



## Chemical-free ion exchange and its application for desalination



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### HIGHLIGHTS

- Chemical-free ion exchange was proposed to purify desalinated seawater;
- Resin regeneration was mainly contributed by electrically enhanced water split;
- Effluent conductivity and energy consumption were 0.8–1.5  $\mu\text{S}/\text{cm}$  and 0.29–1.04k  $\text{Wh}/\text{m}^3$ ;
- No chemical was needed and no wastewater was produced.

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### ABSTRACT

In some coastal areas, the primary freshwater obtained through seawater desalination has been widely used as the feed water in high purity-water production. Due to its high conductivity, however, further lowering ionic species load is needed before the final polishing process such as the mixed bed ion exchange and electrodeionization. In this work, a new process called as chemical-free ion exchange (CFIE) was proposed to replace the conventional two-bed (cation–anion) ion exchange for the purpose above. Results demonstrated that the mixed resin regeneration was achieved mainly by electrically enhancing water split. After regeneration, the resins could resume their ability to desalinate. The conductivities of purified water were 0.8–1.5  $\mu\text{S}/\text{cm}$ , and the energy consumption and water recovery were 0.29–1.04  $\text{kWh}/\text{m}^3$  water and 81.8–94.7%, respectively. The neutral concentrate collected during regeneration could be returned to a pretreatment unit for recovery. No chemical was needed and no wastewater was produced. Repetitive experimental results showed that the CFIE system could run stably.

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### 1. Introduction

Due to the shortage of natural freshwater resources, distillation and membrane separation methods are widely used to produce primary freshwater from seawater [1–4]. The conductivities of the seawater after desalination usually range from 10 to 70  $\mu\text{S}/\text{cm}$  [1,4–10]. To produce high-purity water, such desalinated seawater should be further desalinated. Electrodeionization (EDI) and mixed-bed ion exchange (MBIE) are the two widely used processes in high-purity water production nowadays [11–13]. EDI is mainly applied to the feed water with low hardness and low conductivity, usually below 20  $\mu\text{S}/\text{cm}$  [13]. Due to the complex configuration and expensive investment, EDI is much less popular than MBIE in many large scale applications [13]. Therefore, the desalination based on ion exchange resins is still the main industrial process for water purification. When MBIE is used for purifying the desalinated seawater with a high conductivity, its resins should be regenerated frequently, which is very laborious. To avoid the frequent regeneration of the mixed bed resins, a secondary desalination process should be added before MBIE to adsorb most soluble salts.

The conventional two-bed (cation–anion) ion exchange (TBIE) prior to MBIE is known to be the most typical secondary desalination process in use today. However, once ion exchange resins are saturated, they should be regenerated using either acid solution or alkali solution. The chemical regeneration of resins consumes chemicals, produces wastewater containing high concentration of acid, alkali and salts, and demands a plenty of auxiliary facilities for chemical storage and wastewater treatment. If resins can be regenerated greenly and conveniently, the economic and environmental benefits of ion exchange will be bettered substantially. Some researchers have examined resin regeneration using hot water or DC electricity [14,15], but these methods are seldom used in industry due to their low efficiency and high cost. Inspired by the principle of EDI, Wang [16] proposed a green technique for resin regeneration. After being exhausted, the resins were transferred from an ion exchanger to an improved electrodialyzer first, and then regenerated using the  $\text{H}^+$  and  $\text{OH}^-$  ions generated through the electrically enhanced water split. However, this technique still remains controversial because effective regeneration cannot be ensured [17–20]. Moreover, it is complicated in facilities and laborious in operation. In our previous work, a membrane-free electrodeionization (MFEDI) process was investigated for high-purity water production [21–23]. It could remove ionic species effectively. Nevertheless, this process is only suitable

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for treating water with low conductivities, usually below  $20 \mu\text{S}/\text{cm}$  [21, 23]. When it is used to deal with water with higher conductivities, overly high energy consumption may become a critical factor that limits its wide applications.

