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Case study on the effects of feed water temperature on the performance of a reverse osmosis desalination system

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ABSTRACT

Feed seawater temperature has significant effects on the performance of reverse osmosis (RO) desalination plant. However, developing a relationship between the feed seawater temperature and performance of an RO desalination unit is complex as feed seawater temperature also simultaneously affects several desalination variables in different ways. Operational aspects of the RO system such as power consumption, water salinity and flux, osmotic pressure, and the pressure compaction factor are the main variables that are affected by the feed seawater temperature. In this article, the effects of feed seawater temperature on the performance of a reverse osmosis desalination plant located in Egypt are evaluated experimentally. A simple surface heat exchanger (cooler) was coupled with the second line membranes of the RO plant to reduce the temperature of the seawater temperature before it entered the membrane. From the results, it was found that the annual mean power consumption reduced by 6.7% and the annual mean increase in permeate (product freshwater) flow rate was 0.0475 m^3/h, equivalent to 2.3%. The permeate conductivity improved by an annual percentage of 14.4%. Overall, the total saving in operational costs due to the coupling of the cooling unit to the second line membranes was approximately $2,550 for 1 y.

Keywords: Desalination; Reverse osmosis; Feed seawater temperature; Annual operational costs

1. Introduction

Osmosis is a natural phenomenon in which a solvent (usually water) passes through a semi permeable barrier from the side with lower solute concentration to that with a higher concentration. In reverse osmosis, the process happens in reverse. Present investigations involve the evaluation of a reverse osmosis plant installed in the city of Hurghada, Egypt, near the Red Sea Coast. Scientific literature was reviewed and it was found that only few studies had considered the effect of temperature on the performance of RO plants. In these studies, the main factors which affect the performance of reverse osmosis plants were investigated. It was shown that as the salinity of feed seawater to the membrane is decreased, the productivity of the plant increased, and the number of times the membrane needed to be chemically washed are reduced, for example [1–5]. Glater [6] presented a detailed survey of early works on the beginning of reverse osmosis technology. Jawor and Hoek [7] investigated the effects of product water recovery and feed water temperature on flux, rejection, and inorganic fouling for simulated brackish water. It was found that as feed water temperature increased, salt rejection, and concentration polarization decreased whilst gypsum crystal

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nucleation and growth rates increased with temperature. At 15°C–25°C, many small crystals formed over the entire membrane surface and gypsum scale formation resulted in flux decline at recoveries as low as 10%–20%, whereas at 35°C flux decline was about 70% due to increasing of feed solution osmotic pressure. At the outlet of the RO simulator, the entire membrane surface was covered with crystal fragments forming a cake layer and causing the massive flux decline. This study concluded that high-temperature operation of brackish water RO processes could enable higher recovery and lower energy consumption, but operating at elevated temperatures creates an increased risk of disastrous fouling of the membrane. Guler et al. [8] investigated the effect of feed seawater temperature on the quality of product water in a reverse osmosis process using typical seawater at Urla Bay, Izmir region, Turkey. The experiments were carried out at different feed seawater temperatures in the range of 11°C–23°C using two RO modules. It was concluded that the quality of permeate was highly dependent on the temperature of the feed seawater, with decreasing temperature enhancing permeate quality. A rejection rate of approximately 98%–99% was obtained for cations and anions. The results showed that temperature is an important parameter that must be taken into account in order to obtain a high quality of freshwater.

Franks et al. [9] reviewed the theory involved in the opposing effects of membrane permeability and osmotic pressure on overall feed pressure and determined how enhancement in the membrane permeability of the seawater RO (SWRO) system affected the osmotic pressure in the membranes. It was concluded that an increase in feed water temperature reduced SWRO feed pressure and associated energy consumption but net driving pressure (NDP) and osmotic pressure were inversely affected by temperature. The required NDP was considerably reduced in the latest generation of high-permeability seawater membranes and the assumption of decreasing feed pressure with increasing temperature was only valid at temperatures below 25°C. It was reported that the magnitude of energy savings associated with increasing temperature depends on the range of temperature change and membrane permeability. A 10°C temperature reduction may reduce energy consumption by as much 6.3% (using low-permeability membranes at a lower temperature). However, the same 10°C temperature reduction may have no effect on energy consumption when high-permeability membranes are used at temperatures above 25°C. The effect of increasing temperature on the latest high permeability membranes operated at higher temperatures has been demonstrated theoretically in laboratory tests and small-scale pilot tests.

