



Treatment of model inland brackish groundwater reverse osmosis concentrate with electro dialysis – Part II: Sensitivity to voltage application and membranes



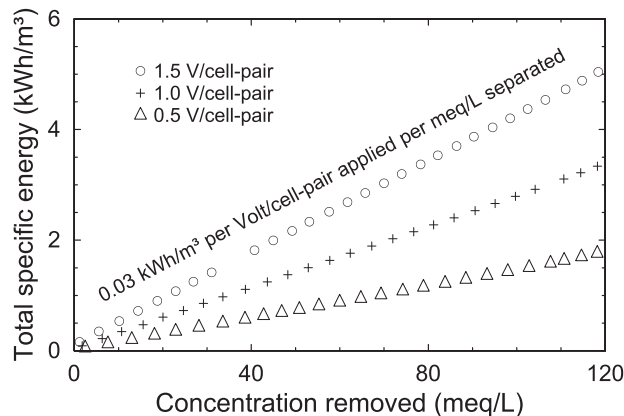
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HIGHLIGHTS

- Synthetic BWRO concentrates of 7.9–14.8 g/L were desalinated by electro dialysis.
- Current densities with CMV-AMV membranes were ~15% greater than with PCSK-PCSA.
- Specific energy consumption was 0.03 kW h/m³ per Volt/cell-pair per meq/L separated.
- Water transfer by electro-osmosis and osmosis was quantified.

GRAPHICAL ABSTRACT



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ABSTRACT

The objective of this research was to investigate the sensitivity of electro dialysis performance to variations in voltage application and membranes when treating brackish water reverse osmosis concentrate waste. Synthetic BWRO concentrates from Arizona and Texas of 7890–14,800 mg/L total dissolved solids were prepared with poly-phosphonate antiscalants. Experimentation was performed using a laboratory-scale electro dialyzer with two sets of membranes (AMV-CMV and PCSA-PCSK) with a nominal transfer area of 64 cm² per membrane. Flow, pressure, conductivity, temperature, and pH were measured continuously, and periodic samples were analyzed for specific anion and cation concentrations. The BWRO concentrates were successfully treated with stack voltage applications of 0.5–1.5 V/cell-pair for salinity removal ratios up to 99% with current density less than 500 A/m². This paper highlights that (1) the specific energy consumption was proportional to the applied voltage and equivalent concentration separated (*i.e.*, approximately 0.03 kW h/m³ per Volt/cell-pair applied per meq/L separated); (2) lower voltage applications decreased the relative separation rate of sulfate compared to chloride; and (3) water transport by electro-osmosis was independent of voltage application or resulting current densities, while it is affected by the ion exchange membranes.

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1. Introduction

1.1. Goals and objectives

The goal of this research was to improve the understanding and feasibility of high-recovery brackish water desalination with combined reverse osmosis (RO) and electro dialysis (ED) systems. The objective of this paper was to quantify the sensitivity of ED treatment of RO concentrate waste to applied voltage with two sets of ion exchange membranes.

1.2. Background

As described in detail in Part I [1] of this series, the effects of hydraulic, electrical, and chemical variables are inherently interconnected in electro dialysis. With respect to electrical variables, the voltage applied to the stack directly controls the rate of separation. The rate of separation is nearly proportional to the current, which also affects the concentration gradients in the diffusion boundary layers at the membrane surface. As a practical application of the second law of thermodynamics, the cost of driving an irreversible process at a faster rate is an increase in energy consumption; in electro dialysis, application of a greater voltage results in a higher specific energy consumption.

For mildly brackish waters (traditional electro dialysis operations), the electrical resistance of the diluate solution typically predominates the total resistance of the stack. However, in brackish and saline solutions (such as RO concentrate), the electrical resistance of the diluate solution may be low enough that the electrical resistance of the ion exchange membranes is not insignificant. (Effects of solution composition are further investigated in Part III of this series [2].) Previous studies on electrical energy consumption and resistance in ED systems are summarized here:

- o Electro dialysis stacks for research are commonly assembled with 5–10 cell-pairs [3–11].
- o The rate of separation/desalination is nearly proportional to applied voltage [5], which is typically in the range of 0.3–1.0 V per cell-pair [3,4,9,10,12] (up to 1.5 V per cell pair [5,7]).
- o The electrical resistance of the membranes represents a significant fraction of the overall stack resistance for solutions greater than approximately 0.2 eq./L [13].
- o The ion exchange membrane influences the relative transport of ions [14]. For example, a stack with CMV/AMV membranes showed little cationic permselectivity between mono- and divalent ions, whereas the CMS/ACS membranes did show preferential selection of monovalent cations [8]. However, many reported studies of electro dialysis have only evaluated one membrane [3–7,9–12,15–20].
- o Specific energy consumption (SEC) is proportional to equivalent concentration and applied voltage, but insensitive to flow [5,9,12].