In this work, we proposed a chemical-free ion exchange (CFIE) system that was derived from MFEDI as a pretreatment unit of MBIE or MFEDI to remove most soluble salts in the desalinated seawater with conductivities of  $20\text{--}70 \mu\text{S}/\text{cm}$ . The CFIE system consists of a mixed bed filled simultaneously with strong-acid and weak-base resins and an anion bed filled only with weak-base resin. The strong-acid resin has an excellent capacity to adsorb cations over a broad band of pH values, whereas the weak-base resin can adsorb anions effectively in the acidic environments and desorb easily under slightly alkaline conditions [24]. These important attributes of the two different types of resins enable CFIE to work successfully. Similar to MFEDI, the CFIE system is operated in a batch mode, alternating with service and regeneration. In the service stage, the water flow passes first through the mixed bed to remove cations and a certain fraction of anions, then through the anion bed to remove the residual anions. In the regeneration stage, the purified water passes through and meanwhile the DC electricity is imposed on the mixed bed, allowing the exhausted resins to be regenerated effectively. The mixed bed effluent produced during electroregeneration is alkaline, and therefore can just be used for chemical regeneration of the exhausted weak-base resin in the anion bed. The concentrate collected during the anion bed regeneration is neutral, and thus can be returned to a pretreatment unit such as RO for recovery in real applications. The CFIE system has many advantages, including simple device, easy operation, no chemicals consumed, and no wastewater produced. The major objectives of this study are to determine the proper resin ratio of the mixed bed, to investigate the electroregeneration mechanism of mixed resins, and to evaluate the performance of the CFIE system.

## 2. Materials and methods

### 2.1. Resins and desalinated seawater

The characteristics of ion exchange resins used in this work are presented in Table 1. Before use, the gel-type strong-acid cation resin (650C, Dow, Shanghai, China) and the gel-type weak-base anion resin (312, Zhengguang Co., Hangzhou, China) were washed with deionized water until the conductivity of the solution was below  $2 \mu\text{S}/\text{cm}$ .

The desalinated seawater produced using distillation methods or membrane separation methods can be considered as the dilute NaCl solution because its main dissolved salt is NaCl [25]. Hence, the desalinated seawater used in this work was prepared synthetically by dissolving NaCl (AR, 99.5%, Aladdin, Shanghai, China) in deionized water, with conductivities being  $20\text{--}70 \mu\text{S}/\text{cm}$ .

### 2.2. Electrode preparation

Reticular  $\text{Ti}/\text{RuO}_2\text{--Sb}_2\text{O}_5\text{--SnO}_2$  electrode and titanium electrode, both with an effective area of  $7.1 \text{ cm}^2$ , were used as an anode and a

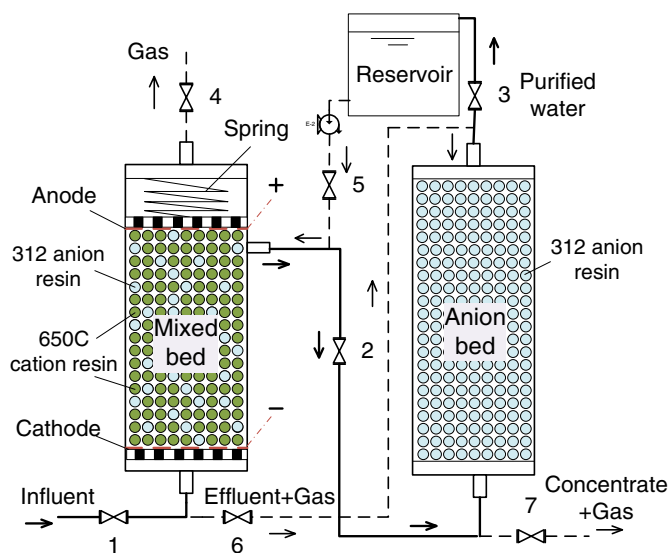


Fig. 1. CFIE system.

cathode, respectively. The  $\text{Ti}/\text{RuO}_2\text{--Sb}_2\text{O}_5\text{--SnO}_2$  electrode was fabricated with a thermal decomposition method using titanium mesh, 3 cm in diameter, as a substrate. The precursor solution was prepared by mixing the individual solutions of  $\text{SnCl}_4 \cdot 5\text{H}_2\text{O}$  (99.9%, Aladdin, Shanghai, China),  $\text{RuCl}_3 \cdot 3\text{H}_2\text{O}$  (38–42%Ru, Aladdin, Shanghai, China) and  $\text{SbCl}_3$  (99.9%, Aladdin, Shanghai, China). After ultrasonic cleaning, the titanium substrate was brushed with the precursor solution, dried at  $80 \text{ }^\circ\text{C}$  for 3 min, and then calcinated at  $500 \text{ }^\circ\text{C}$  for 5 min. This procedure was repeated for about 20 times, and finally the electrode was annealed at  $500 \text{ }^\circ\text{C}$  for an hour. More details regarding the  $\text{Ti}/\text{RuO}_2\text{--Sb}_2\text{O}_5\text{--SnO}_2$  electrode fabrication can be found elsewhere [26].

