AN EXPERIMENTAL INVESTIGATION ON THE OPERATING PARAMETERS AFFECTING THE PERFORMANCE OF REVERSE OSMOSIS DESALINATION SYSTEM

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ABSTRACT

The development of non-conventional water resources in Egypt is essential in order to respond to the continuously increasing demand. The most advanced and charming desalination system is the reverse osmosis (RO) system. In this paper, the effect of the feed water temperature, the feed pressure, the inlet pH and the feed water salinity on the performance of a small-size brackish water reverse osmosis (RO) desalination test-rig are investigated. In the range of experimental runs, the maximum gain in recovery ratio has been obtained from the feed water pressure increase. The increase of feed water temperature or pressure results in a recovery ratio increase while the increase of feed water salinity or feed water pH leads to a decrease in recovery ratio.

Keywords: Desalination, Reverse osmosis, RO performance, Effect of operating conditions

Nomenclature

P	pressure, bar
T	temperature, °C

Greek symbols

Δp	pressure drop across the membrane, bar

Subscripts

f	feed
i	inlet to membrane
o	outlet from membrane

Abbreviations

MSF	Multi Stage Flash
pH	Acidity measure
RO	Reverse Osmosis
RR	recovery ratio (Product water flow rate / Feed water flow rate)
TDS	Total Dissolved Solids (ppm)

INTRODUCTION

Desalination is a process that removes dissolved minerals (including but not limited to salt) from seawater, brackish water, or treated wastewater. A number of technologies have been developed for desalination, including thermal distillation, reverse osmosis (RO), electrodialysis, and vacuum freezing. The two most widely used processes are Multi Stage Flash (MSF) and Reverse Osmosis (RO). For brackish waters, RO is the most widely employed process whereas for seawaters MSF remains the most popular technique. All desalination processes involve three liquid streams; the saline feed water (brackish water or seawater), low-salinity product water (permeate), and very saline concentrate (brine or reject water).

Thermal distillation plants produce a high-quality product water that ranges from 1.0 to 50 ppm TDS, while RO plants produce a product water that ranges from 10 to 500 ppm TDS. In desalination plants that produce water for domestic use, post-treatment processes are often employed to ensure that product water meets the health standards for drinking water as well as recommended aesthetic and anti-corrosive standards.

The market share of RO desalination systems has significantly increased in recent years because of the significant progress in membrane technology and the advantages this technology offers compared to the thermal desalination techniques, including low energy requirement and low temperature operation.

An RO desalination plant essentially consists of four major systems: (a) Pretreatment system, (b) High-pressure pumps, (c) Membrane systems, and (d) Post-treatment.
Pre-treatment system removes all suspended solids so that salt precipitation or microbial growth does not occur on the membranes. Pre-treatment may involve conventional methods (a chemical feed followed by coagulation/ flocculation/ sedimentation, and sand filtration) or membrane processes (micro filtration (MF) and ultra filtration (UF)).

High-pressure pumps supply the pressure needed to enable the water to pass through the membrane and have the salt rejected. The pressure ranges from 17 to 27 bar for brackish water, and from 52 to 69 bar for seawater.

Membrane systems consist of a pressure vessel and a semi-permeable membrane inside that permits the feed water to pass through it. RO membranes for desalination generally come in two types: Spiral wound and Hollow fiber. Spiral wound elements are actually constructed from flat sheet membranes. In the hollow fiber design, a large number of hollow fiber membranes is placed in a pressure vessel. This type of design is not as widely used now as the spiral wound membranes for desalination.

Post-Treatment consists of stabilizing the water and preparing it for distribution. The post-treatment might consist of adjusting the pH and disinfection. If the desalinated water is being combined with other sources of water supply, it is very important to ensure similar water quality characteristics in both water sources.

The performance of membrane elements operating in a reverse osmosis system is affected by many factors such as the feed water composition, feed temperature, feed pressure, and permeate recovery ratio. Membrane compaction and fouling also affect membrane performance. Generally the main factors affecting RO element include:

- The raw water condition and the pre-treatment procedures effectiveness.
- Membrane: type, size and the number of modules used and their arrangement.
- The rate and degree of fouling, and cleaning ability.
- Operating conditions, such as feed pressure, temperature and permeate recovery.
- The efficiency of pumps and energy recovery systems.

The ratio of the amount of permeate produced by the RO relative to the amount of feed going to the RO is called the recovery ratio (RR). Recovery ratio is extremely important in regard to RO performance. High recovery ratio saves on the cost of seawater preparation prior to the osmosis process, and low recovery ratio saves on the energy cost of desalination. The optimal recovery ratio depends on the relative costs of these operations and may vary under different conditions.

The operating parameters of seawater RO system are mainly function of feed water salinity and temperature. For example, for seawater feed of about 38,000 ppm TDS salinity and water temperature in the range of 18 - 28°C, the RO systems are designed to operate at a recovery rate in the range of 40% - 45% and with an average permeate flux in the range of 11.9 - 13.5 L/m^2.hr, Wilf and Schierach [1]. At the above operating conditions the feed pressure is in the range of 55 - 70 bar and permeate salinity is in the range of 300 - 500 ppm TDS.

