Optimization of Electrodialysis Metathesis (EDM) Desalination Using Factorial Design Methodology

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ABSTRACT

A complete set of experimental data on novel Electrodialysis Metathesis (EDM) desalination was analyzed using factorial design. EDM consists of repeating quads of four ion-exchange membranes and solution compartments to allow double decomposition reaction between the cations and anions of a feed and a substitution solution when current is applied between the electrodes. The effect of factors affecting the EDM desalination efficiency, such as voltage, flow rate, membrane type, and feed water source was studied using a full 2^4 factorial experimental design. The General Linear Model was used to evaluate the combined effect of the discrete and continuous factor variables introduced in the design. It was found that voltage, water source and membrane type were the most influential factors on the EDM process. Interaction terms were found to be insignificant. The effect of main factors on EDM desalination follow the order voltage > water source > type of membrane. EDM desalinate well saline waters with TDS concentrations higher than the TDS of surface water by applying 15 volts and using Neosepta membranes. The responses obtained with the GLM were in agreement with the experimental data, thus confirming the ability of the model to predict desalination results. Complete desalination of high salinity water was achieved without formation of precipitates in the stack due to the ability of EDM to convert sparingly soluble salts into highly soluble salts.

1. INTRODUCTION

The application of desalination of salty water has the potential to impact many lives and industries. Water unavailability inhibits human life, farming, and other work industries. Over 97.5% of all water on the planet forms the oceans [1]. Yet, 99% of this water is unavailable for usage because of its high ionic concentrations [2]. A report by the Food and Agriculture Organization claims that in 2008, across numerous areas of the world water scarcity reached 330 million people and water stress affected two billion people [1]. The practice of desalination is valuable for the production of potable water and other valuable desired materials from Earth's salty water sources.

Reverse osmosis (RO) is one of the most widely applied processes to desalinate brine solutions. RO is generally very efficient in removing inorganic materials in water, according to World Health Organization Standards (WHO) [3]. However, the large volume of high salt concentrate generated is costly to discard [4]. Electrodialysis (ED) has also been used as an alternative desalination process [5,6]. One of the limitations of ED is the formation of scale products inside of the stack which ultimately results in low permeate flux and increase of energy consumption.

In a conventional ED system transport of ions to the concentrate or dilute compartment depends on the amount of electrical current flowing between the electrodes. The current density generated by the rate of ionic migration towards the electrodes is defined by the equation

$$i = \frac{I}{A} \quad (1)$$

Where i is current density (A/cm²), I is the current (Ampere) and A is the membrane area (m²). Equation (2) implies the possibility of continuous increase of ion flow per unit membrane area by increasing the current density; however this is not always the case due to limitations caused by concentration polarization [7, 8]. By Ohm's law, current can be related to applied voltage as follows

$$I = \frac{V}{R} \quad (2)$$

Where V is the difference in electrical potential (volts) and R is resistance in ohms (Ω). The resistance of an ED cell pair is the sum of the resistances in the diluate and concentrate compartment and ion-exchange membranes. As ionic strength of the solution decreases it causes the electrical resistance through the electrolyte solution to increase [7].

Electrodialysis metathesis (EDM) is a novel desalination process that allows converting sparingly soluble salts into highly soluble solutions. EDM is a variation of electrodialysis (ED) in which a metathesis reaction occurs. A conventional ED system is composed of repeating cells of two alternating cation- and anion- exchange membranes. Every cell contains two compartments, one containing the feed solution and the other containing the concentrate solution. The membranes are placed between two electrodes and an electrical current passes through them to cause the mobility of the charged ions towards the corresponding electrode. In the EDM system, four alternating ion-exchange membranes form a repeating quad of four compartments and a substitution solution is added to provide the exchangeable ions for the metathesis reaction (Figure 1) [7]. In the reaction, the feed solution, represented by MX, exchange cations and anions with the substitution solution, M'X', to form new product salts, M'X and MX', as represented by equation 1 [7].

