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Effects of operating conditions on ion removal from brackish water using a pilot-scale electrodialysis reversal system

Leila Karimi*, Abbas Ghassemi

Institute for Energy & the Environment (IEE/WERC), New Mexico State University, P.O. Box 30001, Las Cruces, NM, USA, Tel. +1 575 646 3075; email: lkarimi@nmsu.edu (L. Karimi), Tel./Fax: +1 575 646 5474; email: Aghassem@nmsu.edu (A. Ghassemi)

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ABSTRACT

Understanding the effects of operating factors on ion removal in the electrodialysis/electrodialysis reversal (ED/EDR) process can significantly benefit industrial applications, enabling process optimization through different combinations of operational factors. Several studies have shown the effects of specific operating factors on ion removal, and it has been established that superficial velocity influences ion removal. However, previous studies have yielded mixed results on whether increases in superficial velocity increase or decrease ion removal; also, since previous studies are based on laboratory-scale ED systems, the results may not be fully applicable to full-scale desalination due to differences in system characteristics such as membrane area, flow path, and degree of superficial velocity's effect on ion removal. Therefore, this experimental study employs a pilot-scale EDR system that is very similar to a full-scale system in order to explore the effects of applied voltage, superficial velocity, and feed water temperature on ion removal. Additionally, a conceptual explanation is developed to explain the inconclusive results from previous research. The findings of this experiment confirmed that increases in superficial velocity decreased ion removal, and this result can help predict and optimize full-scale operations. In the investigated ranges, increasing voltage and temperature resulted in increased ion removal, while increasing superficial velocity resulted in decreased ion removal. The experiments were conducted at the Brackish Groundwater National Desalination Research Facility in Alamogordo, NM, USA on a General Electric Company pilot-scale EDR system with a maximum product flow rate of 45 L/min, using brackish water with a conductivity of 1,700 µS/cm.

Keywords: Desalination; Pilot-scale electrodialysis; Brackish water; Operating conditions

1. Introduction

The electrodialysis reversal (EDR) process, one of the membrane-based desalination technologies, has been used commercially for over 50 years [1], and is most feasible when the level of total dissolved solids (TDS) in feed water is in the range of 400–6,000 ppm [2]. Although electrodialysis (ED)/EDR has some limitations for the desalination of brackish waters with higher TDS, some researchers have reported success in the use of EDR processes to desalinate saline water with TDS of 30,000 ppm [3]. Compared to reverse osmosis and nanofiltration processes, ED/EDR is more robust against non-ionic species such as silica, which

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*Corresponding author.

causes scaling problems, because the EDR process does not affect any uncharged species in the stream, avoiding their accumulation or aggromerization [4,5].

Beside desalination, ED has wide applications, including the removal of heavy metals such as Cu and Pb [6–8]; applications of this process for sodium chloride production have also been demonstrated in Japan [9]. For the treatment of wastewater laden with heavy metals, ED/EDR offers several advantages, including the ability to recover valuable metals such as Cr and Cu, and the ability to produce a highly concentrated waste stream which makes disposal easier. Additionally, the ED processes are used to recover acids and bases from industrial wastewater [1].

In the EDR process, ion transport flux is described by the extended Nernst–Planck equation [10,11]. As shown in Eq. (1), the total flux of ion i in the EDR process is composed of three components, as follows:

$$J_\mathrm{i} = -D_\mathrm{i}\left(\frac{\mathrm{d}C_\mathrm{i}}{\mathrm{d}x} + z_\mathrm{i}C_\mathrm{i}\frac{F}{RT}\frac{\mathrm{d}\phi}{\mathrm{d}x}\right) + C_\mathrm{i}V \tag{1}$$

where D_i, C_i, F, R, T, ϕ, z_i, and V are ion diffusion coefficient, ion concentration, Faraday constant, molar gas constant, temperature, electrical potential, valence of the ion, and superficial velocity [10,11], respectively. In ion movement toward the ion exchange membrane in the desalting solution, migration and diffusion are the dominant ion transport mechanisms, while, in the direction of flow, convection has more effect and migration and diffusion can be neglected because of the large Peclet number [12]. The Peclet number, which is defined in Eq. (2), is the ratio of convection mass transport to diffusion mass transport. According to the ion transport direction and Eq. (2), the greater Peclet number in the direction of flow is expected since the superficial velocity value is higher than the mass diffusion coefficient:

$$\mathrm{Pe} = \frac{VL}{D} = \mathrm{Re}_\mathrm{L} \times \mathrm{Sc} \tag{2}$$

where V, L, D, Re_L, and Sc are superficial velocity, length of flow path, mass diffusion coefficient, Reynolds number, and Schmidt number, respectively. Based on Eq. (1), the ion transport rate toward the membrane involves ion concentration and applied electrical potential, the ion diffusivity, velocity, Peclet number, and temperature's impact on transport fuctionality. Additionally, the dependency of ion flux on temperature is embedded in the ion diffusion term. Eq. (3), derived from the Stokes–Einstein equation, reveals that the diffusion coefficient of ions changes linearly with temperature and inversely with viscosity [13]:

$$D_\mathrm{i}(T) = \frac{D_\mathrm{i}(T_0) \times T \times \mu(T_0)}{T_0 \times \mu(T)} \tag{3}$$

where $D_\mathrm{i}(T)$ and $D_\mathrm{i}(T_0)$ are diffusion coefficient at temperature T and reference temperature T_0, and $\mu(T)$ and $\mu(T_0)$ are solution dynamic viscosity at temperature T and reference temperature T_0, respectively. Although the diffusion coefficient of each ion is not independent of the others and the effective ion diffusion coefficient should be considered as the effective one for combinations of ions, Eq. (3) can give a good approximation of each individual ion diffusion coefficient at different levels of operating temperature. These basic equations clearly depict the kind of operating factors that can affect the removal of individual ions in the ED/EDR process, and will be discussed in the results and disscussion section later in this paper.

Generally, the EDR process is affected by controllable factors such as superficial velocity, which is the calculated velocity of fluid through the channels regardless of the presence of spacers in the channel, as well as temperature and applied voltage. Based on membrane type, the process can also be influenced by other factors, commonly referred to as noise effects, such as pH, concentration polarization, ambient temperature, fouling, and electrolysis effects, which are prohibitively difficult or costly to control. By knowing how operating factors affect the removal of different monovalent and divalent ions, it will be possible to produce desalinated water with acceptable quality at lower energy consumption, in a more efficient process. Although there are studies conducted to investigate these effects, they have been in the laboratory scale setting, and different results have been reported for batch and continuous experimental procedures.

