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ORIGINAL RESEARCH ARTICLE

Optimization of electrodialysis unit for partial desalination: Batch and continuous operation

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ABSTRACT

In recently few years, application of membrane technologies in sea water desalination is increased compared to other desalination technologies. Electrodialysis membrane technology is still limited in seawater desalination due to the high operation cost and its limitations for high salty water. Electrodialysis desalination cost is proportional to the amount of salt, which must be carried out through the membrane. Seawater desalination with high salt content of NaCl (42 g/L) was applied using IonTech electrodialysis unit. Partial desalination process was studied in two separate experiments, batch and continuous operation. Operation parameters like voltage applied, electrolyte concentration and time of desalination were studied under batch mode process. Continuous operation process was carried out to confirm the partial desalination process of electrodialysis. The limited current density is determined, 1.49 A/m^2 and 1.15 A/m^2 for theoretical and experimental, respectively. The specific energy consumption was calculated, 7.15 kWh/m^3.

Keywords: Electrodialysis; Partial Desalination; Potential Difference; Energy Consumption

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1. Introduction

Scarcity of utilizable fresh water is obstacle for most countries around the world. Therefore, some special processes are needed to desalinate salty water of the oceans and seas[1]. Suitable desalinating methods for water treatment of seawater can be effective to overcome the fresh water scarcity. Electrodialysis (ED) is one of these methods which have been used for many years. The basic principles of ED have been reviewed in the literature[2].

Seawater desalination using electrodialysis was studied by Sadrzadeh and Mohammadi[3]. To evaluate effects of operation parameters, a L9 orthogonal array (four factors in three levels) was employed. Temperature, voltage applied, flow rate and feed concentration effects on separation percentage of ions have been studied. Maximum percentage of salts removal was obtained at the highest voltage applied (9 V), lowest feed concentration (10 g/L), high temperature level (55 ºC) and lowest flow rate level (0.07 mL/s). It was found that, feed concentration is the most influential factor on ED performance (its contribution percentage was calculated to be 82.4%)[3].

The desalination efficiency of an electrodialysis unit is dependent on variable and fixed parameters. These variable and fixed parameters are like applied voltage, feed and permeate concentration, type and concentration of electrolyte, flow rate, ED stack construction, current density, membrane permselectivity and recovery rates[4]. For highly efficient operation conditions of electrodialysis, the process has to be optimized in terms of overall costs considering operating parameters, component design and properties[4].

Electrodialysis offers the high practical advantage of much higher recovery in many applications due to the lowest quantity of dissolved species in the feed stream than the fluid[5-10]. The efficiency of electrodialysis recovery depends on the ionic solids and fouling potential from organics and particles in the feed water[11,12].

Current efficiency in ED is a measure of how effective ions are transported across the ion exchange membranes for a given applied current. Typically, in commercial stack membranes, current efficiencies higher than 80% are desirable to minimize energy operating costs. Low current efficiencies indicate water splitting in the dilute or concentrate streams, shunt currents between the electrodes, or back-diffusion of ions from the concentrate to the dilute could be occurring[11].

The most application of electrodialysis has historically been the desalination of brackish water as an alternative to RO for potable water production and seawater concentration for salt production (primarily in Japan)[7].

Galama *et al*.[13] study the suitability of ED for seawater desalination and energy losses has been quantified. They found that, combining ED with BWRO in a hybrid system does not lead to a reduction in energy consumption compared to ED as standalone technique, when the applied current density becomes lower than 50 A/m^2. At low applied current density (10 A/m^2), ED can perform desalination energetically cheaper at lower operational costs than SWRO.

The combination of electrodialysis (ED) and brackish water reverse osmosis (BWRO) is presented as a promising and economic desalination strategy that could lead to a desalination cost reduction compared to seawater reverse osmosis (SWRO)[14]. Water recoveries for seawater desalination using ED were reported from 50 to 60 %[15,16] and with ED reversal, it is expected higher water recoveries can be obtained[17].

This study aims to evaluate the facilities of partial desalination for sea water using a pilot scale of electrodialysis system with low energy consumption. Optimum operation conditions of electrodialysis system were determined with operation in batch and continuous mode. Limiting current density and energy consumption for the electrodialysis system were determined.

2. Experimental procedure

2.1 Materials

A commercial salt (sodium chloride supplied by Al-Malahat Egyptian Company) was used in all experiments to produce a simulated solution of sea water qualities. The purpose of these was to study the effects of voltage, flow rate and feed concentration on ED pilot scale in batch and continuous mode.

