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A feasibility study of industrial wastewater recovery using electrodialysis reversal

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Abstract

A wastewater reclamation and reuse "mini-plant" was established at the site of China Steel Corporation (CSC) wastewater treatment plant. The purpose of the mini-plant is to demonstrate the technical and economical feasibility of electrodialysis reversal (EDR) process. The mini-plant includes a sand filtration unit and an EDR unit which has a daily treatment capacity of 350 CMD. Raw wastewater had an averaged conductivity of 3860 μS/cm, pH between 7.7 and 8.3, and COD between 30 and 70 mg/L. When the EDR unit operates at a 75% of water reclamation rate, 92% of desalination rate, 98% of chlorine ion removal, 80% of sulfate removal, 99% of calcium ion removal, and 51% of COD removal rate can be achieved. The water quality of product stream is 305 μS/cm for conductivity, 13 mg/L for chlorine ion, 86 mg/L for sulfate, 1.4 mg/L for calcium ion, and of 20 mg/L for COD concentration.

Operation cost of the EDR mini-plant was also estimated in this project. The electricity required for electrodes power supply and pumping is 0.85 kW h per cubic meter of treated water. Total operation cost including electricity fee and chemical cost is about $0.146 per cubic meter of treated water.

Keywords: Electrodialysis reversal; Wastewater reclamation; Reuse

1. Introduction

In view of the potential water source shortage crisis and upcoming water price raise, China Steel Corporation (CSC) is seeking an effective and economic technique to treat and reuse process wastewater. Reverse osmosis (RO) process has been the most commercially applied technology in Taiwan for process wastewater desalination because of its high desalination rate (over 95%). However, membrane fouling and high operating cost raises more uncertainties of its application on large volume wastewater desalination. On the other hand, electrodialysis reversal (EDR) process,

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Table 1
Averaged concentrations of product stream from pilot EDR system [3]

	Conductivity (μS/cm)	COD (mg/L)	Cl^- (mg/L)	SO_4^{2-} (mg/L)	Na^+ (mg/L)	Mg^{2+} (mg/L)	Ca^{2+} (mg/L)
Raw wastewater	2916	50	506	424	239	20	177
EDR influent	2854	35	463	393	220	16	168
EDR product	317	27	19	100	20	2	10
Removal efficiency (%)	89	44	96	76	92	88	94

which can provide higher water reclamation rate and has less fouling, draw more attention in the field test recently [1,2]. Previous pilot study results showed good product stream quality in Table 1 [3] and a much lower operating cost. The mini-plant EDR desalination project is planned to access the optimum design and operating parameters for wastewater reclamation of steel manufacturing process. The technical and economical feasibility of full-scale EDR wastewater reclamation plant is also studied. A long-term continuous operation test is proposed to access the EDR system reliability during dry season and raining season.

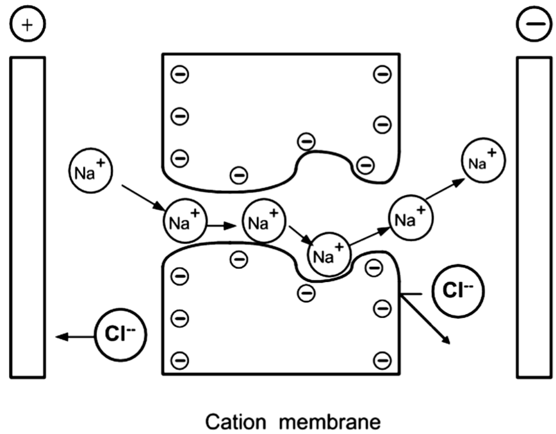

Fig. 1. Migration of ions caused by electric field.

2. Principle of EDR

Electodialysis (ED) is a membrane separation process based on the selective migration of aqueous ions through ion-exchange membranes with outside electric field as the driving force. The migration of ion in an ED cell is shown in Fig. 1. Ion exchange membrane is installed in parallel between the two electrodes. There are two main streams of flow in an ED system. One is progressively desalted and referred as the product stream while the other increases in concentration and referred as concentrated stream. Addition of acid and conditioning chemicals is required for membrane cleaning.

