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Effects of electrode design on electrodialysis reversal performance

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ABSTRACT

Electrodialysis/electrodialysis reversal (ED/EDR) is a promising brackish water desalination processes. As with any other desalination process, ED/EDR can be affected by several operating and design factors, many of which have been investigated thoroughly. The influences of operating factors—such as applied voltage, flowrate, and temperature—are known, as are the influences of several design factors, such as membrane characteristics, spacer configuration, and spacer thickness. However, no published results have explored how electrode design affects the process. This paper uses pilot-scale experiments at the Brackish Groundwater National Desalination Research Facility to investigate how three different electrode designs—full, recessed, and tapered—affect the performance of EDR systems. Performance was measured as the amount of electrical current in the stack, removal percentage, and standardized power consumption (SPC); the key factor for the comparison was considered to be SPC. The experiments were conducted at two levels of feed salinity (1.7 and 3.9 mS cm^{-1}), three levels of feed flowrate (0.44, 0.57 and 0.69 Ls^{-1}), and five levels of applied voltage (30, 32.5, 35, 37.5, 40 V) using three types of electrode (full, recessed, and tapered). Electrode type was found to affect electrical current, removal percentage, and SPC at both investigated salinity levels. It was also found that, although using a full electrode resulted in the highest removal percentage, the SPC of the recessed electrode was lower than the SPCs of the full and tapered electrodes in higher salinity. However, recessed and full electrodes had similar, but better performance in comparison to tapered electrode when brackish water with lower salinity was used.

Keywords: Electrodialysis reversal; Brackish water; Electrode design; Standardized power consumption

1. Introduction

Desalination is a process that removes excess salts from saline water to make it suitable for human consumption and other uses [1,2]. Although desalination has the potential to provide abundant fresh water from readily available saline water sources, the high costs of desalination have limited the use of desalination technologies [3], which could be rendered more efficient and cost-effective.

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Generally, desalination technologies are classified into two main groups: thermal desalination technologies, which are based on the evaporation and condensation process, and membrane-based approaches, where separation occurs by means of membranes. The most commonly used membrane-based technologies include reverse osmosis (RO) and electrodialysis/electrodialysis reversal (ED/EDR) [4,5].

ED is an electrically driven membrane process in which an electrical field moves ions through ion-exchange membranes, which selectively transfer the ions. EDR was introduced in the 1970s as an innovative modification of existing ED technology [6]; EDR works in the same fundamental way as ED, but in EDR the polarity of the DC power is reversed at specified time intervals, allowing for a "self-cleaning" of the membrane surfaces [7].

An EDR stack's basic structure consists of electrode chambers and membrane cell pairs. Each electrode chamber consists of an electrode, a heavy cation exchange membrane, and an electrode water flow spacer. The water-flow spacer prevents the electrode waste from entering the main flow paths of the stack, and this spacer, which typically is thicker than a normal spacer, increases electrode rinse solutions' flowrate to prevent scaling [8]. An electrode chamber is located at each end of the membrane stack and conducts electric current into the stack. Because of the corrosive nature of the anode compartments, electrodes are usually made of titanium and plated with platinum. The membrane stack is composed of many cell pairs, and each cell pair consists of an anion-exchange membrane, a concentrate spacer, a cation-exchange membrane, and a dilute spacer [9]. These basic cell pairs are repeated throughout the interior of the stack, which is capped on both ends by the electrode compartments.

Generally, the EDR process can be affected by different operating factors—such as feed flowrate, applied voltage, feed salinity, temperature—as well as design parameters, such as the type of spacer and membrane characteristics. The effects of operating parameters on EDR performance have been determine through comprehensive study [10], and among the operating factors, applied voltage and feed flowrate have been identified as the most impactful. Applying greater voltage increases the ion migration in the solution phase and ion exchange membrane and increases current density [11,12]. Applying higher feed flowrates has an overall negative effect on ion removal, likely due to reduced ion residence time in the stack. Although increasing the flowrate can increase the mass transfer rate by reducing the concentration boundary layer, at higher feed flowrates, the ions do not have enough time to be transferred from dilute chamber to concentrate chamber [11,13–15].