Among the saline water sources (feed waters) which are desalinated to produce freshwater, the types and quantities of ions vary. Since desalted water for different applications, such as drinking water, can have different acceptable levels for different types of ions, sometimes desalination plants only need to remove particular types of ions; other ions can be left in the desalted water. Consequently, investigating the removal of ions under different operating conditions is crucially important.

The two most important factors that affect the rate of separation are applied voltage and the superficial velocity. Applying greater voltage increases current density, and causes a greater concentration gradient for each ion in the diffusion boundary layer [4]. Kabay et al. [14] reported that voltage variation affected monovalent ion removal more than divalent ion removal under their experimental conditions, which consisted of batch mode ED operation using ternary mixtures composed of NaCl–$CaCl_2$ and KCl–$MgCl_2$ salts. They also showed that the specific energy consumption is significantly affected by voltage variation. Demircioglu et al. [15] demonstrated the significant role of applied voltage on K^+ removal in their experiments. Banasiak et al. [16] stated that the removal of F^- was affected by voltage changes, while the NO_3^- removal was not influenced significantly by voltage variation. However, they explained that the observed effect was due to different initial concentrations of the ions and the ion characteristics.

Superficial velocity, also known as flow rate of feed stream, plays an important role for ion removal in the EDR process. Research, however, has yielded inconclusive results on its effects. Although some researchers reported positive or neutral effects from increasing the feed velocity, which was explained by how increasing the feed velocity decreases the thickness of the concentration boundary layer [4,14,15], several other researchers have reported that increased velocity has adverse effects on ion removal and separation performance. This effect is explained by a lower residence time for ions at increased flow rates, which can have negative effects on ion removal. It is assumed that at higher feed flow rates, the ions do not have enough time to pass through the membrane, and are rinsed from the membrane surface before passing [17–20]. Additionally, both positive and negative effects of superficial velocity on current efficiency and ion removal were reported by Sadrzadeh and Mohammadi in sea water treatment using a small ED system at different flow rates and different feed concentrations [21]. In the present research, a major objective is determining whether increased superficial velocity has an overall positive or overall negative effect on ion removal.

Also, although several valuable studies have been conducted to investigate the effect of operating parameters on the removal of ions in the ED process, nearly all of these studies have been done on very small, laboratory-scale ED systems. In these small systems, the influence of some of the investigated parameters, such as voltage, can be consistent between laboratory-scale and full-scale ED/EDR performance; however, the influence of some other parameters, like fluid velocity, can be different not only at different variable levels, but also at different ED/EDR stack sizes. Additionally, the laboratory-scale ED processes are mostly constrained to low levels of certain factors, such as stream velocity in dilute and concentrate chambers, number of cell pairs, and shape of flow path. Therefore, investigating the influence of operating factors at levels similar to the real values and using a pilot-scale EDR system—which is very similar to the full-scale EDR systems in terms of size of membrane effective area, flow path of streams, and size of electrodes—increases the findings' applicability to full-scale EDR systems. Consequently, in this study, the effects of the main operating factors such as applied voltage, superficial velocity, and temperature of feed water on ion removal were investigated at the pilot scale, with the major goal of resolving previously reported inconsistencies in the effect of superficial velocity on ion removal. Additionally, to explain the different results previously reported, a conceptual explanation is developed.

2. Materials and methods

The pilot-scale experiments were conducted in the Brackish Groundwater National Desalination Research Facility (BGNDRF) using a General Electric EDR setup with an influent flow rate capacity of 45 L/min. BGNDRF is a federal facility which functions under the United States Department of Interior, Bureau of Reclamation (Reclamation). This facility was established by an Act of Congress, and has the mission to support sustainable advanced water treatment research and technology development for inland brackish groundwater sources. This facility is located in Alamogordo, New Mexico, an optimal environment for desalination research, and is positioned in the Tularosa Basin, which possesses a vast supply of groundwater resources and a wide range of water qualities. A wide range of salinity is accessible inside this basin, within a 5-mile radius. The mission of BGNDRF is to conduct research for the development of cost-effective desalination and alternative energy technologies that produce sustainable sources of water and power for urban, industrial, agricultural, and environmental purposes. The facility includes a central research building located on a 40-acre site. Water for work at the facility is obtained from four wells. The available water sources have been categorized as well 1, which has the comparatively low salinity of 1,000–1,200 mg/L at 40°C and for which a cooling tower is available, and three mid-concentration TDS wells, 3, 4, and 2, with salinities of 3,450–6,400 mg/L at 21°C [22]. The schematic of the whole EDR setup, which is located in the fourth test bay in the facility, is shown in Fig. 1. In this set up, a feed pump pressurizes feed water for delivery to the test bay, after which the water is sent to the multi-media filter (MMF). The MMF removes suspended solids from the feed water due to its sieving functions of different media layers. The MMF employs ordered sizes of anthracite (0.85–0.95 mm),

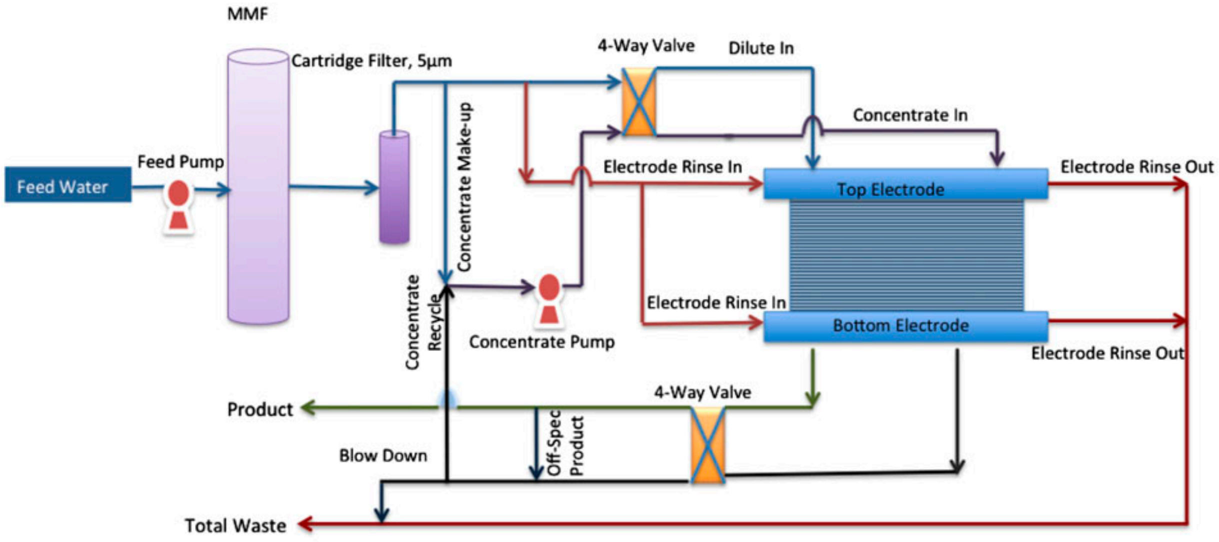

Fig. 1. Schematic of the pilot-scale EDR setup.

