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Desalination of Iraqi surface water using nanofiltration membranes

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ABSTRACT

Nanofiltration (NF) has received increased attention as a possible treatment process providing high rejection of solutes and high water flux rate. Using NF as a desalination process for Iraqi surface water is considered in this research. A small system with one membrane of 4 inch diameter and 1 m long was used to evaluate the performance of NF membrane for the desalination of Tigris River water in Baghdad, and compare it with a reverse osmosis (RO) membrane. The results showed that one could get double the permeate flow rate and spend about 20% less electric power when using NF membranes instead of RO membranes. Permeated water TDS values for NF membrane are low enough to allow for further adjustment for drinking water quality. NF rejection capacity for monovalent ions is lower than that of the divalent ions, and in general the salt rejection capacity is above 95%.

Keywords: Nanofiltration; Reverse osmosis; Surface water; Desalination; Hardness

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1. Introduction

Water is essential for life, yet many millions of people around the world face water shortage and a daily struggle to secure safe water for their basic needs. This is because only less than 0.5% of the Earth's water resources is available as fresh water for direct human consumption or for agricultural and industrial uses. Desalination has now become an accepted water treatment process around the world and is becoming a price-competitive option for more communities [1].

Many methods have been developed to treat and purify water. These methods seek to create a safe water supply free from sediment, minerals, harmful chemicals and microbiological impurities. Among these methods, membrane technology is considered as one of the most important methods for water treatment, and its application is widely expanded all over the world. Several textbooks have been written on the basic mechanisms and the various applications of these processes [2–6]. Although, membrane desalination techniques require high initial setup cost, reuse of salts and permeate partially recompense them [7].

Various pressure-driven membranes have been developed that separate impurities from water based on the size of the impurity. They can be characterized as follows [8]:

- Microfiltration membranes are semi-permeable membranes with pore sizes ranging from 0.1 to 3 micron and operating pressures below 2 bar. Microfiltration

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membranes retain large suspended solids, such as particulate matter, while passing small suspended solids and all dissolved materials.

- Ultrafiltration membranes are semi-permeable membranes with pore size ranging from 0.005 to 0.1 micron and operating pressures between 1 and 10 bar. Ultrafiltration membranes retain suspended solids, oils, bacteria, large macromolecules and proteins, while passing most small organic compounds, acids, and alkaline compounds.
- Nanofiltration membranes are semi-permeable membranes with pore sizes ranging from approximately 0.0005–0.005 micron and operating pressures between 5 and 40 bar. Nanofiltration membranes retain all solids, bacteria, macromolecules, organic compounds, and divalent salts, while passing monovalent salts, acid and alkaline compounds.
- Reverse osmosis (RO) membranes are membranes with pore sizes in the range of 0.0005 micron and operating pressures in RO are generally between 10 and 100 bar. RO membranes retain all solids, bacteria, macromolecules, organic compounds, divalent salts, monovalent salts, acids and alkaline compounds, while passing essentially pure water.

RO is a proven membrane technology for water desalination. Although the cost of RO desalinated water has been significantly reduced, it still remains fairly high, as compared to other drinking water sources, mainly due to the high operating pressures required. Moreover, due to the highly restrictive nature of RO membranes, water treated by RO membranes is stripped of its buffering acids and bases, thereby leaving the product water highly corrosive. If this water is left untreated, it will gradually destroy metal and materials it comes into contact with [9].

NF membrane has attracted a great deal of attention for use in water softening and removal of various contaminants from drinking water sources. NF processes can reduce or remove TDS, hardness, color, agricultural chemicals, and high molecular weight humic and fulvic materials (which can form trihalomethanes when chlorinated) [10].

