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Sea water desalination using electrodialysis

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Abstract

Most widely applied and commercially proven desalination technologies fall into two categories of thermal (evaporative) and membrane based methods. Membrane methods are less energy intensive than thermal methods and since energy consumption directly affects the cost-effectiveness and feasibility of using desalination technologies membrane methods such as reverse osmosis (RO) and electrodialysis (ED), are attracted great attention lately. In this paper water desalination using a laboratory ED setup was described and evaluated. Taguchi method was initially used to plan a minimum number of experiments. A L_9 orthogonal array (four factors in three levels) was employed to evaluate effects of temperature (at 25, 40, and 55°C), voltage (at 5, 7, and 9 V), flow rate (at 0.07, 0.13, and 0.25 mL/s) and feed concentration (at 10,000, 20,000, and 40,000 ppm) on separation percentage of salt ions. Maximum percentage of desalination was obtained at the lowest feed concentration and flow rate levels (10,000 ppm and 0.07 mL/s, respectively) and the highest voltage and temperature levels (9 V and 55°C, respectively). Analysis of variance (ANOVA) was applied to calculate sum of square, variance, ratio of factor variance to error variance and contribution percentage of each factor on response. The results showed that all factors have significant effect on the response. It was found that, feed concentration is the most influential factor on ED performance (its contribution percentage was calculated to be 82.4%). It was finally found that, contrary to the case of waste water treatment (concentrations of lower than 1000 ppm) which flow rate is the influential factor, in desalination of sea water (concentrations of upper than 10,000 ppm) feed concentration is the key parameter.

Keywords: Sea water; Desalination; Electrodialysis; Experimental design; Taguchi; ANOVA

1. Introduction

Desalination is a process that removes dissolved minerals from seawater, brackish water, or treated wastewater. About 71% of the earth surface is covered by water which is in the form of the oceans, seas and the ices in the poles. However, only about 3% of water is fresh and suitable for drinking. The water of the oceans and seas is salty and thus not directly utilizable. Therefore, some special processes are needed to desalinate these waters [1].

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Suitable desalinating methods for water treatment of seawater can be effective to overcome the water shortage. Electrodialysis (ED) is one of these methods which has been used for many years. ED is an electrochemical process for the separation of ions across charged membranes from one solution to another under the influence of an electrical potential difference used as a driving force. This process has been widely used for production of drinking and process water from brackish water and seawater, treatment of industrial effluents, recovery of useful materials from effluents and salt production. The basic principles of ED have been reviewed in the literature [2].

In a typical ED cell, a series of anion and cation exchange membranes are arranged in an alternating pattern between an anode and a cathode to form individual cells. When a DC potential is applied between two electrodes, positively charged cations move toward the cathode, pass through the negatively charged cation exchange membrane and are retained by the positively charged anion-exchange membrane. On the other hand, negatively charged anions move toward the anode, pass through the positively charged anion exchange membrane and are retained by the negatively charged cation exchange membrane. At the end, ion concentration increases in alternate compartments with a simultaneous decrease of ion concentration in other compartments. A schematic view of an ED cell is presented in Fig. 1.

Experiments were conducted using Taguchi experimental design. Taguchi approach developed rules to carry out experiments, which further simplify and standardize the experiment design. In Taguchi method, the results of experiments are analyzed to achieve the following objectives: (1) to find the best or optimal condition for the product or process, (2) to identify the contribution of individual factors and (3) to estimate the response under optimal conditions. A commonly applied statistical treatment, analysis of variance (ANOVA), was also used to analyze the results of experiments and to determine how much

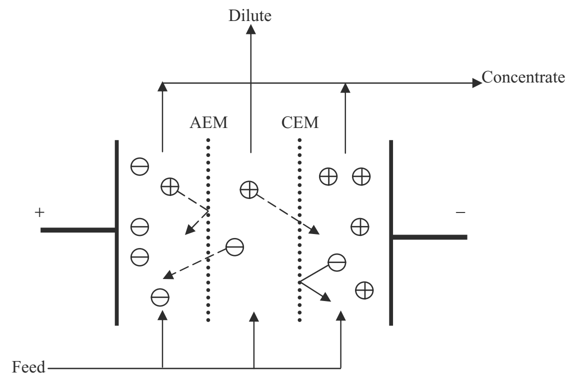

Fig. 1. Schematic view of an ED cell.

variation each factor contributes. By studying the main effects of each factor, the general trends of the influencing factors, can be characterized. In this study, The effect of different operating conditions in water treatment of seawater by an experimental ED cell was studied.