sand (0.85 mm), and garnet (0.42–0.6 mm) to remove suspended particles. The largest particles that can pass through the MMF are 10–15 µ in size [23]. Although the electrodialysis process does not generally require special pretreatment, applying an MMF can help to prevent damage and fouling of the membranes from sands and suspended solids in the feed water. Next, the feed water was passed through a cartridge filter, which was the final step before feed water entered the EDR stack. This filter had a pore size of 5 µm, and removed remaining suspended solids from the feed water.

The GE electrodialyzer was composed of one hydraulic and one electrical stage. The anion exchange membranes, cation exchange membranes, and spacers used in the experiment were GE AR908, GE CR67-HMR, and GE MK-IV, with a membrane effective area of 0.3 m^2 per ion exchange membrane, respectively. The EDR stack components were the same size as the components of a full-scale stack, and the only difference between this stack and a full-scale process was the number of cell pairs: the stack used in the experiments had 40 cell pairs, while in full-scale applications the number of cell pairs exceeds 600. The feed water used was from well 1, which provided brackish water with nominal conductivity of 1,700 µs/cm. The research facility could provide water from well 1 at two different temperatures: 24˚C after passing the cooling tower, or 38˚C directly from the storage tank. This provided the opportunity for researchers to conduct the experiments at two different temperatures. However, the temperature levels vary throughout the year. The feed water chemical condition and composition, which were obtained from analyzing the collected feed water samples in the process, are given in Tables 1 and 2. The feed water had total organic carbon (TOC) levels of 36.62 ppm, turbidity of 0.99 nephelometric turbidity units, and clear coloration.

As shown in Tables 1 and 2, the composition of water changed slightly at each operating temperature. This small difference was observed because some of the water evaporates in the cooling tower, and concentrates the feed water to some extent. Therefore, the conductivity of feed water was subject to change. The electrode rinse solution had the same feed composition, and was dosed with 15% hydrochloric acid. The injected acid was consumed to neutralize the hydroxide ions formed in the cathode, preventing scaling problems in the electrodes.

The experiments were carried out at two levels of temperature and superficial velocity, and six levels of voltage, as shown in Table 3.

The levels of superficial velocity were chosen based on the minimum and maximum flow rates recommended by the manufacturer. The maximum permissible voltage was chosen based on the examined

Table 1
Feed water conductivity and pH

Brackish ground water BGNDRF well 1		
Temperature (˚C)	Conductivity (µs/cm)	pH
24	1,765	8–8.1
38	1,650	8–8.3

Table 2
Feed water composition in the pilot-scale experiments

	Brackish ground water BGNDRF well 1								
	Average concentration of cations (standard deviation), ppm					Average concentration of anions (standard deviation), ppm			
Temperature (°C)	Ca^{2+}	Mg^{2+}	Na^{+}	Sr^{2+}	K^{+}	Cl^{-}	SO_4^{2-}	HCO_3^{-*}	F^{-}
24	50.5 (1.8)	8.6 (0.3)	376.9 (3.2)	<2 (NA)	2.1 (0)	35.9 (1.3)	664.0 (17.6)	185.1 (2.5)	2.0 (0.1)
38	47.0 (3.0)	7.5 (0.5)	363.6 (5.1)	<2 (NA)	2.0 (0)	31.6 (0.7)	628.2 (11.6)	187.2 (1.8)	2.0 (0.2)

*May have a negligible source of CO_3^{2-} due to a feed water pH above 8.

Table 3
Operating condition levels in the pilot-scale experiments

Factor	Factor level	Factor experimental value
Feed linear velocity	1	8.8 cm/s
	2	13.1 cm/s
Temperature	1	24 ℃
	2	38 ℃
Voltage	1	2.6 V
	2	9.8 V
	3	21.7 V
	4	33.4 V
	5	45.3 V
	6	57.7 V

conditions using results from previously conducted limiting current tests. The voltage range was selected to represent a wide range of applied voltage.

The experiments were conducted in continuous system. Therefore, new feed water was used for every experiment. The feed water condition of temperature was controlled. For experiments at higher temperature, the well water was sent to the test bay directly from the storage tank, while experiments at lower temperature, water was delivered to the test bay after passing the cooling tower. The stream flow rates, superficial velocity of the streams, and the applied voltage were controlled through the experimental setup. Before applying electricity to the system, the flow rates were adjusted to provide the proposed superficial velocity. The system was allowed to run for 5 min to reach the steady state condition after applying the electricity to the stack. All of the experiments were conducted at the same polarity—i.e. the EDR system was running at positive polarity for half an hour when the experiments and water sample collections were done. However, to prevent scaling problems, it was also necessary to run the system at negative polarity, in the reversal condition. After polarity reversal, the system was allowed to run for 10 min to reach the steady state condition before sample collection started. Additionally, during the experiments, the flow rates were controlled carefully to reduce the noise effects. For each experiment, 250 ml water samples of feed, product, and concentrate streams were collected, and then the experiment and water sample collection were repeated for the next voltage level. The collected water samples were kept in the refrigerator to prevent any evaporation before they were analyzed. The water samples were analyzed using a Dionex ICS-5000 Dual Channel IC System, an ion chromatography system capable of measuring cations via an analytical compartment and anions via a capillary compartment. Additionally, samples were analyzed for their pH levels to detect the presence of carbonate and bicarbonate. Then, the titrations were done for water samples to determine the amount of any possible carbonate. However, the titration procedure cannot be considered an accurate method for very small amounts of species. Therefore, the samples were analyzed using a TOC analyzer, Shimadzu TOC-VCSH, to determine the total inorganic carbon (TIC). Due to the pH level of the samples, all of the reported TIC was assumed to be from an HCO_3^{-} source, but later experimental results suggested a negligible CO_3^{2-} presence.