The main feature of EDR process is to reduce the conductivity of water. Observation through long-term continuous operation can help to access the desalination rate, flux decline rate, and membrane surface fouling. Thus, EDR treatment efficiency, operating cost, and initial cost can be estimated more accurately. A schematic diagram of EDR process is illustrated in Fig. 2. The polarity of the electrodes of EDR system is periodically reversed and the ion movement direction changes. Accordingly, the concentrated streams become dilute stream and vice versa. The periodic

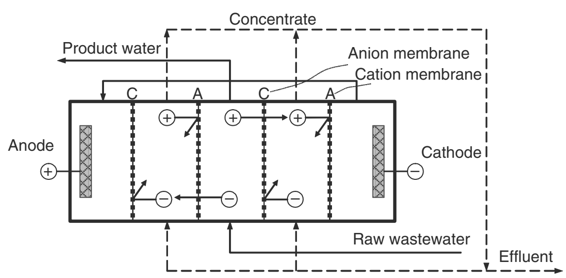

Fig. 2. Schematic diagram of an EDR desalination system.

reverse polarity provides EDR process a self-cleaning mechanism to reduce the surface fouling of ion exchange membrane. Therefore, EDR system is able to maintain a stable flux without the affect of membrane fouling. Comparing to reverse osmosis (RO) system, EDR system is more durable physically and chemically. It can sustain wastewater with higher organic solutes, colloidal particles, and microorganisms content than RO systems. Commercialized EDR system, developed by ITRI and its collaboration company, has been applied to groundwater, river water, and wastewater desalination [4–8].

3. Experimental methods and equipment

3.1. Experimental methods

The experimental EDR mini-plant used in this project was developed and provided by Energy and Environment Research Laboratories (EEL) of ITRI, and Shui Gong She Environmental Engineering Co. LTD. The experimental process includes a sand filtration unit and an EDR unit (Fig. 3). The ion concentrations and conductivity of target wastewater (VC-620 process wastewater) during the experimental period are list in Table 2.

3.2. Specification of EDR system

The experimental apparatus of EDR system is a mini-plant unit, which includes a sand filtration tank, an EDR module, pumps, control valves and a main control panel, with a maximum treating capacity of 350 CMD. A picture of this mini-plant is shown in Fig. 4. The specification of EDR module is list in Table 3. Process logic control incorporated with computer control software was used to record the operating parameters (inflow rate, working pressure, pH, and conductivity) during the experimental period.

3.3. Operation parameters

(1) Test conditions are summary as follows: treated wastewater flow rate: 320 m^3/day, flow rate of product stream: 10 m^3/h, water reclamation rate: 75%, voltage/current: 125 V, 60 A, polarity reverse frequency: once per hour.
(2) Frequency of acid & chemical conditioning: every 7 days, circulate 5% HCl solution to clean membrane surface for 30 min.
(3) The following items need to be sampled and analyzed every day: (a) conductivity,

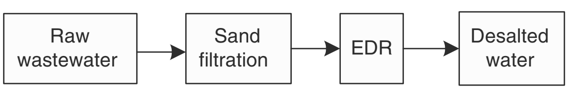

Fig. 3. Flow diagram of the mini-plant flow.

Fig. 4. Picture of EDR mini-plant installed in a container.

Table 2
Water quality of raw wastewater

	pH	Conductivity (µS/cm)	COD (mg/L)	Cl^- (mg/L)	SO_4^{2-} (mg/L)	Na^+ (mg/L)	Ca^{2+} (mg/L)
Range	7.7–8.3	2800–4000	36–72	398–861	345–628	154–325	128–220

Table 3
Specification of EDR module

Module arrangement	Number of membranes (pairs)	Capacity (m^3/day)	Membrane surface area (cm)	Max. operation voltage (V)
3 stages in series	450	260	160 × 80	160–180

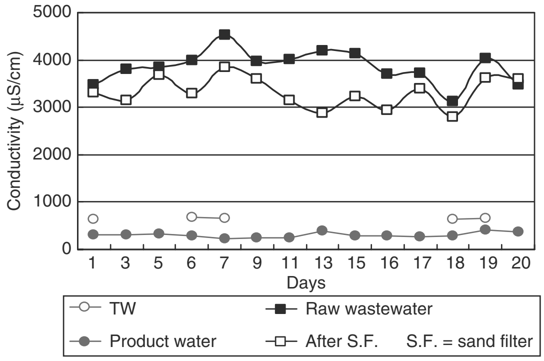

Fig. 5. Conductivity variations in raw wastewater, effluent of sand filtration, city water (TW) and product stream of the mini-plant.

cation/anion concentration (Ca^{2+}, Mg^{2+}, Cl^-, F^-, SO_4^{2-}), desalination rate. (b) pH, influent and effluent COD, and COD removal efficiency.

