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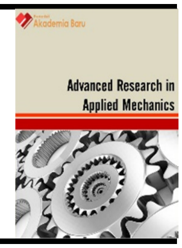

Detailed Sensitivity Analysis of Reverse Osmosis Systems

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H. Yahya[1], S. Shaaban[2,*]

[1] [2] Mechanical Engineering Department, College of Engineering and Technology-Cairo Campus, Arab Academy for Science, Technology and Maritime Transport (AASTMT), Cairo, Egypt

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ABSTRACT

The Reverse osmosis (RO) technique is considered the most promising technique for brackish water and seawater desalination. However, its power consumption is considerably higher than all other techniques. Therefore, the present study focuses on the performance of reverse osmosis plants in hot climate conditions. A typical Reverse osmosis system was designed, constructed and investigated. The ROSA software was also used for the analysis of seven different membrane elements. The experimental data were used in order to validate the simulation results of the ROSA software. A variance-based sensitivity analysis was performed in order to define the most effective operating parameters. The present investigation shows that the tap and brackish water membrane elements are more sensitive to the feed temperature rather than the feed pressure and concentration. Meanwhile, seawater membrane elements are more affected by the feed concentration. The detailed investigation of the different membrane elements shows that wastewater reclamation using reverse osmosis technology could be a significant source of low-cost fresh water for hot climate countries.

1. Introduction

Among the different available techniques, the Reverse Osmosis RO was proved to be the most reliable, cost-effective, and energy efficient in producing fresh water [1]. Therefore, many researchers have developed simulation models for reverse osmosis systems [2-5] in order to investigate and/or optimize their performance. The potential for developing technologies that can help in minimizing the reverse osmosis power consumption has been recently increased due to the global energy crisis and the global warming. Extensive reviews of the achievements in the field of water desalination using renewable energy as well as the factors influencing large-scale seawater desalination plants were presented [6-9].

Water desalination using the reverse osmosis process is a multivariable complex system that requires an insight analysis of the mutual interaction between the different operating and design

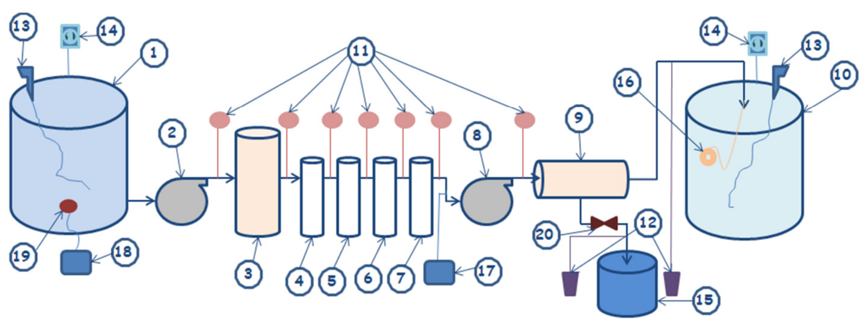
* *Corresponding author.*
E-mail address: Sameh.Shaaban@aast.edu (S. Shaaban)

parameters. The present research work investigates the effect of the feed water temperature on the specific energy consumption of reverse osmosis plants handling brackish or seawater. It also investigates and analyzes the complex and mutual interaction between the feed water temperature and the other operating and design parameters. The objective of the present work is to reduce the specific energy consumption of reverse osmosis plants operating in the hot climate countries.

Another important objective of this research is to define the most cost-effective source of desalinated water for hot climate countries (i.e., reclaiming waste water or desalinating seawater). In order to achieve these objectives, a detailed variance-based sensitivity analysis of seven different membranes was performed. The ROSA software was utilized to estimate the performance of the selected membranes under different operating conditions. One of the selected membranes was experimentally investigated in order to validate the results of the ROSA software.

2. Test Rig Design and Construction

The effect of the different operating parameters on the power consumed by a Reverse osmosis system was experimentally investigated. A simple schematic of the experimental model is shown in Fig. 1.



1. Raw Water Tank
2. Feed Pump
3. Multimedia Filter
4. 5-Micron Cartridge Filter
5. Activated Carbon Cartridge Filter
6. Softner Resign Cartridge Filter
7. 1-Micron Cartridge Filter
8. High Pressure Pump
9. Reverse Osmosis Membrane/Pressure Vessel
10. Product Tank
11. Pressure Gauge
12. Flow Meter
13. Temperature Thermocouple
14. Conductivity/TDS Meter
15. Drain Tank
16. Tank Floater
17. High/Low Pressure Controller
18. Temperature Controller
19. Electric Heater
20. Concentrate Valve

Fig. 1. Simple schematic of the experimental model

The system implements a single stage centrifugal pump operating at a constant pressure of about 2 bar that feeds the saline water from a feed tank to the pretreatment stages. The feed water, depending on its source, may contain various concentrations of suspended solids and dissolved matter. Therefore, five successive pretreatment stages were used in order to prevent membrane contamination, fouling, scaling, and degradation.