2.2 Electrodialysis system

A pilot scale of electrodialysis unit (IONLYZER-40-2040, IONTECH Co., China) was supplied and used in this work as shown in **Figure 1**. It contains three compartments, compartment 1 containing 10 L of untreated feed water (dilute), compartment 2 containing 10 L of saline solution of known concentration (electrolyte) and compartment 3 containing 10 L of sea water (concentrate). **Table 1** shows the specifications and operation conditions of electrodialysis unit.

Table 1. Specifications and operation conditions of electrodialysis unit

Item	Specifications
ED stack	40 IONSEP-HC (20*40 cm) 40 pairs of IONSEP-HC/MC membrane and spacer in the size of 20*40 cm; noble metal electrode; fasteners
IGBT high frequency Switching power supply	DC Output 50V, 10A, AC Input 220V,50/60HZ
Magnetic transfer pumps	Q = 1.2 m^3/h, Head = 5 m
Electrode water pump	Q = 1.2 m^3/h, Head = 5 m
Storage Tanks	Electrode, feed and dilute water tank
Pressure Gauges	Oil-filled
Flow rate for concentrated & diluted solutions	300–600 L/h
Flow rate for electrode solution	100–300 L/h

For ED batch mode operation, 10 L from the feed water source of ED is placed in the dilute compartment for the desired electrodialysis time interval at the required potential difference. Conductivity (µS/cm), TDS (mg/L) and salinity were measured instantly during desalination process using HANA Electrod.

For ED continuous operation mode, two external transfer feed pumps were used, one for diluted stream and the other for concentrated stream.

Table 2. Iontech membrane parameters

Conditions	Data
Membrane area (per sheet)	20*40 cm^2
Number of cell pair	40
Width (between anion and cation exchange membrane)	0.8 mm
Surface membrane resistance	5.5 Ωcm^2

Figure 1. Electrodialysis unit (IONLYZER-40-2040, IONTECH Co., China).

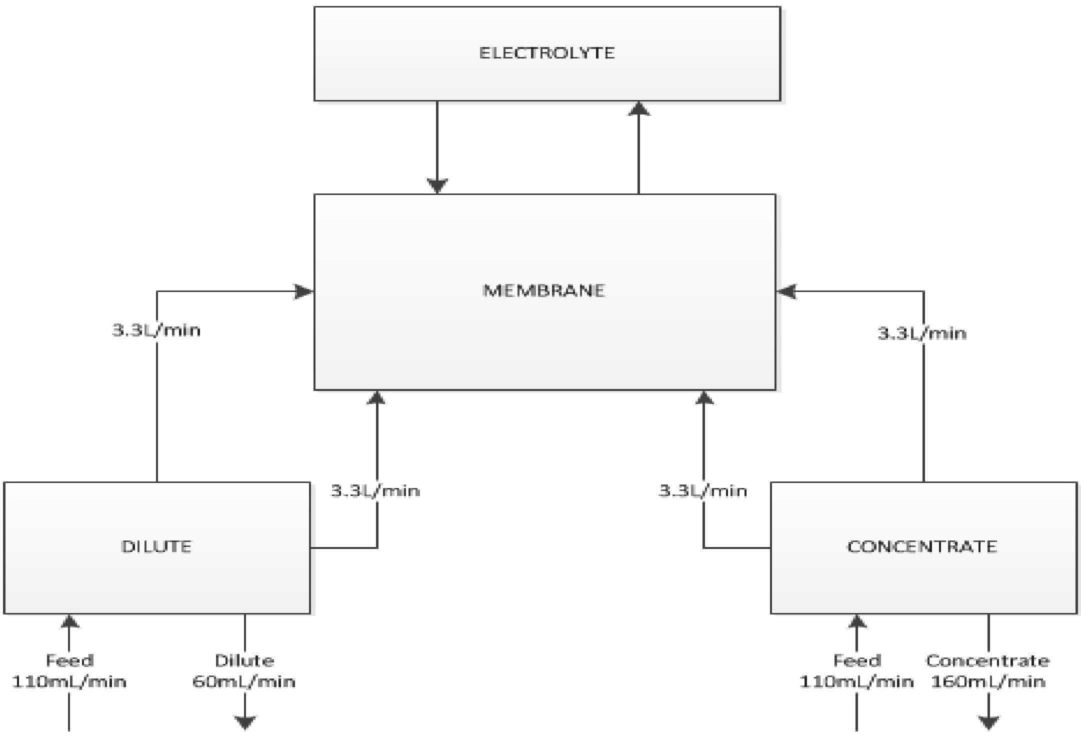

Figure 2. Schematic diagram of continuous operation mode.