The effect of operating conditions on the performance of membrane elements is studied by many researchers. El-Saie et al. [2] explained the experimental RO facility designed for Nuclear Power Plants Authority in Egypt to study the effect of the following parameters on the permeate quality, production, membrane life and aging and system's economy; feed water temperature; feed water pressure and recovery ratio.

Abou Rayan and Khaled [3] presented a case study of the operation and maintenance of 2000 m^3/d RO desalination plant over 6 years of operation. They concluded that the reverse osmosis system is sensible to change in feed water temperature, and the product quality is sensitive to the working pressure.

Goosen et al. [4] evaluated the influence of feed temperature; salinity and flow rate on permeate flow rate and salinity in spiral-wound seawater membrane elements. Their results show that the polymer membrane is very sensitive to changes in the feed temperature. The permeate flux appears to go through a minimum at an intermediate temperature between 20 to 40°C. There was up to a 60% increase in the permeate flux when the feed temperature was increased from 20 to 40°C, while there was up to a 100% difference in the permeate flux between feed temperatures of 30 and 40°C. Also, doubling of the feed flow rate increased the permeate flux by up to 10%, but only at a high solute concentration.

Villafafila and Mujtabab [5] studied numerically the RO desalination process and the sensitivity of different operating parameters (feed flow rate, feed pressure) and design parameters (internal diameter, total number of tubes) on the recovery ratio. Their results showed that the higher the pressure, the higher the recovery ratio is. This is due to the increase in the driving force (difference between feed pressure and osmotic pressure) with the feed pressure. Operating at high pressures for the feed stream also reports a better product quality (lower salt concentration of permeate). When the feed pressure increases, the water flux across the membrane is higher, but the salt flux (determined by the membrane permeability) remains constant.

Arora et al. [6] studied experimentally the RO separation of fluoride present in water with the optimization of different parameters to get maximum fluoride removal efficiency. The effect of feed water composition, its chemical properties, pH and operating conditions, on the membrane separation process was studied. The results showed that pH, feed water composition, flow rate and pressure affect the membrane efficiency, and thus proper control of these factors is essential for successful operation. The results indicate that RO membranes can remove up to 95% of fluoride present in groundwater.

Abbas [7] studied numerically the effects of operating conditions and concluded that increasing the operating pressure and feed flow will generally lead to higher water recoveries and salt rejection. However, increasing the pressure beyond a certain maximum value led to the deterioration of the quality of the product. Also, increasing the feed rate beyond a certain optimum value the water production rate decreased due to the driving force resulting from the high pressure drop.

Song et al. [8] investigated an RO-CEDI (Reverse osmosis-continuous electrodeionization) hybrid process to produce high purity water. The RO system was operated using tap water and the CEDI system experiments were carried out in a cell-pair stack consisting of 3 compartments. During the parametric study of the RO-CEDI hybrid system, the optimal operating conditions were determined based on the water purity. The produced water met the quality requirements as a make-up water in a nuclear power plant.

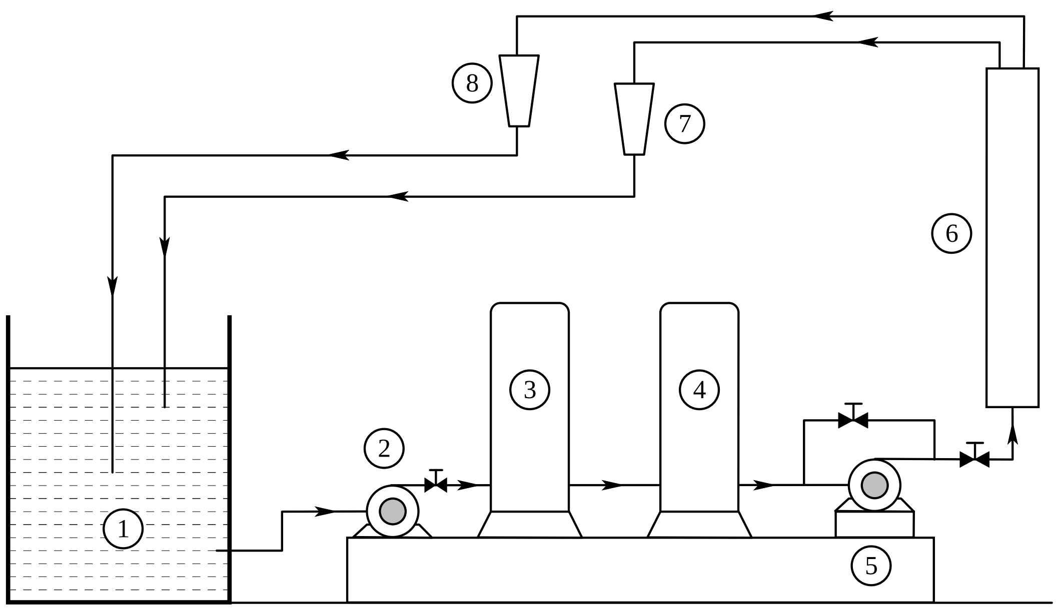
From the preceding review, it is clear that more experimental work is needed. In this work, the main design and operating conditions affecting the performance of RO desalination are studied experimentally using a small-scale brackish water RO test rig.