3. Results and discussions

3.1. Effect of applied voltage and ion size on ion removal

Generally, under normal operating conditions below limiting current, increasing the amount of applied voltage increases the removal of ions and current density. The effect of applied voltage on ion removal depends on certain ion characteristics, such as charge and hydrated radius. Ions with greater electrical charges are affected more strongly by an electrical field than ions with a smaller electrical charge. This effect is distinctly shown for cations and anions in Figs. 2 and 3. In order to show this effect in conducted experiments, the percent removal of each ion was calculated using Eq. (4). Then, the percent removal of ions was plotted vs. the applied voltage to the stack.

$$\%\,\text{Removal} = \frac{(C_{\text{F,i}} - C_{\text{P,i}})}{C_{\text{F,i}}} \times 100 \tag{4}$$

where $C_{\text{F,i}}$ and $C_{\text{P,i}}$ are the concentrations of ion i in the feed and product streams, respectively.

In this experiment, the removal rates of different ions were not compared to a reference species due to the different concentrations of different ions. When the initial concentration of a specific ion is greater than the other ions, more ions of that type are available to be affected by applied voltage which results in better removal of that type ion. By analyzing ion

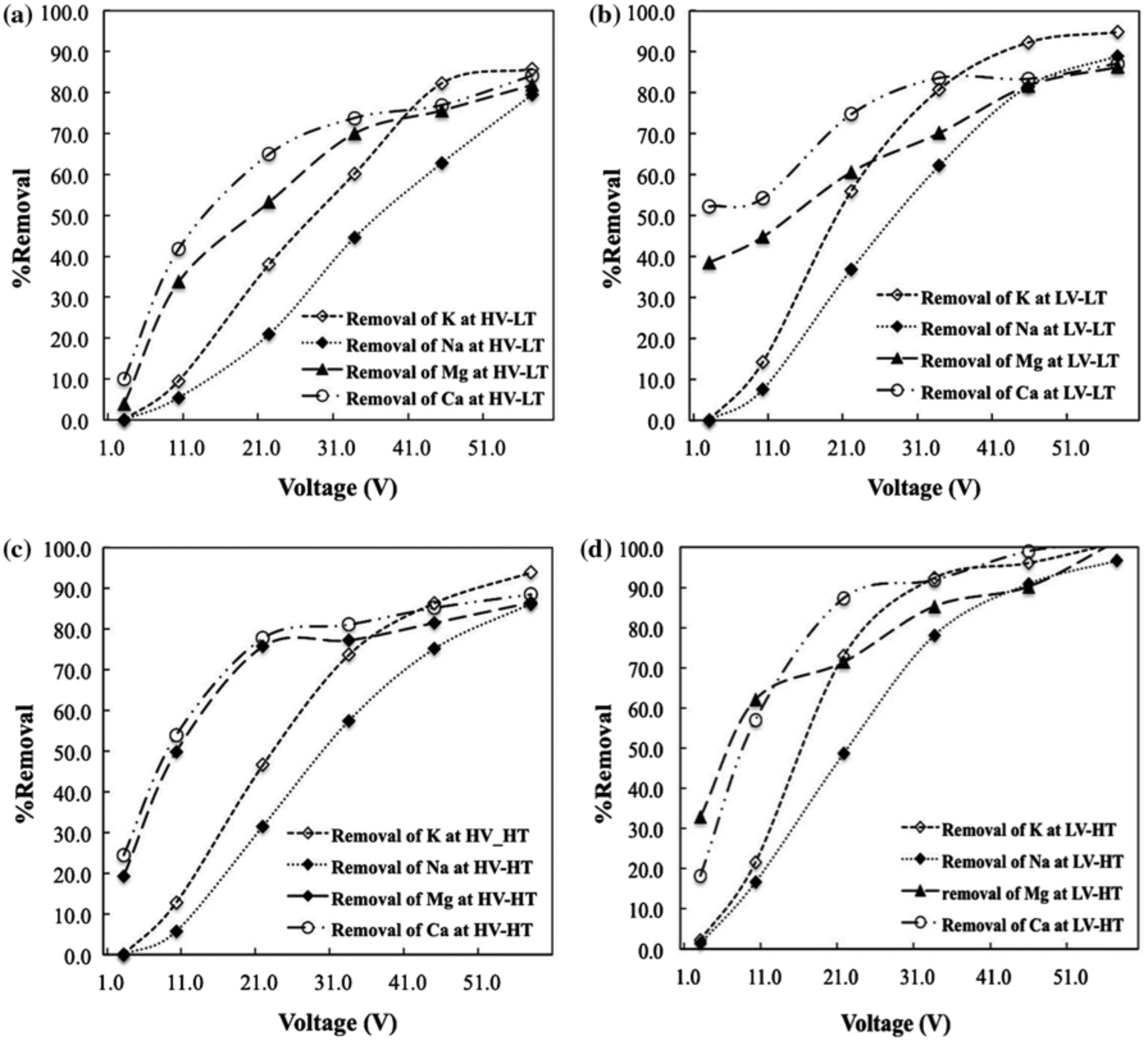

Fig. 2. Effect of voltage on removal of cations at (a) high velocity–low temperature, (b) low velocity–low temperature, (c) high velocity–high temperature, and (d) low velocity–high temperature.