Various samples of feed water with a feed concentration ranging from 100 to 2000 ppm were experimentally investigated in the present study. Another single stage centrifugal pump was used as a high-pressure pump operating from 0.6 to 4 bar head and 0.16 to 0.35 m^3/hr flow rate. A FILMTEC™ TW30-4040, housed in a stainless steel pressure vessel that allows taking a full advantage of the membrane, was used to remove dissolved salts from the feed water. An electrical heater of 12V/600 Watt was connected to the insulated feed water tank and a digital temperature controller was utilized to change and/or control the feed water temperature. Measurements of the feed water salt concentration, pressure, flow rate, and temperature as well as the permeate water salt concentration and flow rate should be carried out accurately. Therefore, pressure gauges, thermocouples, flowmeters, and conductivity meters were calibrated and connected to the system in order to study the operating and the performance parameters of the system.

3. Results and Discussion

The present work investigates the specific power consumption of the reverse osmosis plants in hot climate conditions. The specific power consumption can be defined as the power consumed by a reverse osmosis system to produce a specific volume flow rate of water. Therefore, a FILMTEC™ TW30-4040 membrane was experimentally investigated under different values of the feed water concentration, pressure, and temperature. Feed water with salt concentration ranging from 100 ppm to 2000 ppm was supplied at a feed pressure that varies from 2 bar to 6 bar and water temperature between 15°C to 35°C. The system performance parameters were accurately measured under these operating conditions. For validation purposes, the same experimental model was simulated using the software ROSA under the same operating conditions. Comparisons between the measured and the simulated performance are presented in Figures 2-4. The symbols present the measured data while the lines present the simulation results of the ROSA software.

Figure 2 shows that the specific power consumption is inversely proportional to the feed water pressure at constant feed temperature (25°C). This is due to the increase in the permeate flux with increasing the feed water pressure.

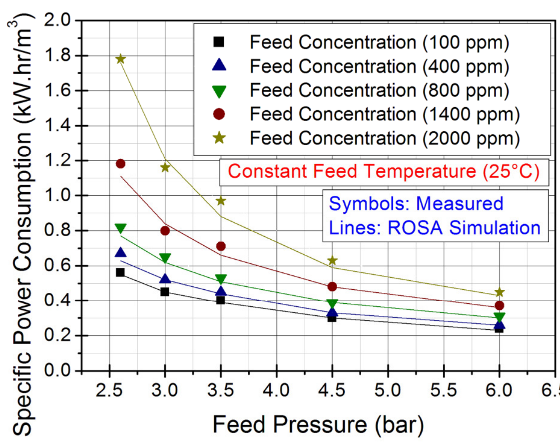


Fig. 2. Effect of pressure and feed concentration on permeate power consumption at constant feed temperature

Figures 3 and 4 show that the specific power consumption is inversely proportional to the feed water temperature at constant feed water concentration (1000 ppm) and directly proportional to the feed water concentration. This because increasing the feed water temperature increases the permeate flux across the membrane. Therefore, the specific power consumption decreases as a result of increasing the permeate flux. Figure 4 shows that, for the same feed water pressure (2.6 bar), increasing the feed water concentration increases the specific power consumption due to the reduction of the permeate flux across the membrane.

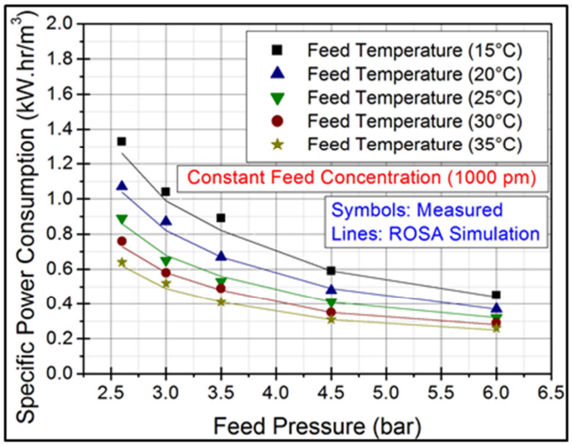


Fig. 3. Effect of pressure and temperature on permeate power consumption at constant feed concentration