EXPERIMENTAL SETUP AND PROCEDURE

The experimental setup is designed and constructed in the Thermal Engineering Laboratory, Faculty of Engineering, Mansoura University. The setup as shown in Fig. 1 consists mainly of water tank, feed water pump, activated carbon filter, cartridge water filter, high pressure water pump, membrane element assembled unit, piping and control valves.

The water tank (1) which is made from polyethylene (58 cm diameter and 90 cm height) is open to the atmosphere. The tank is normally full of brackish water that is used as a feed water source to the system. The tank is also used to collect both the permeate and the brine where they mix to supply the system again (with brackish water approximately with the same TDS) through the feed pump (2). The raw water flows first through the activated carbon filter (3) to remove any odder. The water is then flows through a cartridge filter (4) to remove solid particles. The high pressure pump (5) is used to supply the membrane element assembled (RO) unit (6) with high pressure feed water. The setup is equipped with a number of valves to control the flow rate through the membrane RO unit. The brine and permeate flow rates are measured with the flow meters (7) and (8) respectively.

The membrane element assembled RO unit is 2.5 x 21 inch tape wrap brackish element; model TR70-2521 (Toray Membrane, Europe). Figure 2 shows a detailed drawing of the membrane element with its dimensions. The process parameters including the membrane characteristics, the feed and inlet conditions are shown in Table 1.



(1) Water Tank
(2) Feed water Pump
(3) Activated carbon filter
(4) Cartridge filter
(5) High pressure pump
(6) Membrane element
(7) Product flow meter
(8) Brine flow meter

Figure 1. Flow diagram of the experimental setup

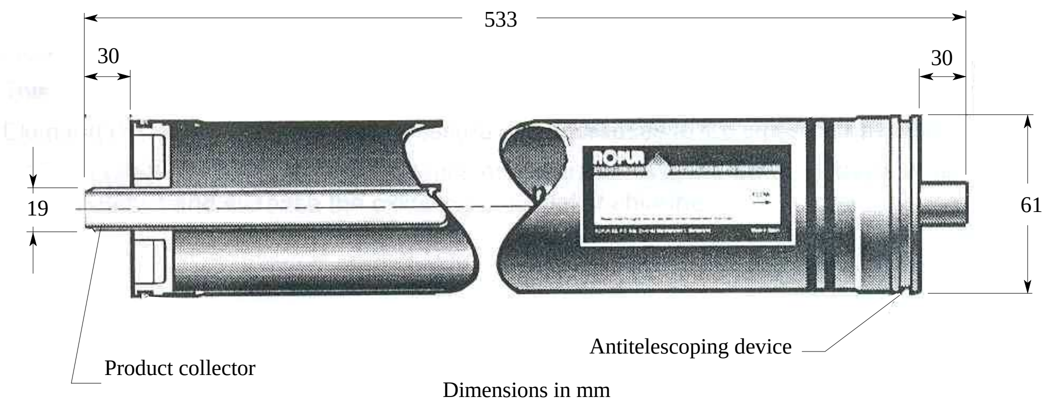


Figure 2. Detailed drawing of the experimental RO unit

Table 1. Process parameters and operating conditions

Parameter	*Value*
Membrane characteristics:	
Membrane type	Crosslinked Aromatic Polyamide, Negative Charge
Element	Spiral wound, Tape Wrap
Length of the membrane element (m)	0.533
Maximum feed flow (L/day)	650
Minimum brine flow (L/day)	250
Maximum operating pressure (bar)	15
Maximum operating temperature (°C)	35
pH range, continuous operation	3 – 11
Average salt rejection (%)	99.2
Minimum salt rejection (%)	98.2
Inlet conditions:	
Feed temperature range (°C)	20 – 35
Inlet pressure range (bar)	130 – 210
Inlet TDS range (ppm)	1500 – 3600
Inlet pH range	3.5 – 8.5

The system is suitably instrumented to measure the temperature, pressure, salinity, flow rate and pH for the feed water, brine and permeate. The pressure is measured with high precision and accurate pressure gages, while the temperature is measured by a digital thermometer. The water pH value is measured and controlled by a pH meter that consists of a glass electrode, reference electrode, and a high-input-impedance dc amplifier. The glass electrode is made from a special glass, which is permeable only to hydrogen ions. The thin bottom of the pH meter acts as a membrane. Hydrochloric acid inside the sealed electrode is in contact with the glass membrane as well as with a reversible electrode at the top. Both the reversible electrodes inside the glass electrode and reference electrode are identical; and therefore the potential differences due to the reference electrodes are zero.