Another study by Suad et al. [10] investigated the effect of operating conditions on the performance of the reverse osmosis membrane, including the effect of high concentrations of salts, pressure, and temperature on the operation of the plant. Various operating pressures at different temperatures of the feed solution were used. The experimental results showed that when the concentration and feed temperature of the salts were increased, the rejection of salts decreased. Sarai et al. [11] theoretically investigated a reverse osmosis system for brackish water desalination using a numerical model. The effect of feed seawater temperature, pressure, salinity, and recovery ratio on the efficiency of the RO system was investigated for a wide range of design considerations. Farhata et al. [12] investigated biofilm development at different water temperatures (10°C, 20°C, and 30°C) inside a membrane fouling simulator (MFS) flow cell. Biofilm parameters such as oxygen decrease rate, biovolume, biofilm spatial distribution, thickness, and composition were measured using imaging techniques. The results showed that with increasing feed water temperature (i) the biofilm activity developed faster, (ii) the pressure drop increased faster, while (iii) the biofilm thickness decreased. It was concluded that membrane installations with a high-temperature feed water are more susceptible to biofouling than installations fed with low-temperature feed water.

Wang et al. [13] evaluated concentration polarization (CP), reverse solute permeation (RSP), and the performance of a scaled-up osmotic power assisted reverse osmosis desalination plant. It was observed that the CP and RSP effects decreased the performance of the plant but for the co-current and counter-current PRO configurations, the dimensionless flow rate decreased, energy consumption was less, and decrease in the performance was not worthy of note. It was found that with increasing PRO feed concentration, osmotic energy generation decreased. Koutsou et al. [14] studied the effect of feed water temperature on the performance of an RO unit coupled with an energy recovery device focusing on the specific energy consumption (SEC) and seawater desalination. It was found that a feed water temperature in the range ~15°C–40°C results in a decrease in SEC in desalinating low salinity waters. Moreover, for high salinities as in sea-water, the increase in osmotic pressure with feed water temperature resulted in minimum SEC at ~30°C whereas an increase in feed water in the desalination of both low- and high-salinity waters adversely affected membrane salt rejection and scaling features.

From the previous studies, it is noted that many studies were performed theoretically, using simulators in laboratory tests and small-scale pilot tests. It was noted that increasing the feed water temperature would increase the permeate flow while the quality of permeate will be reduced. This is a fact illustrated by numerous published work and is supported by physical properties. High-permeability membranes are currently operating at low pressures in full-scale commercial SWRO systems. Because of permeate quality limitations, most of these systems operate in the mid-to low-temperature range. As highly permeable membranes are installed and operated in commercial SWRO systems operating at higher temperatures, there is a need that the diminishing effect of increasing temperatures on feed pressure and energy consumption should be analyzed and verified in full-scale plants. The current work was undertaken to fill this research gap and analyze the impact of feed seawater temperature on the performance of an RO plant in the city of Hurghada, Egypt. However, here the relationship between feed water temperatures, RO system performance, system characteristics, and the environment has been studied in the hot climatic conditions of Egypt. Therefore, the current work differs from other published research since it is concerned with a different RO system/environmental combination.

2. RO plant and experimental setup description

A schematic of the RO plant coupled with a cooling unit and the experimental setup used in the study are shown in Fig. 1. The second line membranes have a recycle stream. This will increase the concentration of the feed water to the second line membranes and will not be equal to the concentration of the feed seawater to the first line membranes which have no recycle stream. The main components of the plant are first line membranes and second-line membranes, two high-pressure pumps (HPP), two cartridge filters, one cooling unit, one sand filter, and one pool with a feed seawater pump whereas the plant included two similar units for producing freshwater with an overall capacity of 30,000 m^3/d. The pool was supplied with feed seawater directly from the Red Sea. The second line (unit) membranes and pool were instrumented to measure the main variables. Moreover, the feed seawater supply line to the second line membranes was coupled with the cooling unit to cool the feed seawater before it entered the membranes. The cooling unit was a simple non-mix surface plate heat exchanger which was coupled only with the second line. The capacity of cooling unit is 2.25 ton refrigeration. The objective was to study the effects of cooled feed seawater, which was supplied only to the second line, on the performance of the RO system membranes, and compare the results with the output of the first line membranes which were supplied with the normal feed seawater from the pool without cooling.