For this purpose, two of the compartments contain the feed and a substitution solution, and are called diluate 1 (D1) and dilute 2 (D2) compartments, respectively. The other two compartments contain each the newly formed non-precipitating product salts, and are called concentrate 1 (C1) and concentrate 2 (C2) compartments as shown in Figure 1. Depending on the intended product solution in the two concentrate compartments, an appropriate substitution salt solution is fed to the D2 compartment to initiate the double decomposition reaction with the feed solution from the D1 compartment. Salts formed in the C1 compartment are predominantly rich in anions and poor in cations from the D1 compartment. Salts formed in the C2 compartment are predominantly rich in cations and poor in anions from the D1 compartment. When sodium chloride is added as the substitution solution, the C1 compartment contains mixed sodium salts, and the C2 compartment contains mixed chloride salts (Figure 1) [7]. The ion exchange membranes, which are conductive and selective [8], allow the double exchange of ions between the saline solutions to produce concentrated salt water in addition to clean water. EDM can convert magnesium chloride and sodium sulfate into magnesium sulfate and sodium chloride [7]. Recent studies showed that slightly soluble calcium sulfate can be converted to soluble calcium chloride through the metathesis reaction with sodium chloride during the desalination of brackish water with EDM [9].

Figure 1 Schematic diagram of the EDM process (C = cation-exchange membrane, A = anion-exchange membrane, C1 = concentrate 1, D1 = diluate 1, C2 = concentrate 2, D2 = diluate 2).

EDM allows the concentration of the brackish solution to be three times more concentrated than reverse osmosis [9], saving resources, as well as allowing a less expensive disposal. Unlike RO and conventional electrodialysis, the EDM concentrate can be separated into two streams of highly soluble salts. This characteristic allows much higher recoveries to be achieved with EDM than with RO or electrodialysis. In addition to form dilute, potable water, EDM can also be used to collecting valuable salts and liquid products for beneficial used, which reduces the amount of solid waste byproducts from the desalination process. Similar to ED, energy requirement for EDM depends on ionic concentration. Consequently, EDM energy increases in proportion to the total dissolved solids (TDS) [10].

The purpose of this study was to determine the effect of process parameter conditions, such as voltage, flow rate, type of ion-exchange membrane, and type of feed water, on the EDM desalination process. A full 2⁴ factorial experimental design was used to evaluate the main effects as well as the interaction effects of the parameters during the process. The results from this study should contribute to the growth of commercial applicable uses of the EDM process.

2. MATERIALS AND METHODS

2.1. The EDM Desalination System

Experiments were conducted using an EDM electrodialysis system consisting of a stack (Ameridia Inc., model EUR2D-5), five 15-liter polypropylene tanks, and a programmable DC Power Supply (AMETEK, model Sorensen XHR). The system included rotameters, pressure gauges, and pumps for the transport and flow rate control of solutions. The feed solution was added to the tank D1. Tank D2 contained the substitution NaCl solution. The C1 and C2 tanks were initially filled with deionized water. The two circulated streams produce the metathesis reaction, forming two new salts in the C1 and C2 compartments. The fifth tank contained the rinse solution for both the anode and cathode. The stack included a stainless steel cathode (plate) electrode, a platinum-protected titanium anode (plate) electrode, and alternating ion-selective commercial ion-exchange membranes. A total of twenty membranes with membrane holders were distributed in five four-compartment repeating quads. Manifolds placed between the membranes helped to guide the flow of solutions coming from the tanks toward the corresponding compartments in every quad. A solution of NaCl, which has the same number of equivalents per liter as the feed solution, was circulated through the compartment D2 to provide the ions for the double decomposition reaction with the ions in the compartment D1. A 0.2 M Na₂SO₄ solution was circulated between the anolyte and catholyte compartments.

Two types of ion-exchange membranes were used. The first were cation-selective (CMX) and anion-selective (AMX) Neosepta ion-exchange membranes from ASTOM. An additional cation-selective (CMB) Neosepta ion-exchange membrane was used at the anode and cathode to protect them from getting in direct contact with potential precipitation components. The second were cation-selective (CM-PP) and anion-selective (AM-PP) Ralex ion-exchange membranes from Mega A. S. The Neosepta membranes came already swelled and the Ralex membranes were swelled in the laboratory for 72 hours prior to usage. All membranes were cut to have 200 cm² effective surface area for ion transport. The main properties of the membrane, including transport number, thickness, and resistance are presented in Table 1.