The conductivity of a liquid is a measure of its ability to conduct electrical current. In water treatment field, it is a measure of ionic compounds dissolved in water. It is a simple and accurate test to control the level of the water salinity. All pH meters measuring the water salinity actually measure its conductivity and use a conversion factor to give a reading as ppm TDS.

In order to investigate the influence of the main operating parameters on the performance of the membrane RO element, a considerable number of experimental runs are carried out. In each run, the parameter under study is kept at a constant value during an interval of time until the steady state condition is attained. Then, other parameter values are measured and recorded. The time intervals range between 30 min to 60 min. In the next run the parameter under study is given another value with a certain predetermined range. Then, the setup is prepared to repeat the above with another parameter.

RESULTS AND DISCUSSION

The RO system is operated under various operating parameters. The influence of the feed water temperature, pressure, salinity and pH value on the system performance is the main objective of the present work. Therefore, the experimental work is divided into four groups. The group is divided into a number of runs, where only one parameter among these is varied and the other three operating conditions are maintained constant, as shown in Table 2. Other parameters changes are measured (when the steady state condition is reached) and recorded during the run.

The brackish water used in the experiments is brought from five wells at Sinai, Egypt, and the saline water from the Red Sea which is used to change (and adjust) the brackish water salinity during the experimental work. Table 3 gives the total dissolved salts and the pH for each well and the Red Sea.

Table 2. Operating conditions in RO system

Experiment	**Operating Conditions**								
	T_f (°C)	P_f (bar)	TDS_f (ppm)	pH_f	P_o (bar)	TDS_o (ppm)	TDS_b (ppm)	pH_o	pH_b
Feed Water Temperature, T_f	Varied	180	M*	M*	160	M*	M*	M*	M*
Feed Water Pressure, P_f	28.35	Varied	2531	7.82	M*	M*	3300 - 3360	7.36	7.89
Feed Water Salinity, TDS_f	30.05	220	Varied	7.78	190	M*	M*	7.93	7.99
Feed Water pH, pH_f	30.11	220	3684	Varied	190	M*	5441	M*	M*

M*: Measured

Table 3. Type of water used in RO system

Water Source	TDS (ppm)	pH (at 20°C)
Well 1	2000	6.65
Well 2	2500	6.70
Well 3	3000	6.90
Well 4	3300	6.95
Well 5	3500	6.95
Red Sea	45,000	8.20

1- Feed Water Temperature

In this group, the feed and outlet pressures are kept constant values at 180 and 160 bars respectively. The group is divided into a number of runs, where the feed water temperature is kept at a constant value by using a separate heater in each. After reaching the steady state condition, other parameters' changes are measured and recorded during the run. In the temperature group, Figure 3 shows the effect of feed water temperature on the permeate salinity ppm TDS. As can be observed, the permeate salinity decreased with temperature increase up to 22ºC, followed by a gradual increase thereafter. As the feed water temperature increases from 20 to 35ºC, the permeate salinity ppm TDS increases from 70 to 170 ppm TDS. The corresponding variations for both the feed water and the brine are shown in Fig. 4. On the other hand, the variation of permeate pH value decreases from 9.2 to 8.7 as the feed water temperature increases from 20 to 35ºC as shown in Fig. 5. Since both the permeate and brine are returned back to the water tank, the pH values for the feed water changes by the same way as that of the brine. The effect of feed water temperature on the permeate flow rate is shown in Fig. 6. The change in feed water temperature results in the change in the rate of diffusion through the membrane. For the same temperature increase, the permeate flow rate increases slightly (from 1.6 to 1.95 L/min). The brine flow rate decreases by the same amount, since the feed water is equal to the sum of permeate and brine flow rates. However, the recovery ratio (RR) increases only from 0.25 to 0.31 for the same temperature range, which is seen to be a limited variation (24 % increase).