3. Problem statement and analysis

The RO plant was initially supplied with feed water from two wells. The objective of the present work was to focus on the inlet temperature of the feed seawater and investigate the effects of the feed seawater temperature on the performance of the reverse osmosis desalination system. Since the budget was limited, it was decided to incorporate existing air conditioning (AC) unit for this purpose. The AC unit was ducted to a surface plate heat exchanger (cooling unit) that contained the cartridge filter of the second line membranes, as shown in Fig. 1. In this way, one of the two desalination lines (i.e., the second line membranes) would have a lower feed seawater temperature. This setup was developed to investigate the effects of feed seawater temperature on the performance of the reverse osmosis desalination system. It should be noted that during the present study several modifications were incorporated into the cooling unit to make it effective with the feed seawater. The modifications included replacement of the old refrigerant (i.e., R-22) with R-134a, replacing the expansion valve to achieve lower evaporator pressure, reducing the blower speed to obtain a lower supply air temperature, and installing a defrosting system since the new operating conditions required lower evaporation temperatures. It was observed that the performance of the second desalination line was improved by the integration of the feed seawater cooling system.

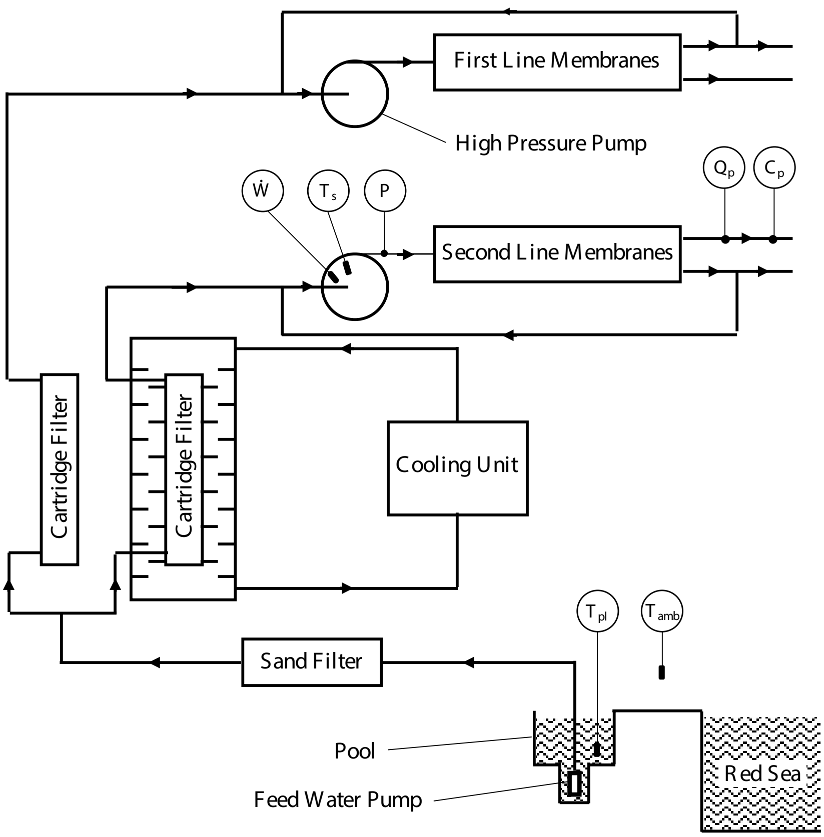

Fig. 1. Schematic of the RO plant coupled first line membranes (without cooling unit) and second-line membranes (with cooling unit) with a cooling unit and instruments.