2. Materials & method

2.1. ED setup

The ED setup consists of a feed tank (TK-01) where waste water is stored, two pumps (P-01 and P-02, RESUN submersible pump, $P = 4\,W$, total head = 0.5 m), a rectifier (DC-01, RST SPASTELL TRF LSF 0.1) and two globe valves (GB-01 and GB-02) to control feed flow rate in the three compartments of a self designed ED cell [3,4]. Fig. 2 shows a simplified diagram of the ED setup.

2.2. Cell and membranes

ED cell is packed with a pair of ion exchange membranes (cation and anion) and a pair of platinum electrodes (anode and cathode). Both electrodes are made of pure platinum. Area of each electrode is $4.2 \times 4.2\ mm^2$. Thickness of dilution cell (center) is 4 mm and thickness of

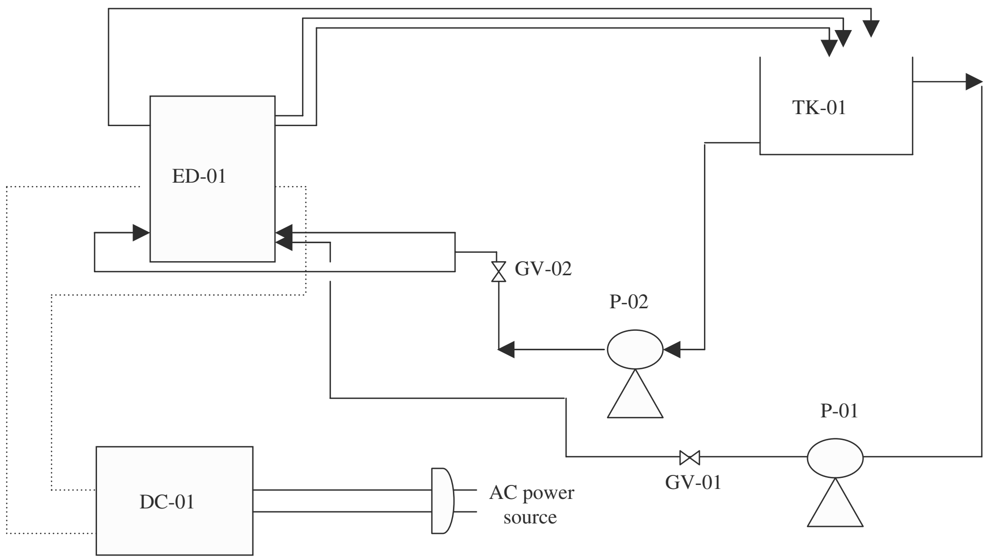

Fig. 2. A simplified diagram of an ED cell.

each concentrate cell (left and right) is 3 mm. AR204SXR412 and CR67, MK111 anion and cation exchange membranes supplied by Arak petrochemical complex and made by Ionics incorporated were used in all experiments. Effective area of each membrane is 60×65 mm^2. IEC values of anion and cation exchange membranes are 2.8 and 2.4 meq/g dry membrane, respectively.

2.3. Materials

An analytical grade salt (sodium chloride supplied by Merck) was used in all experiments to produce solutions with sea water qualities. The purpose of these experiments was to study the effects of voltage, flow rate, temperature and feed concentration on ED cell performance.

2.4. Analytical method

Concentration of cations (Na^+) only in the dilute compartment was measured at various operating conditions. In all experiments, a conductometer (Hanna, model HI 8633, Portugal) was used to measure the amount of salt in water. Water conductivity directly depends on its salt content. This dependency (calibration curve of the conductometer) is shown in Fig. 3.

2.5. Experiment and analysis methods

Two statistical techniques including Taguchi method and ANOVA were chosen for this study. Taguchi method utilizes OA's from experimental design theory to study a large number of variables with a small number of experiments. OA's are subsets of the full factorial experiment which is balanced, i.e., each variable setting occurs the

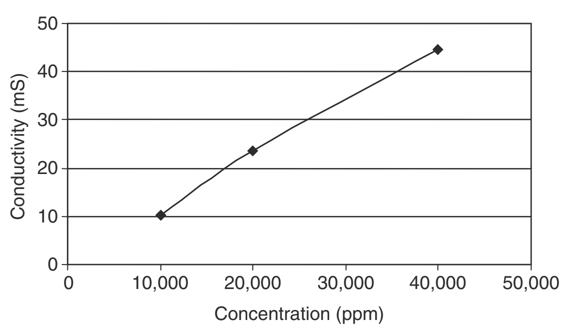

Fig. 3. Calibration curve of the conductometer.