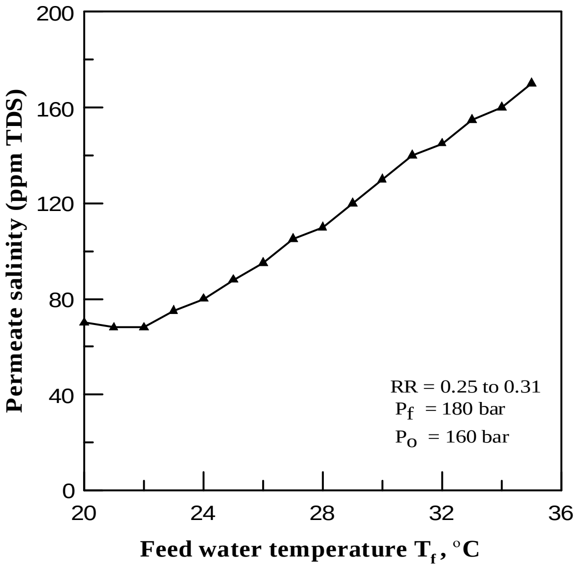


Figure 3. Effect of feed water temperature on permeate salinity

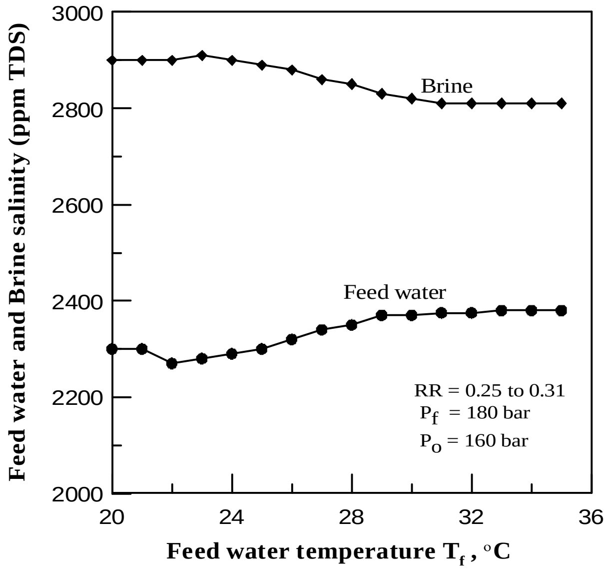


Figure 4. Effect of feed water temperature on feed water and brine salinity

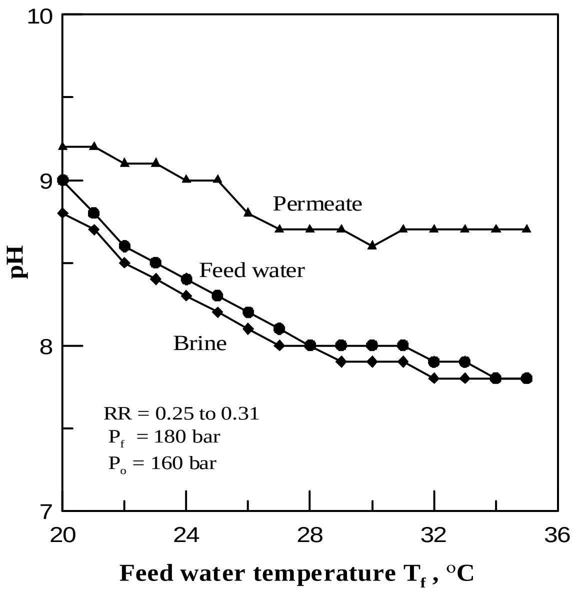


Figure 5. Effect of feed water temperature on feed water, permeate and brine pH

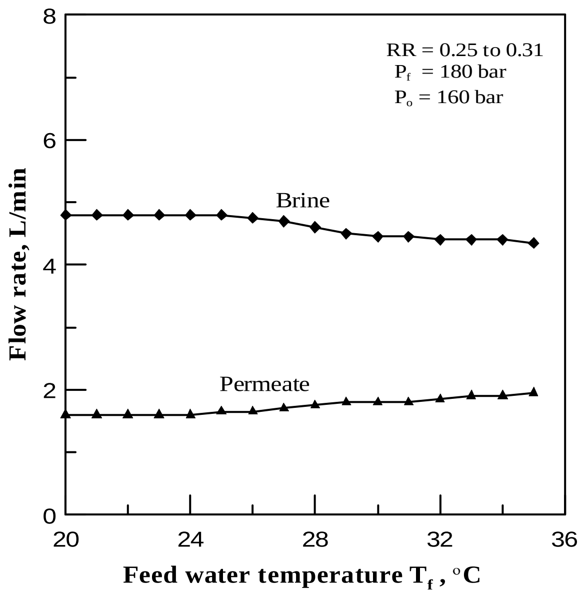


Figure 6. Effect of feed water temperature on permeate flow rate

2- Feed Water Pressure

In the pressure group, the feed water temperature has an average value of 28.35ºC (between 28 - 28.5ºC). The feed water salinity is also kept constant at 2531 ppm TDS. The group is divided into a number of runs, where the feed water pressure is kept at a constant value by using control valves in each run. Figure 7 shows that the outlet pressure increases from 100 to 190 bars as the feed water pressure increasing from 130 to 210 bars. The pressure difference across the RO element is also shown.

As the feed pressure increases from 130 to 210 bars, the permeate salinity ppm TDS decreases from 140 to 90 ppm TDS as illustrated in Fig. 8. Effects on the flow rate are investigated with the same pressure increase. Variation of the feed water pressure affects the permeate flow rate as well as the rejection of the brine. The permeate flow rate increases from 0.65 to 1.5 L/min, Fig. 9, and the brine flow rate decreases from 5.5 to 5 L/min correspondingly. The recovery ratio (RR) increases from 0.106 to 0.231 for the same pressure range, which is 118 % increase and seen to be a considerable variation.

