The proposed model separated the decline of the water permeability coefficient in two stages, the first stage pointed to a more pronounced decline because of initial compaction and irreversible fouling and the second designated a more stable period with lower slope. Their model utilized operating data of brackish water RO desalination plant for ten years. The obtained results with the proposed model indicated a slightly better fit than previous models, nonetheless it gave meaning to two dissimilar behaviors separated in two stages. A simple mathematical model developed by Kotb et al. [11] for two-module feed forward RO system which incorporated most functional arrangement. The model was employed to study the salts accumulation on the membrane walls. The effects of feed specifications, operating conditions and membrane dimensions on the concentration at the wall of each membrane were examined. Atab et al. [12] modeled a RO system for brackish water desalination to produce both potable drinking and agricultural water with a poorer overall and specific energy consumption. A numerical model based on diffusion theory solution was developed in MATLAB Simulink and used for analyzing the design performance of an RO system. The effect feed water temperature, salinity, pressure and recovery ratio on the efficiency of the whole system was studied for an inclusive range of design considerations. An economic assessment and RO system design for this application was carried out.

From the previous researches, it can be noticed that the RO systems performance depends greatly on feed water temperature, feed water flow rate and salinity. Therefore, the objective of the present work is to investigate experimentally the effect of the aforementioned parameters together on a residential unit (small scale test rig) using brackish water which is available in any remote areas in Egypt and thin-film composite membrane . Moreovere, provide correlations for salinity of permeate, permeate flow rate, feed pressure, recovery ratio percent and salt rejection ratio percent as functions of feed water flow rate, feed water temperature and feed water salinity.

2. Experimental setup

2.1 Process description

According to the salinity of most brackish water in Egypt, which varies between 500 to 3000 PPM, RO system is designed for achieving the following: suitability for brackish water, control of operating pressure, wide range of the operating temperature, avoid water hammer, decreasing the fouling effect and scaling on the membrane and measuring the whole parameters such as pressure, temperature, TDS of the feed water and permeate, and volume flow rate for the feed water and permeate. The test rig is schematically represented in Figure 1, which depicts the main components of the present RO desalination unit. The test rig is composed of three sections. The first one is termed as pretreatment section which includes saline water tank, low-pressure pump, jumbo filters, and three different cartridge filters in addition to, PVC hoses, connections, and valves. In the pretreatment section, the raw saline brackish water is fed to the jumbo filters from the feed tank through the low-pressure pump. These filters are used to remove other chemical tastes, odors plus dirt, making saline water cleaner, sediments, clearer, chlorine and safer to protect the different parts of the test rig. Hereafter, the filtered water is passed through three different cartridge filters. The desalination process section is the second section which includes the high-pressure pump and the membrane of the RO unit. In this process; the high-pressure pump raises up the water's dynamic pressure to overcome the osmotic pressure of the saline pretreated water, and hence causing water permeation from the saline side of the membrane to the fresh water side. Then, salts are rejected from the membrane as concentrated saline water through the drain pass (Brine) to the drain tank. The third section is the post treatment processes which consist of a carbon filter that polish off water to remove any remaining taste. Finally, the permeate water is discharged to permeate water tank.



1-Feed water tank	5-Pressure gauge	9-Booster pump	13-Drain tank
2-Temperature sensor	6-Jumbo filters	10-RO membrane	14-Floating level sensor
3-Control valve	7-Cartridge filters	11-Flash controller	
4-Feed water pump	8-Flow meter	12-Permeate tank	

Figure 1: Schematic diagram of RO System.

2.2 Components of reverse osmosis unit

2.2.1 Feed water tank (1)

In the present test bench, the brackish water is fed and stored in feed water tank. Hereafter, this tank is used for supplying the system with raw water as well as frequently used for buffering to allow continuous operation of the reverse osmosis system (e.g., during backwash of filters). The tank was made from polyethylene having a capacity of 1 m^3, with an outer diameter of 115 cm, height of 117 cm and slot diameter of 43cm.

2.2.2 Feed water pump (4)

An ordinary booster pump is used to source the saline brackish water from the feed tank to the rest of the system. This pump should cover the whole test conditions at different flow rates and overcome the total pressure loss inside the pretreatment section. The pump electric powered with an 81 W motor and it supplies feed water at a flow rate range 10 – 37 L/min.

2.2.3 Jumbo filters (6)

The jumbo filters are consisting of three stages. The first stage is pre-filter designed to remove sediments besides other biological contaminants. Carbon block filter is the second stage used to decrease contaminants by 99.99% or more, including Volatile

Organic Compounds (VOC), lead and other odors, heavy metals and taste. The third stage is Ultrafine Depth Filtration which is a powdered activated carbon filters.