2. Material and methods

As described in detail in Part I [1] of this series, this experimentation was designed to observe the effects of (1) velocity, (2) voltage, (3) ion exchange membranes, (4) feedwater composition, and (5) hydraulic recovery of electro dialysis treatment of inland brackish groundwater RO concentrate. This paper focuses on the effects of applied voltage (the driving force for ionic separation) with two sets of ion-exchange membranes, and the experimental parameters are shown in Table 1. Three

Table 1
Experimental parameters and discrete value ranges.

Parameter	Range
Superficial diluate velocity	2.4, 4.8 cm/s
Stack voltage	0.5, 1.0, 1.5 V/cell-pair
Stack membrane sets	(CMV/AMV), (PCSK/PCSA)
Feed water composition	AZ, TX
Recovery of RO concentrate	50% (nominal)

Table 2
Ion exchange capacities and thicknesses of select ion exchange membranes.

Membrane	Capacity (meq/g)	Specific area resistance (Ω cm ²)	Thickness (μ m)
AMV	2.2 [28]; 1.98 [29]	2–3 [27]	111
CMV	2.0 [28]; 1.95 [30]	2–3 [27]	119
PCSA	ca. 1.5 [11]	1–1.5 [19]	193
PCSK	ca. 1.0 [11]	0.75–3 [19]	182

discrete voltage applications were tested: 0.5, 1.0, and 1.5 V/cell-pair. (The voltage application accounted for voltage losses at the electrodes, as detailed in Part I [1] of this series.) Two combinations of ion exchange membranes were tested, and select membrane properties are shown in Table 2. The effects of the applied voltage and ion exchange membranes were observed with respect to chemical, electrical, and hydraulic performance such as the rate of separation of bulk salinity (*i.e.*, conductivity) and individual ions, current density, specific energy consumption, and osmosis as described in Part I [1].

A brackish groundwater treatment study in Maricopa County, Arizona by the US Bureau of Reclamation [21] detailed the composition (TDS = 1585 mg/L, pH = 7.5) of Well S5 in Avendale (southwest of Phoenix). Similarly, a water composition analysis of groundwater (TDS = 3730 mg/L, pH = 7.8) that supplies the North Cameron RO facility in Cameron County, TX was performed by Ana-Lab Corp. (Kilgore, TX) in 2007. By conservatively assuming 100% RO rejection and RO recoveries of 80% and 75%, respectively, the concentrate to raw concentration factors (ratios) were 5.0, and 4.0, respectively. Thus, the TDS of the simulated concentrate wastes was 7.9 and 14.8 g/L, respectively, and the major ion composition is shown in Table 3. The Texas water also included silica and boron.

For select minerals with a high degree of saturation, the log of the solubility constant (K_{sp}), the log of the ion activity product (*IAP*), and the corresponding saturation index (*SI*) and saturation ratio (*S*) are presented in Table 4. The simulation also predicted supersaturated conditions for the following minerals: quartz [SiO_2], aragonite [CaCO_3], vaterite [CaCO_3], chalcedony [SiO_2], cristobalite [SiO_2], huntite [$\text{Mg}_3\text{Ca}(\text{CO}_3)_4$], sepiolite [$\text{Mg}_4\text{Si}_6\text{O}_{15}(\text{OH})_2 \cdot 6\text{H}_2\text{O}$], chrysotile [$\text{Mg}_3(\text{Si}_2\text{O}_5)(\text{OH})_4$], and monohydrocalcite [$\text{CaCO}_3 \cdot \text{H}_2\text{O}$]. Discussion of the saturation index and saturation ratio, as well as simulations for the Arizona concentrate are provided in Part I [1].

Table 3
Model brackish groundwater RO concentrate waste characteristics for AZ and TX.

Quality Parameter	Maricopa Co., AZ	Cameron Co., TX
Total dissolved sol. (mg/L TDS)	7890	14,800
Ionic strength (mM)	159	242
Ionic content (meq/L)	133	230
Conductivity (mS/cm)	11.5	19.2
Hardness (meq/L)	94	58
Alkalinity (meq/L)	16	22
Na ⁺ (mg/L)	879	3922
Ca ²⁺ (mg/L)	1030	612
Mg ²⁺ (mg/L)	515	326
Ba ²⁺ (mg/L)	2	–
Sr ²⁺ (mg/L)	–	30
K ⁺ (mg/L)	–	62
Cl [–] (mg/L)	3346	4440
SO ₄ ^{2–} (mg/L)	991	3964
HCO ₃ [–] (mg/L)	1013	1354
Br [–] (mg/L)	–	20
NO ₃ [–] (mg/L)	87	–
H ₂ SiO ₃ (mg/L as SiO ₂)	–	50
H ₃ BO ₃ (mg/L as B)	–	43

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