

Comprehensive utilization of brackish water in ED — thermal system

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Abstract

Electrodialytic desalination/concentration of brackish water (TDS ca. 10 g/L) in an integrated ED — thermal desalination system was examined. The ED unit stacks geometry, and the ED system arrangement and operating conditions were optimized to identify minimum desalination/concentration costs. The ED stack with relatively low 0.19 mm membrane to membrane distance, and three stage ED system arrangement was investigated to identify optimum process parameters. The minimum total desalination/concentration cost found at 255 g/L NaCl concentrate content was equal to \$0.22/m³ assuming \$0.03/kWh electric power cost and \$1/m³ fixed evaporation cost independently on the thermal plant capacity. Under optimal conditions the salt utilization cost was found to be \$25.6/t of salt produced.

It was also concluded that since optimum concentrate TDS found is high, the amount of water to be evaporated is relatively low. Thus the thermal unit costs increases the utilization costs to large extent and a mere system for electro-dialytic desalination — concentration up to TDS of 300 g/L (close to NaCl saturation level) seems to be economically privileged. Despite high electric current density, relatively low value of energy consumption, equal to 275 kWh/t of salt was observed at optimum conditions.

Keywords: Brackish waters; Desalination; Electrodialysis; Evaporation

1. Introduction

ED is widely applied for brackish water desalination as at low source water salinity (up to TDS of 5–10 g/L) it is more economically effective than RO and thermal methods. On the other

hand ED is also applied for brine (of seawater salinity) concentrating to ca 190 g/L, and when followed by evaporation and crystallization result in evaporated salt, however, the diluate desalination degree is rather low (ca 35%). This low desalination degree avoids high concentration difference between diluate and concentrate and its resulting shortcomings: back diffusion

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and osmotic solvent transport, both increasing treatment costs [1–3]. Also the low salinity of the diluate itself may cause high voltage drop and energy consumption. If the desalted water of lower salinity is to be produced, the influence of all the above factors on process indices have to be minimized.

In the case of inland brackish water desalination plants concentrate disposal is of concern [4,5]. Thus further treatment of this waste is explored and its concentration followed by evaporation is considered also. ED, especially EDR seems to be applicable [6].

In Poland, coal mine saline waters treatment necessity constitute a challenge. Comprehensive utilization is then needed to avoid salt discharge into Odra and Vistula, main Polish rivers. ED was investigated as pre-concentration treatment of such waters only. Water of ca. 10 g/L salinity was electro-dialytically desalted/concentrated into four ED units of 0.4 mm membrane to membrane distance, arranged in cascade. The comprehensive (ED — evaporation — crystallization system) utilization cost found was \$47.4/t of salt produced [7]. When ED-EDR concentration of coal-mine brine of salinity ca 58 g/L up to 140 g/L was considered, the energy consumption found, at 0.19 mm membrane to membrane distance, was equal to 200 kWh/t of salt produced while up to saturation electro-dialytic concentration consumed ca 350 kWh/t [8].

2. The objective

The objective of the work was to reveal the possibility of comprehensive utilization of coal-mine brackish water (of TDS 10 g/L) in ED — thermal system leading to evaporated salt and low-salinity water obtaining. As mentioned in the introductory section, the electro-dialytic concentration is limited by back diffusion, osmosis and high diluate ohmic voltage drop, being the results of either high salinity difference between diluate and concentrate into ED unit or low diluate

salinity. In general, the concentration difference related phenomena may be mitigated by countercurrent flow arrangement and, if required, multistage processing, however, the process parameters have to be optimized to minimize comprehensive utilization considering ED and thermal desalination followed by crystallization cost. This was revealed in this work with emphasis on ED parameters.

3. Methods and apparatus

Model NaCl solution of Cl^- 7.27 g/L content was electro-dialytically treated in the lab-scale ED stand. The targeted desalinated water chloride content was 1.04 g/L, since according to Polish regulations, only waters containing less than 1.5 g/L of salt can be discharged, or reused in some mining processes.

In our previous research, described in more detail in [7], four stage electro-dialytic desalination/concentration was conducted at 0.4 mm membrane to membrane (m/m) distance. Presently the unit of 0.19 mm m/m distance, that allows higher desalination degree, was applied. Therefore three in place of four stages were found to be applicable in the examined case. The salinity distribution into the cascade of ED units was then as in Fig. 1.