Dependence on feed water quality and the level of purification required, NF is preferable to RO and ion exchange for some applications. This is due to [10–12]:

- Nanofiltration membranes remove bacteria, arsenic, silica, and organic compounds, while ion exchange water softener do not.
- Softening water with nanofiltration membranes does not require dumping large quantities of chloride ions into the drain water, while softening water with ion exchange chemistry dose.
- The small amount of divalent salts passed through the nanofiltration membrane results in nanofiltered water with a sufficient hardness to provide water with better flavor than that produced by ion exchange chemistry or RO membranes.
- In contrast to RO membranes, nanofiltration membranes do not strip the water of its buffering acids and alkaline compounds. While RO filtered water is very acidic, nano-filtered water is buffered at a higher pH and is safe for plumbing.

Since the early seventies a steady growth of various membrane processes in the manufacture of drinking water is found [8]. In the beginning, membrane processes for drinking water production were only applied in the US and the Middle East. Nowadays the applications are rapidly expanding all over the world. World-wide, 9.106 m^3 of water is processed per day by RO and 106 m^3 by NF and UF [8]. With respect to the fundamentals of the nanofiltration process, major progress has been made since the early nineties [13–15].

1.1. *Iraqi surface water*

Iraqi surface water from the Tigris and Euphrates Rivers supplies the Iraq's land area with water, including urban areas and their associated industries. The quality of surface water throughout the country varies widely but generally is poor. Heavy mineralization, suspended solids and, frequently, high salinity characterize Iraq's water supply. The minerals in the water include concentrations of carbonates, sulfates, chlorides, calcium, magnesium, and, in some locations, nitrates. Iraq's rivers also contain biological materials, pollutants, and are laden with bacteria. Unless water is purified with chlorine epidemics of such diseases as cholera, hepatitis, and typhoid could occur. Surface water is characterized as very hard water. Iraqi Ministry of Environment monitors the Tigris and Euphrates Rivers through test stations distributed along the rivers banks from their entry to Iraq (at North of Iraq) till they meet together and form another river named "Shat Al-Arab" (South of Iraq). The collected data showed that water hardness varies from 200 to 1000 mg/l as $CaCO_3$, as shown in Fig. 1 [16]. Due to this high hardness, it is believed that nanofiltration will work as good as reverse osmosis for the production of drinking water from surface water due to their high rejection rate of divalent ions, such as Ca and Mg ions. All the desalination plants in Iraq use RO membranes. For 3 years now, Iraq, as well as other Middle East countries, has suffered from very low rainfall quantities. This reduces the quantity of water available in the main rivers and contributes to the reduction of raw water quality. Water hardness increases significantly in the Tigris and Euphrates Rivers, and salt water from the Arabic gulf were introduces to the south of Iraq leading to a severe increase in water dissolved solids.

This study contributes to the investigation efforts toward using efficient technologies to produce affordable

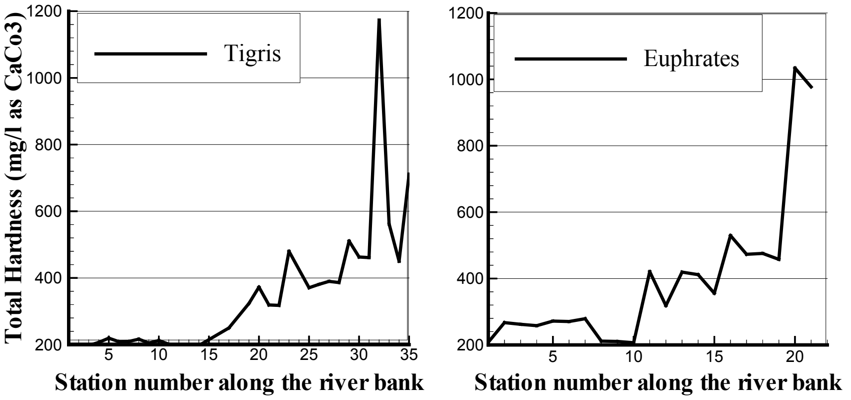

Fig. 1. Hardness values for the Tigris and Euphrates Rivers measured in 2007 at test stations distributed along the river banks [16].

drinking water in Iraq using less power consumption, where the threat of water shortages and electric power shortage are considered severe problems.