Several researchers have also studied the influence of design parameters on the performance of the EDR process. Both spacer design and membrane characteristics have attracted significant research attention. The effects of spacer characteristics and cell configuration on the hydrodynamics of the desalting cell and the thickness of the boundary layer have been investigated, and it has been shown that the mass transfer rate increases when inert spacers are used in the flow chambers at a Reynolds number lower than the critical value in the free desalting cells [16]. Additionally, it has been found that using ion-conductive spacers in the ED/EDR process increase the ionic mass transfer rate by decreasing electrical resistance in the stack [17–19].

Research on membrane characteristics has found that ion transport is affected by the characteristics of the polymer matrix, the type and concentration of fixed ions, and the degree of crosslinking in the membrane structure [10]. These characteristics can be controlled to some extent in the manufacturing process. Additionally, common ion-exchange membranes can be modified to increase or decrease their permeability for certain ions. For instance, implementing a polycation layer on the surfaces of a cation exchange membrane can decrease its divalent cation permeability due to intense repulsion between divalent cations and the polycation layer [20,21].

Despite the thorough and valuable research on how operating [22–24] and design parameters affect the performance of the EDR process, no published research has yet explored the influence of electrodes, essential EDR components that provide the driving force for desalination. In this research, it was hypothesized that the shape of the electrodes and the configuration of their surface area with respect to the solution manifolds could impact the performance of EDR systems.

2. Materials and methods

The experiments were performed at the Brackish Groundwater National Desalination Research Facility in Alamogordo, New Mexico, using brackish feed water and GE Water and Process Technology's MK-IV-2 EDR stack, detailed in Table 1. The schematic of the whole EDR setup, which is located in the fourth test bay in the facility, is shown in Fig. 1.

In Bay 4, the brackish source water flows into the pretreatment system, comprised of a multi-media filter (MMF) and a 5-micron cartridge filter [25]. The utilized MMF has anthracite (0.85–0.95 mm) on the top,

Table 1
EDR stack specifications

Type		GE Mk-IV 2
EDR stack	Polarity reversal cycle	15 min
	Electric/hydraulic stage	1
	Number of cell pairs	40
Membrane	Heavy cation-exchange	GE CR67-HMR
	Cation-exchange	GE CR67-LLMR
	Anion-exchange	GE AR204-SZRA
	Membrane dimensions	102 cm × 46 cm × 0.06 cm
	Effective membrane area	0.47 m^2/membrane
	Spacer model	Mk-IV
	Spacer surface area	0.34 m^2/membrane (flow path = 2 m)
Electrode information	Type and active area	Full: 3,299.348 cm^2 Recessed: 3,183.219 cm^2 Tapered: 3,299.348 cm^2

then gradually coarser sand (0.85 mm), followed by garnet in gradually larger sizes (0.42–0.6 mm). The MMF removes suspended particles from the source water down to a 10–15 micron size [26]. Downstream of the MMF, a cartridge filter (5 μm) is employed to protect the membranes from fine suspended particles in the feed water and prevent damage to either the pumps or the membranes.

As shown in Fig. 1, the pretreated water splits into three streams: dilute in, concentrate make-up, and electrode rinse solution. The majority of the source water enters the dilute flow paths as the dilute in stream. This water is demineralized before leaving the stack as product water. A smaller part of the source water becomes the concentrate make-up stream, which combines with the concentrate recycle and enters the concentrate flow paths as the concentrate in stream. This stream carries the ions transferred from the dilute stream. The concentrate stream leaving the stack is divided into two portions, one of which is drained as concentrate blow-down, and the other of which enters the concentrate recycle. The last part of the source water becomes the electrode in stream. This stream is used to flush the electrode chambers of gases and precipitates, which are formed as part of the electrochemical reactions at the surface of the electrodes [27].

Based on existing design practices and knowledge of the GE EDR stack configurations, three electrode designs were selected for this research. These electrodes were classified based on their geometry as either full, recessed, or tapered, as shown in Fig. 2.