Table 1 Properties of commercial ion-exchange membranes [11-14].

Property	Neosepta		Ralex	
	CMX	AMX	CM-PP	AM-PP
Transport number	> 0.98	> 0.98	> 0.95	> 0.95
Thickness, mm	0.17	0.14	< 0.70	< 0.75
Resistance, Ohm-cm ²	2-3.5	2-3.5	< 8	< 8

2.2. 2⁴ Factorial Experimental Design and EDM Performance

A 2^4 factorial experimental design with a total of 16 experiments was developed to study the effect of voltage, flowrate, membrane type, and water source on the EDM performance. Each factor was evaluated at two different levels. The levels of the factors were considered based on the assumption of linear relationship of factor effects at all levels [15]. Table 2 shows the low and high levels at which the factors were tested. The high level was represented with a plus sign (+1) and the low level with a minus sign (-1). Ralex and Neosepta membranes were used to represent the lower and higher level of the type of membrane, respectively. Likewise, synthetic surface water and groundwater were used to represent the lower and higher levels of the water source, respectively [16,17]. The two water sources had the same type of ions, but the concentration of the main salinity-contributing ions (Ca^{2+} , Na^+ , and Cl^-) was much higher in the groundwater. Table 3 shows the ions composition of the two water sources, which were prepared using reagent grade salts of CaCl_2 , NaCl , Na_2SO_4 , and NaHCO_3 . Selection of the levels 0.2 gpm (0.76 l/min) and 0.6 gpm (2.27 l/min), as well as 10 V and 15 V for flow and voltage, respectively, was made based on values preliminary obtained with the EDM stack (not showed here).

Table 2 Factors and levels in the 2^4 factorial experimental design.

Factor	Flow rate	Voltage	Water source	Membrane type
-1	0.2 gpm	10 V	Groundwater	Neosepta
+1	0.6 gpm	15 V	Surface water	Ralex

Each experiment was conducted in batch mode for six hours, or until the conductivity of the feed solution approaches near zero value. A Thermo Scientific Orion Star A329 conductivity meter was used to measure the conductivity of the solutions in the different compartments of the EDM system as a function of time. The significant factors affecting the EDM performance were determined by analyzing the conductivity responses with the statistical software Minitab® 17.

Table 3 Ion composition of water sources [16,17].

Ions	Groundwater		Surface water	
	(mmol/L)	(meq/L)	(mmol/L)	(meq/L)
Ca^{2+}	5730	11460	3.9	7.8
Mg^{2+}	8.3	16.6	30.4	60.8
Na^+	3680	3680	225	225
K^+	16.5	16.5	4.6	4.6

Cl ⁻	15000	15000	251	251
SO ₄ ²⁻	17.3	34.6	15	30
HCO ₃ ³⁻	813	813	17.20	17.20

3. RESULTS AND DISCUSSION

3.1. Effect of Process Parameters on EDM Desalination

Sixteen EDM experiments were conducted by changing the levels of voltage, flow rate, membrane type, and water source according to the 2⁴ factorial experimental design. The desalination performance was evaluated by measuring the conductivity changes in the feed salt solution contained in tank D1 with respect to time. The time to complete the desalination, i.e. conductivity of feed solution approaching near zero value, was different for each of the experimental runs. Some samples reached near zero conductivity after 3.5 hours, some other took longer, and few others didn't reach zero conductivity after six hours. The conductivity in the C1 and C2 compartments increased at the same time that it decreased in the feed compartment, meaning that the cations and anions were selectively accumulating in the two compartments forming highly soluble solutions. Therefore, the precipitation of problematic ions, such as calcium and magnesium, which usually occurs inside of traditional ED systems [7], was not observed in any of the experiments. Examples of the results observed in some of the individual runs are discussed in the following sections.