The external feed pumps were set at constant feed flow rate with the same of discharged outlet with continuous circulation of electrodialysis pumps (diluted, concentrated and electrolyte). The difference in diluted and concentrated discharge is due to high polarization on ED membranes. A schematic diagram of the continuous operation mode was shown in **Figure 2**.

2.3 Analytical methods

Concentration of NaCl in the dilute and concentrate compartments was measured at various operating conditions. In all experiments, a conductivity-meter (HANA-HI 2550) was used to measure the amount of salts as Total Dissolved Salts (TDS) and conductivity in water. Water conductivity directly depends on its salt content.

2.4 Procedure

In this study, desalination efficiency of ED operation in batch and continuous mode was determined by measuring of conductivity, TDS and salinity. The quality characteristic was TDS Removal Efficiency (%) which was calculated as follow:

$$Removal\ Effeciency, \% = \frac{C_o - C}{C_o} \times 100 \qquad (1)$$

where C_0 and C are feed and dilute concentrations (mg/L), respectively.

3. Results and discussion

3.1 Batch mode operation

A synthetic solution of commercial sodium chloride salt—supplied from Al-Malahat Egyptian Company—was prepared with concentration 42 g/L. The prepared synthetic solutions were simulated to Red Sea water sample. Different parameters of electrodialysis unit operation were studied for optimize batch mode operation conditions. Applied voltage, electrolyte type and concentration, retention time, circulation rate and removal efficiency have been studied.

3.1.1 Effect of applied potential difference

A series of experiments was carried out at different applied potential differences ranged from 6.0 to 18.0 volt to determine ions removal efficiency. The following conditions are kept constant as: total electrodialysis time was 60 min, type of electrolyte was sodium chloride (NaCl) and concentration of electrolyte was 0.5 M.

The effect of potential difference and time on Removal Efficiency of Red Sea water sample was studied. The obtained results are given in **Figure 3**. High TDS removal efficiency was achieved with applying 15 V potential differences. The results reveal that, with increase in the applied potential difference, conductivity values decrease with time which means high salts removal efficiency. Decreasing of TDS (mg/L) means high salts removal efficiency. The best (optimum) applied potential difference is 15.0 volt.

3.1.2 Effect of electrolyte concentration

A series of experiments was carried out at different electrolyte concentrations ranged from 0.1 M to 0.7 M of NaCl solutions to determine ions removal efficiency. The following conditions are kept constant as: potential difference was 15 Volt, total electrodialysis time was 60 min and type of electrolyte was Sodium chloride (NaCl).

The obtained results are given in **Figure 4**. It was concluded that, with increase in electrolyte concentration, low conductivity values obtained (high removal efficiency). The difference in the concentration values with respect to removal efficiency is sharp in case of Red Sea water as it contains high salinity. From these results, it was concluded that the best electrolyte concentration is 0.5 M NaCl solution at the applied conditions. Choose sodium chloride to be the electrolyte for ED, because it is a cheap source for electrolyte operation.

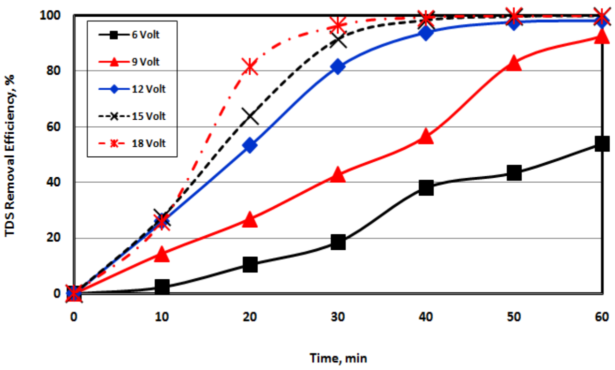

Figure 3. Effect of potential difference and time on TDS removal efficiency.