The electrode types are characterized as follows:

(1) Full design: the electrode area fully covers the active membrane area, but also extends into the manifold area.
(2) Recessed design: there is a geometry mismatch between the areas of the electrode and the spacer (the effective desalination area in a cell).
(3) Tapered design: the geometry of the electrode matches the spacer's area (the effective desalination area in a cell).

The experiments were conducted under limiting current density at two levels of feed salinity (1.7 and 3.9 mS cm^{-1}), three levels of feed flowrate (0.44, 0.57 and 0.69 Ls^{-1}), and five levels of applied voltage (30, 32.5, 35, 37.5, 40 V), using three types of electrodes (full, recessed, and tapered). The levels of feed flowrate were chosen based on the minimum and maximum feed flowrates recommended by the manufacturer. The maximum applied voltage was chosen based on the examined conditions using results from previously conducted limiting current tests. In each cycle of polarity reversal, the time was set for a 15-min reversal. By trial and error, it was determined that after 10 min of reversal, the system attained a steady state. Then, various measurements are taken accordingly.

3. Results and discussion

The performances of three different electrodes—full, recessed, and tapered—were compared in terms of electrical current amount and removal percentage (percentage reduction of electrical conductivity in the dilute stream), and the ratio of power consumed for separation to the removal (WmS^{-1} cm). In this paper, this factor is called standardized power consumption (SPC), and it served as the primary factor for comparing the performance of the EDR process using the

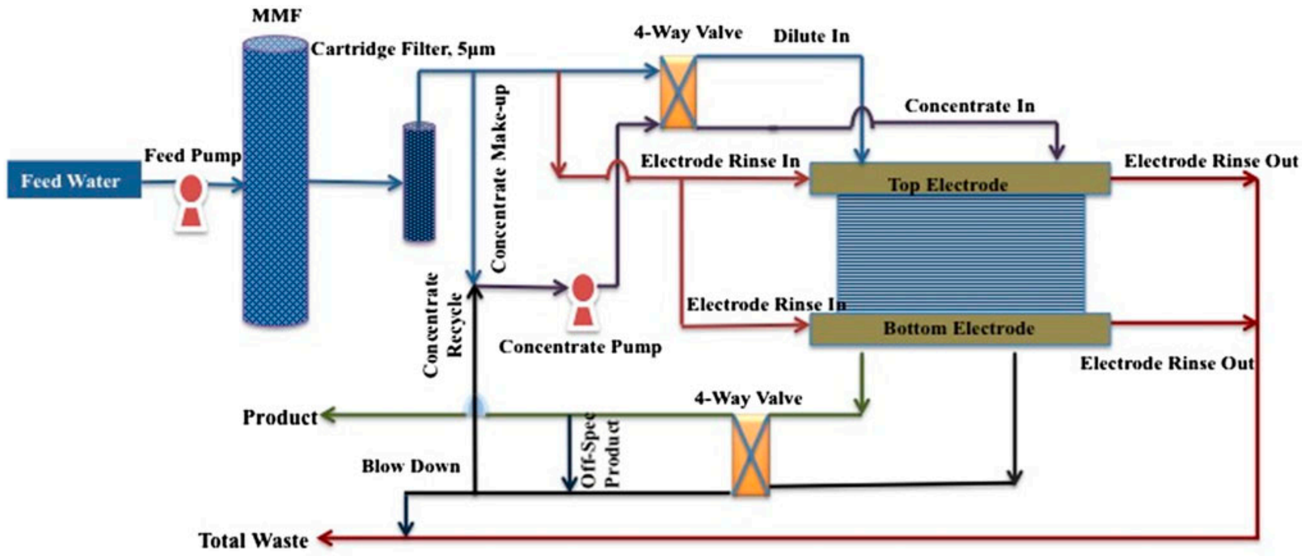

Fig. 1. Schematic of the pilot-scale EDR setup [28].