4. Results and discussions

4.1. EDR desalination rate

The conductivity of raw wastewater, effluent of sand filtration, and product stream are shown in Fig. 5. Raw wastewater conductivities varied between 3100 to 4500 µS/cm where averaged conductivity was 3860 µS/cm. All of product stream conductivities were less than 400 µS/cm with the averaged value of 305 µS/cm. The desalination rate of the mini-plant is shown in Fig. 6. When the EDR system is operating with 75% of wastewater reclamation rate, 92% of averaged desalination rate was achieved. These data were taken from dry season when raw wastewater with higher salinity was discharged.

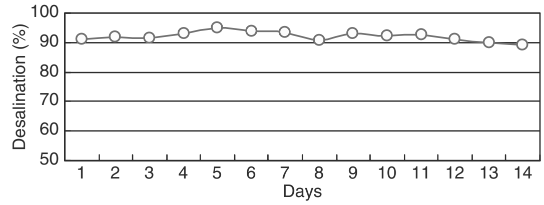

Fig. 6. Desalination rate of EDR system.

4.2. Calcium and fluoride ion removal

Fig. 7 shows the variations of calcium ion in raw wastewater and product stream during the dry season. Calcium ion concentrations in raw wastewater ranged between 100 and 220 mg/L and dropped to below 3 mg/L in product stream. Fig. 8 shows the fluoride ion variations in raw wastewater and product stream. Fluoride ion concentrations were about 15 mg/L in raw wastewater and were treated to below 1 mg/L in product

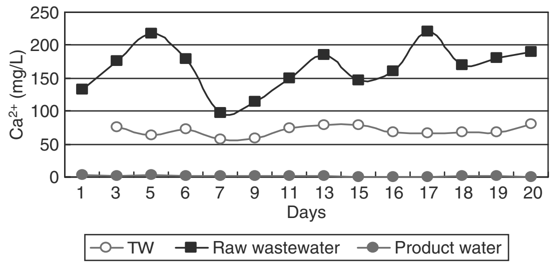

Fig. 7. Calcium ion variations in EDR raw wastewater and product stream.

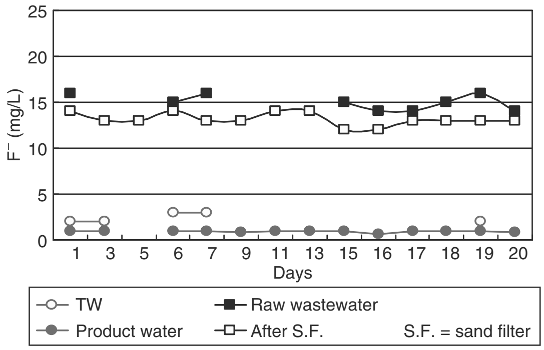

Fig. 8. Fluoride variations in EDR raw wastewater and product stream.

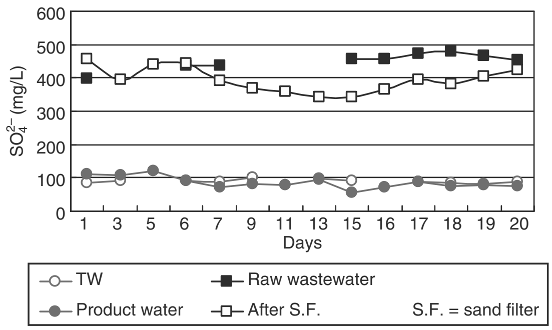

Fig. 10. Concentration of sulfate in raw wastewater and product stream.

stream, which were even lower than the fluoride contents in city water (TW).

4.3. Chloride ion and sulfate removal

Chloride ion variations in raw wastewater and product stream are recorded in Fig. 9. Chloride ion concentrations in raw wastewater varied between 590 and 1100 mg/L with an averaged concentration of 888 mg/L. Chloride ion concentrations in product stream was maintained below 20 mg/L, much lower than in city water (averaged 96 mg/L of chloride).

Comparing to other monitored ions, the EDR system is less efficient in sulfate removal. Sulfate concentrations shown in Fig. 10 were between 400 and 480 mg/L in raw wastewater and were reduced to below 90 mg/L in product stream, which were in the same level of city water.

