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FULL LENGTH ARTICLE

Desalination of Red Sea water using both electrodialysis and reverse osmosis as complementary methods

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Abstract Desalination process separates nearly salt free water from sea or brackish water. So, desalination process is becoming a solution for water scarcity all over the world. Two membrane methods of water desalination namely electrodialysis (ED) and reverse osmosis (RO) are used in this study as complementary methods. The results show that both ED and RO can be used as integrated system. This system is economic and cost effective compared with each individual method provided using the ED system before the RO. In this study, it was approved that seawater can be used as it is an electrolyte. TDS of Red Sea water was decreased from 42070 ppm to 2177 ppm achieving 94.8% removal efficiency using ED for half of its optimum time. Total removal efficiency of 99.4% can be obtained using the combined system of ED and RO.

1. Introduction

In this century, the most crucial problem afflicting people around the world is global water scarcity. The rapid growth in population has resulted in greater demand on the quantity of drinking water, leading to catastrophic water shortage in arid and water-stressed region areas [1]. It is projected that by year 2030, the global needs of water would increase to 6900 billion m^3 from the current 4500 billion m^3 [2]. So, about 53% increase in the amount of drinking water is needed by year 2030. Consequently, the present surface water resources will no longer be sufficient to meet the future needs for mankind.

With the fact that only around 0.8% of the total earth's water is fresh water [3]. The global installed desalination capacity by water sources and the use of seawater as feed brine have contributed more than half of the total capacity produced worldwide [4]. Desalination is necessary in arid countries [2] and in cases where good-quality water is required for industrial purposes and fresh water is not available [5].

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Membrane based processes include reverse osmosis (RO), membrane distillation (MD) and electrodialysis (ED) [6]. For the treatment of brackish groundwater, electrodialysis or electrodialysis reversal is robust against scaling problems [7,8] and they can effectively remove disinfection byproduct precursors, such as bromide and organic matter [9]. The most important industrial application of ED is the production of drinking water from brackish water and seawater as well as demineralization of solutions of widely varying industrial fluids encountered in the food, chemical and pharmaceutical industries [10,11].

During the past 30 years, reverse osmosis (RO) is increasingly used in seawater and brackish water desalination, water treatment and wastewater reclamation due to the superior and stable quality of the water produced and the relatively low cost [12].

In this study, the desalination process was carried out using both the electrodialysis and reverse osmosis as complementary methods to avoid their disadvantages. Electrodialysis process was applied firstly followed by reverse osmosis.

2. Experimental

2.1. Materials and methods

2.1.1. Electrodialysis system

Electrodialysis system contains three compartments, compartment 1 contains 2 L untreated water (dilute), compartment 2 contains 2.5 L Na_2SO_4 solution of known concentration or water used as electrode rinse (electrolyte) and compartment 3 contains 2 L distilled water, tab water or sea water (concentrate). Under the influence of direct current, ions in the input source (dilute) migrate toward the anode. They leave the dilute compartment, move through the anion exchange membrane and stop by the cation exchange membrane in the concentrate compartment. This circulation of water was assured by pumps. Table 1 shows the specifications and operation conditions of electrodialysis unit. For electrodialysis operation, 2 L from the feed water source of ED system is placed in the dilute compartment for the desired electrodialysis time interval at the required potential difference. The variables which are studied are potential difference, concentration of electrolyte and electrodialysis time. During the test, water samples are taken periodically from dilute and concentrate streams at the desired electrodialysis time and the total dissolved solids (TDS) and salinity were measured.

2.1.2. Reverse osmosis system

Specifications of the high pressure pump of the RO system are given below:

Diaphragm pump YZY-800-A2

Volts	24 VDC	Working pressure	70 PSI
Amps	0.8 A	Working flow	800 ml
In pressure	28 PSI	Open flow	2000 ml

Membranes: FILMTEC™ TW30-2514 Small Commercial Elements with the following specifications:

Membrane type: Polyamide thin-film composite	
Active area (m^2): 0.7	Applied pressure (bar): 15.5
Stabilized salt rejection (%): 99.5	Permeate flow rate (m^3/d): 0.7

2.1.3. Analytical methods

pH, conductivity and salinity were measured using pH meter WTW Inc. Lab pH 730.

Total dissolved salts were measured by TDS Meter (HO 14D).

Hardness and alkalinity were determined by the titration method according to Standard Methods for the Examination of the Water and Wastewater 20th edition, 1999.