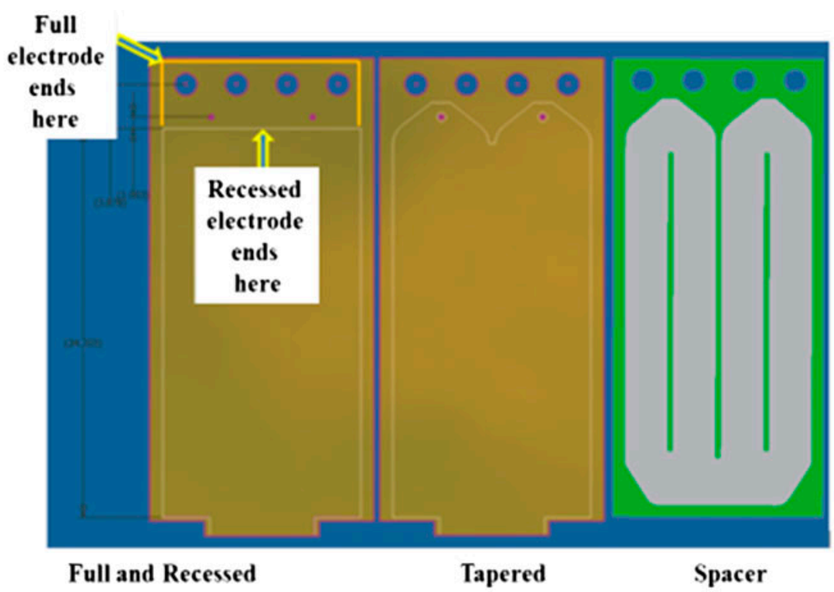

Fig. 2. Illustration of electrode designs.

different electrode types. The SPC can reflect how much power is used for the same conductivity reduction in the dilute stream. Therefore, SPC can be considered as a criteria for comparing the performance of different electrode types in the EDR process. Regression analysis was performed to determine how the studied variables (applied voltage, flowrate, and electrode type) affected electrical current, removal percentage, and SPC. Minitab™ Statistical Software [29] was utilized to complete the regression analysis.

General regression analysis was carried out to show the statistical significance of each operating factor's impact on the current, removal ratio, and the efficiency of the EDR process at two levels of feedwater salinity–low salinity (1.7 mS cm^{-1}) and high salinity (3.9 mS cm^{-1}). Tables 2 and 3 show the regression analysis results for the electrical current measured in the stack at each level of feed salinity. In this analysis, the full electrode was chosen as the base of comparison, and the two other electrode types, recessed and tapered, were compared to the full electrode.

Table 2
Regression analysis results for current using low-salinity brackish water

Variable	Coefficient	Std. error	t-statistic	Prob.
Constant	−4.48	0.42	−10.61	<0.01
Feed flowrate (Ls^{-1})	7.93	0.36	22.13	<0.01
Applied voltage (V)	0.39	0.01	37.60	<0.01
Electrode type				
Recessed	−0.59	0.09	−6.52	<0.01
Tapered	−0.36	0.09	−3.96	<0.01
R^2	93.74%		F-statistic	486.60
Adjusted R^2	93.55%		Prob. (F-statistic)	0.00
Predicted R^2	93.23%		Number of observations	135

Table 3
Regression analysis results for the current using high-salinity brackish water

Variable	Coefficient	Std. error	t-statistic	Prob.
Constant	−3.27	0.39	−8.37	<0.01
Feed flowrate (Ls^{-1})	2.44	0.33	7.37	<0.01
Applied voltage (V)	0.74	0.01	76.72	<0.01
Electrode type				
Recessed	−1.04	0.084	−12.51	<0.01
Tapered	−0.69	0.08	−8.22	<0.01
R^2	97.91%		F-statistic	1,525.55
Adjusted R^2	97.85%		Prob. (F-statistic)	0.00
Predicted R^2	97.76%		Number of observations	135

Eqs. (1)–(3) show the governing regression equations for the current in the stack when full, recessed, and tapered electrodes, respectively, are used for the EDR desalination of brackish water with low salinity:

$$I = -4.48 + 7.93\,Q + 0.39\,V \quad \text{Full electrode} \tag{1}$$

$$I = -5.07 + 7.93\,Q + 0.39\,V \quad \text{Recessed electrode} \tag{2}$$

$$I = -4.84 + 7.93\,Q + 0.39\,V \quad \text{Tapered electrode} \tag{3}$$

where I (A), Q (Ls^{-1}), and V (V) are current, feed flowrate, and voltage, respectively.