### 2.3. CFIE system

The CFIE system is schematically shown in Fig. 1. The heights of the mixed bed and the anion bed were 30 cm and 40 cm, respectively. Both beds had an inner diameter of 3 cm. A pair of electrodes was fixed in the mixed bed, and the mutually mixed 650C and 312 resins were packed between this pair of electrodes. A spring was used to compress the resin layer. The anion bed was filled with 312 resin. A reservoir was used to store the purified water that would be supplied for the subsequent regeneration stage.

The CFIE system was operated as follows. In the service stage, valves 1 to 3 were open and valves 4 to 7 were closed; the synthetic desalinated seawater entered the system through valve 1 and passed the ion exchange beds upward; the purified water came out through valve 3. As the conductivity of purified water was beyond a given level, regeneration started. During this period, valves 1 to 3 were closed and valves 4 to 7 were open; the purified water that was stored in the reservoir in the service stage was pumped to the CFIE system through valve 5, and passed the ion exchange beds downward. At the same time, DC electricity was supplied to regenerate the exhausted resins in the mixed bed; the alkaline solution produced during the mixed bed regeneration passed the anion bed downward to regenerate the weak-base resin chemically. The gas generated at the top anode was exhausted relying on its buoyant force, and that generated at the bottom cathode was taken away by the effluent stream. More details regarding gases release can be found elsewhere [21].

Table 1  
Properties of ion exchange resins.

Designation	650C cation resin	312 anion resin
Type	Strong-acid	Weak-base
Matrix structure	Polystyrene	Polyacrylic acid
Function group	Sulfo ( $-\text{SO}_3\text{H}$ )	Tertiary amine ( $-\text{NHR}_2\text{OH}$ )
Porosity	Gel	Gel
Size (mm)	0.59–0.66	0.45–0.75
Water content (%)	46–51	56–63
Bulk density (g/mL)	1.22	1.01–1.09
Exchange capacity (eq/L)	$\geq 2.0$	$\geq 1.6$

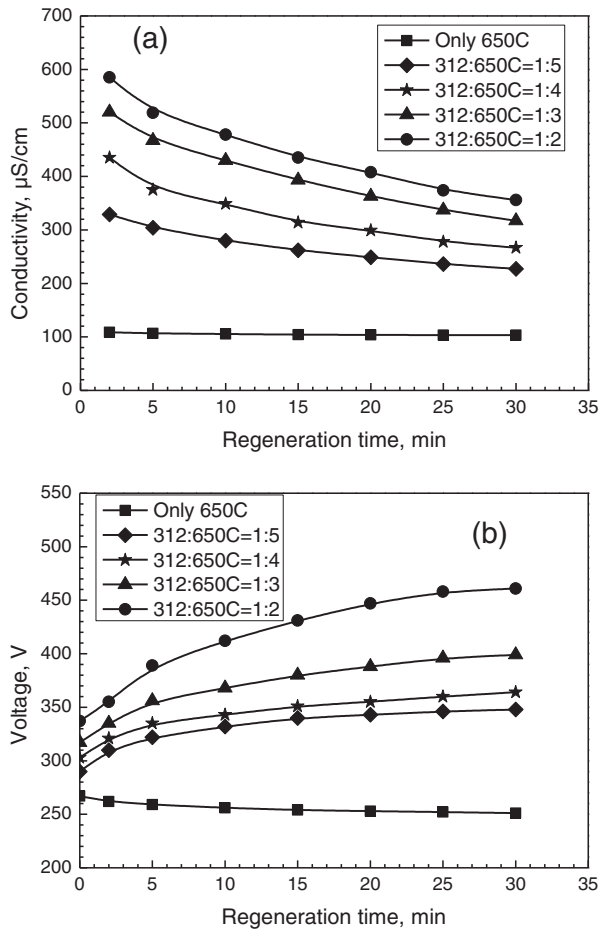


Fig. 2. Regeneration performance of mixed bed at a current density of 200 A/m<sup>2</sup> and a flow velocity of 15 m/h: (a) conductivity variations and (b) voltage variations.