2. Materials and methods

2.1. Surface water

Water samples were collected from Baghdad municipal network, which is from the Tigris River water after conventional treatments. This water was used as feed water to the desalination unit with either RO or NF. Feed water was pretreated to guarantee no free chlorine in it. Feed water TDS was synthetically changed by recycling reject water, or permeate, from the same operating units. Recycling rejected water increases the TDS by adding even more hardness ions to the raw feed water, and this will enhance evaluating the membranes performance for various feed water characteristics. TDS values were selected to cover the range normally found in Iraqi river water, i.e. from 800 up to 2000 mg/l. Raw water characteristics (from the Tigris River) are shown in Table 1.

2.2. Equipment and membranes

All experiments were conducted on a pilot plant scale. A test skid unit is arranged as shown in Fig. 2. The unit consists of one low pressure pump, two micron filters (5 and 1 micron), one high pressure pump and one stainless steel membrane vessel of size 4 inch by 1.0 m. The membrane vessel was equipped with either RO membrane type Hydraunatics ESPA1-4040, or NF membrane type Hydraunatics ESNA1-4040. For each experiment, only one membrane is used in the unit. The unit is equipped with several flow meters, pressure gauges and electric conductivity meters that facilitate evaluating the various operating parameters. Polyethylene tanks were used to prepare feed water and to store rejected or permeated water.

Table 1
Physicochemical analysis for feed water used in a membrane testing system

Parameter	Iraqi Drinking water Guideline (2009)	Measured values during the tests (2009)
Turbidity, NTU	5	5
pH	6.5–8.5	7.4–8.0
TDS, mg/l	1000	800–2000
Electrical conductivity, μS/cm		1400–3700
Total hardness, mg/l as $CaCO_3$	500	590–1500
Sodium (Na), mg/l	300	90–240
Potassium (K), mg/l		2.6–4.0
Calcium (Ca), mg/l	50	88–220
Magnesium (Mg), mg/l	50	57–160
Chloride (Cl), mg/l	250	270–900
Sulphate (SO_4), mg/l	250	90–240
Bicarbonate, mg/l		177–230

2.3. Analysis

Conductivity was measured using online instrument attached to the unit and another verification was done using method 2510 [17]. Total dissolved solids (TDS) were measured using method 2540C [17]. pH was measured using method 4500-pH [17]. Flow rates and pressures were measured using online rotameter and liquid filled burden gauges respectively. In addition to the skid mounted conductivity meters, laboratory portable pH and conductivity meters from Hanna, USA were used for further check and quick measurements. Hardness and Ca ion were measured using EDTA Titrimetric methods (Method No. 2340C and 3500-Ca B respectively) [17],

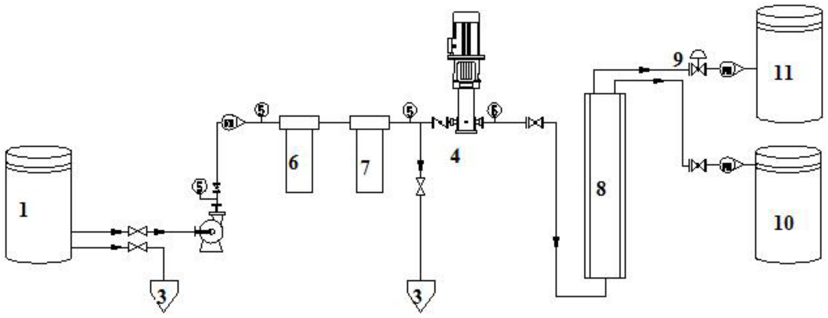

Fig. 2. Schematic diagram for membrane testing system arrangement. 1 Feed water tank; 2 Feed water pump; 3 Drain; 4 High-pressure pump; 5 Pressure gauges; 6 Flow meters; 7 Micron filters; 8 Pressure vessel for RO or NF membrane; 9 Regulating valve; 10 Permeate tank; 11 Concentration tank.

while Mg ions were calculated following the standard method No. 3500-Mg B [17]. Detailed ions analysis was conducted in the laboratories of the Iraqi Ministry of Science and Technology, Water Research Center.