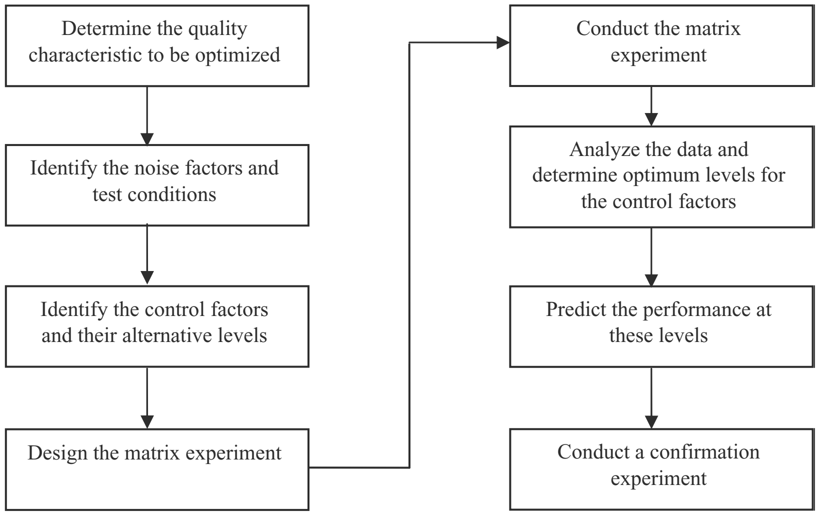

Fig. 4. Flowchart of Taguchi method.

same number of times and none of two experiments are the same (or even mirror images). Using OA's significantly reduces the number of experimental configurations to be studied. OA's were originally discovered by Tippett in 1934. However, Taguchi simplified their use by providing tabulated sets of standard OA's and corresponding linear graphs to fit specific projects [5,6]. A brief overview of the process followed by Taguchi approach to parameter design is provided in Fig. 4.

In this study, the quality characteristic was SP which was calculated as follows:

$$SP = (C_0 - C)/C_0 \times 100 \quad (1)$$

where, C_0 and C are feed and dilute concentrations, respectively.

Noise factors were room temperature, pH variation in the cell, occurring electrolysis on the electrodes, concentration polarization and voltage variation.

Four factors each with three levels (low, medium and high) were chosen based on previous results in related works and qualitative experiments [3,4]. The matrix experiment was designed by selecting an appropriate OA (L_9 array) for control parameters. Controllable factors and their levels in the L_9 array are presented in Table 1.

3. Results and discussion

The matrix experiment was conducted under the limiting current density and the results for all levels of factors are illustrated in Figs. 5–10. The usual approach is to examine the graphs and

Table 1
Controllable factors and their levels

Run	Controllable factors			
	C (ppm)	T (°C)	V (V)	F (mL/s)
1	10,000	25	5	0.07
2	10,000	40	7	0.13
3	10,000	55	9	0.22
4	20,000	25	7	0.22
5	20,000	40	9	0.07
6	20,000	55	5	0.13
7	40,000	25	9	0.13
8	40,000	40	5	0.22
9	40,000	55	7	0.07

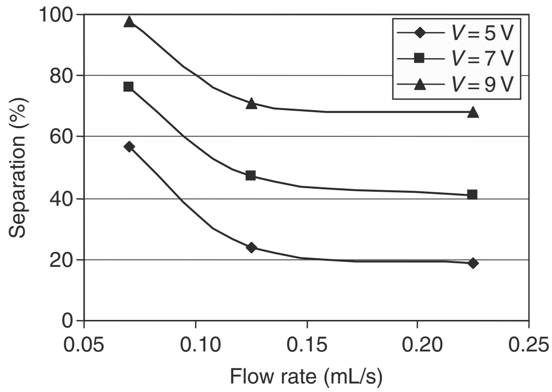

Fig. 5. Effect of flow rate on separation percent at different voltages.

pick the winner. In Figs. 5–7 the effects of flow rate on separation percent at different voltages, temperatures and feed concentrations are illustrated.

Effect of operating conditions on separation percent of Na^+ ions, is similar to what reported in previous works [7,8]. It was verified that, temperature and voltage are directly proportional to separation percent, while increasing flow rate and feed concentration decreases separation percent. Hence, in the case of higher temperatures and voltages, electrical resistance of the feed solution decreases and subsequently ED separation

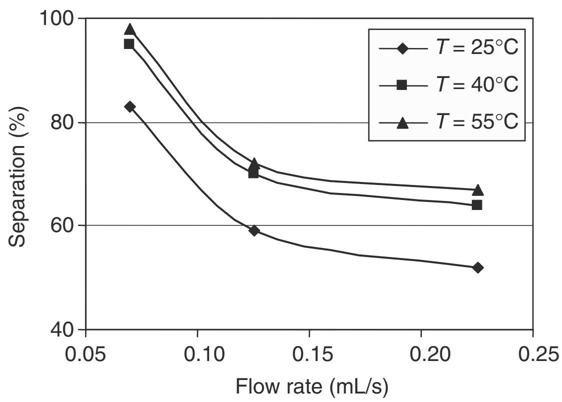

Fig. 6. Effect of flow rate on separation percent at different temperatures.