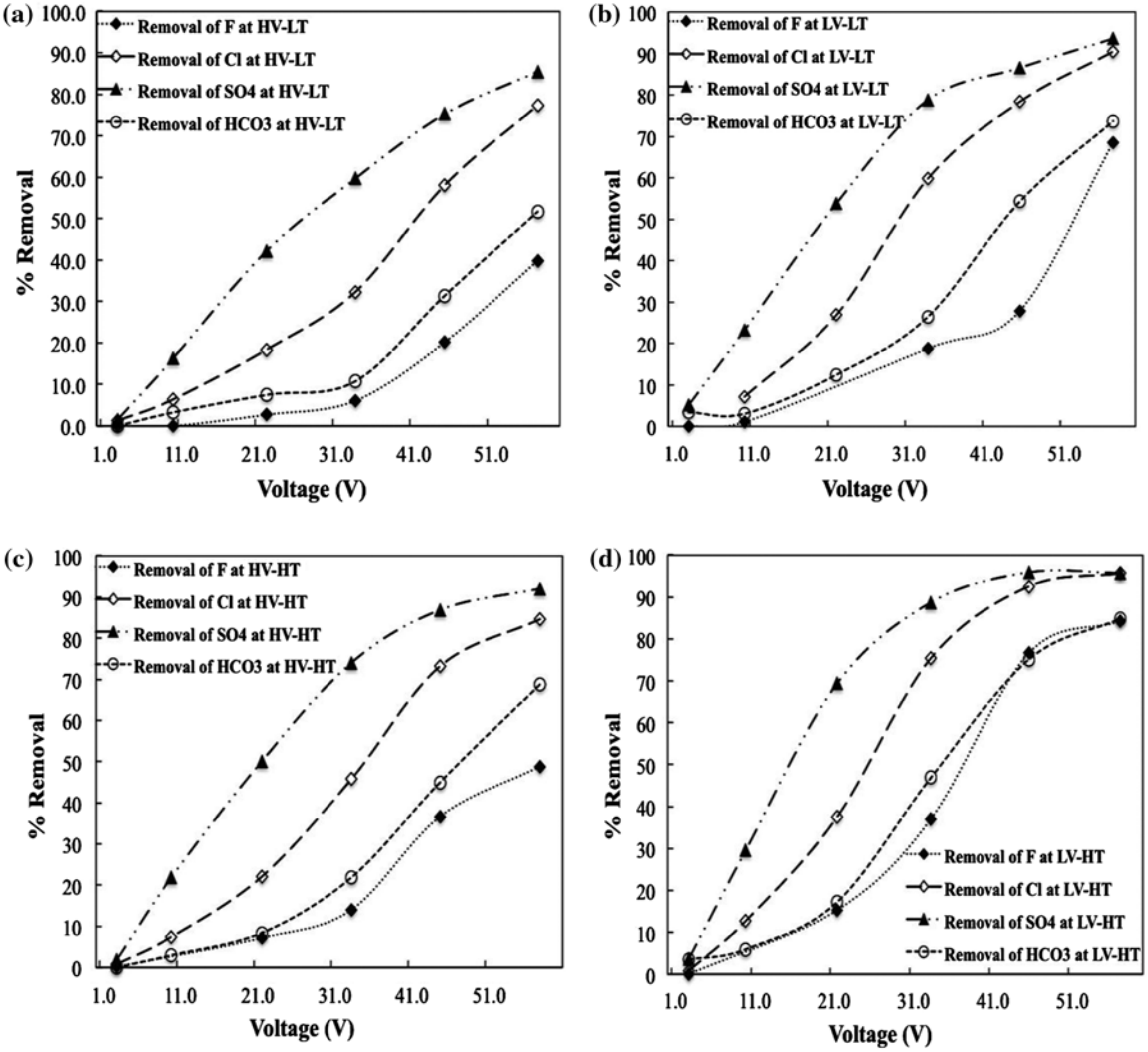

Fig. 3. Effect of voltage on removal of anions at (a) high velocity–low temperature, (b) low velocity–low temperature, (c) high velocity–high temperature, and (d) low velocity–high temperature.

removal based on percent change rather than absolute removal in comparison to a reference ion, it is possible to normalize the effect of different initial ion concentrations.

The data from Fig. 2 depicts how the divalent cations, Ca^{2+} and Mg^{2+}, were removed better than monovalent cations such as K^+ and Na^+. However, while this trend was shown in almost all of the plots of this figure at lower voltage, at higher applied voltages the percent removal of the ions converged to a unique value, especially at lower velocity and higher temperature, under which conditions the greatest amount of removal was observed. According to the graphs within Fig. 2, the effect of applied voltage on the removal of ions was not consistent in all ranges of applied voltage. Additionally, it was shown that when applied voltage was constant, the percent removal of Ca^{2+} was greater than the percent removal of Mg^{2+}. Since Ca^{2+} has a smaller hydrated radius than Mg^{2+} [24, 25], the better removal of Ca^{2+} could be explained by its smaller size. The effect from the size of ions' hydrated radii was also observed in the higher removal percentage of K^+ as compared to the removal percentage of Na^+. K^+ has a smaller hydrated radius than Na^+ [24, 25], so as with Ca^{2+} and Mg^{2+}, K^+ ions were removed more effectively than Na^+ ions.

The same effects from voltage, electrical charge, and hydrated ion size that were observed with cations were also observed in the removal of anions, as shown in Fig. 3. Divalent anions, such as SO_4^{2-}, were removed better than monovalent anions, such as Cl^-, F^-, and

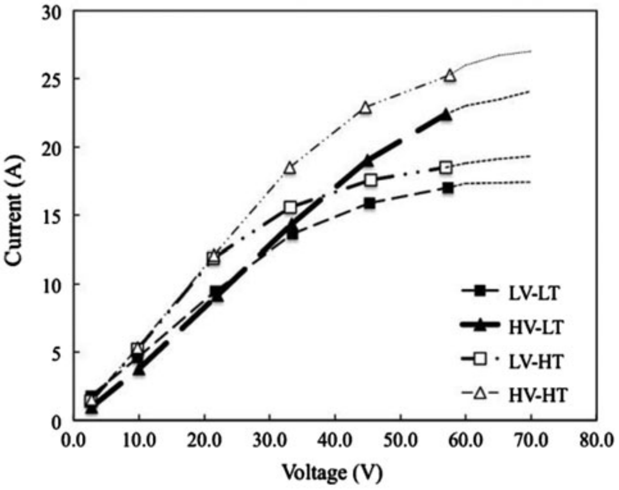

Fig. 4. Variation of current vs. voltage.

HCO_3^-. Since HCO_3^- has a larger hydrated radius than F^- [26], it was expected that less removal of HCO_3^- would be observed in comparison to F^-. The observed difference in the removal of these two monovalent anions implies that the total inorganic carbon, which was initially identified as HCO_3^- on the basis of the pH measurements and titration results that confirmed the absence of CO_3^{2-} in samples with a pH level lower than 8.3 [27], must have had a negligible amount of CO_3^{2-} which was not high enough to be detected by titration method.

During the experiments, the current was measured and recorded. Current was not considered as an independent variable for ion removal studies because the current efficiency varies with ion concentration; therefore, according to the previous studies, the voltage can be considered as a more universal and independent parameter to analyze different rates of ion removal under different conditions [7,8,15,21]. Fig. 4 shows the variation of current vs. applied voltage at different operating conditions.