#### 2.4. Analysis methods

Conductivity was measured using a Sension 5 conductivity meter (Hach, OH, resolution: 0.01 μS/cm); Na<sup>+</sup> concentration was analyzed with an atomic absorption spectrophotometer (AA-6300, Shimadzu, Japan) and pH value was measured using a pH/ISE meter (Orion Dual StarTM, Thermo Scientific, Singapore). Chlorine was measured using the iodometric titration method.

### 3. Results and discussion

#### 3.1. Resin ratio selection for mixed bed

It is well known that the ratio of anion resin to cation resin is very important for any mixed beds. Therefore, the resin ratio for the mixed bed should be selected properly. In order to accelerate experiments, all 650C resin and 312 resin used were pre-saturated with NaOH and HCl, respectively, and the results are shown in Fig. 2. It was found that, while the bed was filled only with 650C resin, the average regeneration effluent conductivity and voltage were only 105 μS/cm and 250 V, respectively. With the addition of 312 resin, the effluent conductivity increased significantly, accompanied by an increase in voltage. For example, as the volume ratio of 312 resin to 650C resin was 1:5, the average regeneration effluent conductivity and voltage increased to 260 μS/cm and 330 V. As the volume ratio of 312 resin to 650C resin increased to 1:2, the average regeneration effluent conductivity and voltage were further elevated to 425 μS/cm and 430 V. It should be pointed out that high regeneration effluent conductivity and low voltage are

strongly desired in industrial applications for raising water recovery and saving regeneration energy. Based on such considerations, the proper volume ratio of 312 resin to 650C resin in the mixed bed was determined to be about 1:3.

#### 3.2. Electro-regeneration mechanism of mixed bed resins

As demonstrated in Fig. 2, an addition of 312 resin into 650C resin gave a boost on electro-regeneration efficiency. In order to explore the mechanism of resin electro-regeneration, the regeneration behavior of the bed filled either with only the 650C resin or with the mixed 650C and 312 resins was investigated.

During electro-regeneration, the anode, located on the top of the bed, can generate H<sup>+</sup> ions for the exhausted 650C resin regeneration, and the amount of H<sup>+</sup> ions produced through the water electrolysis reaction can be calculated using Eq. (1) according to Faraday's law.

$$m_1 = \frac{It}{F} \quad (1)$$

where  $m_1$  is the amount of H<sup>+</sup> ions, moles;  $I$  is the current, A; and  $t$  is the electrolysis time, s. In this work,  $I$  was 0.142 A,  $t$  was 1800 s, and thus  $m_1$  was estimated to be  $2.6 \times 10^{-3}$  mol.

The Na<sup>+</sup> concentration variations of the regeneration effluents of the mixed bed are shown in Fig. 3. When the bed was filled only with 650C resin, the average concentration of Na<sup>+</sup> ions in effluent was only 11.1 mg/L. Since the water consumption was 5.3 L during regeneration, the total amount of Na<sup>+</sup> ions released from the 650C resin to solution was 58.8 mg, i.e.,  $2.5 \times 10^{-3}$  mol, which was close to the amount of H<sup>+</sup> ions produced on the anode, i.e.,  $2.6 \times 10^{-3}$  mol. Apparently, cation resin regeneration was contributed exclusively by the water electrolysis reaction that occurred on the anode. On the other hand, when the bed was filled with the mixed 650C and 312 resins, the average concentration of Na<sup>+</sup> ions in the regeneration effluent was as high as 72.8 mg/L, and the total amount of Na<sup>+</sup> ions released from the 650C resin to solution reached 385.8 mg, i.e.,  $16.8 \times 10^{-3}$  mol. Therefore, it could be calculated that the water electrolysis reaction that occurred on the anode only supplied 15.5% H<sup>+</sup> ions for cation resin regeneration. The rest of 84.5% H<sup>+</sup> ions should be provided by the electrically enhanced water-splitting reaction [18,27,28].