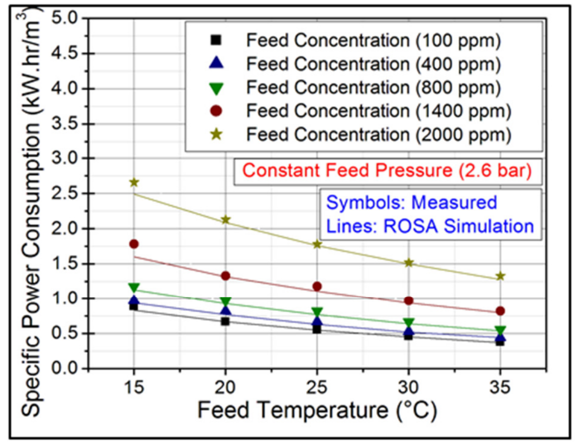


Fig. 4. Effect of temperature and feed concentration on permeate power consumption at constant feed pressure

The experimental results show good qualitative and quantitative agreement with the simulation results of the ROSA software. Therefore, the simulation model was validated and other types of membranes will be simulated using the ROSA software rather than being experimentally investigated. The experimental results highlighted a significant effect of the feed water temperature on the specific power consumption. This effect is mutually interacting with other operating parameters like the feed water pressure and salt concentration. Moreover, the membrane type could also be a significant parameter. Therefore, a variance-based sensitivity analysis was carried out in order to obtain a clear vision of the most significant parameters that affect the specific power consumption of reverse osmosis systems.

The specific power consumption (SPC) can be considered as a function of the input parameters (i.e., feed concentration C_f, pressure p, and temperature T). This function can be written as follows. [**Error! Reference source not found.**]

$$SPC = f(C_f, p, T) \tag{1}$$

The input parameters (i.e., feed concentration C_f, pressure p, and temperature T) are considered independent of each other, therefore the total effect index for each independent parameter can be obtained from the following equations

$$S_T(SPC)_P = 1 - \frac{V(SPC){\sim}P}{V(SPC)} \tag{2}$$

$$S_T(SPC)_T = 1 - \frac{V(SPC){\sim}T}{V(SPC)} \tag{3}$$

$$S_T(SPC)_{CF} = 1 - \frac{V(SPC){\sim}CF}{V(SPC)} \tag{4}$$

The variance-based sensitivity analysis was carried out for seven different samples of membranes. The validated ROSA simulation model was used in order to estimate the performance of these membrane elements under different operating conditions. Table 1 summarizes the main performance attributes of the investigated membrane elements. Figures 5-7 introduce the total effect index of the feed pressure, temperature and concentration on the system specific power consumption.

Table 1
Specifications of the investigated membrane elements

Element	Water type	Performance attributes
XLE-440	Brackish	Low Energy - Low Salt Rejection -High Productivity
BW30-400	Brackish	High Energy - High Productivity
TW30-4040	tap	High Energy - Low Productivity
SW30-4040	Sea	High Energy - Low Salt Rejection -Low Productivity
SW30HR-380	Sea	High Energy - High Salt Rejection
SW30HRLE-400i	Sea	Low Energy - High Salt Rejection
SW30XLE-400i	Sea	Low Energy - High Salt Rejection -High Productivity

Figure 5 demonstrates that the total effect index of the feed pressure on the specific power consumption $S_T(SPC)_P$ for brackish water membrane elements is greater than that of the tap and the seawater membrane elements. The specific power consumption of the tap water membrane element is slightly less sensitive to the feed pressure compared to the seawater membrane elements. The extra low energy membrane has the lowest sensitivity to the feed pressure. The specific power consumption of the tap and brackish water membrane elements is much sensitive to the feed temperature compared to the seawater membrane elements as shown in Figure 6. This highlights the feasibility of wastewater reclamation at low cost for hot climate countries using the reverse osmosis technology. Figure 7 shows that the total effect index of the feed concentration on the specific power consumption $S_T(SPC)_{CF}$ for the seawater membrane elements is greater than those of the tap and brackish water membrane elements. Therefore, the specific power consumption of reclaiming wastewater in hot climate conditions will be much lower than that of desalinating the seawater.