The limiting current density for the first (of 1.04 g/L diluate chloride content) and second (of 2.31 g/L diluate chloride content) cascade steps was evaluated by analyzing ED unit R vs $1/I$ curves. Since enormously high value, higher than optimal, was suspected in the third cascade step, its value was not determined.

Limiting current densities were determined using laboratory ED stand of 9 cm² active membrane area (3 × 3 cm) equipped with four pairs of A-192 and K-192 (Asahi Kasei Co.) membranes. Membrane to membrane distance for both, desalination and concentration compartments was equal to 0.19 mm. Both concentrate and diluate linear flow velocities varied in the range of 2.92 to 12.28 cm/s.

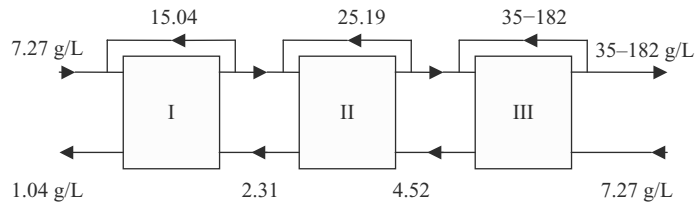


Fig. 1. Concentration distribution (Cl⁻) into envisioned cascade.

In order to include back diffusion, osmotic and electroosmotic transport the following relations, computed based on the available literature [3,9] were used:

osmotic water flux through membranes, J_{H_2O} :

$$J_{H_2O} = 0.158 \cdot \Delta\Pi \cdot S, \text{ L/m}^2 \text{ h} \quad (1)$$

where S — total effective membrane area, m², osmotic pressure at given NaCl content, Π :

$$\Pi = 0.79 \cdot C_{\%NaCl}, \text{ MPa} \quad (2)$$

where $C_{\%NaCl}$ — NaCl mass percentage, %, electroosmotic water flux, J'_{H_2O} :

$$J'_{H_2O} = 7.98 - 2.214 \cdot C_d, \text{ L/A h} \quad (3)$$

current efficiency, CE:

$$CE = 0.9 - 0.001956(C_k - \overline{C_d}) \quad (4)$$

where C_d and C_k — diluate and concentrate chloride content g/L, $\overline{C_d}$ — mean diluate salt content g/L.

The pressure drop for 0.19 mm spacer applied was measured in laboratory, as a function of linear velocity using a mercury manometer. The pressure drop affected by the spacer and membrane walls only was thus measured. It was found that the pressure drop was a linear function of flow velocity, u , and length, l , as follows:

$$\Delta p = 19.68 \cdot u \cdot l, \text{ Pa} \cdot \text{s/m}^2 \quad (5)$$

In the calculation the following costs were taken into account:

- the electric energy cost for pumping and for the current passage;
- costs of membrane, and other capital and maintenance costs.

The cost was calculated for a commercial ED unit with 40 cm width working membrane. The length of working membrane was not fixed; it was assumed that it is a result of required degree of desalination but it should not exceed the value of 200 cm. The 4 cm margins were considered as a gasket. The value of pumping energy was estimated for industrial ED unit assuming the entrance and exit passageway lengths equal to 3 cm, the velocity of solution in the entrance and exit passageway 3 times higher than in the current-passing section. It was also assumed that the pressure drop in a commercial ED unit should not exceed the value of $2 \cdot 10^5$ Pa.

The energy cost was assumed as equal \$0.03/kWh (low cost energy from co-generation system), the efficiency of rectifiers and pumps 0.95 and 0.85 respectively, the membranes' life 10 years (80,000 h). The total investment costs was assumed as equal \$320 per square meter of membrane. Maintenance costs were estimated as 25% of investment costs. It was assumed that ED concentrate evaporation unit cost is equal to \$1.0/m³ of distillate. The costs of further evaporation accompanied by salt crystallization were assumed to be \$8.0 per 1 t of salt obtained.