Eqs. (4)–(6) are the governing regression equations for the current in the stack when full, recessed, and tapered electrodes, respectively, are used for EDR desalination of brackish water with a high salinity:

$$I = -3.27 + 2.44\,Q + 0.74\,V \quad \text{Full electrode} \tag{4}$$

$$I = -4.32 + 2.44\,Q + 0.74\,V \quad \text{Recessed electrode} \tag{5}$$

$$I = -3.96 + 2.44\,Q + 0.74\,V \quad \text{Tapered electrode} \tag{6}$$

As shown in Tables 2 and 3, the amount of current in the EDR stack was significantly affected not only by applied voltage and flowrate, but also by the type of the electrode. Additionally, based on the presented equations for the stack's current with each electrode, it was found that—at the same amount of applied voltage and the same flowrate—the amount of electrical current followed the order of $I_{\text{Full}} > I_{\text{Tapered}} > I_{\text{Recessed}}$ for both low- and high-feed salinities.

The regression analysis results for removal ratio in the stack for both levels of feed salinity are shown in Tables 4 and 5, respectively.

Eqs. (7)–(9) are the governing regression equations for the removal ratio in the stack when full, recessed, and tapered electrodes, respectively, were used for desalination of brackish water with lower salinity.

$$\%\ \text{Removal} = 0.36 - 0.78\,Q + 0.02\,V \quad \text{Full electrode} \tag{7}$$

Table 4
Regression analysis results for the removal ratio using low-salinity brackish water

Variable	Coefficient	Std. error	*t*-statistic	Prob.
Constant	0.36	0.04	8.81	<0.01
Feed flowrate	−0.78	0.034	−22.71	<0.01
Applied voltage	0.02	<0.01	19.50	<0.01
Electrode type				
Recessed	−0.04	0.01	−4.87	<0.01
Tapered	−0.03	0.01	−3.43	<0.01
R^2	87.63%		*F*-statistic	230.20
Adjusted R^2	87.25%		Prob. (*F*-statistic)	<0.01
Predicted R^2	86.66%		Number of observations	135

Table 5
Regression analysis results for the removal ratio using high-salinity brackish water

Variable	Coefficient	Std. error	*t*-statistic	Prob.
Constant	0.27	0.03	10.79	<0.01
Feed flowrate	−0.58	0.021	−27.35	<0.01
Applied voltage	0.01	<0.01	18.17	<0.01
Electrode type				
Recessed	−0.02	0.01	−4.50	<0.01
Tapered	−0.02	0.01	−3.12	<0.01
R^2	89.43%		*F*-statistic	274.90
Adjusted R^2	89.10%		Prob (*F*-statistic)	<0.01
Predicted R^2	88.60%		Number of observations	135

$$\% \text{ Removal} = 0.31 - 0.78\,Q + 0.02\,V \quad \text{Recessed electrode} \tag{8}$$

$$\% \text{ Removal} = 0.33 - 0.78\,Q + 0.02\,V \quad \text{Tapered electrode} \tag{9}$$

Eqs. (10)–(12) are the governing regression equations for the removal ratio in the stack when full, recessed, and tapered electrodes, respectively, were used for desalination of brackish water with higher salinity.

$$\% \text{ Removal} = 0.27 - 0.58\,Q + 0.01 \quad \text{Full electrode} \tag{10}$$

$$\% \text{ Removal} = 0.25 - 0.58\,Q + 0.01\,V \quad \text{Recessed electrode} \tag{11}$$

$$\% \text{ Removal} = 0.25 - 0.58\,Q + 0.01\,V \quad \text{Tapered electrode} \tag{12}$$

As shown in Tables 4 and 5, the removal ratio, like the current, was significantly affected not only by applied voltage and feed flowrate, but also by the type of the electrode. Additionally, based on the presented equations for removal ratio (conductivity reduction ratio) for each electrode, it was found that at the same amount of applied voltage and flowrate, the removal ratio followed the order of $(\text{removal ratio})_{\text{Full}} > (\text{removal ratio})_{\text{Tapered}} > (\text{removal ratio})_{\text{Recessed}}$ when the EDR process was performed for the desalination of brackish water with lower and higher salinities. This can be explained by the differences between the effective desalination area covered by each electrode in the stack.