3- Feed Water Salinity

In the feed water salinity group, the feed water temperature varies within 1ºC with an average value of 30.05ºC. The feed water pressure is also kept constant at 220 bars. As mentioned before, the feed water salinity is varied by mixing the feed water (brackish or tap water) with seawater. After operating the system for some time to reach steady state, the other parameters' changes are measured and recorded during the run. Figures 10 and 11 show the changes in the permeate and brine salinity according to the feed water salinity. The permeate salinity increases from 85 to 180 ppm TDS while the brine salinity increases from 1980 to 4750 ppm TDS as the feed water salinity increases from 1500 to 3600 ppm TDS. For the same feed water salinity increase, the permeate flow rate decreases from 1.5 to 1.25 L/min as shown in Fig. 12. The brine flow rate increases from 4.2 to 4.5 L/min correspondingly. Considering the recovery ratio, it decreases only from 0.263 to 0.217 (17.5 % decrease) for the same feed water salinity range.

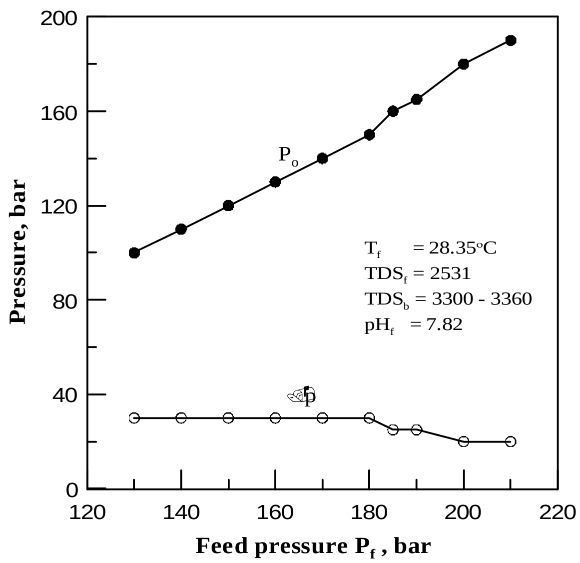


Figure 7. Effect of feed pressure on outlet pressure and pressure difference across the membrane