4. Results and discussions

4.1. Performance of the original RO plant

Before deciding to incorporate a brine cooler into the RO plant, the performance of the original RO system was monitored. This was achieved by observing the operation of the first line in the station (Fig. 1). The monitoring period for the first line was from April 2009 to April 2010. The measurement instruments were calibrated every 3 months of operation. The measured and monitored variables included feed seawater flow rate, permeate flow rate, HPP electrical power consumption, conductivity, and pH value of the product water, and operating pressures at the inlets and outlets of the sand filter, cartridge filter, HPP, and membrane. The measured data were collected for 5 different operational sampling days of the year during the running of the RO plant. The results for 5 d are displayed in Figs. 2–5 which shows the impact of feed seawater temperature on the HPP surface temperature, HPP power consumption, permeate flow rate, and permeate conductivity. The results for each day are presented as a separate set. It should be noted that the measurements were recorded after every 15 min and were averaged over each hour.

The variation in HPP surface temperature vs. pool water temperature for 5 sample days is shown in Fig. 2.

Each of the five curves in Fig. 2 can be divided into two segments. In first segment which represents the early hours of operation after start-up, the rise in HPP surface temperature is vertical whilst in the second segment indicating settled operation of the RO station, the temperature rise tends to be flat. Overall the trend of increasing HPP surface temperature vs. pool water temperature is exponential which shows pool water temperature increases and the surface temperature of the HPP increases which affects the performance and life of the pump.

The variation in power consumption of the HPP vs. feed seawater temperature for the 5 sampling days is presented in Fig. 3.

Fig. 3 shows that as the pool seawater temperature increased, the power consumption of the pump increased exponentially which lead to an increase in the discharge pressure resulting in greater electrical consumption. The HPP power consumption is directly related to the feed seawater temperature. Moreover with increasing feed seawater temperature, the rate of accumulation of salts increases in different layers of the membrane. Moreover, increasing pool water temperature leads to increasing water salinity resulting in the accumulation of more sediment through the different paths of the plant membrane. The results show that the temperature of the feed seawater was at its highest on day 1. The membranes used in the plant were unable to desalinate the seawater to the required specifications because of the characteristics of the feed seawater were changed in the pool due to the climatic conditions. For example, the salinity is increased and reached 48,000 ppm although the setup was designed to handle less than 40,000 ppm. Also, the feed seawater temperature was 10°C–15°C higher than intended for the setup design. The variation in permeate conductivity vs. pool water temperature is shown in Fig. 4.

The curves in Fig. 4 show small changes in permeate conductivity with rising feed seawater temperature in the early hours of each of the 5 d. This is because chemicals were used to wash the RO plant before each day of monitoring. Later on, there is a small increase in permeate conductivity as the temperature of the brine rises. From the results obtained it can be easily concluded that, in order to lower HPP surface temperature, decrease HPP power consumption, and raise permeate quality, the feed seawater should be cooled to as low a temperature as is feasible which means that reducing the feed seawater temperature has beneficial effects on the main variables discussed so far. The variation in pool water temperature vs. operational time of the RO plant for 5 sampling days is shown in Fig. 5.

Fig. 5 shows the increase in pool water temperature with plant operational hours for the different sample days. The rate of increase in the pool temperature is based on the ambient temperature, frequencies of ebb and flow, and rate of water removal and plant suction. There is a wide deviation in the pool water temperature values of the operational samples taken for each of the 5 d of the study.

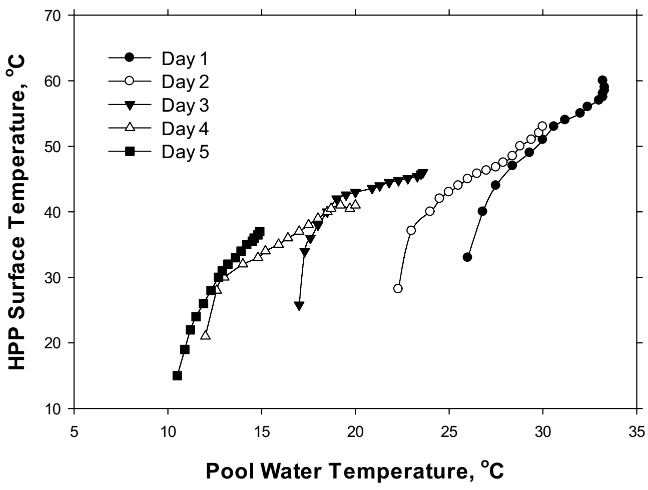

Fig. 2. Variation in HPP surface temperature vs. pool water temperature for 5 sample days.