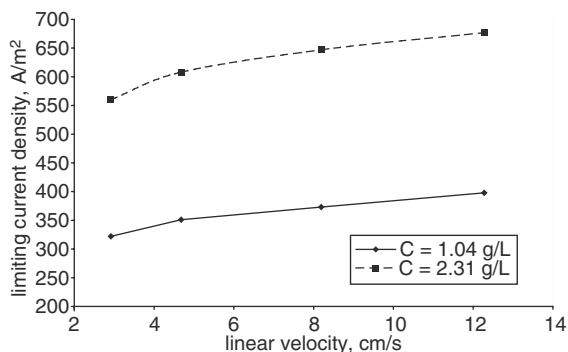


Fig. 2. Limiting current density vs. velocity at different Cl^- concentrations.

4. Results and discussion

Limiting current density vs. flow velocity curves are presented on Fig. 2.

In order to determine voltage drops per membrane pair for each cascade step the following was assumed: at the first cascade step, the current density is equal to 0.8 of its limiting value; at the second treatment step two current densities 0.7 and 0.8 of the limiting value were considered independently. At the third cascade step, the voltage drops were determined in the range of 500–1000 A/m^2 at diluate mean chloride content of 5.64 g/L and targeted final concentrate chloride

content of: 36.4; 48.53; 61.85; 74.11; 92; 120; 150 and 181.98 g/L and varying linear flow velocity. The results are tabulated below (Tables 1–3).

Mean current densities for 1st and 2nd cascade step were calculated assuming gradual decrease in current intensity along the unit, at constant voltage drop. Based on the above the limiting current density for diluted (ingoing) solutions was predetermined in the lab ED unit. Then 0.7 or 0.8 (adequately) of the limiting value was used to determine voltage drop required. Next, the current intensities for the solutions leaving ED unit of 2.31 g/L (1st step) and 4.52 g/L (2nd step), were measured at given voltage drop. Average current intensity was considered for further calculation. The above manner calculated values are tabulated in Tables 4 and 5.

The estimated costs of electro dialysis are tabulated in Table 6 while total costs of comprehensive utilization are presented in Fig. 3.

The energy consumption found for concentration/desalination in the proposed system when electro dialysis is applied up to saturation was 275 kWh/t of salt. This value is much lower than reported by others when electro dialytic brackish water desalination is considered. When brackish water is desalted from 2.6 to 0.96 g/L of Cl^- content the energy consumption is equal 1100 kWh/t salt

Table 1

Voltage drop into the first cascade step

Cl^- content, g/L	Linear flow velocity throughout ED, cm/s	Current density, $0.8i_{\text{lim}}$, A/m^2	Voltage drop on pair of membrane, V
1.04	2.92	258	0.41
1.04	4.68	280	0.38
1.04	8.19	298	0.34
1.04	12.28	318	0.33
2.31	2.92	448	0.37
2.31	4.68	486	0.34
2.31	8.19	518	0.30
2.31	12.29	542	0.28

Table 2
Voltage drop at second cascade step

Cl ⁻ content, g/L	Linear velocity of flow throughout ED, cm/s	Current density, A/m ²		Membrane pair voltage drop, V	
		0.7 <i>i</i> _{lim}	0.8 <i>i</i> _{lim}	at 0.7 <i>i</i> _{lim}	at 0.8 <i>i</i> _{lim}
2.31	2.92	392	448	0.307	0.351
2.31	4.68	426	486	0.281	0.320
2.31	8.19	452	518	0.245	0.281
2.31	12.28	474	542	0.227	0.260
4.52	2.92	392	448	0.262	0.299
4.52	4.68	426	486	0.207	0.236
4.52	8.19	452	518	0.195	0.224
4.52	12.28	474	542	0.164	0.181

Table 3
Exemplary voltage drops at third cascade step. Concentrate Cl⁻ content 36.4 g/L

Diluate Cl ⁻ content, g/L	Linear flow velocity, cm/s	Voltage drop at varying current density, V				
		500 A/m ²	600 A/m ²	700 A/m ²	800 A/m ²	900 A/m ²
5.64	2.92	0.351	0.421	0.491	0.562	0.632
5.64	4.68	0.300	0.359	0.419	0.478	0.538
5.64	8.19	0.272	0.326	0.380	0.435	0.489
5.64	12.28	0.256	0.308	0.359	0.410	0.462

removed [10]. Four times lower energy demand in our system is the result of low m/m distance and its related low voltage drop despite high electric current density applied.