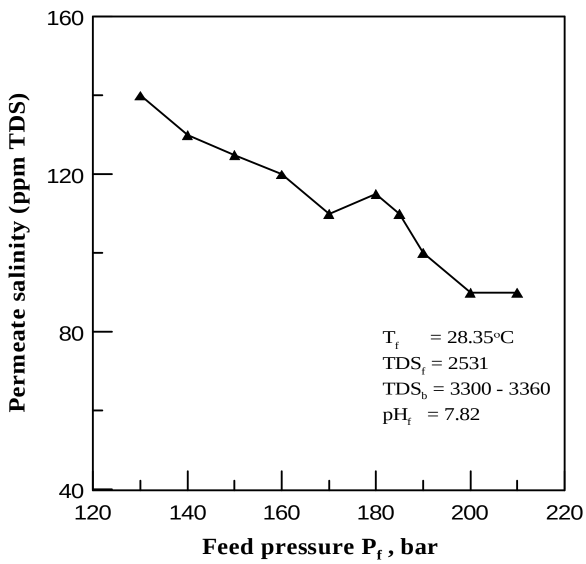


Figure 8. Effect of feed pressure on permeate salinity

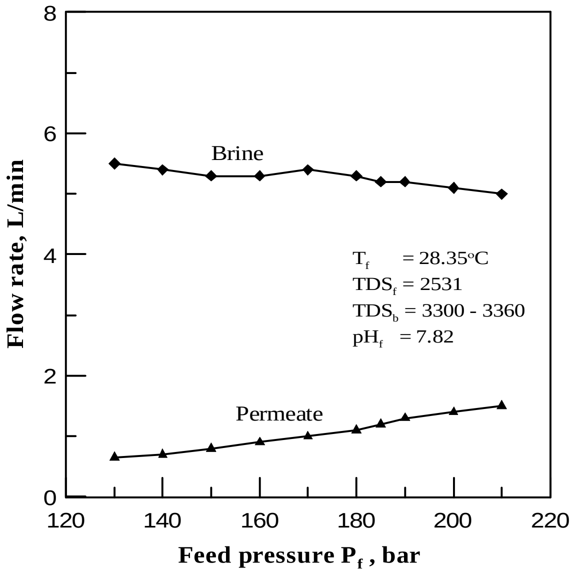


Figure 9. Effect of feed water pressure on permeate and brine flow rates

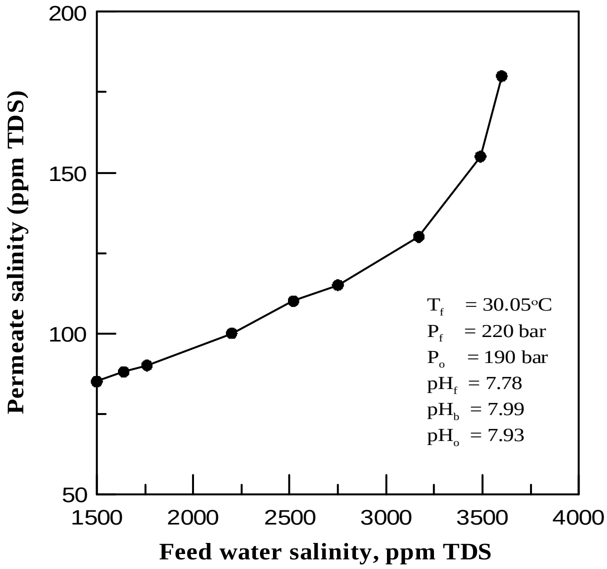


Figure 10. Effect of feed water salinity on permeate salinity

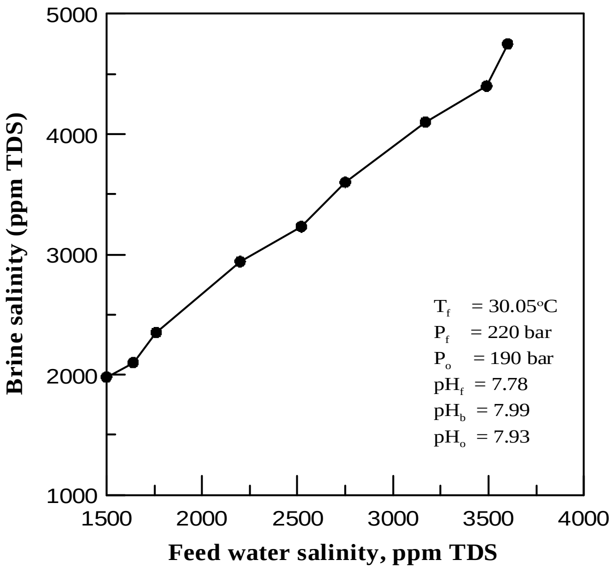


Figure 11. Effect of feed water salinity on brine salinity

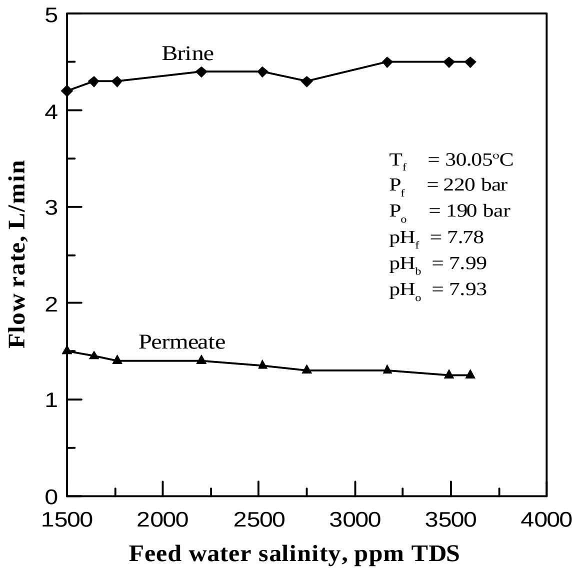


Figure 12. Effect of feed water salinity on permeate and brine flow rates

4- Feed Water pH

In the feed pH value group, the feed water temperature is kept constant at 30.11ºC. The feed water pressure is also kept constant at 220 bars. The group is divided into a number of runs, where the feed water (brackish or tap water) pH value is kept at a constant value by adding seawater in each run. The pH affects the separation performance by its effect on the hydration and absorption capacity of the solutes on the membrane. The effects of the feed water pH are shown in Fig. 13. The permeate pH value increases from 3.9 to 8.1 as the feed water pH value increases from 3.6 to 8.5. Additionally, the permeate salinity ppm TDS increases from 330 to 490 ppm TDS as illustrated in Fig. 14 and the brine salinity decreases from 5470 to 5400 ppm TDS, Fig. 15. For the same feed water pH value increase, the permeate flow rate decreases from 1.9 to 1.6 L/min as shown in Fig. 16. The brine flow rate increases from 3.8 to 3.9 L/min correspondingly. The recovery ratio decreases only from 0.33 to 0.29 (12 % decrease) for the same feed water pH value range.