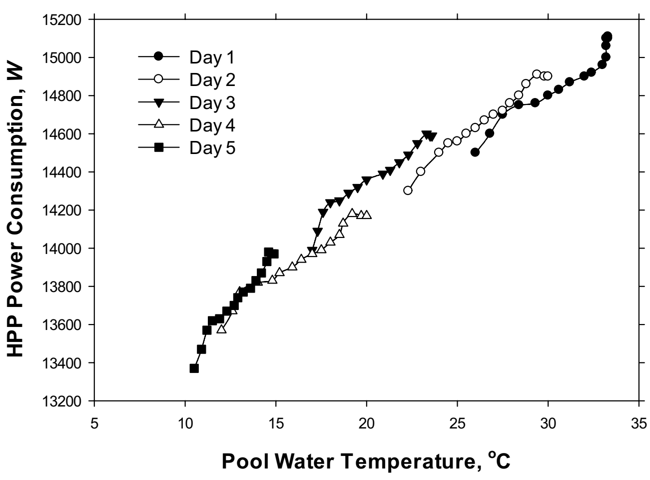

Fig. 3. Variation in power consumption of the HPP vs. brine temperature for the 5 sampling days.

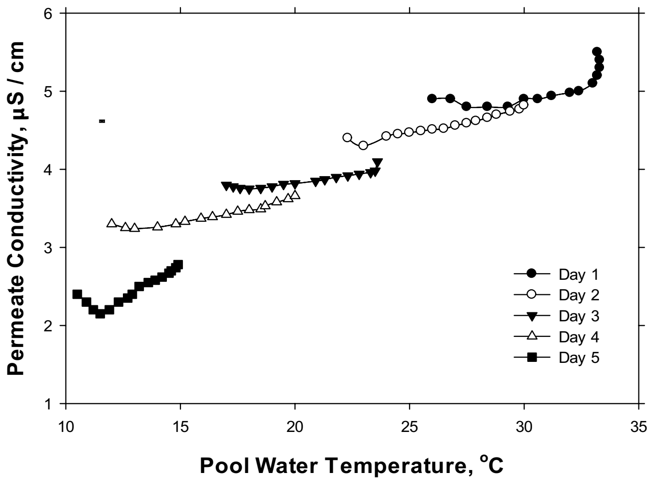

Fig. 4. Variation in permeate conductivity vs. pool water temperature.

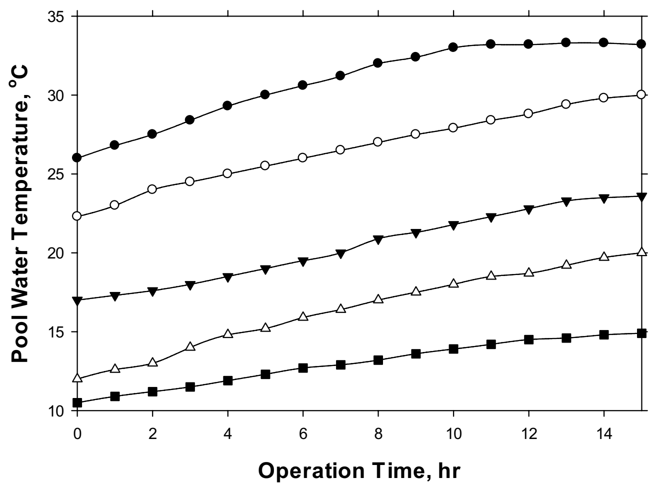

Fig. 5. Variation in pool water temperature vs. operational time of the RO plant for 5 sampling days.