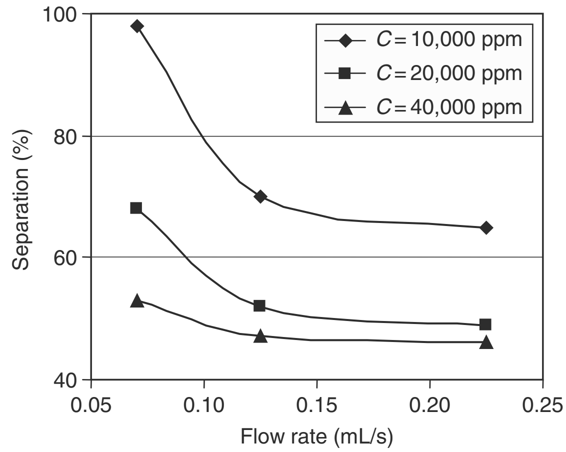

Fig. 7. Effect of flow rate on separation percent at different feed concentrations.

performance increases. Notice that there is almost no difference between separation percent for $T_{40°C}$ and $T_{55°C}$. It can be concluded that, greater amounts of temperature than 40°C have almost no effect on separation performance.

At higher feed concentrations, in spite of the fact that solution conductivity increases, separation percent decreases due to concentration polarization phenomenon at high concentrations

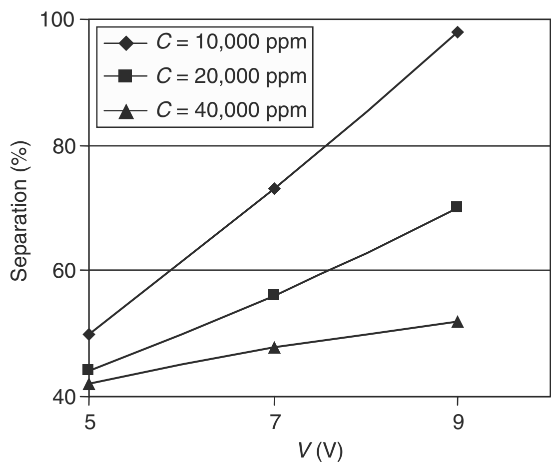

Fig. 8. Effect of voltage on separation percent at different feed concentrations.

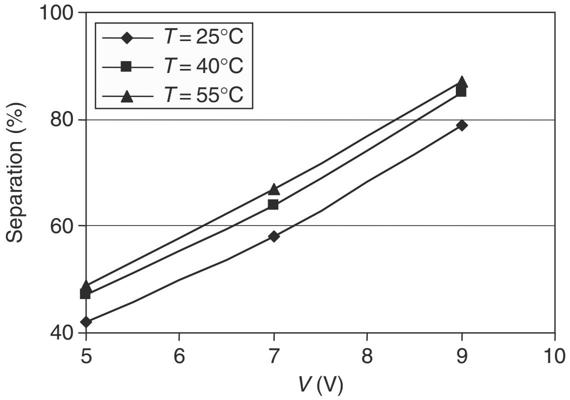

Fig. 9. Effect of voltage on separation percent at different temperatures.

and limited ion exchange capacity of the membranes. Hence, it was approved that ED is more efficient at lower concentrations and can be applied as a post-treatment process for desalination of wastewater or seawater.

At higher flow rates, separation percent values fall and separation performance decreases. Because a greater flow rate means a lower residence time, ions that are between the membranes do not have enough time to transfer through the membranes.

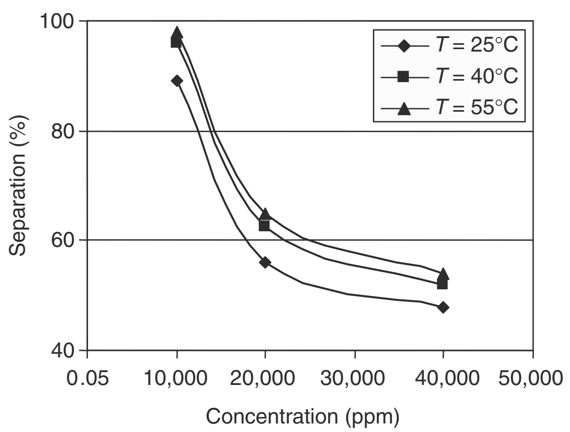

Fig. 10. Effect of feed concentration on separation percent at different temperatures.

