



Quantitative studies of electro dialysis performance

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ABSTRACT

Variations in functional parameters strongly affect the performance of the electro dialysis process, a promising approach for desalinating brackish water. Although the effects of operational factors have been qualitatively investigated in previously published works, the simultaneous effects of three important operational factors, applied voltage, superficial velocity, and temperature, have not yet been quantitatively described or presented in the form of a mathematical model. Therefore, the simultaneous effects of these operational parameters have not been shown in functional form in the previously published works. In this research, a laboratory-scale electro dialysis setup was used to qualitatively and quantitatively study the effects of operational factors by employing a set of full-factorial experiments with three replications at different levels of applied voltage per cell pair, superficial velocity, temperature, and feedwater composition. The nonlinear power-law functions were found for the effects of superficial velocity, applied voltage per cell pair, and initial feed concentration, while an Arrhenius-type function was found for the effect of temperature.

1. Introduction

Among the different desalination processes, electro dialysis is a promising technology for desalinating brackish water, a purpose for which electro dialysis/electro dialysis reversal is well suited because of its low energy use, less pretreatment requirements, and robustness in the presence of less-soluble salts, such as calcium sulfate [1–3]. The robustness of this process compared to pressure driven processes is because of the flow direction in dilute and concentrate channels, polarity reversal which alternates dilute and concentrate chambers as well as the washing and scrubbing the membranes in case of fouling and scaling [3,4]. Additionally, its performance is not affected by the presence of non-charged species, such as silica [5].

In comparison to pressure-based and thermal desalination technologies, electro dialysis provides a higher degree of control over desalination degree (product quality) because the operational factors in electro dialysis directly affect the quality of the product. Although increasing parameters, such as pressure can improve water recovery in RO process that can affect the product quality to some extent, in ED/EDR process the main driving force for salt separation is applied voltage and its adjustment significantly affects the product quality. The direct connection between operational factors and product qualities also

makes it possible to study the effects of operational parameters on the product quality and predict the desalination degree based on the operational parameters. Such knowledge makes it possible to optimize electro dialysis performance by adjusting the levels of operational factors.

The most important adjustable operational factors that influence the performance of electro dialysis systems and the quality of desalinated water are applied voltage and feed flow rate. Two other impactful factors are temperature and feedwater composition, but these factors are less controllable because they are based in the characteristics of feedwater resources. Several valuable studies qualitatively report how each of these parameters—applied voltage, feed flow rate, feedwater composition [6–8], and temperature—affect electro dialysis performance and the quality of the desalinated water. However, existing studies have not developed mathematical functions to represent the simultaneous effects of these parameters on desalination using electro dialysis.

The general effects of each factor are well known and grounded in theory. As depicted in the Nernst-Planck equation, the dominant ion transport mechanisms in the electro dialysis process are diffusion and electro-migration. Diffusion occurs due to concentration gradient, while electro-migration occurs due to electrical potential gradient. From this

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theoretical basis, a positive effect of voltage on ion electro-migration is expected, and this positive effect of voltage has been reported in several published works [3,9–14]. At very low voltages, the removal of ions is negligible because of the electrical resistance of the ion exchange membranes [15]; at higher applied voltages, the percent removal of ions approaches 100% [11]. Not all ions are affected equally by voltage, however, and different ions' responses have been noted to result from different ion diffusivities [10–12] and different ion-ion interactions in the solution and in the phases of the ion exchange membrane [16].

Alongside voltage, another impactful and highly controllable operational factor is feedwater superficial velocity. This factor is associated with two opposite effects on ion removal in the electro dialysis process. On the one hand, increases in the velocity reduce the thickness of the concentration boundary layer [3,17–21], thereby tending to increase ion removal. On the other hand, increases in the velocity decrease the ions' residence time in the ED stack [11,15,22–28], thereby tending to decrease ion removal per stack path. Different researchers had described the overall effects of feed velocity or flow rate on ion removal as either positive [3,29] or negative [15,22–28], but Karimi and Ghassemi clarified the reason behind these inconsistent observations and reported effects, showing increased feed flow rate to have an overall negative effect on ion removal [30].

A less-controllable operational factor that affects ion removal and desalination degree is temperature. Although the effect of temperature on product quality in electro dialysis is not as high as its effect on product quality in reverse osmosis, its influence is still significant [2]. Increasing the temperature of feedwater improves the ion diffusivity, which increases ion mobility in the concentration boundary layer and membrane phase [27,28,31]. Although increasing the temperature of feedwater decreases the energy consumption of the electro dialysis process [2], cost analyses have not been conducted for the process of heating feedwater, so it is currently most sensible to heat feedwater using waste thermal sources that do not impose additional expenses.