The highest temperature of day 1 was the highest reached at 32.5°C, whilst the lowest value was for day 5 at 12.3°C. This large variation between pool water temperatures affects the performance of the RO plant significantly. Actually, the seawater temperature in the sea was fixed and reached approximately 15°C, so, the properties of seawater in the pool were affected directly with operational conditions and environmental parameters such as ambient temperature and wind at the site. The effect of feed water in the pool on the different operational plant parameters such as freshwater productivity, salinity, and power consumption for each cubic meter of permeate was investigated. The dependency of each of the variables on feed seawater temperature is dynamic and multiple. The dependency is dynamic because the RO variables that have an effect on permeate flow rate such as scale formation change with time. The dependencies are multiple as the monitored variables also depend upon each other and are a function of feed seawater temperature. For example, permeate conductivity depends on the permeate flow rate, which itself is a function of feed seawater temperature. Furthermore, the performance of the studied RO plant also depends on the tidal motion of the Red Sea. The next section considers the magnitude of the enhancement of the RO plant performance in response to decreased feed seawater temperatures.

4.2. Impact of the feed seawater cooling unit

In order to conduct this comparative analysis of the extent of brine temperature related improvements in terms of the performance of the RO plant, a second desalination line including a brine cooling unit was coupled to an RO plant, as shown in Fig. 1. The two production lines (i.e., first-line membranes and second-line membranes) had identical specifications, boundary conditions, and initial conditions. The only difference between the two lines is the brine cooler (surface plate heat exchanger) and the cartridge filter in the second line membranes which lead to a decrease in the feed seawater temperature before entering the HPP. The performance of both desalination lines was monitored continuously throughout the operational period, except during maintenance and chemical washing. For clarity, the measured data were averaged for each month and presented for the year. The average reduction in the seawater temperature when using the cooling unit for each month of the year is shown in Fig. 6 which illustrates the effect of coupling the cooling unit on the feed seawater temperature of the second line membrane of the plant. The maximum decrease was 3.2°C during the month of July.

The variation in monthly feed seawater temperatures for the first desalination line (without a cooling unit) and the second desalination line (with a cooling unit) for each month of the year is shown in Fig. 7.

Fig. 7 shows the effect of the coupled cooling unit (heat exchanger) on the feed water line and its subsequent effect on the performance of the RO plant. The temperature of the feed seawater is decreased due to the cooling unit (heat exchanger) in the second line membrane. The variation in monthly HPP power consumption of the first desalination line (without cooling unit) and the second desalination line (with cooling unit) for each month of the year is presented in Fig. 8.

Fig. 8 illustrates the lowering of HPP power consumption due to the incorporation of the feed seawater cooling unit. The difference between the HPP power consumption for the two lines increases as the pool water temperature rises. The greatest reduction in power consumption was 9.4%, during July, and the minimum reduction occurred in April at 4.6%. The annual mean reduction in power consumption was 6.7%. The variation in monthly permeate flow rate (m^3/h) for the first desalination line (without cooling unit) and the second desalination line (with cooling unit) for each month of the year are shown in Fig. 9.

Fig. 9 illustrates the influence of brine temperatures, lowered by the cooling unit, on the permeate production rate. The permeate flow rate for the second line is higher than that of the first line throughout the year. The annual mean increase in the permeate flow rate reached 0.0475 m^3/h, which is equivalent to a 2.3% increase. The variation in monthly permeate conductivity of the first desalination line (without

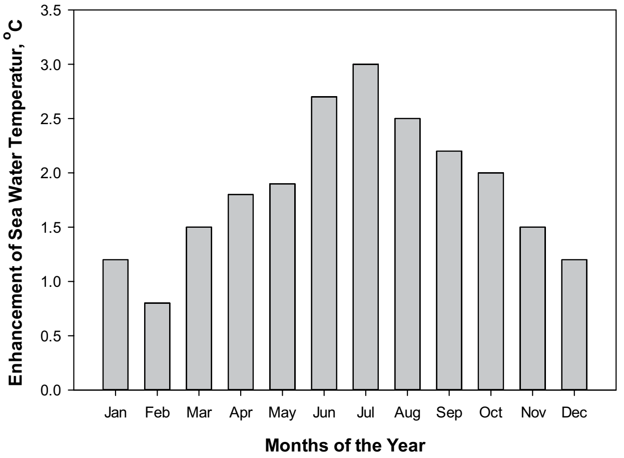

Fig. 6. Average reduction in seawater temperature achieved by using the cooling unit for each month of the year.