Other parameters such as salt rejection, a factor expressing the ability of RO membranes to reject dissolved solids, and unit recovery were calculated as follows:

Salt rejection = 1 – Permeate water TDS / Feed water TDS

Ions rejection = 1 – Permeate water conc. / Feed water conc.

Unit recovery =
Permeate water flow rate / Feed water flow rate

Electric power consumption was estimated from its direct proportional relation to the values of the pressure of the feed water into the membrane.

3. Results and discussion

Experiments were conducted for the period from July to November 2009, in the chemical laboratories of University of Technology, Baghdad.

Fig. 3 shows the relation between the permeated flow rates of the system with NF or RO membrane for various feed water pressure values (high pressure). The experiments were repeated for two values of feed water TDS; 800 and 2000 mg/l. It can be seen from the figure that permeated flow rate for the system with NF membrane is more than double that for the system with RO membrane. It can also be noted that the applied range of feed water TDS had minor effect on the system performance for both RO and NF membranes. The unit recovery was calculated from the feed and permeated water flow rates, and the results are shown in Fig. 4. The results are identical to those obtained in Fig. 3 because feed water flow rate was almost constant along all the experiments. Here also one could conclude that the system recovery when using NF membranes is almost double that when using RO membrane.

It is worthy to notice that reducing feed water pressure has a direct effect on the unit power consumption. In other words, for the Iraqi surface water, one could get about double the permeate water flow rate and spend about 20% less electric power on desalination systems

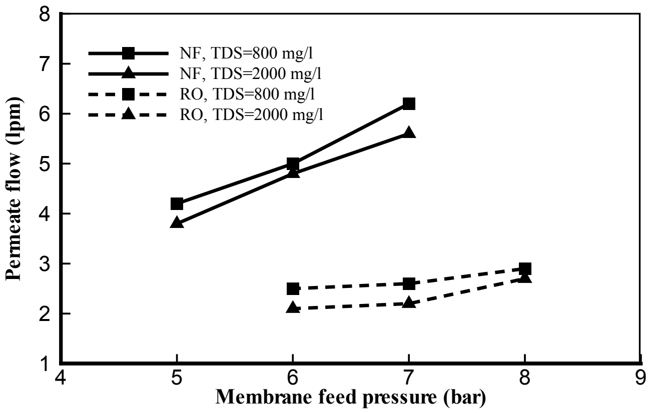

Fig. 3. Relation between permeate flow rate for the system with RO/NF membrane at different feed water pressure and feed water TDS values.

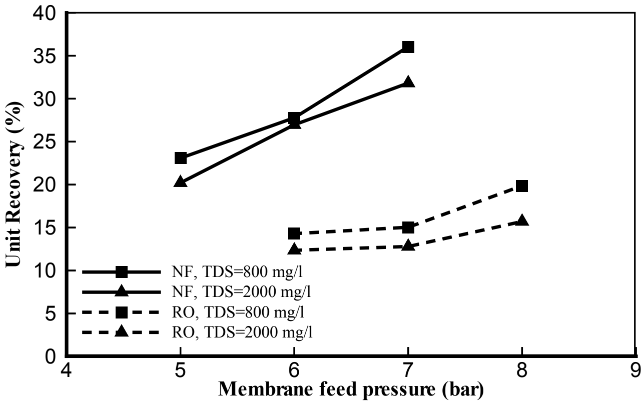

Fig. 4. Relation between the system recovery with RO or NF membrane at different feed water pressure and feed water TDS values.