2.2.4 Cartridge filters

The cartridge filters system includes three different cartridge filters having 20" (50.8 cm) length and 2.5" (6.3 cm) diameter, the operating pressure is ranged from 45 psi to 85 psi and the operating temperature range is from 4ºC to 45ºC. The first one is sediment filter (five-micron diameter) is used to prevent fouling of suspended particles greater than 5 microns. While, the second one is an activated carbon cartridge filter which is used to remove dissolved organic materials and chlorine compounds. Finally, the third is one-micron stage of a block carbon filter cartridge to minimize precipitation and scaling on the membrane.

2.2.5 Booster pump (9)

Two high-pressure booster pumps are used to maintain the designed feed flow rate and the designed feed pressure. The discharge pressure of the pump is organized to maintain the intended permeate flow rate and not exceed the maximum allowed feed pressure to the RO membrane. The specifications of the pump are: Input: AC 230 V/50 HZ, Capacity: 0.95 m^3/day

2.2.6 RO membrane (10)

The used membrane in the present study is thin-film composite membrane. It is made from Polyamide (PA) that will allow certain ions or molecules to pass through it by diffusion and occasionally "facilitated diffusion". The components of the RO membrane are illustrated in Figure 2. The rate of water permeation depends on the applied pressure, salts concentration in brackish water, and temperature of the solution on either side, as well as the permeability of the membrane to each solution. Reverse osmosis membrane dimensions are depicted in Table 1 and Figure 3, respectively. A CSM RE1812-80 membrane element of Thin Film Composite (TFC) type is used in the present work. The membrane specifications are demonstrated in Table 2.

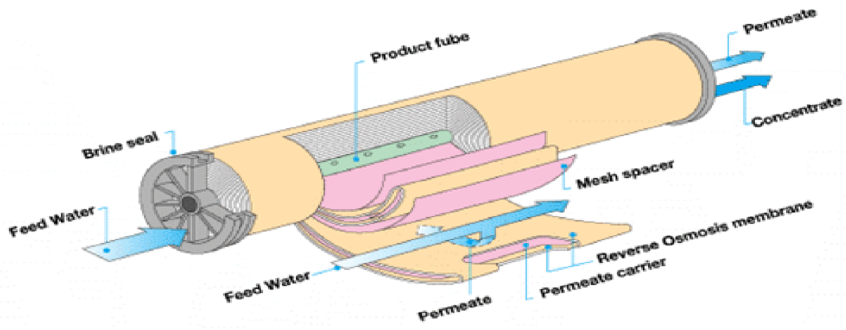


Figure 2: Components of a reverse osmosis membrane.

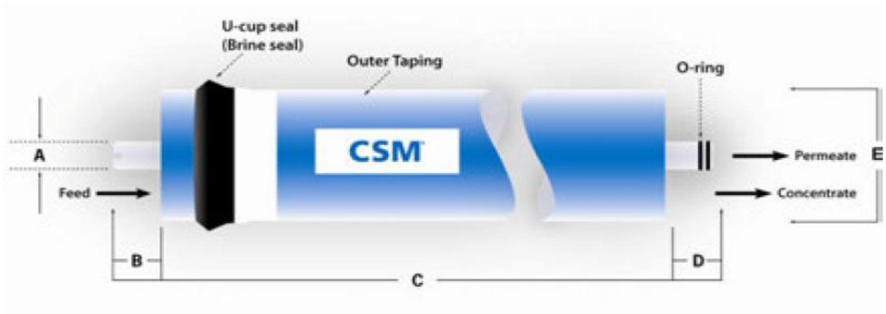


Figure 3: Reverse osmosis membrane dimensions.

Table 1: Dimensions of RO Membrane

Model name	A	B	C	D	E
RE1812-80	0.67" (17mm)	0.87" (22mm)	11.73" (298mm)	0.98" (25mm)	1.77" (45mm)

Table 2: Specifications of TFC membrane

Product name	CSM (made in Korea)
Model name	RE1812-80
No of membrane	Four TFC membrane
Permeate flow rate	0.302-0.378 m^3/day (80-100 GPD)
Max pressure	8.79 kg/cm^2 (125 psi)
Max temperature	318.15 K (45°C)
Average water rejection	98%

2.2.7 Inline post carbon filter stage (polishing filter)

In the post treatment process, the permeate passes through a carbon filter to polish off the water and remove any remaining taste and scent in the water. This last filter ensures that the product is outstanding drinking water.

