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Detailed analysis of reverse osmosis systems in hot climate conditions

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ABSTRACT

Hot climate countries require large amounts of desalinated water. The Reverse osmosis (RO) technique is currently considered the most reliable technique for brackish water and seawater desalination. However, its power consumption is considerably higher than all other techniques. Therefore, the present study investigates 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 utilized 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 design and operating parameters. The present investigation shows that the tap and brackish water membrane elements are more sensitive to the feed water temperature rather than the feed water 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

Fresh water can be obtained in unlimited quantity by desalinating the seawater. 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]. A major disadvantage of the reverse osmosis system is its high energy demand. Therefore, many researchers have developed simulation models for reverse osmosis systems [e.g., [2–8] 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. Gelsler et al. [9] presented an energy recovery unit that implements a pressure exchange system in order to achieve considerably lower energy consumption in comparison to the conventional systems. Powering the reverse osmosis plants using renewable energy resources could significantly reduce the cost of energy. Extensive reviews of the renewable energy application in water desalination, as well as the factors influencing large-scale seawater desalination plants, were presented in Ref. [10–16]. Laborde et al. [17] presented an optimization case study for a small-scale reverse osmosis system powered by solar energy. They showed that the membrane type, area, and configuration as well as the recovery rate, and the high-pressure unit efficiency crucially affect the energy consumption. Guria et al. [18] introduced a multi-objective optimization study using the Genetic Algorithm (GA) for the desalination of seawater and brackish water using spiral wound or tubular modules. They found the membrane area to be the most important design parameter in the desalination of brackish water and seawater using spiral wound modules. Poullikkas et al. [19] developed an optimization model using a genetic algorithm for the production cost of water desalination using photovoltaics (PV). Khayet et al. [20] develop predictive models for the simulation and the optimization of reverse osmosis desalination processes. Fadaee and Radzi [21] reviewed the applied multi-objective methods that can be used for the hybrid renewable energy systems. Fraidenraich et al. [22] presented a theoretical study of the specific energy consumption of reverse osmosis devices. El-Ghonemy [23] tested a small-scale reverse osmosis system and compared his results with other available data. Vince et al. [24] developed an optimization technique for the design of reverse osmosis processes using a multi-objective optimization approach. They found that the investment cost and the operating and maintenance cost remain approximately constant for the optimal configurations. Meanwhile, the cost variations result from the influence of the operating conditions on the energy cost and the membrane replacement cost. Tzen et al. [25] presented an autonomous hybrid seawater desalination reverse osmosis system that uses the wind and solar energies. They proved that the matching of the two renewable energy resources is a feasible alternative solution for the system optimization. Bourouni et al.

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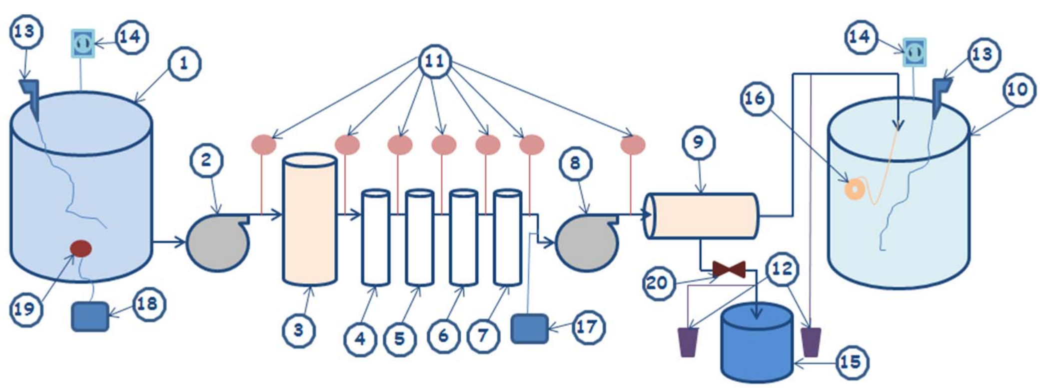
List of symbols

Q_p	Permeate flux (l/m^2 hr)
R	Salt rejection (%)
SPC	Specific power consumption (kW hr./m^3)
C_f	Feed concentration (ppm)
C_p	Permeate concentration (ppm)
p	Feed pressure (bar)
T	Feed temperature (°C)
$S_T(\phi_p)_p$	Total effect index of the feed pressure on the permeate flux (−)
$S_T(Q_p)_T$	Total effect index of the feed temperature on the permeate flux (−)
$S_T(Q_p)_{CF}$	Total effect index of the feed concentration on the permeate flux (−)
$V(Q_p)\sim p$	Variance of the permeate flux at constant feed pressure (l/m^2 hr)
$V(Q_p)\sim T$	Variance of the permeate flux at constant feed temperature (l/m^2 hr)
$V(Q_p)\sim CF$	Variance of the permeate flux at constant feed concentration (l/m^2 hr)
$V(Q_p)$	Total variance of the permeate flux (l/m^2 hr)
$S_T(R)_p$	Total effect index of the feed pressure on the salt rejection (−)
$S_T(R)_T$	Total effect index of the feed temperature on the salt rejection (−)
$S_T(R)_{CF}$	Total effect index of the feed concentration on the salt rejection (−)
$V(R)\sim p$	Variance of the salt rejection at constant feed pressure (%)
$V(R)\sim T$	Variance of the salt rejection at constant feed temperature (%)
$V(R)\sim CF$	Variance of the salt rejection at constant feed concentration (%)
V(R)	Total variance of the salt rejection (%)
$S_T(SPC)_p$	Total effect index of the feed pressure on the specific power consumption (−)
$S_T(SPC)_T$	Total effect index of the feed temperature on the specific power consumption (−)
$S_T(SPC)_{CF}$	Total effect index of the feed concentration on the specific power consumption (−)
$V(SPC)\sim p$	Variance of the specific power consumption at constant feed pressure (kW hr./m^3)
$V(SPC)\sim T$	Variance of the specific power consumption at constant feed temperature (kW hr./m^3)
$V(SPC)\sim CF$	Variance of the specific power consumption at constant feed concentration (kW hr./m^3)
V(SPC)	Total variance of the specific power consumption (kW hr./m^3)

[26] presented a model based on the genetic algorithm for the coupling of a small reverse osmosis unit to different renewable energy systems. Li et al. [27] validated a previously developed optimization methodology in an industrial brackish water reverse osmosis desalination plant. They reported that a 10% reduction in the pump energy consumption was achieved when the recovery was increased from 80% to 90%. This study clearly proved the effectiveness of the model-based optimization in reverse osmosis plants operation. Sassi and Mujtaba [28] presented steady state performance predictions and optimization of the reverse osmosis process using a set of implicit mathematical equations. They achieved up to 50% reduction in the operating costs and the energy consumption using a pressure exchanger as an energy recovery device.

Water desalination using the reverse osmosis process is a multi-variable complex system that requires an insight analysis of the mutual interaction between the different operating and design parameters. Hot climate countries, like Egypt and the other Arabic countries, need high quantities of desalinated water. This significantly increases the energy demand of these countries relative to the power supply and thereby affects the development of other sectors. Therefore, it is crucial to reduce the specific energy consumption of their reverse osmosis plants. The use of PV panels is not feasible for most Arabic countries due to the very high ambient temperature and the suspended dust from the desert. The wind energy is feasible for power generation at limited places. Therefore, practical solutions for the Arabic countries require an



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.