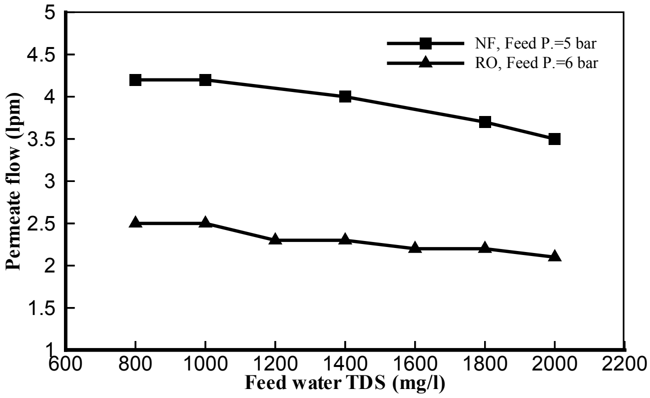

Fig. 5. Relation between permeate flow rate for the system with RO/NF membrane at different feed water TDS values.

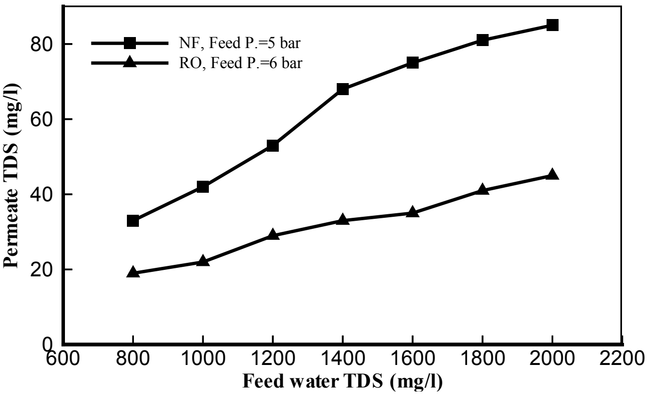

Fig. 6. Relation between permeate TDS values for the system with RO/NF membrane at different feed water TDS values.

by using NF membranes instead of RO membranes. Manufacturer advices to use 5 bar for the NF operating pressure, and hence the next experiments will deem this value and 6 bar for an RO membrane.

Fig. 5 shows the relation between the permeate flow of the system when using NF or RO membrane for various feed water TDS. It can be shown that the permeate flow rate was reduced by around 16% when feed water TDS raises from 800 to 2000 mg/l. Almost the same reduction value was obtained for both RO and NF membrane. This is justified due to the fact that the excess dissolved solids in water tend to consume the higher power through their osmotic pressure regardless of the type of the membrane in use. As a conclusion of this result, desalination systems will produce less water in the south provinces in Iraq, where water is more saline, than those in the middle or in the north. However, once again, the advantage of using NF membranes arises through getting about double the product water when compared with systems using RO membranes.

Fig. 6 shows the effect of increasing feed water TDS on the permeate water quality (in terms of TDS). Permeate water TDS increases with feed water TDS in almost with a linear relationship. The slop of the relation for the NF membrane is higher than that of the RO membrane. This is due to the effect the larger pore size of the NF membrane than those of the RO membrane. Nevertheless, both membranes permeate water quality were very good, and the TDS values were extremely low, which allow for further adjustment of the final drinking water quality, regardless of the feed water hardness values.

Membranes performance in terms of salt rejection capacity is shown in Figs. 7–9. Fig. 7 shows the effect of increasing feed water pressure and feed water TDS on the membrane performance in terms of salt rejection. RO membrane shows higher salt rejection (99%) than NF membrane (about 96%). Salt rejection reduces as feed water TDS increases. Increasing feed water pressure showed small changes in the salt rejection for both RO and NF membrane. For NF the salt rejections increase

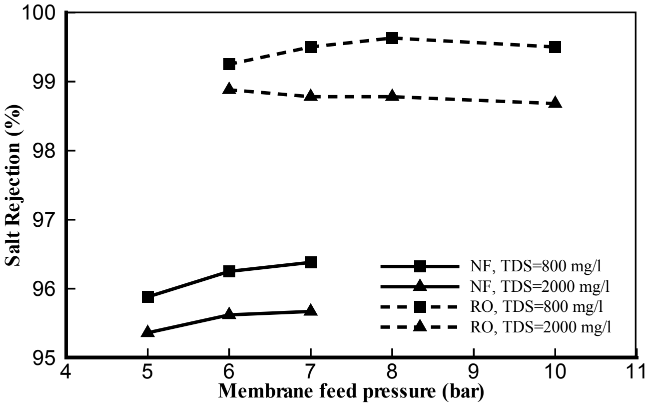

Fig. 7. Relation between the unit salt rejection with RO or NF membrane at different feed water pressure and feed water TDS values.