3.1.1 Effect of Voltage and Flow Rate

Figure 2A shows that by increasing the applied voltage from 10V to 15 V in the EDM stack that contains Neosepta membranes and simulated groundwater a faster desalination occurred. This is possible because the difference in electrical potential is the driving force of ion transport across the membrane [18]. By increasing the voltage, additional driving force is provided to increase the rate of ionic migration through the EDM system. EDM experiments conducted by Bond et al. [10] using RO concentrate and applied voltage within a range of 3 to 12 volts showed a linear relationship between current and therefore the rate of ion extraction when the voltage was increased in the 3 to 12 volts tested.

Figure 2B shows that increasing the flow rate from 0.2 gpm to 0.6 gpm in the EDM stack resulted in relatively faster conductivity depletion. This behavior was expected since current density is proportional to flow rate [19]. Increasing the flow rate enhances the linear velocity which reduces the boundary layer

on the dilute side of the membrane and help decreasing the resistance, resulting in more surface contact for transfer of ionic species [19], thereby leading to an increased mass transport across the membrane [20,21,19]. Therefore the current density increases which is expected to create an increase in the ion removal. At the same time, the increase in flow rate reduces the residence time of the solution in the EDM system and hence reduces the ion removal. Current density and residence time are counteracting each other in the EDM stack. As a result the conductivity wouldn't have to decrease much with increase in flow rate [19]. A much careful evaluation of the effect of flow rate on the EDM performance would be necessary to determine its real impact.

Figure 2 Conductivity variations of feed salt solution in D1 tank with Neosepta membranes and groundwater: (A) Effect of voltage at 0.6 gpm; (B) Effect of flow rate at 10 V.

3.1.2 Effect of Membrane Type and Water Source

Figure 3A shows that Neosepta membrane produced a faster reduction in conductivity than Ralex membrane at high flow rates and low voltages, although both types of membranes contained the same functional groups that are responsible for the transport of counter-ions and repulsion (R-SO_3^- and $-\text{NR}_3^+$). This may be explained by the difference in the properties of the two types of membranes. The Neosepta membrane has smaller thickness and smaller resistance compared to the Ralex membrane (Table 1), which resulted in higher transport of ions. Additionally, the Neosepta membrane has a slightly greater transport number (Table 1) which improves the ability of the ion-exchange membrane to transport ions.

Figure 3B shows the results when feed water with low and high conductivity, i.e. surface water and groundwater, respectively, are desalinated. In this experiment, the running conditions were high flow rate, low voltage and Neosepta membranes. The surface water and groundwater sources reached near zero conductivity almost simultaneously. The fast desalination of groundwater may be attributed to a larger concentration gradient across the membrane, which may have promoted a faster initial ionic transport across the membrane. The concentration of the main salinity-contributing ions (Ca^{2+} , Na^+ , and Cl^-) was much higher in groundwater than in surface. This was reflected in the conductivity, and consequently, in the total dissolved solids of the two water sources. The conductivity of 2 mS/cm is equivalent to an approximate TDS of 1,400 mg/L. The conductivity of 10 mS/cm is equivalent to an approximate TDS of 6,000 mg/L. A TDS of 1,400 mg/L is designated as fresh or surface water (0 mg/L- 2,200 mg/L) while a TDS of 6,000 mg/L is designated as brackish groundwater (2,200 mg/L – 8,300 mg/L). The TDS concentration, and therefore the conductivity, is determined by the concentration of ions in solution and the mobility of those ions. The ration between the two conductivities tested in this experimental research was 5. This means that there were five times more ions at the higher level than at the lower level of the factorial design available to move towards the cathode or anode. By testing low ions concentration (surface water) and relatively high ions concentration (brackish groundwater) (called groundwater in this study), it was possible to determine that the type of water plays a role in the EDM desalination process.

The rapid decrease in groundwater conductivity may also be explained by the fact that the electrical resistance to ion transport is much lower in a concentrated solution [22]. The observed results are consistent with the concept of mass transport dependence on the concentration gradient given by the Nernst Planck theory [23].

Figure 3 Conductivity variations of feed salt solution in D1 tank at 0.6 gpm and 10V: (A) Effect of membrane type with groundwater source; (B) Effect of water source using Neosepta membrane.

