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Brackish water desalination in RO–single pass EDR system

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ABSTRACT

Electrodialysis reversal (EDR) treatment of inland brackish water reverse osmosis concentrate was examined. The resistance to $CaSO_4$ and $CaCO_3$ scaling in our single-pass and low residence time EDR is better than in the one that was originally developed by Ionics. Our approach is as follows. The RO concentrate of $CaSO_4$ and $CaCO_3$ content being close to the saturation level (or slightly supersaturated) is concentrated by EDR 4–5 times. This enables the concentrate volume to decrease and, probably, its disposal cost to the same extent. Assuming brackish water composition as follows (mg/L): Mg^{2+} — 95.4; Ca^{2+} — 208.4; Cl^- — 1166; SO_4^{2-} — 868.8; HCO_3^- — 170.8; NO_3^- — 179.8 and 60% RO recovery, concentrate composition was calculated using Dow Chemical Co. RO system analysis (ROSA) software. Simulated RO concentrate containing (mg/L): Mg^{2+} — 237.7; Ca^{2+} — 519.2; Cl^- — 2886; SO_4^{2-} — 2164; HCO_3^- — 414.4; NO_3^- — 424.3 was then treated in a laboratory EDR stand at 79.1% diluate recovery. The analysis of EDR stack voltage drop vs. EDR process time curves showed that scaling did not occur despite 358.9% calcium sulfate saturation level and 2.29 Langelier Index value. The overall RO–EDR water recovery was equal to 91.6% despite the high scaling potential of investigated water. The expected cost of EDR was found to be promising, especially as compared to evaporation. E.g. the RCC vapor compression evaporation (turned out to be useful for treatment of $CaSO_4$ containing brine) energy consumption was equal to ca. 20 kWh/m^3 while our EDR laboratory test showed the demand (in similar salinity range) of ca. 3 kWh/m^3 at the estimated unit EDR cost \$0.30/m^3. EDR has especially high potential in the case of waters containing calcium sulfate and calcium bicarbonate as dominant solutes. Thus, $CaSO_4$ and $CaCO_3$ may be crystallized in the EDR concentrate and disposed. This will allow zero-discharge technology to develop.

Keywords: Brackish water desalination; RO concentrate disposal; EDR; RO–EDR hybrid system

1. Introduction

For many RO brackish water desalination plants the necessity to attain high water recovery is a challenge. First, source water is limited, second, RO concentrate disposal is a special concern. The achieved water recovery varies from 60 to 85% depending on the feed water salinity and its scaling potential [1,2]. The question of brine disposal from inland desalination plants is widely investigated and has been analyzed and described many times [3–5].

The usefulness of surface water discharge, disposal to sewer and land application is usually limited and site-specific. Deep well injection is widely used in the USA, but the risk of contamination of underground drinking water deposits is high [5]. Evaporation ponds/salt processing ponds seem to be a good option especially in dry and hot climate areas; the question of leakages has to be however considered. In insufficiently hot regions

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large pond surface area is needed. Therefore preliminary volume reduction of saline wastewater might be necessary to maintain pond effectiveness. The concept of zero liquid discharge technology is difficult to realize due to the necessity of the concentration of wastewater with extremely high scaling potential and the corrosive character of treated solutions [3,6–9].

The cost of brine disposal can vary considerably depending on the method employed and is site-specific [3] but is likely to become significant in many desalination plants. Beneficial uses of brine are a promising option for solving the brine question as they reduce the overall volume and cost of brine disposal. The cost of RO concentrate treatment is estimated at 5–33% of desalted water cost [1]. In the USA the cost is estimated at $0.26-0.33 per 1 m^3 of produced desalted water or $308–380 per ton of removed salts [2].

The brief analysis of brackish water RO (BWRO) brine disposal question mentioned above shows that evaporation ponds/salt processing ponds or zero liquid discharge facilities should be investigated to increase their performance. But these methods require a concentration of wastewater with an extremely high scaling potential. Two methods meet the requirements concerning the treatment of waters with high scaling potential: 1) special evaporation systems that tolerate the presence of crystals, and 2) EDR.