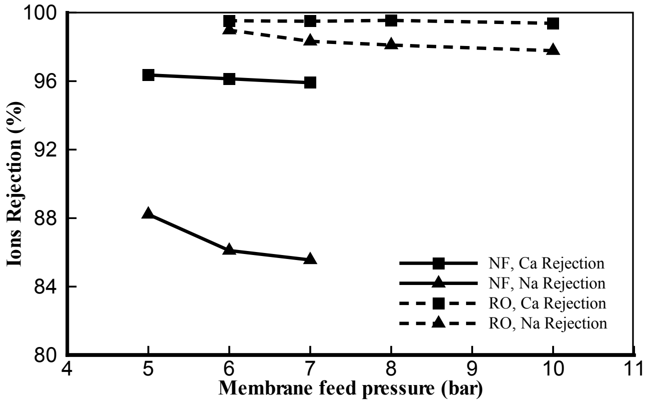

Fig. 8. Relation between the Ca and Na rejection capacity with RO or NF membrane at different feed water pressure values at feed water TDS = 800 mg/l.

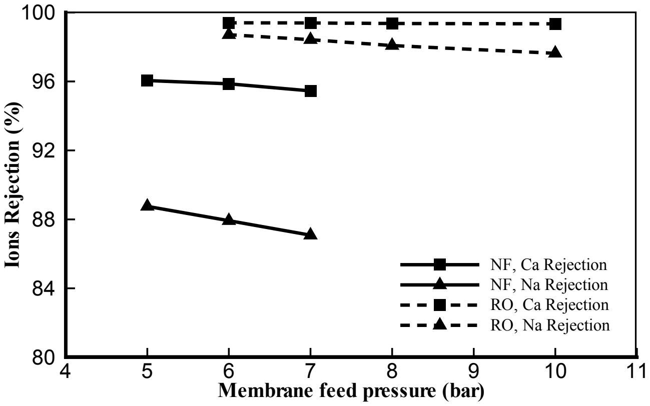

Fig. 9. Relation between the Ca and Na rejection capacity with RO or NF membrane at different feed water pressure values at feed water TDS = 2000 mg/l.

with increasing feed pressure (and hence increasing flux), indicating the importance of the contribution of diffusive transport at low flux and convective transport at high flux [8]. Figs. 8 and 9 show a comparison between monovalent and divalent ions rejection capacity at the condition of changing feed water pressure and feed water TDS for both NF and RO membranes. Calcium (Ca) and sodium (Na) ions values were selected to represent divalent and monovalent ions respectively. It is clear from the figures that RO membrane rejection capacity is high (> 98%) for both monovalent and divalent ions, and increasing the feed water TDS did not affect this capacity. Increasing the pressure up to 10 bar slightly reduced this capacity especially for monovalent ions (97%). NF membrane, on the other hand shows a clear difference between the monovalent rejection capacity (88%) and divalent rejection capacity (96%). Once again, increasing feed water TDS did not affect this capacity. Increasing the feed water pressure up to 7 bar slightly reduces this capacity especially for monovalent ions (86%). These results are important because the Iraqi surface water hardness will be reduced to an acceptable limit even at high concentrations of feed water hardness (1500 mg/l as $CaCO_3$) when using NF membranes instead of RO membranes in desalination process.