The regeneration process of the mixed bed resins can be illustrated in Fig. 4. The H<sup>+</sup> ions, produced by the water electrolysis reaction on the anode, were released to solution to regenerate the exhausted 650C resin. Meanwhile, under the force of a direct-current field, the Na<sup>+</sup> ions in 650C resin migrated downward and the Cl<sup>-</sup> ions in 312 resin

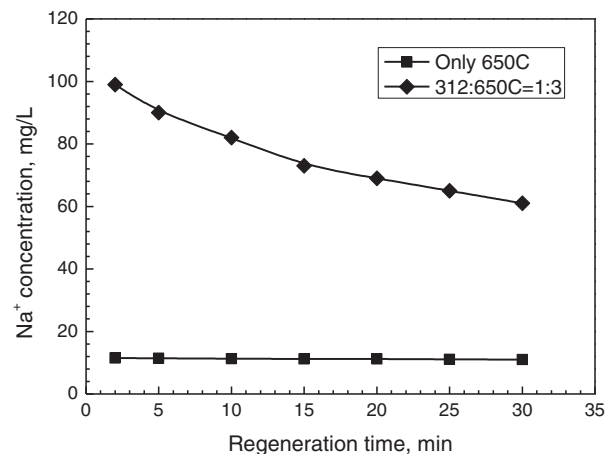


Fig. 3. Na<sup>+</sup> concentration variations of the mixed bed effluents produced during regeneration at a current density of 200 A/m<sup>2</sup> and a flow velocity of 15 m/h.

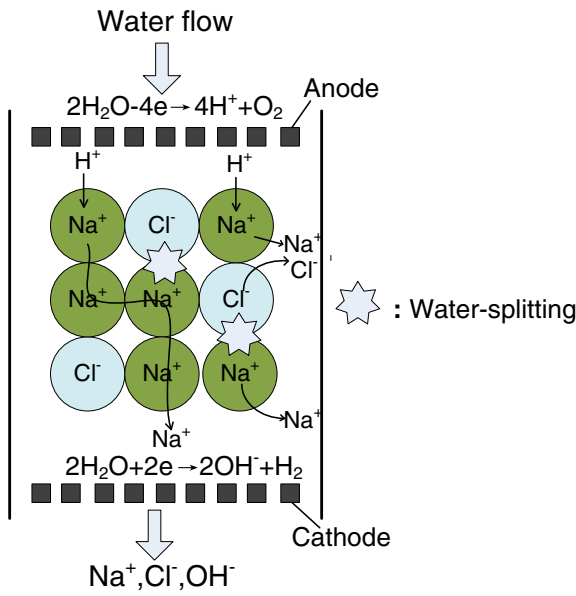


Fig. 4. Electro-regeneration process of mixed bed resins.

migrated upward, which resulted in a rapid depletion of the ions adsorbed at the interfaces of the cation and anion resin particles and caused water to split there. Subsequently, the H<sup>+</sup> and OH<sup>-</sup> ions produced by water-splitting could substitute the counter-ions in the exhausted resins and realize resin regeneration. It is worth mentioning that the water-splitting reaction is much easier to occur on the contact face of weak-base and strong-acid resins than on that of strong-base and strong-acid resins due to the strong bonding force of the weak-base resin for OH<sup>-</sup> ion [21,23]. This explains why adding 312 resin into 650C resin could improve the regeneration efficiency amazingly.

### 3.3. Purification performance of CFIE using new resins

For comparison purpose, the purification performance of the CFIE system filled with new resins was investigated. As shown in Fig. 5, the conductivity of the mixed bed effluent in the service stage was below 1 μS/cm first, then increased sharply, and finally remained around 170 μS/cm; the corresponding pH value was about 5.8 initially, then dropped quickly, and eventually stayed around 3.5. Such results should be associated with the gradual exhaustion of the 312 resin which had much lower total capacity than the 650C resin in the mixed bed in this work. After the 312 resin was saturated completely, only the 650C

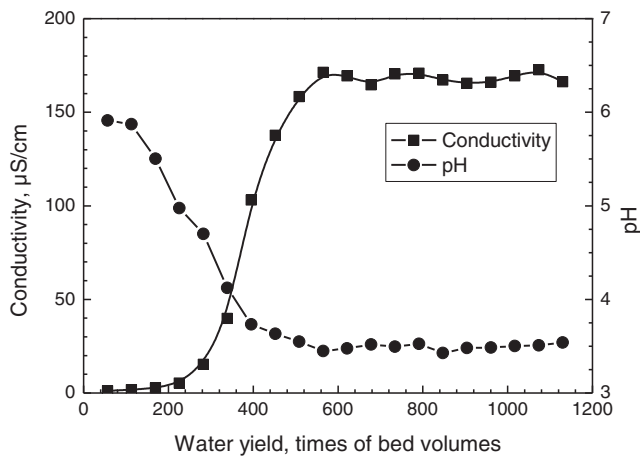


Fig. 5. Conductivity and pH variations of the mixed bed effluent produced in the first desalination cycle at an influent conductivity of 50 μS/cm and a flow velocity of 20 m/h.