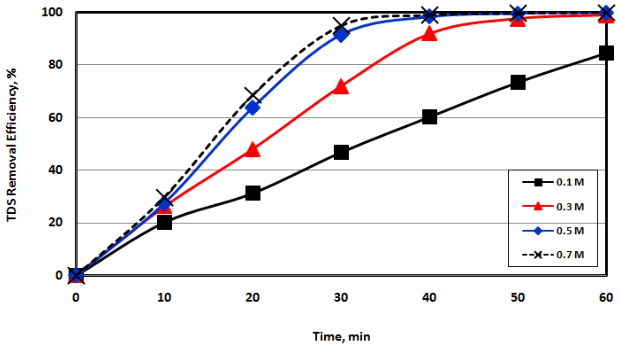

Figure 4. Effect of NaCl electrolyte concentration and time on TDS removal efficiency.

3.1.3 Effect of electrodialysis time on chloride concentration

The behaviour of each ion most probably follows that of Total Dissolved Salts (TDS). Chlorides ions were taken as an example of ions removed during electrodialysis as they are the major ions in the Red Sea water composition. The obtained results are given in **Figure 5**. The applied potential difference is 15 Volt and 0.5 M sodium chloride electrolyte concentration. The results reveal that, chloride ions have a removal efficiency (RE) of about 92% in the first 20 minutes. The achieved chloride ions removal efficiency was almost constant at about 99.7% ± 0.1% after about 30 minutes.

From the previous work, the best operating conditions for electrodialysis unit with batch mode were concluded and represented in **Table 3**.

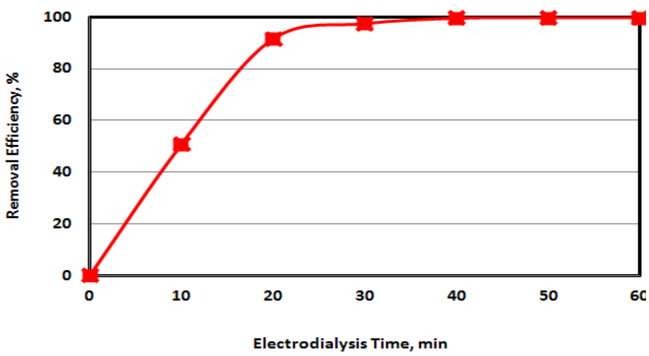

Figure 5. Effect of electrodialysis time on chloride removal efficiency.

TDS and current passed were plotted as a function of time at the optimum operation conditions as shown in **Figure 6**.

3.1.4 Morphology analysis

A sample from concentrated stream of the Electrodialysis was taken (highly concentrated) and evaporated till dryness. Then the precipitate was characterized and analyzed using SEM and EDX. The obtained results are shown in **Figure 7** and **Figure 8** and **Table 4**. **Figure 7** shows that the crystallized solids have needle-like shape with length of about 3 to 5 Microns and width of 0.1 to 0.3 Microns. In addition, **Figure 8** shows the EDX analysis of the precipitated solids. It shows that chloride ions are the main anions. Divalent cations like Mg^{2+} and Ca^{2+} have low contents compared with monovalent cations such as Na^{+} and K^{+}.

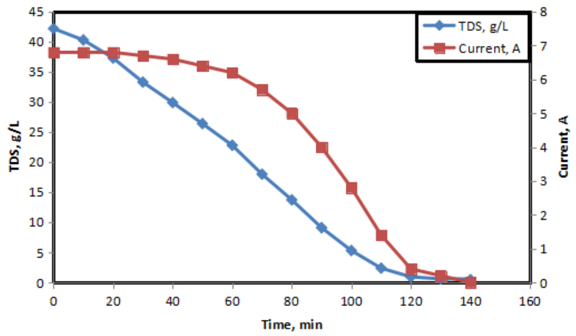

Figure 6. TDS (g/L) and current (A) as a function of time at optimum operation conditions.

Table 3. Optimum operating conditions of ED system with batch mode for sea water sample

Parameters	Value
Applied potential difference, Volt	15
Electrodialysis retention time, min	30
Type of electrolyte	Sodium chloride
Electrolyte concentration, M	0.5
Flow rate of electrolyte, L/min	6.6 (Fully opened)
Flow rate of diluted and concentrated streams, L/min	3.3

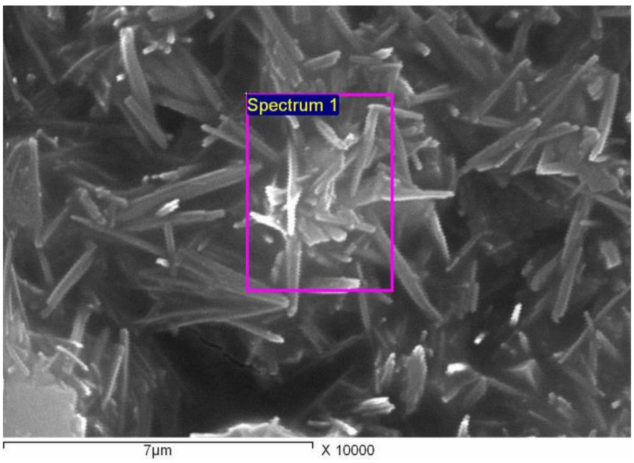

Figure 7. SEM photomicrograph of crystallized salts from electrodialysis.