3.1.3 Effect of lowest and highest operating conditions on Feed salt conductivity

Figures 4 and 5 compare the conductivity-time variations for some of the experimental runs considering the effect of the four process parameters of the experimental design. When desalinating groundwater using Neosepta membranes with high flow rate and high applied voltage, a steeper conductivity slope is observed than the slope obtained when desalinating the same type of water using Ralex membranes, high flow rate and high voltage (Figure 4). However, there is a small difference between the conductivity variations when desalinating surface water using either Neosepta or Ralex membranes under the conditions of high flow rate and high applied voltage (Figure 5). Likewise, independently of the type of water source treated, both types of membrane require more time to reduce the conductivity of the feed solution when low applied voltage and low flow rate is used.

Figure 4 Conductivity variations of feed salt solution in D1 tank with groundwater at lower and higher flow rate and voltage with respect to type of membrane.

Figure 5 Conductivity variations of feed salt solution in D1 tank with surface water at lower and higher flow rate and voltage with respect to type of membrane.

The conductivity variations for the different combinations of process parameters displayed in Figure 2 through Figure 5 show that apparently each of the parameters plays an important role in the EDM desalination process. However due to the fact that flow rate caused a counteracting effect of current density and residence time on the process it is difficult to determine if the observed results are caused by an overlapping effect of flow rate with voltage, water source or type of membrane.

3.2 Full 2⁴ Factorial Design of Experiments

Contrary to conventional experimental design, which investigates every process parameter by changing one by one, the previously planned 2⁴ factorial experimental design applied in this study provided a response to all the process parameters (factors) at a time [24]. The factorial design was used to accurately identify the factors affecting EDM desalination and the interaction effects of the factors on the conductivity response. The factorial design helped to identify if a factor showed more effect and influenced the variation of one factor on the other factors. This was important because usually, the interactions between all the factors are neglected with conventional experiments, which makes it difficult to achieve real optimal performance conditions. The 2⁴ factorial experimental design included one-, two-, three-, and four-factor combinations of the factors. The response to a factor or combination of factors was measured as the difference between the initial and final conductivity (mS/cm) in the feed tank after 3.5 hours of operation. The number of hours was selected based on the minimal time that any of the runs took to reach near zero conductivity. Large conductivity responses represent fast conductivity reduction and therefore good desalination performance. With the purpose of simplifying the identification of the parameters, each parameter was assigned a letter, i.e. flow rate (A), applied voltage (B), water source (C), and type of membrane (D).

The main factor effects and interactions of the experimental design were determined using the General Linear Model (GLM) of the Minitab® 17 software. The GLM has the flexibility to incorporate multiple quantitative and qualitative independent variables. In the GLM model, categorical (qualitative) predictors are included as factors while continuous (quantitative) predictors are included as covariates for the factors. In the analysis, GLM combined ANOVA model with regression analysis to incorporate the two covariates, which were related to the response variable. This combination is also known as ANCOVA model [25]. The GLM tested the main and interaction effects of the factors, while controlling for the effects of the covariate. The standard model equation that incorporates covariates into the ANOVA model assuming only one factor is given by the equation

$$y_{ij} = \mu + \alpha_i + \beta_1 x_{1ij} + \cdots + \beta_p x_{pij} + \varepsilon_{ij} \quad (4)$$

where y_{ij} is the response, α_i is the corrected effect on y for factor i , β' s are the coefficient for the covariates, and x_p are the covariates, and ε are the error in the response. The corrected effect means that the covariates $x_1, \dots, x_p$ are taking into account. This model generalizes to more than one factor variable. For example, for two main effects, an interaction effect, and the presence of covariates, equation (4) converts to the equation [25]

$$y_{ijk} = \mu + \alpha_i + \beta_j + (\alpha\beta)_{ij} + \gamma_1 x_{1ijk} + \cdots + \gamma_p x_{pijk} + e_{ijk} \quad (5)$$

where γ 's are the coefficients for the covariates, and α, β are the ANOVA notations.

In the Minitab's GLM, the lower and higher levels of the type of membrane and membrane source were the categorical factors, and the lower and higher levels of the voltage and flow rate were the continuous covariates. The main effects of the factors and covariates were identified based on the P-values with > 95% of confidence interval. An analysis of variance table and a mathematical model in the form of a regression equation were generated by the GLM to explain the EDM behavior under the effect of the different process parameters tested. The software allowed to obtaining the statistical parameters, main effect plots, and normal probability plots of the standardized effects that helped identifying the parameter conditions for optimal EDM performance. Table 4 lists the experimental runs for the 16 combinations of the experimental design with the assigned lower and higher levels, as well as the responses after 3.5 hours.