The application of brine concentrators is limited by two factors: high capital cost (because of the corrosive nature of many brines, brine concentrators are usually constructed of high-quality materials) and high energy consumption. E.g. the RCC vapor compression evaporation (turned out to be useful for treatment of $CaSO_4$ containing brine) energy consumption is equal to 15.9–26.4 kWh per 1 m^3 of feed water [5].

EDR was developed and first demonstrated during the late 1960s by Ionics Inc. In the Ionics EDR the concentrate is recirculated to attain high permeate recovery. EDR achieved high water recoveries at brine stream $CaSO_4$ saturation levels in excess of 190% and +2.2 Langelier Saturation Index (LSI), that determines the $CaCO_3$ saturation level, with no chemical addition to the feedwater [10,11]. The Ionics EDR usefulness for reclaiming RO blowdowns was demonstrated in many plants. It was also successfully applied for BWRO concentrate volume reduction. In the latter, the EDR system has operated in excess of 12,000 h at LSI of EDR brine below +2.2 [12]. The addition of brine stabilizing chemicals permitted long-term operation at even higher scaling indices [11].

In the case of EDR process developed by Ionics the concentrate is recycled to achieve high recovery ratio. Resulting residence time is thus very high that limits maximum permissible level of $CaSO_4$ and/or $CaCO_3$ supersaturation. In the authors' EDR device different diluate and concentrate linear velocities values are applied instead of recirculating of concentrate. Thus concentrate's linear flow velocity is several times lower than diluate's one so certain diluate concentration decrement results in several times higher increment in the concentrate salt content. The ED process with different diluate and concentrate flow velocities has not been carried out until now because of the risk of membrane bulging. Fortunately, applying the 0.19 mm thin net spacer with high strand density protects the membrane against bulging. The intermembrane distance influences also the rate of both diluate and concentrate salt content changes along the ED membrane. The amount of salt passing a certain membrane surface in a certain period of time results from the current density value. When added to a small volume of the solution, being inversely proportional to the intermembrane distance, it would increase its concentration to a large extent [13–17]. The avoidance of concentrate recirculation and low mean residence time are the essential advantages of authors' EDR. It was demonstrated that EDR in this mode can operate with no chemical addition at $CaSO_4$ saturation levels of ca. 400% and +2.4 LSI [15–17].

2. Experimental

The idea of this work is to combine EDR and RO in order to decrease the cost of inland RO desalination plant concentrate disposal and to increase the overall desalted water recovery. Our approach is as follows. The RO concentrate, close to saturation level of $CaSO_4$ and/or $CaCO_3$ (or slightly supersaturated), is concentrated by EDR about 4–5 times. This enables the concentrate volume to decrease and, probably, its disposal cost to the same extent.

The Sahel region of Tunisia brackish water composition [18] was chosen in this work as an example of water with extremely high scaling potential. This water exhibits high risk of crystallization of both $CaSO_4 \cdot 2H_2O$ and $CaCO_3$.

It was assumed that brackish water is desalted using BW30 FILMTEC™ RO membrane with 60% permeate recovery. The RO streams compositions were calculated using Dow Chemical Co. ROSA software. The feed water and calculated RO streams compositions are presented in Table 1.

Both calcium sulphate and calcium carbonate saturation levels in the RO feed and retentate concentrate were considered in order to characterize the scaling potential of each of them. Calcium sulphate saturation level δ was expressed as:

$$\delta = \frac{C_{\mathrm{Ca}^{2+}} C_{\mathrm{SO}_4^{3-}} \gamma_{\pm}^2 C_w^2}{K_{sp}}$$

where $C_{\mathrm{Ca}^{2+}}$, $C_{\mathrm{SO}_4{}^{2-}}$, C_w are the calcium ions, sulphate ions and water content. The $CaSO_4$ solubility product (K_{sp}) at 25°C was equal to $6.26 \cdot 10^{-5}$ [19]. The mean calcium sulphate activity coefficients $\gamma_{\pm}$ were calculated in the manner

Table 1
Brackish water RO process streams compositions at 60% permeate recovery

Component	Concentration, mg/L						Scaling calculations	
	Ca^{2+}	Mg^{2+}	SO_4^{2-}	Cl^-	HCO_3^-	NO_3^-	δ^*,%	LSI
Feed	208.4	95.4	868.8	1166	170.8	179.8	19.35	0.5
Permeate	1.3	0.6	5.4	20.0	3.3	16.8	—	—
Concentrate	519.2	237.7	2164	2886	414.4	424.3	61.06	1.38

* Calcium sulphate saturation level

suggested by Bromley [20]. At the same time, the calcium carbonate scaling potential at given pH, calcium content, total alkalinity and temperature was characterized by means of the LSI, which is commonly used for carbonates containing water scaling potential characterization. The results of scaling calculations are presented in Table 1.