Calcium and Magnesium were measured by titration with EDTA and the procedure was applied according to VOGEL's textbook of quantitative chemical analysis, fifth edition, 1989.

Chlorides were determined using silver nitrate (Mohr Method) according to VOGEL's textbook of quantitative chemical analysis, fifth edition, 1989.

Sodium element was analyzed using atomic absorption spectrophotometer (AA-6600) SHIMADZU.

Potassium, Sulfate, Ammonium, Nitrate, Nitrite, Silica, Iron, Manganese were analyzed by spectrophotometer DR 2000 Hach Company.

2.1.4. Calculations

R is the TDS removal efficiency in %. R is defined as the following equation:

$$R = C_i - C_f \div C_i \times 100\%$$

where C_i and C_f are initial and final TDS concentration of the concentrated solution, respectively in ppm.

2.2. Procedure

The electrodialysis (ED) system was applied before the reverse osmosis (RO). During the test time (1 h), samples were taken every 10 min for measuring of salinity and total dissolved solids.

Table 1 Specifications and operation conditions of electrodialysis unit.

Ion exchange membrane (NEOSPTA-TOKUYAMA SODA)			
Cationic membrane	CMX Sb 12	Anionic membrane	AMX Sb 10
Effective area	2 dm	Anode	Ti/Pt
Cathode	Stainless steel	Dilute compartment	180 L/H
Concentrate compartment	180 L/H	Electrode chamber Anode	150 L/H
Electrode chamber Cathode	50 L/H	Current	10 a Max
Voltage			1 V/Cell Max

3. Results and discussion

3.1. Red Sea water specifications

Red Sea water specifications are given in Table 2.

3.2. Effect of applied voltage

The applied cell voltage is a critical operating condition in electrodialysis processes as the voltage determines the current in the cell and hence the desalination efficiency as well as energy consumption.

A series of experiments were carried out using different applied voltages from 6 V to 18 V to follow salinity and TDS with time. The achieved results are given in Figs. 1 and 2. These results reveal that the salinity decreases to less than 10% after 30 min using applied voltage from 12 V to 18 V. Similarly, the TDS decreases to less than 1000 TDS under the same conditions.

3.3. Effect of electrolyte concentration

A series of experiments were carried out using different sodium sulfate concentrations (as an electrolyte) from 0.1 M to 0.7 M to follow the salinity and TDS with time. The achieved results are given in Figs. 3 and 4. These results reveal that the lower salinity and lower TDS are achieved at electrolyte concentration ranging between 0.5 M and 0.7 M). The salinity is less than 10% and TDS less than 1000 ppm. So, 0.5 M electrolyte concentration is selected as optimum electrolyte concentration.

3.4. Effect of electrolyte type

A series of experiments were carried out using different electrolyte types (sodium sulfate, sodium chloride and sodium nitrate) of 0.5 M concentration to follow the salinity and TDS with time. The achieved results are given in Figs. 5 and 6. These results reveal that the lowest salinity and lower TDS are achieved with sodium sulfate electrolyte. The other two electrolytes gave near results. NaCl electrolyte gives the lowest removal efficiency.

In addition, Table 3 shows the chemical analysis of water produced from ED system after 30 min. This product is fed to RO system for further desalination.

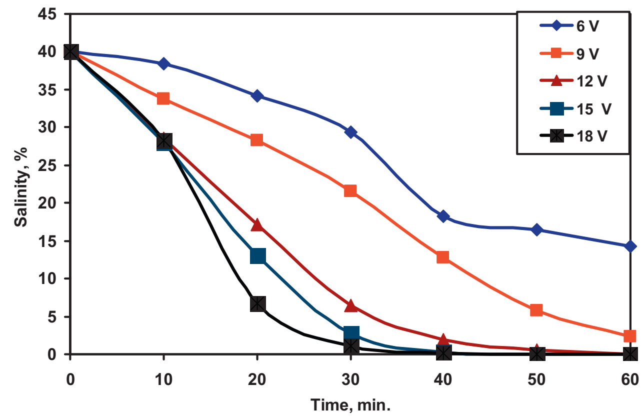

Figure 1 Effect of time on salinity at different applied voltages.