2.2.8 Permeate and drain tank

There are two identical polyethylene tanks to store permeate and concentrated brine. The permeate tank is equipped with a float valve to shut down the operation if the level of water reaches the prescribed limit in the tank. Each tank has a capacity of 1 m^3, an outer diameter of 115cm, height of 117cm and slot diameter of 43cm. Before any series of this experimental work the tanks are protected from dust and microbiological contamination by conducting a primary chemical cleaning.

2.3 Measurement, Instrumentations and Control

The present reverse osmosis unit is equipped with different instruments to measure and control the operating parameters such as temperature, pressure, TDS and mass flow rate of both feed water and permeate. Pressure gauges with an accuracy of (± 0.1 bar) are used to measure the pressure. The feed temperature in the feed water tank is adjusted by using a temperature controller having an accuracy of (± 0.2^{o}C), flow meters with an accuracy of ± 4 %. Waterproof TDS measuring device having a measuring range from 0.0 PPM to 10000 PPM and an accuracy of 2% is used to measure the feed and permeate salinities. Moreover, the RO unit includes control devices such as high and low-pressure switches which are located in the suction line of the low and high-pressure feed pump, respectively. There are number of valves are included to protect the RO unit such as mixing valve, ball float valve, solenoid valve, drain saddle valve and shut off valve.

2.4 Experimental procedure

The saline feed water is prepared through the mixing of granulated iodine-free NaCl with the water (180-190 ppm) municipal supply. Then the required temperature of the feed water is adjusted by temperature controller. After reaching the required temperature the low-pressure pump is switched on. Automatically after 5 seconds the high-pressure pump is operated. The feed flow rate is then adjusted to the tested value via the mixing valve. The pressure at different locations, salinity and flow rates of feed and permeate streams are recorded each 10 minutes**,** till their values become nearly constant i.e. (steady state condition is achieved in time period ranged from 30 to 40 minutes). When the steady state condition is prevailed, all readings are recorded and then the data reduction is made.

2.5 Data reduction

The recovery ratio percentage, R, is calculated as follow:

$$R = \frac{v_p}{v_f} \text{ x } 100 \qquad (1)$$

Where, v_f is the measured feed flow rate, and v_p, is the permeate flow rate.

Also, from the measured feed concentration x_f and permeate concentration x_p, the salt rejection ratio percentage is calculated from the following equation:

$$SRR = \frac{x_f - x_p}{x_f} \; x \; 100 \; \% \qquad (2)$$

The net driving pressure is given by:

$$NDP = \Delta P - \sigma\phi\Delta\pi \qquad (3)$$

3. Results and discussions

The permeate concentration, permeate flow rate, feed pressure, recovery ratio percent and salt rejection ratio percent are considered as the performance indicators of the present RO unit. Figures (4 – 8) represent the effect of feed temperature on the previous performance indicators.

The effect of feed temperature on the permeate concentration for all feed concentration and feed flow rate at 1.5 L/min is depicted in Figure 4. It can be concluded from the figure, that as the feed temperature increases the permeate salinity increases and this is due to the increase of salt solubility and this occurs for all feed concentration. Also the figure shows that, as the feed concentration increases the permeate concentration increases. This can be accredited to the decrease in the net pressure which driving the separation process.

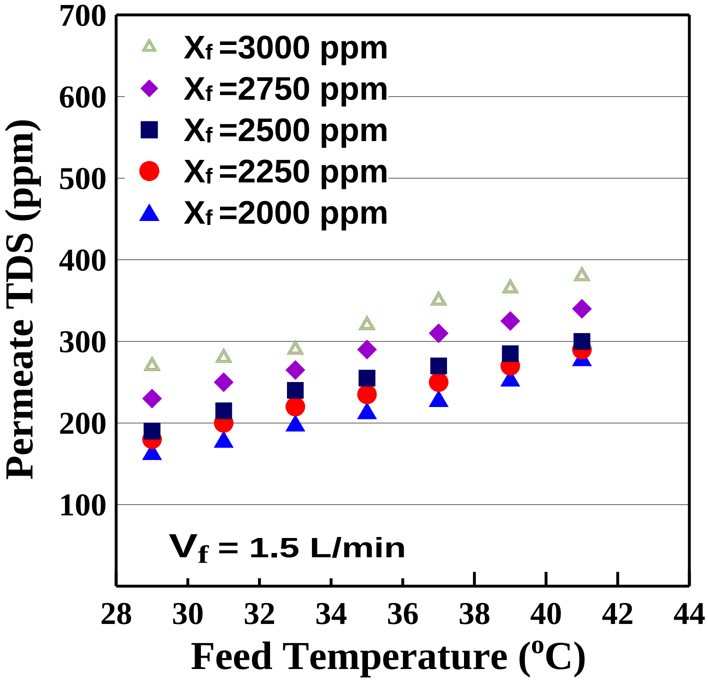


Figure 4: Effect of feed temperature on permeate concentration.