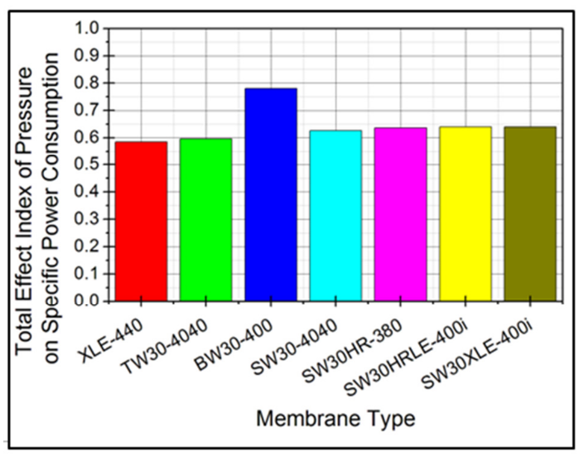


Fig. 5. Total effect index of the feed pressure on the specific power consumption

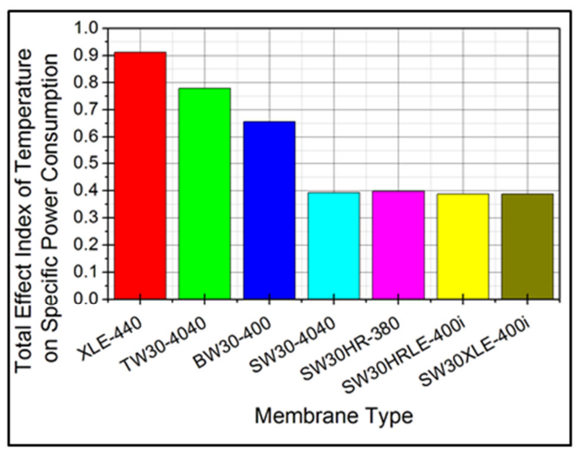


Fig. 6. Total effect index of the feed Temperature on the specific power consumption

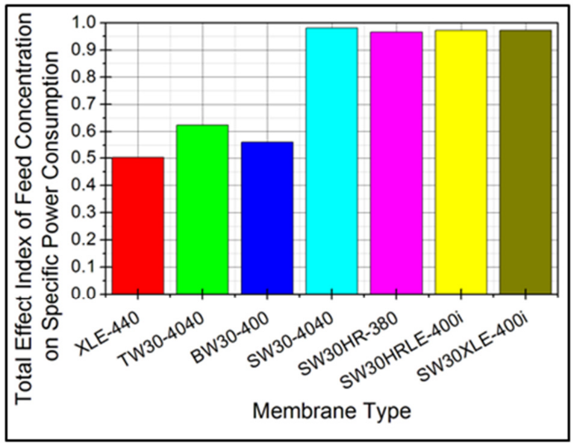


Fig. 7. Total Feed Concentration Effect Index on Specific Power Consumption

The above analysis shows that all operating conditions significantly affect the performance of reverse osmosis plants. The present study showed clearly that there is a high potential for reducing the specific power consumption of reverse osmosis plants operating in hot climate conditions. The specific power consumption of the tap and brackish membrane elements is more sensitive to the feed water temperature. Therefore, wastewater reclamation could present a cost-effective solution for hot climate countries.

4. Conclusion

The present study thoroughly investigated the effect of the different operating parameters on the performance of reverse osmosis systems with different membrane elements. It focuses on the specific power consumption of the different membrane elements. Special attention was paid to the effect of the feed water temperature. This is because hot climate countries need more desalinated water compared to other countries. A variance-based sensitivity analysis was implemented for seven different samples of membranes. The investigated membrane elements are suitable for tap, brackish, and seawater. The following conclusions can be drawn:

a. The feed temperature has a significant effect on the salt rejection of all membrane types. The temperature effect is convergent for the tap, brackish, and seawater membrane elements.
b. The specific power consumption of the tap and brackish water membrane elements is significantly sensitive to the feed water temperature. The feed pressure and concentration have convergent effects on the specific power consumption of the tap and brackish water membrane elements. Therefore, the present study highlights the wastewater reclamation using reverse osmosis technique as an important source of fresh water in hot climate conditions from both the permeate flux and the specific power consumption points of view.
c. The specific power consumption of the seawater membrane elements is more dependent on the feed concentration compared to the feed pressure. It also clearly depends on the feed temperature. Therefore, reverse osmosis plants operating in hot climate conditions can perform better than those operating in low-temperature conditions.
d. In general, wastewater reclamation could be a more cost-effective solution for hot climate countries compared to the seawater desalination. A full economic study of the wastewater reclamation in hot climate conditions is recommended for future work.

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