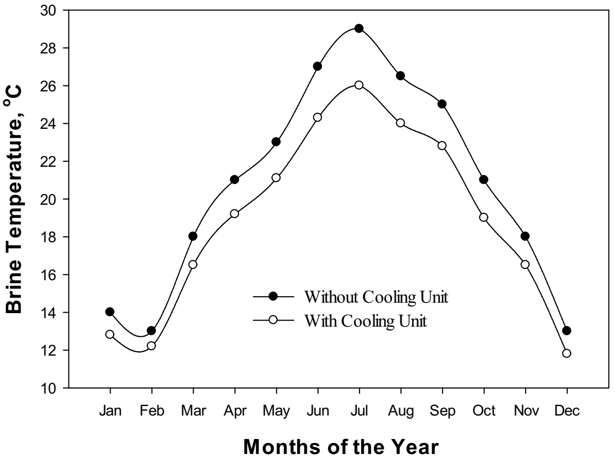

Fig. 7. Variation in monthly brine temperature of first desalination line (without cooling unit) and second desalination line (with cooling unit) for each month of the year.

cooling unit) and the second desalination line (with cooling unit) for each month of the year is shown in Fig. 10.

Fig. 10 shows the improvement in permeate quality when the feed seawater is cooled. The permeate conductivity for the second line is less than that of the first line by an annual percentage of 14.4%. The magnitude of improvement in the performance of the RO plant with respect to HPP surface temperature, HPP power consumption, permeate flow rate and permeate quality is displayed in Figs. 6–10. The results show that improvement magnitude is directly proportional to the magnitude of reduction in feed seawater temperature. However, the attractiveness of the results depends on the financial benefits, which are considered in the following section.

5. Reduction in operational costs

Based on the results presented in the previous sections, the annual electrical energy consumption for the second RO line is less than that of the first line by 7,170 kWh. Based on the USA unit price for electricity of $0.18, the saving in electrical energy is equivalent to about $1,250. In addition, the coupling of the feed water cooling unit to the second desalination line improved the annual production of permeate by 380 m^3 as compared with the first line. This amount is based on a 0.0475 m^3/h mean increase in permeate production over the year 2009 due to the coupling of the feed water cooling unit to the second desalination line, and an 8,000 h increase in annual operational hours. Assuming a unit price for the water of $2.2/m^3 in Hurghada, the equivalent value for the annual increase in second-line production of water is $835. It is well-known that the conductivity of water is a measure of its quality; the lower the conductivity the higher the quality. The conductivity of the second line permeate was better (i.e., lower) than that of the first line over the year 2010 by an average percentage of 14.4%. In other words, lower feed water temperature will reduce operational costs for a specified permeate quality. On the other hand, lower permeate salinity (i.e., conductivity) means slower accumulation of

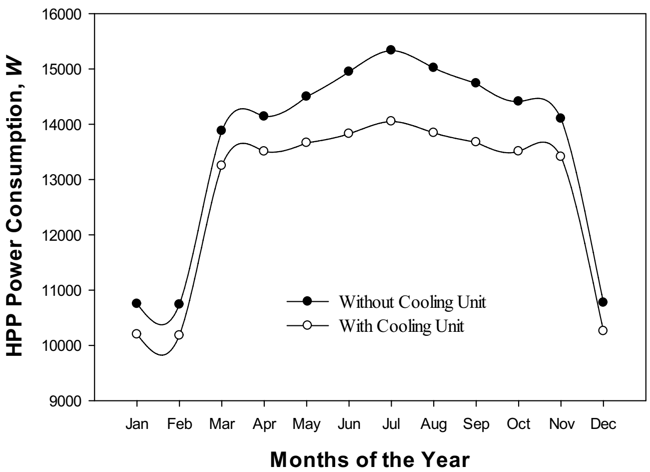

Fig. 8. Variation in monthly HPP power consumption of the first desalination line (without cooling unit) and the second desalination line (with cooling unit) for each month of the year.