Fig. 4 shows that the measured current during the experiments at different conditions was affected by ion removal and superficial velocity (flow rate) differently at lower and higher levels of voltage at both low and high temperatures. It illustrates that the current at high voltages increased at both levels of temperature when superficial velocity increased, while its value was not affected by superficial velocity variations at lower levels of voltages. In order to verify this observation and confirm the inconsistent current behavior shown in Fig. 4, the percent change in product flow rate (L/s) was multiplied by total ion removal (molar), and plotted vs. voltage in Fig. 5(a) and (b) alongside the percent change in current, which was calculated for different conditions.

The theoretical value for current through the stack can be calculated from Faraday's law as follows:

$$I = \frac{zFQ\Delta C_i}{\eta N_{cp}} \tag{5}$$

where I, z, F, Q, ΔC_i, η, and N_{cp} are electrical current (A), ion valence, Faraday constant (As/eq), flow rate (cm^3/s), desired ion concentration difference between feed and dilute streams (mol/cm^3), current efficiency, and number of cell pairs, respectively. The plotted values in Fig. 5(a) and (b) explain the different behavior of measured current at the different levels of voltage shown in Fig. 4. Although, based on Eq. (5), a positive effect on current was expected from an increase in superficial velocity, such positive effect was compromised by the negative effect on the current from reduction in ion removal. Additionally, the greater slope of current at higher velocity, as shown in Fig. 4, demonstrates that the limiting current should be achieved at higher levels of voltage (virtual dot lines). This observation confirms the positive effect of velocity on decreasing the concentration polarization and reducing the thickness of the boundary layer. However, at lower superficial velocity levels, limiting current can be obtained at lower voltage levels, as shown in Fig. 4 using the dotted lines.

Table 4
Mobility of individual ions at different operating conditions

		Mobility ($m^2/V/s$) × 10^8							
		Cations				Anions			
V (cm/s)	T (℃)	Ca^{2+}	Mg^{2+}	Na^+	K^+	F^-	Cl^-	CO_3^{2-}	SO_4^{2-}
8.8	24	6.04	5.39	5.09	7.47	5.63	7.75	4.52	8.13
	38	7.95	7.09	6.70	9.83	7.41	10.20	5.95	10.69
13.1	24	5.94	5.29	5.00	7.34	5.53	7.62	4.44	7.99
	38	7.97	7.10	6.71	9.84	7.42	10.22	5.96	10.71

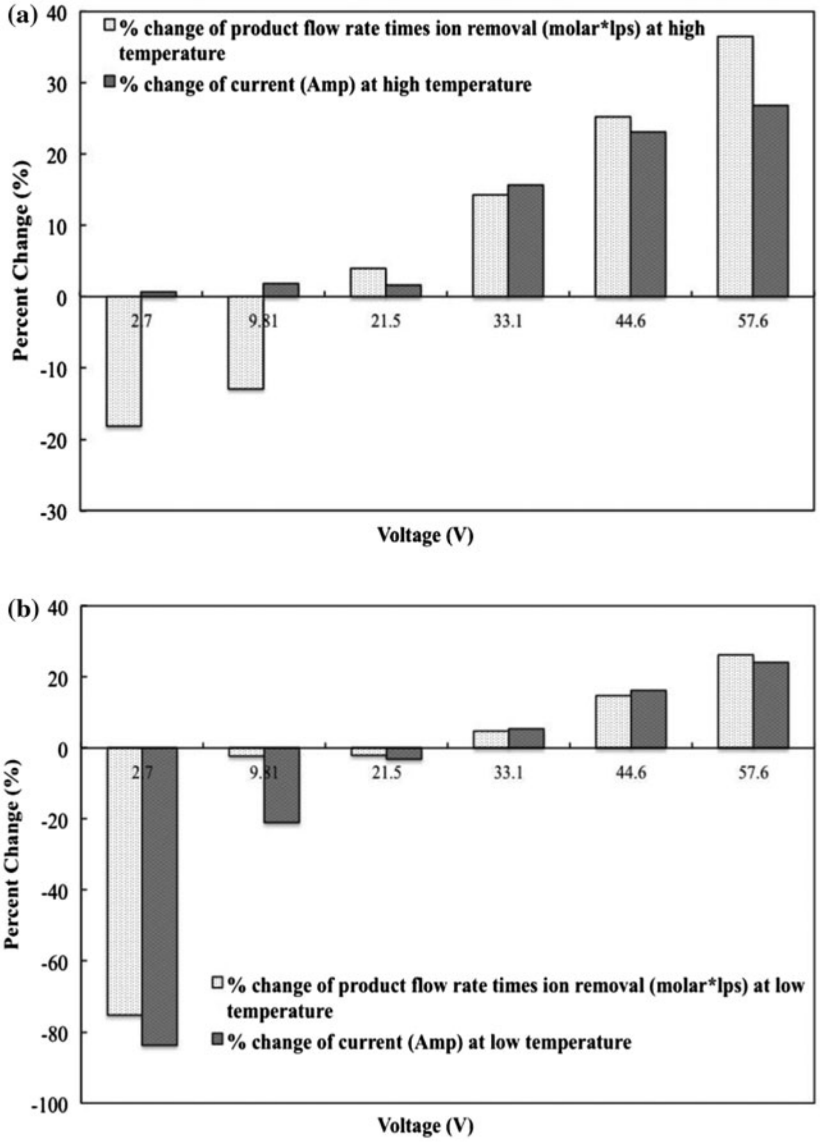

Fig. 5. Values for percent change of product flow rate times total ion removal and percent change of current at different levels of voltage at (a) high temperature and (b) low temperature.

3.2. Effect of superficial velocity and temperature on ion removal

As discussed before, two of the other parameters that affect ion removal in the EDR process are superficial velocity, also called flow rate, and the temperature of the dilute stream. Based on the results obtained from this experiment, the impact of these parameters on the removal of cations and anions is shown in Figs. 6 and 7.

Notably, several previous experiments have reported that increases in the superficial velocity can have either positive or negative effects on ion removal. Positive effects are attributed to increased turbulence of flow, decreased thickness of the boundary layer, and reductions in the concentration polarization. Negative effects are attributed to decreased residence time. As can be seen in Figs. 6 and 7, the plotted curves from this experiment confirmed the overall negative influence of increased superficial velocity.

This observed reduction trend in the removal of all ions can be explained by decreased residence time, a characteristic which can be defined as follows:

$$t_{\text{resid}} = \frac{L}{V} \tag{6}$$

where t_{resid}, L, and V are residence time, flow path length, and superficial velocity, respectively.