As a secondary result, the effect of feed water temperature on the product water quality and quantity was examined. Such effect is shown in Figs. 10 and 11. In Iraq, water temperature is above 35°C in summer and about 10°C (or less) in winter. Two temperatures were tested; 39 and 26°C. From Fig. 10 it can be noticed that permeate flow rate was reduce by 7–16% for feed pressure of 6–10 bar when the feed water temperature drops from 39 to 26°C. Permeate water TDS (Fig. 11) also drops from about 65 mg/l to less than 6 mg/l. This can be attributed to the reduction in the membrane pore size by the influence of water temperature. Increasing feed water temperature to retain the original high flow rate will consume higher energy than those gained by increasing the system flow rate. Thus system flow rate reduction is unavoidable. All the above results were in agreement with those obtained by many other researchers in the field [18–20].

4. Conclusions

Although many of the results obtained in this work might be obvious to experts in membrane desalination technology, the application of the adequate membrane in desalination Iraqi surface water needs such evidence to calculate the total benefits and to optimize water desalination systems currently in service and reduce operating cost and electric power consumption. The following conclusions could be stated based on the above results.

1. For the Iraqi surface water, one could get double the permeated water flow rate and spend about 20% less

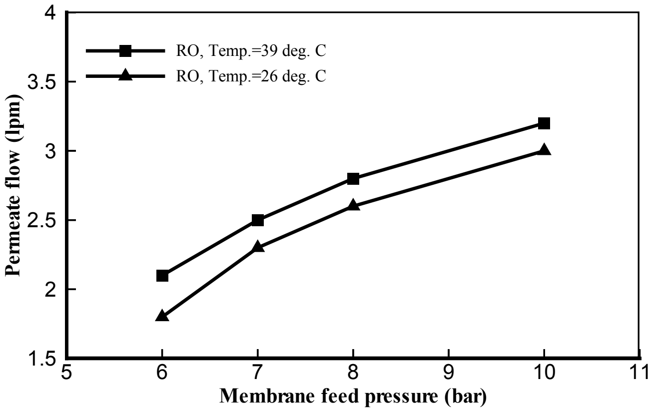

Fig. 10. Relation between permeate flow rate for the system with RO membrane at different feed water pressure at two feed water temperature values.

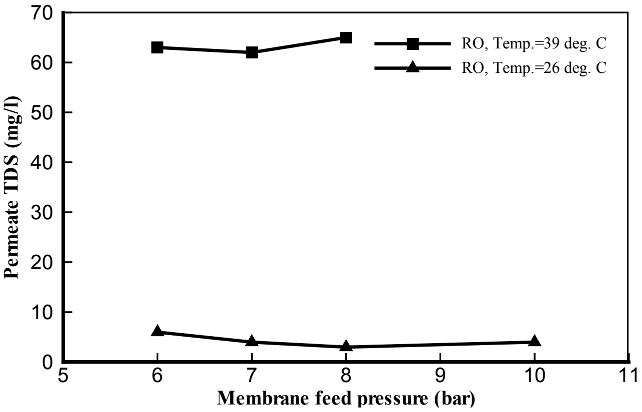

Fig. 11. Relation between permeate water TDS for the system with RO membrane at different feed water pressure at two feed water temperature values.

electric power on desalination systems by using NF membranes instead of RO membranes.

2. TDS values for RO and NF membrane permeate water increases as feed water TDS values increase. However, both membranes permeated water quality were very good, and TDS values were extremely low, which allow for further adjustment of the final drinking water quality.
3. RO membrane salt rejection capacity is, in general, higher than that of the NF membrane. Increasing the feed water TDS or changing the feed water pressure creates small variations in salt rejection capacity values. NF membrane rejection capacity for monovalent ions (88%) is lower than that of divalent ions (96%). This rejection capacity guarantee to reduce hardness levels to below the acceptable limits even at elevated hardness values from the Iraqi surface water.
4. Both systems permeated water flow rate and TDS values reduces significantly with the reduction in feed water temperature. However, from the point of power consumption in Iraq, such reduction is unavoidable.
5. Finally, a long-term operation of NF/RO system will be further tested in some pilot test in order to examine the system reliability in terms of operation; such as fouling chemical consumption, etc.

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