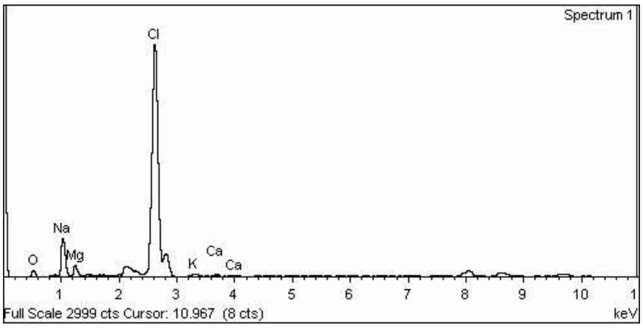

Figure 8. EDX analysis of crystallized salts from electrodialysis concentrated stream.

Table 4. EDX analysis of crystallized salts from concentrated sea water

Ions	Weight (%)
Cl^-	53.5
O^{2-}	21.1
Na^+	18.9
Mg^{2+}	5.1
K^+	0.8
Ca^{2+}	0.6
Total	100.0

3.1.5 Limiting current density

The limiting current density, i_{lim}, can be determined theoretically according to the following equation[6]:

$$i_{lim} = k\frac{CzF}{T_m - T_s} \quad (2)$$

where, C is the concentration of the diluate, z the electrochemical valence of the ions in the solution, F Faraday constant, T_m and T_s the ion transport numbers in the membrane and the solution, respectively. The coefficient k in the equation is the mass transfer coefficient, representing the influence of the hydrodynamics, flow channel geometry, spacer design, etc. Limiting current density is proportional to the ion concentration in the diluate and the mass transfer coefficient, which are related to the cell geometry and the feed solution flow velocity[6].

According to this relationship, the limiting current density can be calculated as follow:

$$i_{lim} = 1.55 \times 10^{-5}\frac{0.5 \times 1 \times 96487}{0.95 - 0.45} \quad (3)$$

So, i_{lim} = 1.49 A/m^2.

The limiting current density can be determined from the relationship between the current and corresponding potential, or from the measurement of the cell resistance and the pH value in the diluate cell as a function of the current density[6–18].

In this study the limiting current was determined by measuring the potential and the cell resistance as a function of the applied current. **Figure 9** shows the curve used for the determination of the limiting current from the experimental result obtained with a batch mode operation. The started dilute solution used was 42 g/L of NaCl and the concentration of the electrolyte was 0.5 M of NaCl with a linear feed velocity 6.6 L/min. From the curve in **Figure 9**, the experimental limiting current density was 1.15 A/m^2.

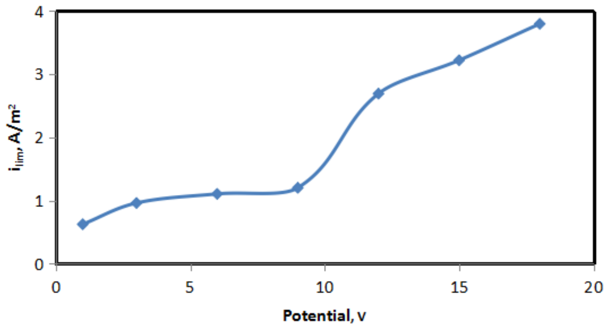

Figure 9. Current-voltage curve for the determination of limiting current density.