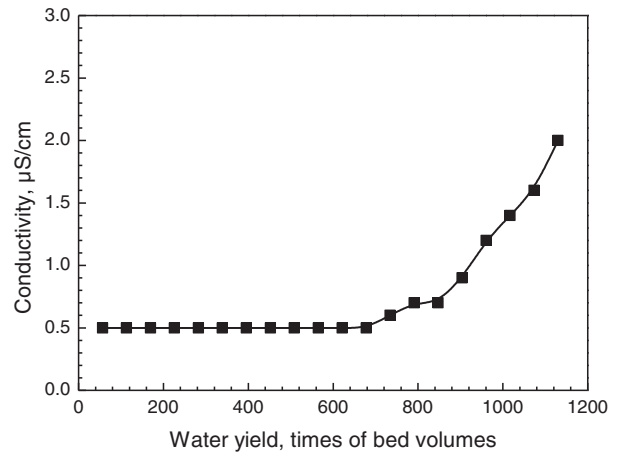


Fig. 6. Conductivity variation of the purified water produced in the first desalination cycle at an influent conductivity of 50 μS/cm and a flow velocity of 20 m/h.

resin worked, and accordingly the effluent of the mixed bed became a dilute HCl solution, leading to a dramatic drop in pH value. As well known, HCl solution has much higher conductivity than NaCl solution under the same molar concentration. This explains why the mixed bed effluent finally exceeded the influent in conductivity.

As shown in Fig. 6, the conductivity of the purified water, namely the anion bed effluent produced during service, was ~0.5 μS/cm at the early stage of the entire desalination process, then increased gradually, and reached ~2.0 μS/cm when the water yield reached to 1130 times of bed volumes, i.e. 560 L. Such purified water can be accepted as the feed water for the subsequent polishing process, such as MBIE and MFEDI.

### 3.4. Regeneration performance of CFIE

After adsorption, the CFIE system began to be regenerated, and the experimental results are shown in Figs. 7 and 8. The initial conductivity of the mixed bed effluent produced during regeneration reached a maximum value of 490 μS/cm, revealing the fast ion release from the resin phase to the solution phase. Subsequently, the effluent conductivity decreased gradually from 490 μS/cm to 355 μS/cm due to a decrease in the concentration of ions adsorbed in resins [23]. As shown in Fig. 7, the mixed bed effluent was strongly alkaline, indicating that the electrolytes in effluent were composed of NaCl and NaOH. This was attributed to the water electrolysis reaction which occurred on the anode that was favorable for the 650C cation resin regeneration.

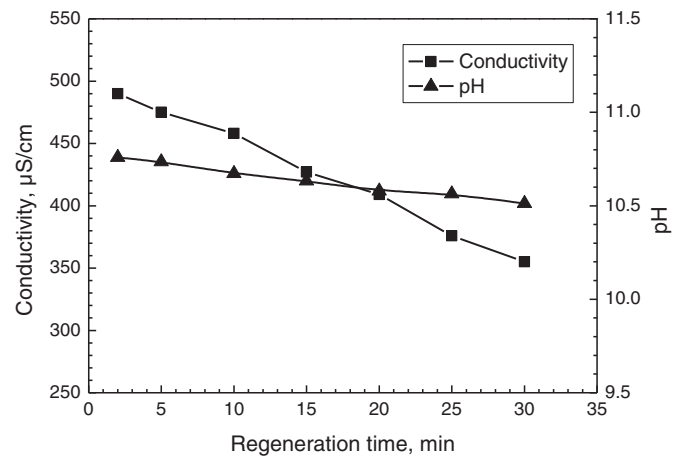


Fig. 7. Conductivity and pH variations of the mixed bed effluent produced during regeneration at a current density of 200 A/m<sup>2</sup> and a flow velocity of 15 m/h.