Table 4
Mean current densities into the first cascade step

Linear flow velocity, cm/s	Current density, A/m ²		
	0.8 <i>i</i> _{lim} at diluate Cl ⁻ of 1.04, g/L	Corresponding current density at 2.31 Cl ⁻ , g/L	Mean current density
2.92	258	495	376
4.68	280	546	413
8.19	298	594	446
12.28	318	640	476

5. Conclusion

The minimum total desalination/concentration cost found at Cl⁻ 155 g/L (255 g/L NaCl) concentrate content was equal to \$0.22/m³ assuming \$0.03/kWh electric power cost and \$1/m³ fixed evaporation cost independently on the thermal plant capacity. Under optimal conditions the salt utilization cost was found to be \$25.6/t of salt produced.

It was also concluded that since optimum concentrate TDS found is high, the amount of water to be evaporated is relatively low. Thus the thermal unit costs increases the utilization costs to large extent and a mere system for electrodiolytic desalination — concentration up to TDS of 300 g/L (181.98 g/L of Cl⁻ that is close to NaCl saturation level) seems to be economically

Table 5
Mean current densities into the second cascade step

Linear flow velocity, cm/s	Current density, A/m ²			Current density, A/m ²		
	0.7 <i>i</i> _{lim} at diluate 2.31 Cl ⁻ g/L	Corresponding current density at 4.52 Cl ⁻ g/dm ³	Mean current density	0.8 <i>i</i> _{lim} at diluate 2.31 Cl ⁻ g/dm ³	Corresponding current density at 4.52 Cl ⁻ g/dm ³	Mean current density
2.92	392	459	425	448	526	487
4.68	426	578	502	486	659	572
8.19	452	568	510	518	690	604
12.28	474	656	565	542	749	645

Table 6
Optimum ED conditions

Cascade step	Concentrate Cl ⁻ content, g/L	Velocity, cm/s	Current density, A/m ²	Effective membrane length, m	Pressure drop, kPa	Cost, \$/m ³
I	15.04	12.28	479	0.1894	89.28	0.0488
II	25.19	12.28	645	0.2527	104.58	0.0616
III	36.4	12.28	800	0.2631	107.08	0.0783
III	48.53	12.28	800	0.2707	108.92	0.0806
III	61.85	12.28	900	0.2486	103.57	0.0756
III	74.11	12.28	900	0.254	105.45	0.0845
III	92.00	12.28	900	0.2686	108.41	0.0885
III	120.00	12.28	900	0.2903	113.67	0.0948
III	150.00	12.28	900	0.3179	120.33	0.1027
III	181.98	12.28	900	0.3537	128.98	0.1132

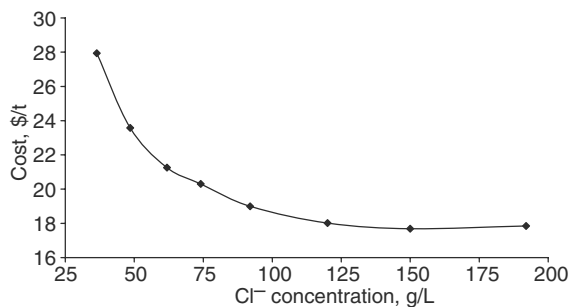


Fig. 3. Total cost of ED as a function of ED concentrate chloride content.

privileged as the cost of comprehensive utilization at this ED concentrate Cl⁻ content is equal \$25.85 per ton of evaporated salt and is only slightly higher than optimum one.

It was found that electro dialysis with 0.19 mm intermembrane distances results in a desalination rate so high that its assumed level was reached passing from 0.1894 to 0.3537 m along the membrane only (Table 6). So it is then strongly recommended to apply much lower electric current densities, than the estimated optimum ones. On the other hand, the energy cost assumed is low and may be considered only locally under specific conditions, i.e. when power-heat cogeneration

is applicable. The more common energy cost (equal or higher than \$0.06/kWh) would increase the optimum membrane length to more reliable value since higher energy cost will force lower optimum electric current densities. Usually, the electro-dialytic units of fixed membrane length, i.e. 40 or 100 cm, but no of the desired one are manufactured. This fixed length may also affect the current density and cost as well and these factors have to be optimized separately for given unit, however not much influence is suspected, based on our previous research [11,12].

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