Simulated RO concentrate was then prepared based on RO concentrate composition presented in Table 1 and was treated in a laboratory EDR stand. An EDR unit with 51 cm working length and 0.19 mm spacer thickness equipped with CMV and AMV Asahi Glass membranes was applied in the laboratory experiments [16]. The electrodes polarity was changed every 17 min while at the beginning of each cycle the system was operated in off-spec mode for 0.5 min, resulting in 16.5 min of effective desalination per cycle. Both calcium sulphate and calcium carbonate supersaturation levels in EDR concentrate were considered in order to characterize the scaling potential of each of them.

The EDR process was carried at diluate and concentrate flow velocities equal to 8.0 and 1.7 cm/s, respectively, and 300 A/m^2 mean electric current density. The power consumption in the EDR step was equal to 2.4 kWh per 1 m^3 of EDR feed (i.e. RO concentrate) or 3.0 kWh per 1 m^3 of EDR diluate.

The EDR diluate and concentrate compositions at 79.1% diluate recovery are presented in Table 2.

As it is shown in Table 2, blended desalted water composed of the RO permeate and EDR diluate meets drinking water quality requirements yielding in overall RO–EDR water recovery equal to 91.6%.

The analysis of ED stack voltage drop with EDR process time shows that scaling did not occur despite 358.9% calcium sulphate saturation level and 2.29 LSI value that determines high calcium carbonate supersaturation.

The cost estimation of EDR stage was then made. The cost was calculated for an industrial EDR unit with 0.5 m wide working membrane and 80% effective membrane surface. The energy cost was assumed as equal \$0.06/kWh, the efficiency of pumps 0.85, the membranes' life 10 years. The total investment costs were assumed as equal \$320/m^2 membrane and maintenance costs as 25% of investment costs. The estimated unit EDR cost was equal to \$0.30 per 1 m^3 of EDR feed (or \$0.38 per 1 m^3 of EDR diluate).

3. Conclusions

The effectiveness of brackish water desalination in the RO–EDR system was proved in laboratory tests. In this system BWRO concentrate is treated by a single pass, low residence time EDR. The analysis of the EDR stack voltage drop with the EDR process time shows that scaling did not occur despite 358.9% calcium sulphate saturation level and 2.29 LSI value. The overall RO–EDR water recovery was equal to 91.6% despite high scaling potential of investigated water. It was demonstrated that EDR in the presented mode can operate at such a high supersaturation level which up till now has been achieved with

Table 2
EDR diluate and concentrate compositions at 79.1% diluate recovery

Component	Concentration, mg/L						pH	δ	LSI
	Ca^{2+}	Mg^{2+}	SO_4^{2-}	Cl^-	HCO_3^-	NO_3^-			
Diluate	81.9	26.8	366.3	238	118	48.1	6.92	—	—
Concentrate*	2174	1037	8968	12908	1536	1867	7.37	358.9**	2.29**
Blended: RO permeate + EDR diluate	29.1	9.7	130.1	95.3	42.9	33.2	—	—	—

*Concentrate composition including off specification product, TDS 37790

**The δ and LSI values were calculated for actual EDR concentrate composition that was as follows (mg/L): Mg^{2+} — 1168; Ca^{2+} — 2449; Cl^- — 14640; SO_4^{2-} — 10097; HCO_3^- — 1734; NO_3^- — 1918 chemical addition to the concentrate stream only. The lack of antiscalants allows for the controlled crystallization of $CaSO_4 \cdot 2H_2O$ and $CaCO_3$ in the concentrate stream. In the case of waters containing calcium sulphate and calcium bicarbonate as dominant solutes (over NaCl), crystallization of the aforementioned species might decrease the total concentrate salinity to a large extent. This will allow zero-discharge technology to develop.

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