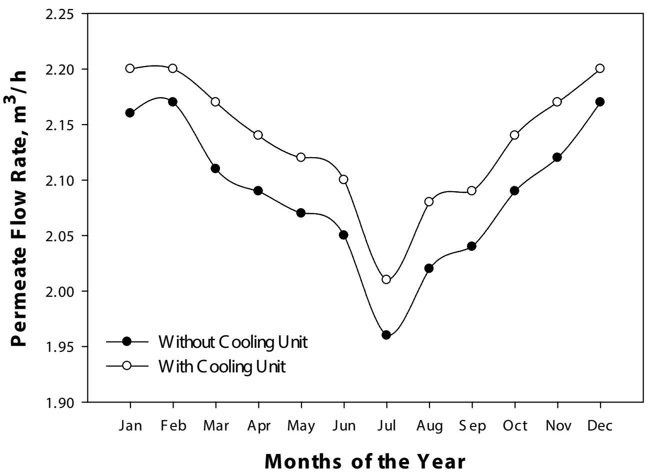

Fig. 9. Variation in monthly permeate flow rate (m^3/h) of the first desalination line (without cooling unit) and the second desalination line (with cooling unit) for each month of the year.

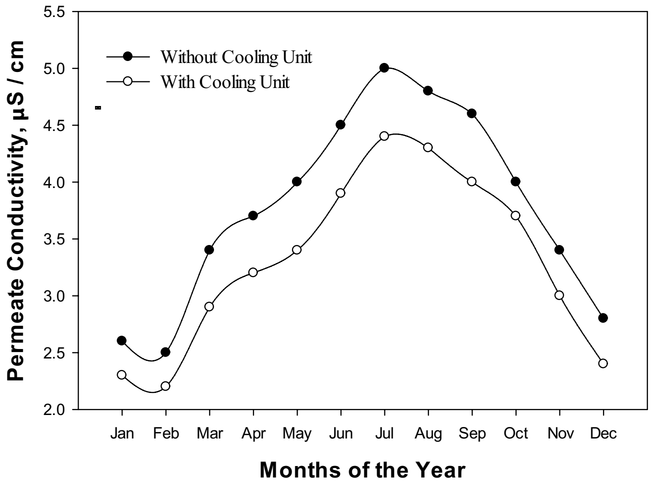

Fig. 10. Variation in monthly permeate conductivity of the first desalination line (without cooling unit) and the second desalination line (with cooling unit) for each months of the year.

salts in the interior layers of membranes, which reduces the frequency with which the membranes need to be chemically cleaned. Besides being costly, chemical cleaning also shortens the working life of membranes. Throughout the test period, the number of chemical washes required for the first and second RO lines was 12 and 9, respectively. That is to say, incorporating a feed water cooler reduced the number of chemical cleans required by 25%. This is equivalent to about $465/y. Overall, the total saving in operational costs due to coupling of the feed seawater cooling unit to the second production line was approximately $2,550 for 1 y.

6. Conclusions

The feed water source for the RO station in the city of Hurghada on the Red Sea Coast of Egypt was shifted from nearby water wells to seawater because the wells started drying and finally collapsed but the temperature and salinity of seawater are higher than those of well water. This increase in the feed seawater temperature and salinity due to ambient conditions and ebb/tide phenomena further worsened the performance of the RO system. From the results of the present study during the first phase, it was concluded that as feed water temperature was increased, water output quality decreased, and pump power consumption increased. Moreover, it was noted that the operational cost arose due to the increased need for chemical washing of membrane, the life expectancy of which was reduced.

In the second phase, an air-water surface heat exchanger (brine cooler) was coupled to the second line of the RO desalination plant whilst the first line of the plant was operated normally without a cooler. The performance of the two lines was measured and compared under normal conditions. The experimental results showed that the feed water cooling unit improved the RO system performance, in particular the productivity rate, power consumption, salinity, permeate quality, and pump surface temperature and lowered its operational costs due to a reduced need for chemical washing for the membrane. The experimental measurements show that the annual mean power consumption, permeate (product fresh water) flow rate, permeate conductivity were improved by 6.7%, 2.3%, and 14.4%, respectively. Overall, the total saving in operational costs due to coupling of the cooling unit to the second line membranes was approximately $2,550 for 1 y.

Symbols

C_p _ Specific heat, kJ/kg, °C.
Q_p _ feed seawater flow rate, m^3/h
T_a _ Ambient temperature, °C
T_{pl} _ Pool temperature, °C
T_s _ Surface temperature, °C
P _ pressure, Pa
W _ power, W

Subscripts

a _ Ambient
HPP _ High pressure pump
p _ Permeate
pl _ Pool

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