In terms of maximizing the separation percent, T_{high} (55°C), C_{low} (10,000 ppm), F_{low} (0.07 mL/s) and V_{high} (9 V) were chosen.

Effect of voltage on separation percent at different feed concentrations and temperatures are depicted in Figs. 8 and 9. As can be seen, simultaneous increase in voltage and temperature as well as decrease in feed concentration optimize the separation percent. Fig. 10 shows the effect of feed concentration on separation percent at different temperatures. According to this figure, the same results as above was obtained.

After conducting experiments based on Taguchi method, ANOVA needs to be employed for estimating error variance and determining the relative importance of various factors. ANOVA demonstrates whether the observed variation in the response is due to alteration of level adjustments or experimental standard errors. ANOVA procedure results in calculation of sum of squares (SS), degree of freedom (d.o.f.), mean square (variance) and associated F-test of significance (F). SS of factors is calculated as follows:

$$SS_A = \sum_{i=1}^{K_A} \left(\frac{A_i^2}{n_A^i} \right) - \frac{T^2}{N} \qquad (2)$$

where, K_A is the number of levels of factor A ($K_A = 3$ for all factors in this study), n_{Ai} the number of all observations at level I of factor A ($n_{Ai} = 6$ in this study), A_i the sum of all observations of level i of factor A and T is the sum of all observations. SS of error is computed using the following equation:

$$SS_e = SS_T - (SS_A + SS_B + ...) \qquad (3)$$

where, SS_T is the total SS:

$$SS_T = \sum Y_j^2 - \frac{T^2}{N} \qquad (4)$$

where, N is the number of all observation and Y is the separation percent. Variance is calculated by dividing the sum of squares by the degree of

Table 2
Calculated statistical results based on Na^+ experimental data

Factor	d.o.f	SS	Variance	F	P
T (°C)	2	77.24	38.62	94.19	1.5
F (mL s^{-1})	2	382.65	191.32	466.63	7.5
C (ppm)	2	4169.79	2084.9	5085.12	82.4
V (V)	2	431.24	215.62	525.9	8.5

freedom, $V_A = SS_A/\nu_A$. ν_A is estimated by $\nu_A = K_A - 1$. F-value is calculated as follows:

$$F_A = \frac{V_A}{V_e} \quad (5)$$

where, V_e is the error variance ($V_e = SS_e/\nu_e$), ν_e is the error degree of freedom, estimated by $\nu_e = \nu_T - (\nu_A + \nu_B + \cdots)$. The total degree of freedom (ν_T) is calculated subtracting N from 1 ($N - 1$). Using ν_A and ν_e, F values are initially extracted from statistical tables at various risks (α). If the extracted F-value is smaller than the calculated one, the statistical significance of effect is concluded. Calculated statistical results are presented in Table 2. P, in this table, is the percent of contribution of each factor on the response ($P_A = SS_A/SS_T \times 100$).

ANOVA reveals that calculated F values exceed the tabulated values. For $\alpha = 0.05$ and 0.01, tabulated F values are 4.26 and 8.02, respectively. It means that variance of all factors is significant compared with variance of error and all of them have significant effect on the response. Also, P values of flow rate and voltage are almost the same and are smaller than those of feed concentration. This means that feed concentration is the most influential factor. According to the P value of temperature, it can be concluded that temperature is the least influential factor.

4. Conclusion

In this study, the effect of operating conditions (temperature, concentration, flow rate and voltage) on performance of an electrodialysis cell was studied. Taguchi data analysis method was utilized to study four parameters in three levels (L_9 OA). Effect of concentration (10,000, 20,000, 40,000 ppm), temperature (25, 40, 55°C), flow rate (0.07, 0.13, 0.22 mL/s) and voltage (5, 7, 9 V) on separation percent of individual ions in the solution was scrutinized. As a result, higher temperature and voltage and fewer flow rate and concentration were recommended to modify performance of ED cell. ANOVA analysis was applied to evaluate the relative importance of the effects of various factors. It was realized that all factors have significant effect on the response and feed concentration has the largest contribution to the total sum of squares and correspondingly has a major effect on separation percent. It has also found out that, simultaneous increase in voltage and temperature as well as decrease in feed concentration and flow rate optimize the separation percent. Electrodialysis was found to be very effective for seawater desalination specifically at lower concentrations.

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