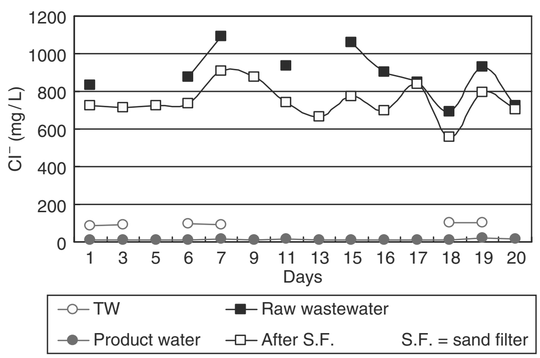

Fig. 9. Chloride variations in EDR raw wastewater and product stream.

4.4. COD removal

The averaged COD removal efficiency is 51% during the experimental period. Raw wastewater COD, ranging from 30 to 75 mg/L, was reduced to 14 to 40 mg/L in product stream. The organic compounds in raw wastewater will not be removed by EDR system if they are not charged. The charged organics can be removed in EDR system and their removal rates depended on molecular weight and charges. Fig. 11 shows that about half of the COD in raw wastewater was removed in EDR system. These imply that a certain amount of organics in raw wastewater was charged. The COD in concentrated stream were less than 100 mg/L, which met the EPA

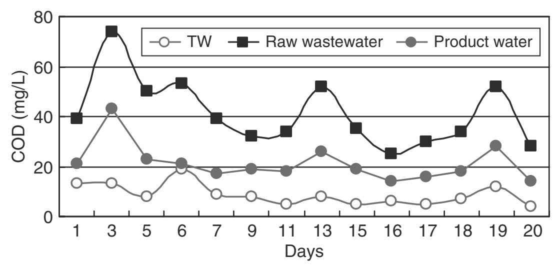

Fig. 11. COD variations in raw wastewater and product stream.

effluent standards and can be discharged directly to the receiving stream.

4.5. Overall removal efficiency

The averaged removal efficiencies of each monitored item were summarized in Table 4. Averaged concentrations of these items of city water were also listed in the table for comparison. When operating at 75% of water reclamation rate, raw wastewater conductivity of 3860 μS/cm, COD concentration between 30 and 70 mg/L, and pH between 7.4 and 7.8, the EDR mini-plant has an averaged desalination rate of 92%, chloride ion removal rate of 98%, sulfate removal rate of 80%, calcium ion removal rate of 99%, and COD removal rate of 51%. The averaged concentrations of product stream are 305 μS/cm of conductivity, 13 mg/L of chloride ion, 80 mg/L of sulfate 1.4 mg/L of calcium ion, and 20 mg/L of COD.

5. Operation cost evaluation

The operation cost of EDR system includes the following three items: (a) electricity for desalination, (b) electricity for pumps, (c) chemicals for membrane cleaning. Each of these items is estimated as follows:

(1) D.C. power supply for desalination

125 V × 60 A/10 m^3/h × \$0.061/kW h = \$0.046/m^3 (electricity fee is \$0.06 per kilowatts per hour)

(2) Electricity for pumps

Power required	(in Hp)	(in kW/h)
Raw wastewater pump	5	3.75
Electrode cells pumps	1	0.75
Product stream pumps	5	3.75
Concentrated stream pumps	5	3.75
Supplemental pump	0.5	0.75
Air compressor	1	0.75
Total		13.5

The electricity fee for every cubic meter of treated water is calculated as

13 kW/h × \$0.061/kW/10 m^3 = \$0.082/m^3

(3) Chemical cost for membrane cleaning
The main chemical used in membrane cleaning is chlorine acid, which is \$0.06 per kilogram. So the chemical cost is estimated as

0.3 L HCl/m^3 = \$0.018/m^3

Total operation cost is the sum of the three items:

Total operation cost = (a) + (b) + (c) = \$0.046/m^3 + \$0.082/m^3 + \$0.018/m^3 = \$0.146/m^3

6. Summary

The field test of the EDR mini-plant gave good results on CSC raw wastewater desalination.

Table 4
Summary of removal efficiencies for EDR system

Averaged concentration	Conductivity (μS/cm)	pH	Ca^{2+} (mg/L)	F^- (mg/L)	SO_4^{2-} (mg/L)	Cl^- (mg/L)	COD (mg/L)
Raw wastewater	3860	7.8	166	16	437	888	41
Product stream	305	6.2	1.4	0.9	86	13	20
City water	656	7.4	70	2.4	90	96	9
Removal rate (%)	92		99	94	80	98	51

Over 90% of desalination rates were achieved. The water qualities of all the monitored items of the product stream were better than city water. The operation cost of the EDR system is estimated in this project. The total operation cost is $0.146 per cubic meter of treated water.

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