Although both the electrical current and the removal ratio can indicate the significant differences among the electrode designs, neither measurement can be used as an independent criterion for comparing the electrodes' effectiveness. On the one hand, higher removal means higher electrode effectiveness and higher current efficiency. On the other hand, more current means more energy consumption. Therefore, the ratio of power consumed to the amount of ion removal (SPC) was considered as the primary criterion for comparing the efficiency of the electrodes in the EDR process.

Tables 6 and 7 show the regression analysis results for SPC in the stack at both levels of feed salinity.

Table 6
Regression analysis results for SPC ratio using low-salinity brackish water

Variable	Coefficient	Std. Error	t-statistic	Prob.
Constant	−482.0	34.5	−13.98	<0.01
Feed flowrate (Ls^{-1})	989.3	29.30	33.82	<0.01
Applied voltage (V)	11.31	0.85	13.28	<0.01
Electrode type				
Recessed	0.63	7.37	0.09	0.93
Tapered	49.81	7.37	6.76	<0.01
R^2	91.39%		F-statistic	345.13
Adjusted R^2	91.13%		Prob. (F-statistic)	<0.01
Predicted R^2	90.72%		Number of observations	135

Table 7
Regression analysis results for the SPC ratio using high-salinity brackish water

Variable	Coefficient	Std. error	t-statistic	Prob.
Constant	−656.60	53.10	−12.36	<0.01
Feed flowrate	1,342.80	45.10	29.80	<0.01
Applied voltage	17.30	1.31	13.20	<0.01
Electrode type				
Recessed	−21.7	11.4	−1.91	0.05
Tapered	21.4	11.4	−1.89	0.05
R^2	91.39%		F-statistic	345.13
Adjusted R^2	91.13%		Prob. (F-statistic)	<0.01
Predicted R^2	90.72%		Number of observations	135

Eqs. (13)–(15) are the governing regression equations for the SPC when full, recessed, and tapered electrodes, respectively, were used in the EDR desalination of brackish water with lower salinity:

$$\text{SPC} = -482.0 + 989.3\,Q + 11.31\,V \quad \text{Full electrode} \tag{13}$$

$$\text{SPC} = -481.4 + 989.3\,Q + 11.31\,V \quad \text{Recessed electrode} \tag{14}$$

$$\text{SPC} = -432.2 + 989.3\,Q + 11.31\,V \quad \text{Tapered electrode} \tag{15}$$

where SPC (W mS^{-1} cm) was calculated based on the applied voltage, current measured in the process, and the reduction in the conductivity of product.

Eqs. (16)–(18) are the governing regression equations for the SPC when full, recessed, and tapered electrodes, respectively, were used in the EDR desalination of brackish water with higher salinity.

$$\text{SPC} = -656.6 + 1342.8\,Q + 17.3\,V \quad \text{Full electrode} \tag{16}$$

$$\text{SPC} = -678.3 + 1342.8\,Q + 17.3\,V \quad \text{Recessed electrode} \tag{17}$$

$$\text{SPC} = -635.2 + 1342.8\,Q + 17.3\,V \quad \text{Tapered electrode} \tag{18}$$

Based on the reported p-values for the SPCs of recessed and tapered electrodes in Table 5, it can be concluded that there was no significant difference between the effectiveness of full and recessed electrodes when low salinity water was used, while there was a significant difference between the effectiveness of these electrodes when brackish water with higher salinity was used. At low salinities, although the differences in current and removal ratio were significant between full and recessed electrodes, there were no significant differences between the SPCs of the full and recessed electrodes. In contrast, there were significant differences in the SPCs of full and tapered electrodes at both salinity levels.