Table 4 Experimental results for the 2⁴ factorial design.

Run	Factor combination	Factors				Response (mS/cm)
		Flow rate (A)	Voltage (B)	Water source (C)	Membrane type (D)	
1	1	-1	-1	-1	-1	4.68
2	A	+1	-1	-1	-1	7.86
3	B	-1	+1	-1	-1	9.73
4	AB	+1	+1	-1	-1	10.23
5	C	-1	-1	+1	-1	4.42
6	AC	+1	-1	+1	-1	5.54
7	BC	-1	+1	+1	-1	6.67
8	ABC	+1	+1	+1	-1	6.67
9	D	-1	-1	-1	+1	3.54
10	AD	+1	-1	-1	+1	4.50
11	BD	-1	+1	-1	+1	6.20
12	ABD	+1	+1	-1	+1	8.27
13	CD	-1	-1	+1	+1	2.36
14	ACD	+1	-1	+1	+1	4.05

15	BCD	-1	+1	+1	+1	5.32
16	ABCD	+1	+1	+1	+1	6.62

The analysis of variance table generated by the GLM is presented in Table 5. All main effects and two-way interactions are displayed in the model. Based on the P-values at the level of significance of 0.05, voltage, water source and type of membrane had statistically significant effect on the response. The flow rate had a P-value greater than 0.05, therefore it was concluded that this parameter doesn't have a significant effect on explaining the conductivity response. This was expected since increasing flow rate may increase the current density but at the same time decreases the residence time of the ions in the system, and in both cases the removal of ions and therefore the conductivity may be impacted. The P-values for the two-factor combinations was higher than 0.05 (95% confidence interval); therefore, the interaction between the main effects was not significant. This means that the individual effect of each of the significant factors (voltage, water source and membrane type) on the conductivity response doesn't change in the presence of the other factors.

Table 5 General Linear Model: Conductivity (mS/cm) versus flow rate (gpm), voltage (V), water source, and membrane type.

Factor		Values				
Water source		Groundwater, Surface water				
Membrane type		Neosepta, Ralex				
Covariate		Low	High			
Flow rate (gpm)		0.2	0.6			
Voltage (V)		10.0	15.0			
Analysis of Variance						
Source		DF	Adj SS	Adj MS	F-value	P-Value
A		1	37.953	37.953	5.39	0.068
B		1	180.095	180.095	25.58	0.004
C		1	129.525	129.525	18.40	0.008
D		1	152.723	152.723	21.70	0.006
AB		1	7.164	7.164	1.02	0.359
AC		1	5.210	5.210	0.74	0.429
AD		1	1.161	1.161	0.16	0.701
BC		1	18.628	18.628	2.65	0.165
BD		1	1.008	1.008	0.14	0.721
CD		1	19.386	19.386	2.75	0.158
Error		5	35.195	7.039		
Total		15	882.265			
Model Summary						
S	2.65313					
R-sq	96.01%					

R-sw (adj)	88.03%
R-sq (pred)	59.15%

The results from the GLM were validated with the Normal Probability plot of the residuals (Figure 6A) and the Residuals versus the fit of the residuals (Figure 6B). The normal plot of the residuals was used to check the normality of the treatment data. The plot of the residual was used to check for the constant variance. The plot in Figure 6A resembled a straight line meaning that the distribution of the residual was normal. The plot in Figure 6B showed no pattern, which means that the constant variance assumption in the GLM was satisfied. Therefore, the assumptions for both normality and constant variance were met.

Figure 6 (A) Normal probability plot; (B) residuals versus fit of Residuals. Response is conductivity (mS/cm).

The design was re-analyzed by choosing only the significant factor (voltage, water source, and type of membrane) in the model, and the results showed that the normality and constant variance assumptions were met again (results not showed here).