According to this equation, the residence time decreases 33% over the constant flow path in the EDR stack when the linear velocity is increased from 8.8 to 13.1 cm/s. The observed reduction in ion removal is due to the decrease in the residence time, meaning the ions had less time to pass through the membranes and transfer from dilute stream to the concentrate stream.

According to the obtained results, the reduction in residence time did not affect the removal of all ions linearly and consistently. The nonlinearity of this relationship can be explained by the hidden positive effect of superficial velocity on the thickness of the boundary layer, which affects ion removal rate. Additionally, the non-homogeneous influence of residence time reduction on the removal of different ions can be justified by accounting for the different behavior of ions and their removal rate in the EDR process due to their different characteristics.

To develop a conceptual explanation for why several previous experiments report overall positive or neutral effects on ion removal from increases in superficial velocity, it can first be noted that these results are reported only from experiments using batch processes and a constant experimental duration for different superficial velocities. In batch experiments, the system operates as a closed loop, where the outputs of the system cycle back as inputs. In such a system, therefore, if the experiment's time duration is held constant for different levels of velocity, an increase in superficial velocity increases not only the velocity, but also the number of times that

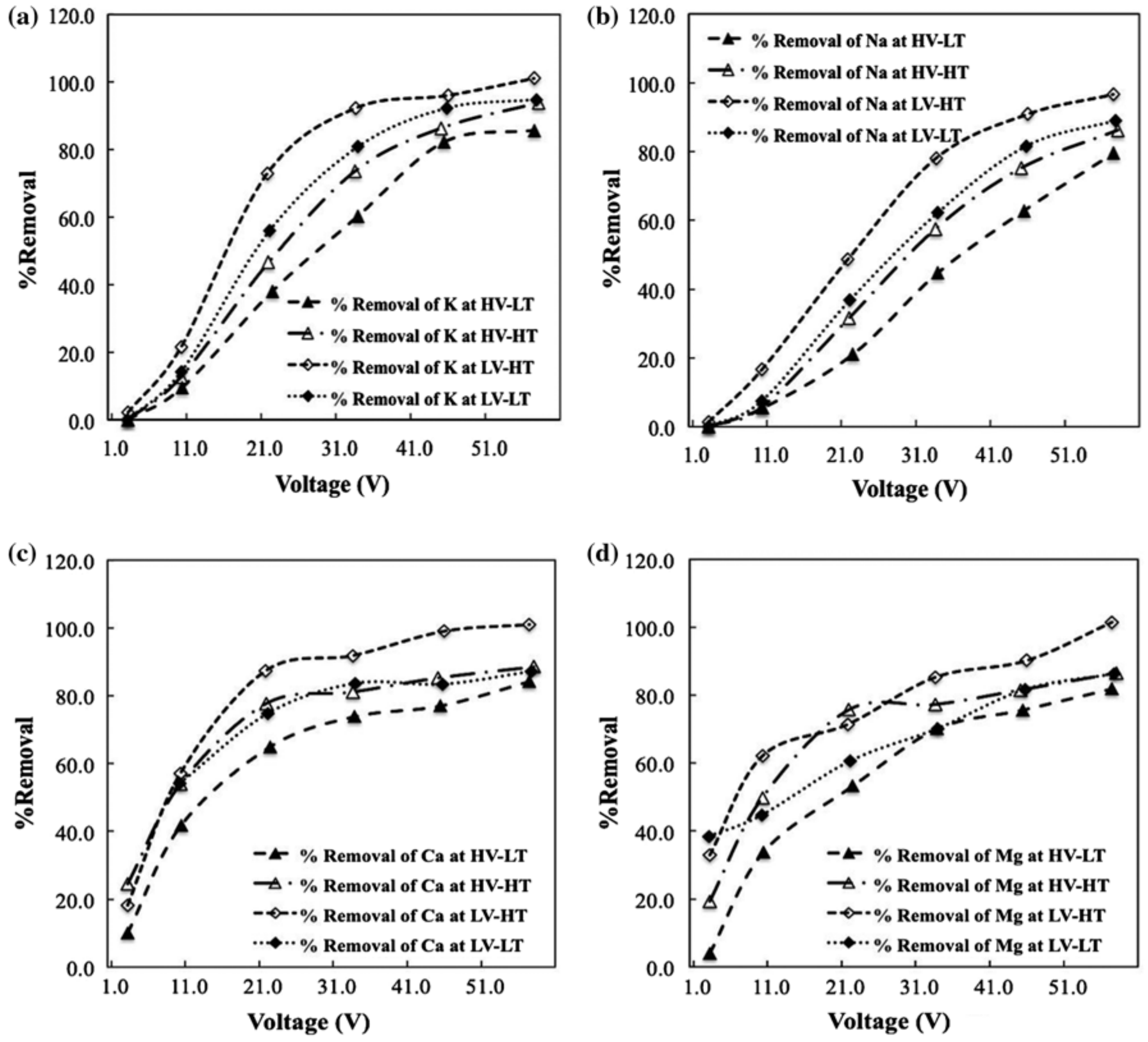

Fig. 6. Effect of velocity and temperature on removal of cations, (a) K^+, (b) Na^+, (c) Ca^{2+}, and (d) Mg^{2+}.