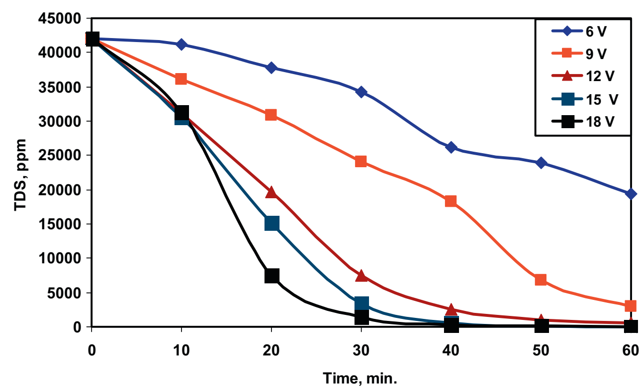

Figure 2 Effect of time on TDS at different applied voltages.

3.5. The (RO) system

The results were taken after many experiments done to reach less amount of water rejected and the major produced, and this can be made because the entered water was low in the TDS. This can also be made by using garrote to control the amount of water rejected or filtrate through the membranes and also this affects the TDS of the water. So the results shown in Table 3 were total chemical tests for the final produced water. It was found from the experiments that if the water, which would enter to the RO system, was low in TDS, we can adjust

Table 2 Red Sea water specifications.

Item	Value	Item	Value
pH	7.7	Chloride (Cl^-) (ppm)	23,607
Conductivity (Ms/cm)	60.3	Sulfate ($SO_4^=$) (ppm)	1260
Total hardness as ($CaCO_3$) (ppm)	8375	Total alkalinity as ($CaCO_3$) (ppm)	98
Ammonium (NH_4^+) (ppm)	0.39	Silica (SiO_2^-) (ppm)	9.72
Calcium (Ca^{++}) (ppm)	738	Nitrate (NO_3^-) (ppm)	12.4
Magnesium (Mg^{++}) (ppm)	1570	Nitrite (N^-) (ppm)	0.41
Iron (Fe^{++}) (ppm)	0.58	Manganese (Mn^{++}) (ppm)	0.35
Bicarbonate alkalinity as ($CaCO_3$) (ppm)	98	Carbonate alkalinity as ($CaCO_3$) (ppm)	0
Hydroxide alkalinity as ($CaCO_3$) (ppm)	0	Total dissolved salts (TDS) (ppm)	42,070
Sodium (Na^+) (ppm)	12,339	Salinity (%)	40.6
Potassium (K^+) (ppm)	287		

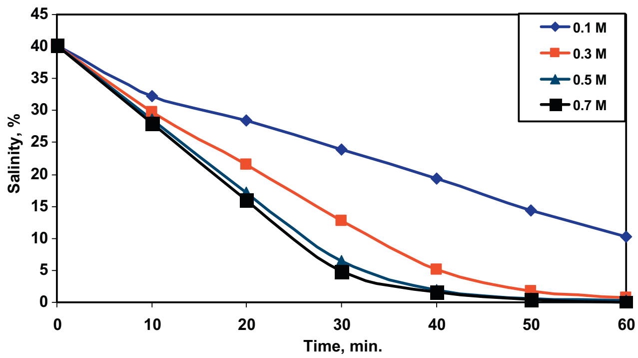

Figure 3 Effect of time on salinity at different Na_2SO_4 electrolyte concentrations.

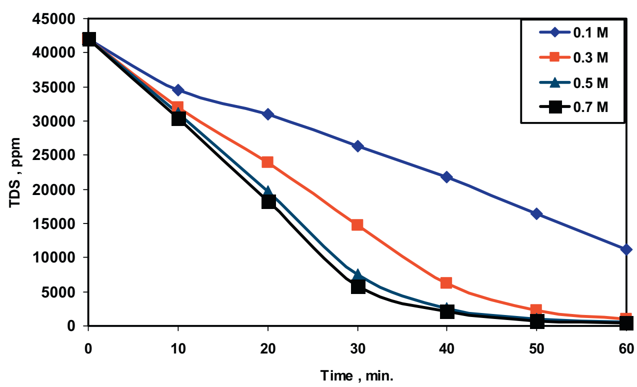

Figure 4 Effect of time on TDS at different Na_2SO_4 electrolyte concentrations.