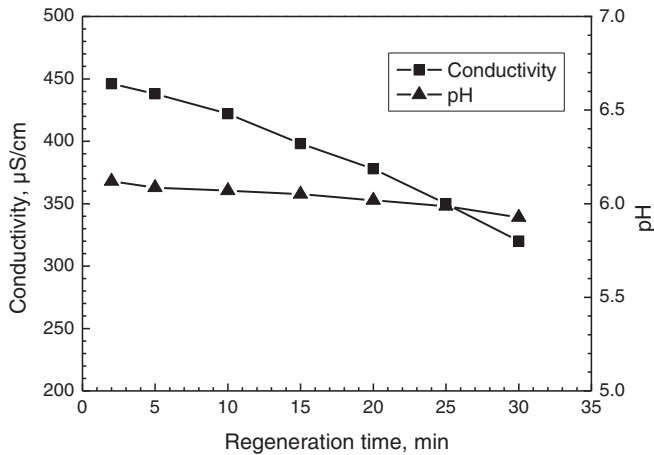
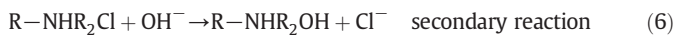
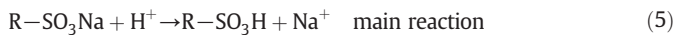
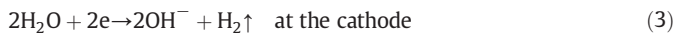


Fig. 8. Conductivity and pH variations of the CFIE concentrate produced during regeneration at a current density of 200 A/m<sup>2</sup> and a flow velocity of 15 m/h.

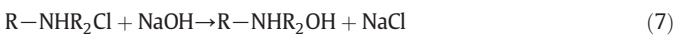
After that, the 312 resin in the anion bed was regenerated by the alkaline mixed bed effluent chemically. This process converted the NaOH in the mixed bed effluent into NaCl, and hence the concentrate was nearly neutral as presented in Fig. 8. Since the conductivity of NaCl was lower than that of NaOH under the same molar concentration, the conductivity of the CFIE concentrate decreased from 445 µS/cm to 325 µS/cm. The neutral concentrate, with an average conductivity of 380 µS/cm, can be returned to a pretreatment unit, such as RO, for recovery in real applications.

The chemical reactions during regeneration can be expressed as follows:

In the mixed bed:



In the anion bed:



where R-SO<sub>3</sub>H and R-NHR<sub>2</sub>OH represent the H-type 650C resin and OH-type 312 resin; R-SO<sub>3</sub>Na and R-NHR<sub>2</sub>Cl represent the Na-type 650C resin and Cl-type 312 resin, respectively. In the mixed bed, Eqs. (2) and (3) occurred at the anode and cathode respectively, and Eq. (4) occurred on the contact surface of the 650C and 312 resins. Obviously, the H<sup>+</sup> ions coming from Eqs. (2) and (4) could regenerate the exhausted 650C resin through Eq. (5). The OH<sup>-</sup> ions generated in Eq. (4) could regenerate the exhausted 312 resin through Eq. (6). In the anion bed, the exhausted 312 resin was regenerated by NaOH present in the mixed bed effluent through Eq. (7).

During 30 min regeneration, it was calculated that  $0.66 \times 10^{-3}$  mol, i.e. 14.7 mL O<sub>2</sub>, was generated at the top anode and  $1.32 \times 10^{-3}$  mol, i.e. 29.4 mL H<sub>2</sub>, was produced at the bottom cathode using Eq. (1) according to Faraday's law. Since only small amounts of O<sub>2</sub> and H<sub>2</sub> gases were generated during regeneration and their emissions were separated, the safety of the CFIE system could be ensured well.

The chlorine, which could be dissolved in water and converted to HClO, was not detected in the mixed bed effluent using the iodometric titration method. This is attributed to the low concentration of chloride.

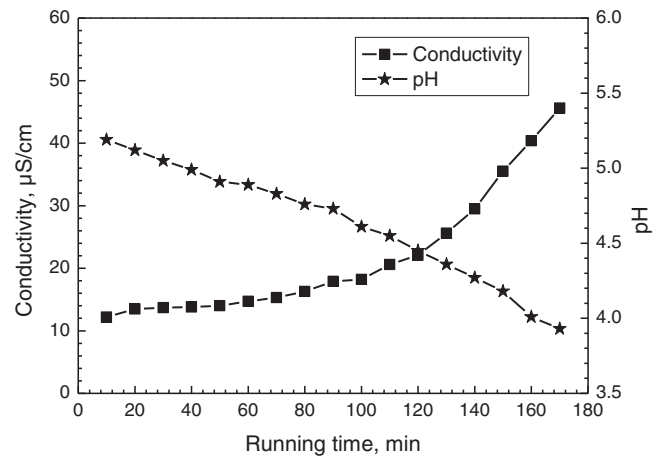


Fig. 9. Conductivity and pH variations of the mixed bed effluent produced during desalination after resin regeneration at an influent conductivity of 50 µS/cm and a flow velocity of 20 m/h.