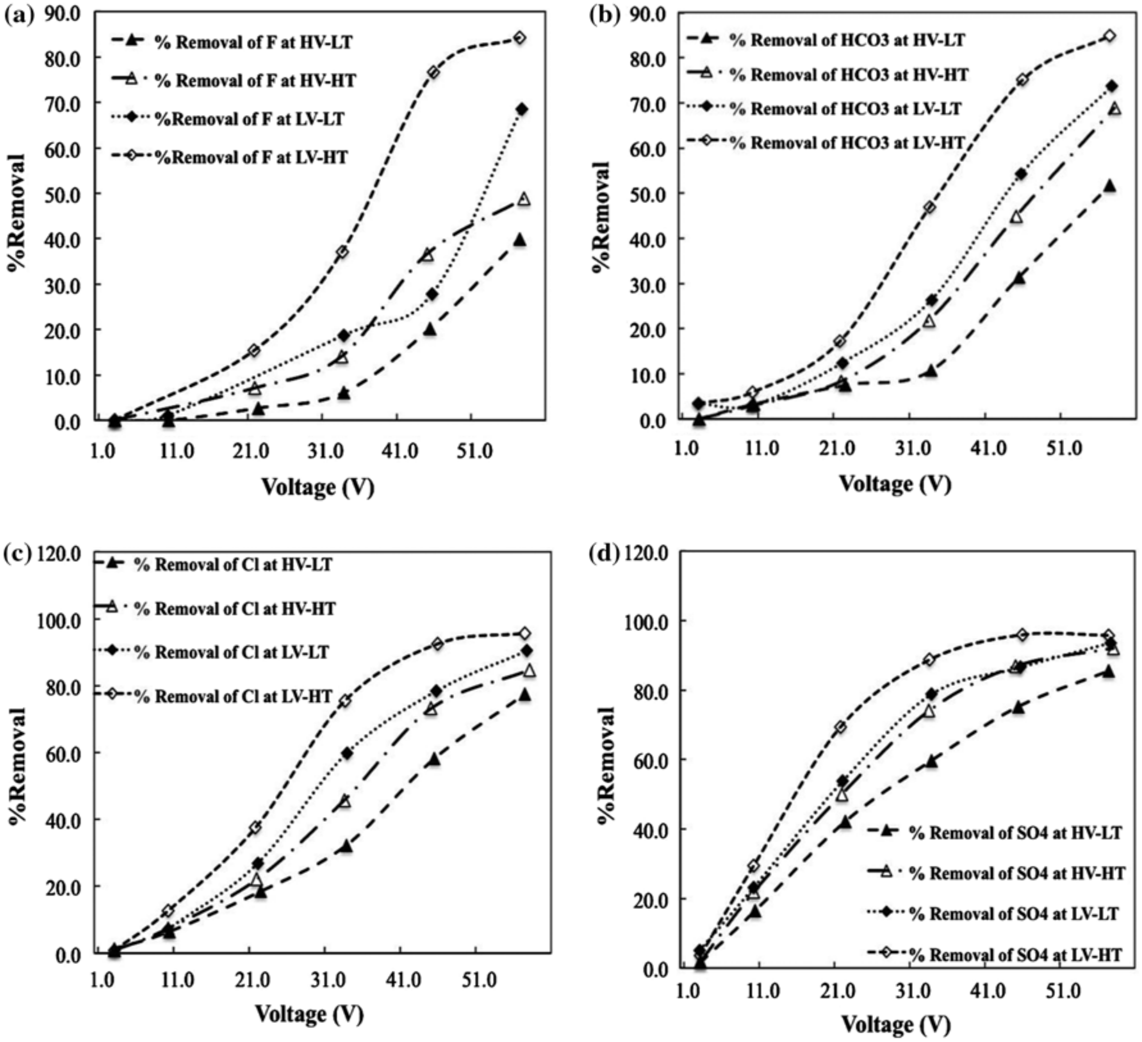

Fig. 7. Effect of velocity and temperature on removal of anions, (a) F^-, (b) HCO_3^-, (c) Cl^-, and (d) SO_4^{2-}.

the solution passes through the membrane. Therefore, experiments using a batch system with a constant time duration for different velocities may be recording the positive effect of additional passages through the ED stack, which could offset the negative effect of increased velocity to yield overall positive or neutral results.

One of the other operating factors which impacts ion removal is operational temperature. According to the curves shown in Figs. 6 and 7, increasing the temperature of feed water from 24 to 38˚C improved ion removal for both cations and anions. It appears that increasing the temperature improves ion mobility and consequently increases the ion removal. The ion mobility at different temperatures can be calculated using the Nernst–Einstein equation as follows:

$$u_i = \frac{|z_i| F D_i}{RT} \tag{7}$$

where u_i, z_i, F, D_i, R, and T are ion mobility, ion charge, Faraday constant, ion diffusion coefficient, molar gas constant, and absolute temperature, respectively. By incorporating the effect of temperature on the diffusion coefficient of ions using Eq. (3) into the Nernst–Einstein equation, the ratio of ion mobility was calculated and reported in Table 4 for individual ions. The results showed that when temperature was increased from 24 to 38˚C, individual ion mobility increased 1.3 times for both cations and anions when the diffusion coefficients of ions were assumed to be independent of each other. However, because of the nature of the Nernst–Planck equation, Eq. (1), in which the temperature term is the denominator term of ion flux, this ratio is not the same as the observed ratio at which ion removal increased under the effect of temperature.

4. Conclusion

Since operating factors play an important role in the technical, economic, and product quality aspects of the desalination process, the influence of operating factors on pilot-scale EDR was investigated in this paper. Of special interest, due to inconsistent findings in previous research, was the question of whether increases in superficial velocity have positive or negative effects on ion removal. Generally, the experiments conducted in this research at the pilot-scale confirmed that feed superficial velocity and feed temperature both affect the removal of anions and cations in the pilot scale electrodialysis desalination process. Increases in the superficial velocity of the feed stream in the given range had a negative effect on ion removal due to decreases in the ion residence time. Although the superficial velocity increases had a positive effect by decreasing the concentration polarization and the thickness of the boundary layer, the negative effect from the decrease in residence time had a greater influence in the range of velocities studied. Additionally, the observed effect on the removal of different ions from superficial velocity was not consistent across the whole range of applied voltage, as shown in Figs. 5–7. Moreover, increases in temperature in the examined range improved ion removal at both levels of superficial velocity. In addition, the applied voltage in the stack had a different effect on different ions due to their electrical charges and different hydrated radii. However, at higher levels of voltage, the removal of ions converged to a unique value; so, the comparative effect of voltage on different ions can be better investigated at lower levels of voltage. Studying the effects of the above-mentioned operating factors on pilot-scale EDR confirmed that the EDR process can be controlled at specific levels of operating conditions in order to obtain the desired removal of specific ions in full-scale applications.

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Symbols

C_i	—	ion concentration (mol/cm^3)
D_i	—	ion diffusion coefficient (cm^2/s)
F	—	Faraday constant (A s/eq)
I	—	electrical current (A)
L	—	flow path length (cm)
N_{cp}	—	number of cell pairs
Q	—	flow rate (cm^3/s)
R	—	molar gas constant (J/mol K)
Re	—	Reynolds number
Sc	—	Schmidt number
T	—	temperature (K)
T_0	—	reference temperature (K)
t_{resid}	—	residence time (s)
u_i	—	ion mobility (cm^2/V s)
V	—	superficial velocity (cm/s)
z_i	—	charge of the ion

Greek

ϕ	—	Electrical potential (V)
μ	—	Dynamic viscosity (Pa s)
η	—	Current efficiency

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