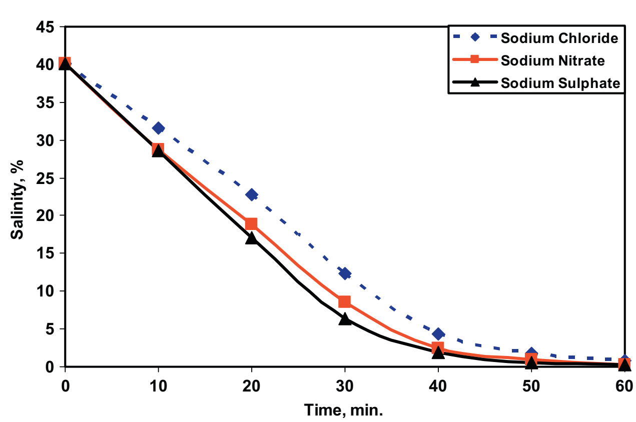

Figure 5 Effect of time on salinity at different electrolyte types.

the system so that we can break the usual results of the system by half of the entered amount rejected and gain more produced water by two thirds or more and the rejected can be a third or less according to the TDS of the entered water. The produced amount from ED system was 1520 ml, and by using garrote the amount of the produced water from RO was 1450 ml and this gives the ratio of loosing water = 12.12%.

From Table 4 the recovery ratio reaches 99% for almost all the essential elements. Also, the table reveals the presence of the important elements in the drinking water.

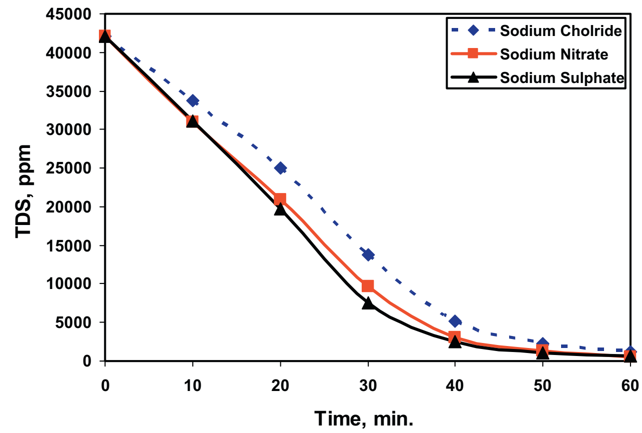

Figure 6 Effect of time on TDS at different electrolyte types.

Table 3 Chemical analysis for ED produced water after 30 min.

TDS	2177 ppm
Cl^-	1367 ppm
$SO_4^{=}$	10 ppm
Salinity	3.8%
Conductivity	6.89 Ms/cm

Table 4 Chemical analysis for final produced water.

Elements to be analyzed (Units)	Results	Recovery ratio (%)
pH	7.38	–
Conductivity (Ms/cm)	0.465	–
Total hardness as ($CaCO_3$) (ppm)	23	99.7
Calcium (Ca^{++}) (ppm)	2.5	99.6
Magnesium (Mg^{++}) (ppm)	4.03	99.7
Total alkalinity as ($CaCO_3$) (ppm)	11.5	–
Bicarbonate alkalinity as ($CaCO_3$) (ppm)	11.5	–
Carbonate alkalinity as ($CaCO_3$) (ppm)	0	–
Hydroxide alkalinity as ($CaCO_3$) (ppm)	0	–
Sodium (Na^+) (ppm)	113	99
Potassium (K^+) (ppm)	2.9	98.9
Chloride (Cl^-) (ppm)	108	99.5
Sulfate ($SO_4^{=}$) (ppm)	2.3	99.8
Ammonium (NH_4^+) (ppm)	0.01	97.4
Nitrate (NO_3^-) (ppm)	2.81	77.4
Nitrite (N^-) (ppm)	0.003	99.2
Silica (SiO_2^-) (ppm)	0.12	98.7
Iron (Fe^{++}) (ppm)	0.04	93.1
Manganese (Mn^{++}) (ppm)	0.01	97.1
Total dissolved salts (ppm)	243	99.4
Salinity (%)	0.0	100

4. Conclusion

The results of this study show that electrodialysis is capable of being used to desalinate brackish water as well as water with higher salt concentration. The total dissolved salts can reach 45,000 ppm with a salinity 40% without expensive methods of pretreatment. The results showed that as the salts increase in the electrolyte the transfer of ions increases. Also, it can be used in integrated system before RO system to play the role of pretreatment and to decrease the high salinity of the feed water, and by this with using the RO system we can produce more water than usual with low amount in the rejected water which also is low in salinity.

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