Feedwater composition is not conventionally categorized as an operational factor, but its effect on electro dialysis desalination cannot be ignored. Consequently, feedwater composition is included in the term “operational factors” throughout this paper. Both the initial concentration of ions in the feedwater and the ionic composition of the feedwater affect the quality of the desalinated water produced by the electro dialysis process. As the initial concentration of ions in the feedwater increases, ion removal rate and total ion removal increase because more ions are present to be affected at the same time by any applied voltage [14,31–34]. Ion composition also plays a critical role because of the electrostatic interactions between ions with different electrical charges. Therefore, ion removal in the presence of only monovalent ions is different from ion removal in the presence of divalent ions [24,35].

Although the effects of applied voltage, feed velocity, temperature, and feedwater composition have been qualitatively investigated in previously published works, the simultaneous effects have not been quantitatively described or presented in a mathematical model. Therefore, the effects of operational parameters have not been shown in functional form in the previously published works. In this paper, we present the effects of these parameters both qualitatively and quantitatively. To show how these parameters affect ion removal in electro dialysis, empirical models are presented and discussed.

2. Materials and methods

2.1. Design of experiments and variables

The experiments were carried out based on a full factorial design with three replications. Different levels were used for the four experimental variables of feed composition, flow rate, applied voltage, and temperature, as shown in Table 1. The levels of variables were chosen to cover the practical application ranges, and, for feed velocity, an

Table 1
Design of experiments*.

Variables	Levels
Feed composition, ppm	Mono-salt: NaCl: 200 and 1000; CaSO ₄ : 200 and 1000 Binary-salt mixture: NaCl 200 + CaSO ₄ 200; NaCl 1000 + CaSO ₄ 1000
Temperature, °C	15, 35
Superficial velocity, cm/s (flow rate, ml/s, residence time, sec)**	1.6 (5.8, 5.1), 2.1 (7.8, 3.8), 2.6 (9.8, 3.0), 3.7 (13.8, 2.1), 4.2 (15.8, 1.9)
Applied voltage per cell pair V	0.3, 0.7, 1.0, 1.3, 1.7

* Three replications.

** Reynolds numbers are available in Table SI-2.

especially wide range was employed to study this variable's aforementioned dual effects and investigate the feasibility of differentiating its positive and negative effects. Feedwater compositions were defined to allow the study of ion removal when the dominant ions are monovalent, divalent, or a mixture of both types.

2.2. Experimental design and procedure

2.2.1. Experimental apparatus

A complete laboratory-scale electro dialysis reversal (EDR) setup was designed and built to conduct the laboratory scale experiments. Using the designed setup, it was possible to run the experiments while monitoring and recording the data with high accuracy. The system was run as a continuous system in which the effects of parameters could be detected clearly. The schematic of the setup is shown in Fig. 1.

The setup was equipped with three micro gear pumps (Langer Pump WT3000-1FA) able to communicate with any personal computer and programmable logic controller (PLC). These pumps were used to pump the Dilute In, Concentrate In, and Electrode In streams. The three micro gear pumps were connected to three clear solution columns on the upper back of the setup. These columns were installed to keep the downstream pressure head of the micro gear pumps constant while the level of the solution in the containers decreased during experiments due to consumption of dilute and concentrate solutions. During the experiments, the solutions were continuously pumped into installed columns by three miniature gear pumps, provided by Cole Parmer and controlled by an adjustable power supply.

Although two of the three solutions, Dilute In and Concentrate In, were dumped to the drain, the electrode rinse solution was recycled back to the same reservoir because no significant changes in its composition were observed during the preliminary tests of this research, nor were any significant changes in the composition of the electrode rinse solution during experiments reported in previously published works [10].

The operating conditions were monitored at the inlet and outlet of the stack using sensors for inline temperature, pH, conductivity, flow, and pressure. The entire EDR stack was powered by an adjustable power supply provided by B&K Precision. A complete list of the setup components is available in the supplementary information section, Table SI-1.

2.2.2. Electro dialysis stack

The electro dialysis cell unit used in this setup is PCell ED 64 002, a laboratory scale electro dialyzer with the nominal capacity of 4–8 L/h per dilute and concrete cell. The utilized cation and anion exchange membranes were GE CR67-HMR and GE AR908, respectively, with an active area of 64 cm². The mesh spacer used in the stack to make the dilute and concentrate chambers had a thickness of 0.4 mm and a direct flow path. The details of the laboratory-scale ED/EDR stack are shown in Table 2.

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