Since the three main effects had no interaction with other factors, their main effect plots were meaningful and are presented in Figure 8. The plots showed that the significant factors perform best (providing the highest conductivity response, mS/cm) at their higher levels. Therefore, it can be concluded that when performing EDM desalination, Neosepta membranes are preferred over Ralex membranes, 15V over 10V, and source water with higher ions concentration (groundwater) over that with lower ions concentration (surface water) [2]. These results were in agreement with the initial analysis presented in Figures 2 and 3.

Figure 7 Main effect plots (water source, membrane type and voltage) for conductivity (mS/cm).

The reanalyzed GLM gave a degree of freedom of 3 for the main effects, 4 for the lack of fit error, 8 for pure error, and 15 for the overall model. The total adjusted sum of squares (SS) for the model was the same as with the model containing all the main factors and interactions (SS= 882.26). The statistical parameters of the reanalyzed model, including P values for the main effects, are presented in Table 6. The R-square of the model (74.87%) was higher than the predicted value (64.26) % and fitted well the results of the model.

Table 6 Statistical parameter for 2^4 design.

Term	Coefficient	SE Coefficient	T-Value	P-Value
Constant	27.34	1.66	16.42	0.000
B	4.983	0.961	5.18	0.000
C	-5.85	1.92	-3.04	0.010
D	-6.54	1.92	-3.40	0.005
S	3.84435			
R-Sq	79.90			
R-Sq (adj)	74.87			
R-Sq (pred)	64.26			

The importance of the main effects, voltage, water source, and type of membrane, is reflected by the calculated p-values in Table 6. The P-value for voltage is greater than the p-value for water source and membrane type. This indicates that the amount of voltage applied is more important than the water source and the type of membrane used for desalination with EDM. The applied voltage, which represents the difference in electrical potential, will directly affect the current. Since current is directly proportional to current density, the rate of ionic migration towards the electrodes will be determined by the amount of voltage applied. The water source (based on ions composition and concentration) to be treated by EDM is the second factor of importance, leaving the type of membrane as the least influential parameter for EDM performance. The absence of interactions between voltage, water source, and type of membrane implies that the membrane performance doesn't depend on the composition of the water source or the voltage applied and vice-versa. The reason for this behavior is that the main role of the membrane is to provide the barrier for the separation of cations and anions, independently of how much voltage is applied and what components are present in the water source.

The regression model for the observed effects on conductivity was also obtained and the regression equations to predict the conductivity of the EDM process are given in Table 7.

Table 7 Regression equations for the 2^4 experimental design.

Factor combination	Equation
Groundwater - Neosepta	Conductivity (mS/cm) = $2.42 + 1.993 V$
Groundwater - Ralex	Conductivity (mS/cm) = $- 4.12 + 1.993 V$
Surface water - Neosepta	Conductivity (mS/cm) = $- 3.43 + 1.993 V$
Surface water - Ralex	Conductivity (mS/cm) = $- 9.96 + 1.993 V$

Based on the GLM of the 2^4 factorial design, the optimal parameters for best conductivity response in the EDM desalination process were determined as voltage = 15 V, Type of water = groundwater, and type of membrane = Neosepta.

4. CONCLUSION

A complete set of experimental results on electrodialysis metathesis (EDM) were analyzed using factorial experimental design. A 2^4 factorial experimental design was applied to determine the influence of process parameters on the performance of EDM desalination. It was found that the main effect of applied voltage on conductivity reduction, and therefore EDM performance, is greater than the effect of water source (ions concentration) and membrane type. Results show that the effect of main factors on

EDM desalination follows the order voltage > water source > type of membrane. Flow rate was found statistically insignificant, which means that the observed responses on reduction of conductivity can be explain without considering the effect of flow rate. This is possible due to the role that this parameter plays on causing that current density and residence time of ions in the EDM stack counteract each other. Negligible interaction effects were observed for the three parameters, meaning that the effect of the individual factors on the EDM performance is completely independent from the effect of the other factors. EDM can perform well when desalinating saline waters with TDS concentrations higher than the TDS of surface water, and by applying 15 volts and using Neosepta membranes. The general linear model (GLM) was able to model the effect of a combination of discrete and continuous factors on the EDM process by taking the continuous factors as covariates for the discrete factors.

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