Figure 5 shows the variation of permeate flow rate with the feed temperature for different feed concentration and feed flow rate 1.5 L/min. From the figure, it is clear that the effect of feed temperature on the permeate flow rate is insignificant especially for high feed salinity but it is affected greatly by the feed concentration. Moreover, from the figure, as the feed concentration increases the permeate flow rate decreases and this may be due to the decreasing in the driving pressure.

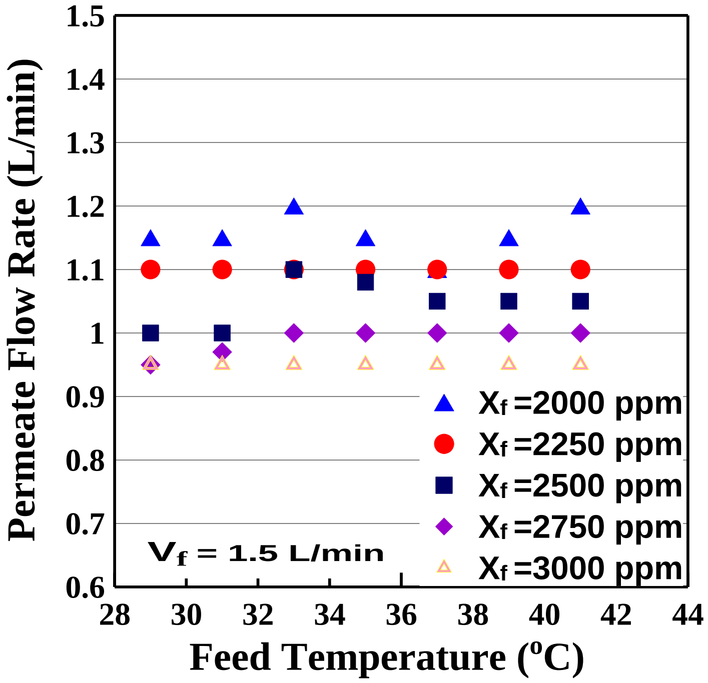


Figure 5: Effect of feed temperature on permeate flow rate.

Herein, Figure 6 illustrates the effect of feed temperature on the feed pressure for different feed concentration at feed flow rate 1.5 L/min. Generally, the feed pressure decreases slightly as the feed temperature increases. It is found that the feed concentration has an insignificant effect on the feed pressure.

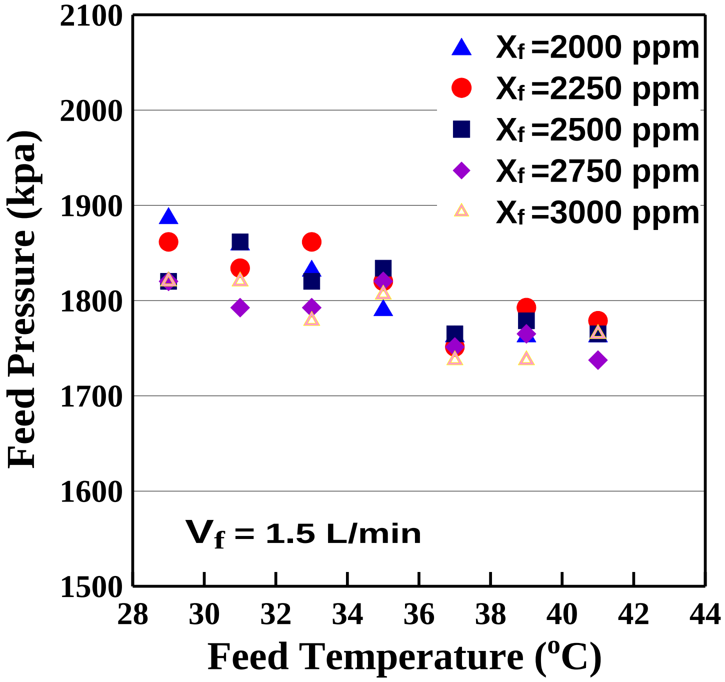


Figure 6: Effect of feed temperature on feed pressure.

Figure 7 illustrates the feed water temperature effects on the recovery ratio for different feed concentration ranged from 2000 ppm to 3000 ppm and feed flow rate 1.5 L/min. Insignificant effect of feed temperature on the recovery ratio percent for the studied range of feed concentration as shown in Figure 7. Higher recovery ratio percent is obtained for lower feed concentration.