3.1.6 Energy consumption

In this work, partial desalination using electrodialysis was applied, started with feed solution concentration 42 g/L and desalinated water 4 g/L with desalination efficiency 91%. Power and energy consumption for this pre-desalination step was calculated according to the following equations:

$$I = i_{lim} \times A \quad (4)$$

$$P = I^2 \times R \quad (5)$$

$$E_{spec.} = \frac{P}{Flow} \quad (6)$$

where, i_{lim} is the experimental limiting current density (1.15 A/m^2), A is the total effective membrane area of ED stack (2.08 m^2), I is the total applied current (A), R is the membrane resistance (5.5 Ω/cm^2) and flow is the dilute electrodialysis stream flow (4.4 × 10^{-3} m^3/h). The calculated power consumption, P was 13.38 W and the calculated specific energy consumption, $E_{spec.}$ was 7.15 kWh/m^3. The results of this work is promising, according to W.S. Walker *et al.*[19], the specific energy consumption is proportional to the applied voltage and the ionic concentration that is separated. So, for treatment of a concentrate solution of 15000 mg/L at a moderate voltage applications (e.g., 1.0 V/cell-pair), the specific energy consumption of ED would be approximately 7.0

kWh/m^3 (including electric and hydraulic energy consumption), which is less than many thermal desalination alternatives (e.g., 20-30 kW h/m^3).

In this work study case, the specific energy consumption was7.15 kW h/m^3, which is comparable with the total energy consumption estimated for industrial plant was equal to 6.8–8.7 kW h/m^3 of desalinated water[20].

3.2 Continuous mode operation

In the following, the main operating conditions and the results of the use of ED as an applied technique for ions removal from Red Sea water is given. A schematic diagram of the continuous operation mode was shown in **Figure 2**. In the beginning, the ED conditions are operated batch wise under the following conditions: potential difference was 15 Volt, TDS of Red Sea water sample was 42000 ppm, type of electrolyte was Sodium chloride (NaCl) and electrolyte concentration was 0.5 M.

The obtained results are given in **Figure 10**. The results reveal that, with increase in electrodialysis time, the conductivity values decreased. This means the removal efficiency of salts is increased. From these results, it was concluded that the best electrodialysis retention time for the continuous batch mode operation is 105 minutes that gives the required TDS from 3.84 g/L for the Dilute solution and 64.9 g/L for the Concentrate solution.

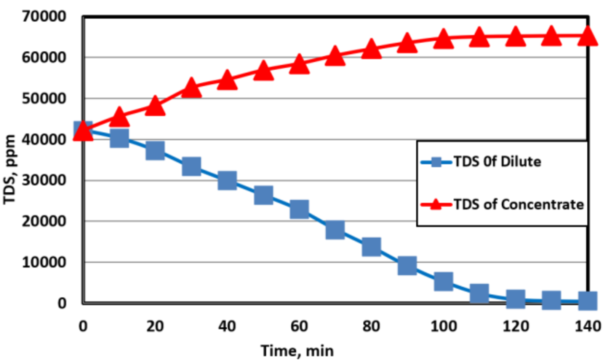

Figure 10. Effect of time on TDS of dilute and concentrate of ED.

Based on the previous test and using 105 minutes as the best retention time, the continuous preliminary feeding and discharge rates are calculated. The optimum operating conditions for electrodialysis unit with a continuous mode are represented in **Table 5**.

Table 5. The optimum operating conditions for electrodialysis unit with a continuous mode

Parameters	Value
Applied potential difference, Volt	15
Electrodialysis retention time, min	105
Type of electrolyte	NaCl
Electrolyte concentration, M	0.5
Flow rate of electrolyte, L/min (circulation)	6.6 (Fully opened)
Flow rate of diluted stream, L/min (circulation)	3.3
Flow rate of concentrated stream, L/min (circulation)	3.3
Initial feeding rate of saline water to Dilute tank, ml/min	110
Initial feeding rate of saline water to Concentrate tank, ml/min	110
Initial discharging rate of produced water from Dilute tank, ml/min	60
Initial discharging rate of saline water from Concentrate tank, ml/min	160
Initial feeding rate of saline water to Dilute tank, ml/min	110
Initial feeding rate of saline water to Concentrate tank, ml/min	110

4. Conclusion

The following parameters were studied using Electrodialysis system with determination of removal efficiency: concentration of saline water, retention time, applied voltage, concentration of sodium chloride electrolyte.

The optimum Electrodialysis parameters of batch mode were determined as 15 Volt applied potential difference, 30 minutes retention time with circulation. 0.5 M sodium chloride as electrolyte solution. The produced water was fed to Reverse Osmosis system. The tests are still continuing. Moreover, salts after evaporation of concentrated solution of Electrodialysis system were characterized and chemically analyzed.

The limited current density is determined, 1.49 A/m^2 and 1.15 A/m^2 for theoretical and experimental, respectively. The specific energy consumption was calculated, 7.15 kWh/m^3.

Conflict of interest

The authors declare that they have no conflict of interest.

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