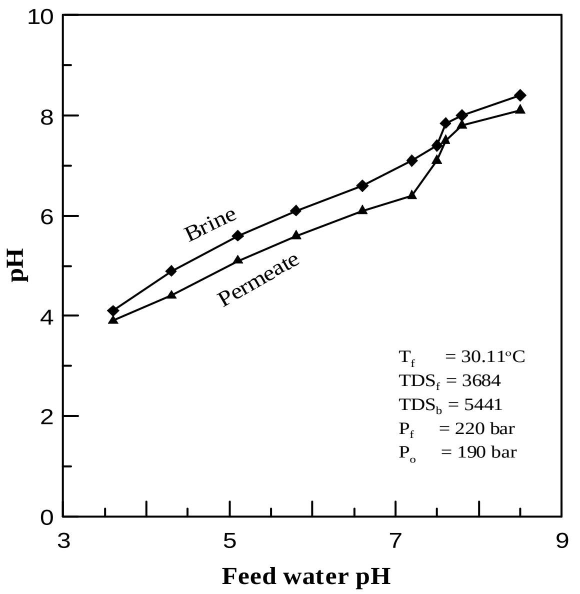


Figure 13. Effect of feed water pH on permeate and brine pH

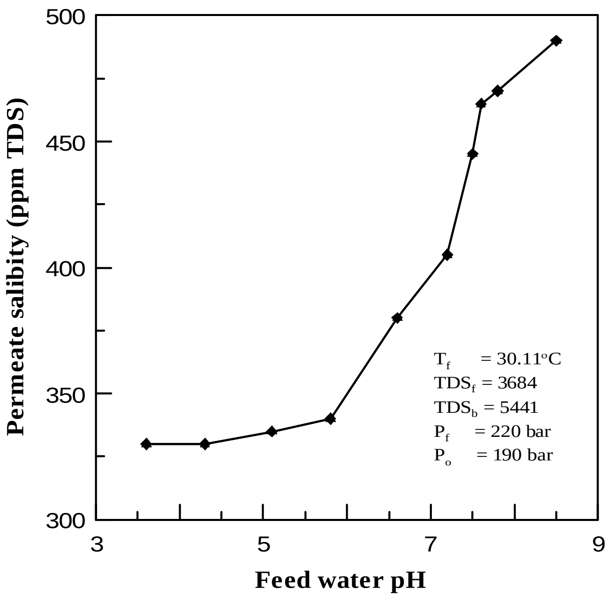


Figure 14. Effect of feed water pH on permeate salinity

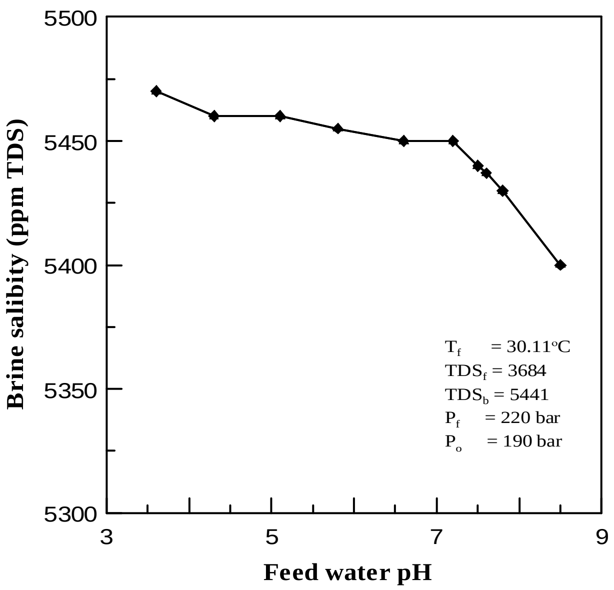


Figure 15. Effect of feed water pH on brine salinity

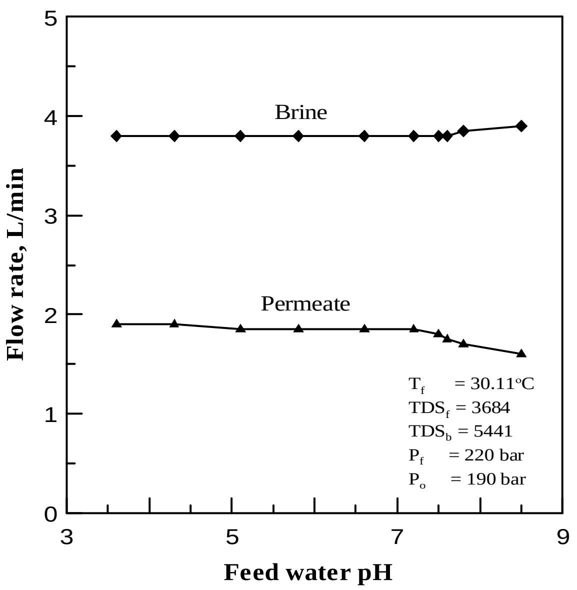


Figure 16. Effect of feed water pH on permeate and brine flow rates

CONCLUSIONS

The effect of operating parameters like feed water temperature, pressure, salinity, and pH on RO membrane performance was studied. Based on the above discussion and results it can be concluded that:

1) Higher feed water temperature increases permeate flow rate and decreases brine flow rate. Also, it decreases the pH for feed water and consequently permeate water and brine pH value.
2) Higher feed water pressure leads to higher permeate flow rate and lower brine flow rate. It also decreases the permeate salinity.
3) Higher feed water salinity reports lower permeate flow rate and higher brine flow rate. Both permeate and brine salinity increases with the increase of feed water salinity.
4) Higher feed water pH decreases the permeate flow rate and increases the brine flow rate. All results match that of previous work.

In the range of experimental runs, the maximum gain in recovery ratio has been obtained from the feed water pressure increase. The increase of feed water temperature or pressure results in a recovery ratio increase while the increase of feed water salinity or feed water pH leads to a decrease in recovery ratio.

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