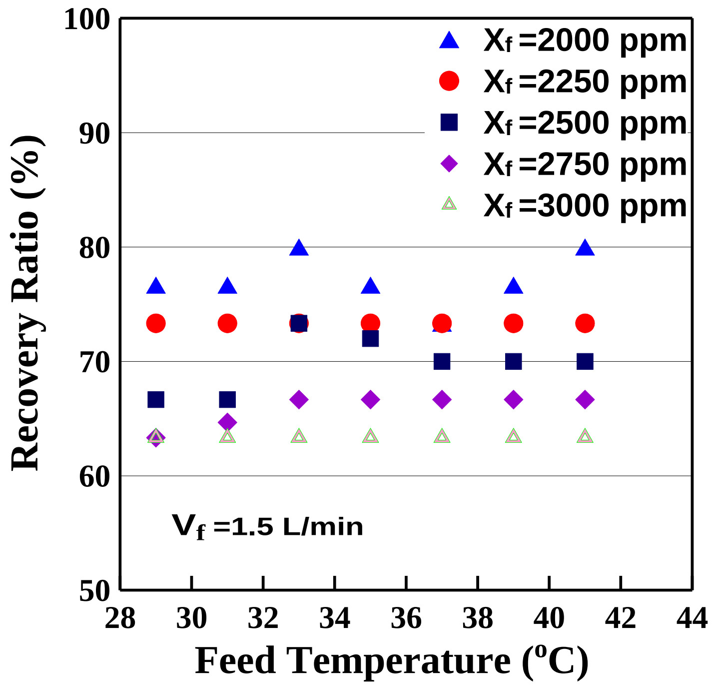


Figure 7: Effect of feed temperature on recovery ratio.

The variation of salt rejection with the feed water temperature at different feed concentration for feed flow rate of 1.5 L/min is illustrated in Figure 8. The salt rejection ratio percent decrease monotonically with increase of feed temperature as shown in this figure.

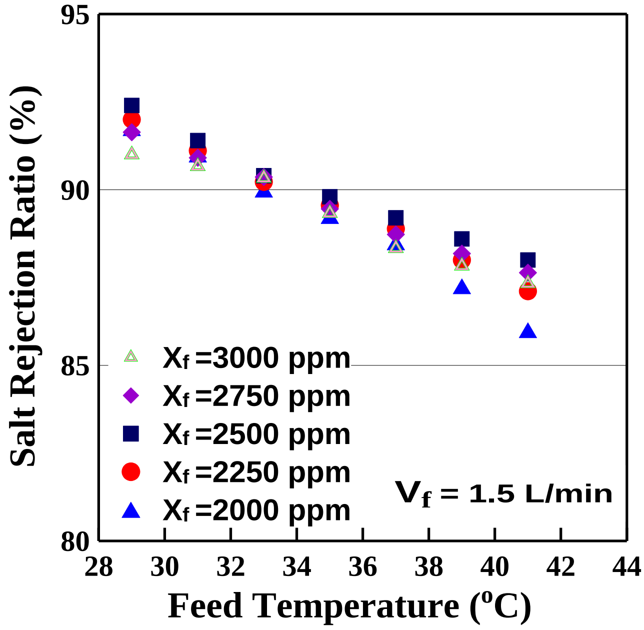


Figure 8: Effect of feed temperature on salt rejection ratio.

4. Conclusions

From the above presented results, the following two main conclusions can be drawn:

1. The results revealed that, increasing the feed temperature from 29°C to 41°C, increase the permeate salinity and decrease feed pressure and salt rejection ratio percent. While, there is an insignificant change in the recovery ratio percent and permeate flow rate with the increase of feed temperature.
2. Increasing the feed concentration from 2000 to 3000 PPM leads to decrease in permeate flow rate and recovery ratio percent. While, increasing the feed concentration results in an increase in salinity of permeate.

Nomenclature

P	Pressure
R	Recovery ratio percent
SRR	Salt rejection ratio
T	Temperature
V	Flow rate
X	Salt concentration
α	Hydraulic pressure losses factor ($\alpha = Pc/Pf$)

π	Osmotic pressure, bar
Σ	Membrane reflection coefficient
Φ	Concentration polarization (CP) factor

Subscripts

b	brine
f	feed
p	permeate

Abbreviations

BWRO	Brackish Water Revers Osmosis
NDP	Net driving pressure
PPM	Part Per Million
PVC	Polyvinyl Chloride
PWT	Pelton wheel turbine
RO	Reverse osmosis
TDS	Total dissolved solids
TFC	Thin Film Composite

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