The observed results can be attributed to how, although the full electrode removes significantly more ions than the recessed electrode, the full electrode also requires much more current than the recessed electrode for low-salinity EDR. This can imply that the benefits from the full electrode's higher removal ratio do not outweigh the drawback of its higher power consumption.

As for the comparison between the full and tapered electrodes, the small *p*-values in Tables 6 and 7 (<0.01 and 0.05) confirm the significant difference between the power consumed by full and tapered electrodes to produce a 1 mS cm^{-1} change in conductivity at both feed salinities. By comparing the constants of Eqs. (13)–(15), it was found that the tapered electrode, which had the smallest absolute value for the constant, had the highest power consumption, while full and recessed electrodes had similar power consumptions for a 1 mS cm^{-1} change in conductivity at the experimental conditions. This finding illustrates that the efficiencies of full and recessed electrodes were higher than the efficiency of tapered electrode, in terms of power consumption for the same amount of ion removal.

Additionally, comparing the constants in Eqs. (16)–(18) confirms that the tapered electrode, which had the smallest absolute value for the constant, had the highest power consumption, while full and recessed electrodes had lower power consumptions per 1 mS cm^{-1} change in conductivity at the experimental conditions. Therefore, for the EDR desalination of brackish water for both salinity levels, the tapered electrode had a lower efficiency than full and recessed electrodes.

These results can be explained by the relationship between the shape of the electrode and the shape of the flow path. The conductive area of the recessed electrode does not cover the whole flow path. Therefore, the effective area for ion removal decreases, resulting in a lower ion removal ratio. With full electrodes, the conductive area covers not only the whole flow path, but also the manifolds in the stack. This arrangement allows higher ion removal, but more current leakage through the manifolds. In a tapered electrode, there is no mismatch between the shape of the electrode and the shape of the flow path. The conductive area has the same shape and area as the flow path in the electrodialysis stack; however, the removal ratio is not significantly different from the recessed electrode when high salinity brackish water is used, which means ion removal occurs even in uncovered flow path in recessed electrode due to stray current.

The findings depict that the current efficiencies of EDR stacks in desalination of higher brackish water salinities with full electrodes were lower than the current efficiencies of EDR stacks with recessed electrodes. It is hypothesized that, with full electrodes, current leakage may significantly occur in the manifolds, increasing energy consumption without significant increase in ion removal in the stack. Such manifold shorting current, which is a function of electrode design, is a parasitic current to the whole desalination process and decreases current efficiency.

Additionally, a comparison of the coefficients of voltage and flowrate in Eqs. (13) and (16) shows that the SPC was more sensitive to voltage and flowrate variation when brackish water with higher salinity was used.

4. Conclusion

The pilot-scale experiments conducted in this research confirm that the electrode type affected the amount of current, the removal ratio, and the SPC in the EDR desalination process. At the same flowrate and same amount of applied voltage, the amount of electrical current followed the order of $I_{\text{Full}} > I_{\text{Tapered}} > I_{\text{Recessed}}$ for both low- and high-feed salinities. The removal ratio, like the current, followed the order of $(\text{removal ratio})_{\text{Full}} > (\text{removal ratio})_{\text{Tapered}} \geq (\text{removal ratio})_{\text{Recessed}}$ for the desalination of brackish water at both low and high salinities. These differences can be explained by the differences among the effective desalination areas covered by electrical field provided by each electrode in the stack.

Although both the electrical current and removal ratio can represent the significant differences among the different electrode designs, the SPC was considered as the key factor for comparing the performance of the electrodes in the EDR process. With the SPC as the basis for comparison, it can be seen that there were significant differences among the performances of full, recessed, and tapered electrodes. Therefore, under studied conditions, recessed electrode had better performance in comparison to full and tapered electrodes for brackish water with high salinity due to low resistance of water in the manifold resulting in higher current leakage. However, recessed and full electrodes had similar, but better performance in comparison to tapered electrode in lower salinity.

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