In this work, the conductivity of the purified water used for regeneration was ~1 µS/cm, and the corresponding NaCl concentration was estimated to be ~0.5 mg/L only. In such a dilute NaCl solution, the chlorine evolution at the anode was therefore insignificant.

### 3.5. Purification performance of CFIE after regeneration

After regeneration, the CFIE system turned to service immediately. As shown in Fig. 9, the conductivity of the mixed bed effluent ranged from 12.2 µS/cm to 18.2 µS/cm within initial 100 min, then rose quickly, and reached 45.6 µS/cm finally. Meanwhile, the pH value of the effluent decreased from 5.2 to 3.9. The phenomena observed above could be explained as follows. In the regeneration process, more 650C resin was electrically regenerated than 312 resin in the mixed bed; in the early stage of service, most of NaCl in influent was absorbed by 650C and 312 resins, and the rest of NaCl was converted into HCl by 650C resin. Thus, the effluent was acidic, and its conductivity was much lower than 50 µS/cm. As desalination proceeded, much more NaCl was converted into HCl by 650C resin due to the gradual exhaustion of OH-type 312 resin in the mixed bed. Therefore, the mixed bed effluent became more acidic and its conductivity began to increase significantly. Fig. 10 shows the conductivity variation of the purified water, i.e., the effluent of the anion bed, in the service stage after regeneration. At the very beginning, the conductivity was only ~0.9 µS/cm, indicating that the exhausted anion resin had resumed their ability to adsorb Cl<sup>-</sup> ions

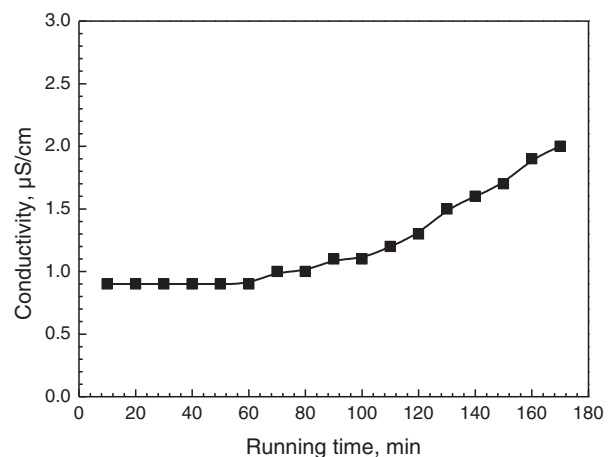
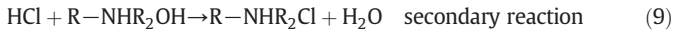


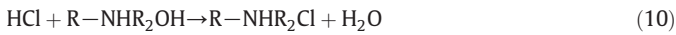
Fig. 10. Conductivity variation of the purified water produced during desalination after resin regeneration at an influent conductivity of 50 µS/cm and a flow velocity of 20 m/h.

after regeneration. As expected, the conductivity then increased slowly as the service time increased. After 2.85 h, the conductivity reached 2.0 μS/cm, suggesting that the resins needed to be regenerated again. Such purified water with an average conductivity of 1.2 μS/cm could be also accepted as the feed water for MBIE and MFEDI. It should be noted that the service time was shortened and the quality of purified water was lowered slightly after regeneration. This was understandable because the resins in CFIE were only partially regenerated for the energy saving purpose and the regenerated resins distributed haphazardly throughout the whole resin layer as shown in Fig. 4.

The purification process of the CFIE system can be described below:  
In the mixed bed:



In the anion bed:



As demonstrated in Fig. 10, after regenerated for 30 min at a current density of 200 A/m<sup>2</sup> and a flow velocity of 15 m/h, CFIE could continuously purify the synthetic desalinated seawater with a conductivity of 50 μS/cm for 2.85 h at a flow velocity of 20 m/h. This means that the CFIE system used in this work produced a total of 40.5 L, i.e. 81.8 times of bed volumes, of purified water during service and consumed 5.3 L, i.e. 10.7 times of bed volumes, of purified water during regeneration for each operational cycle.

The energy consumption, the water recovery, and the desalination rate of CFIE could be calculated according to Eqs. (11)–(13), respectively.

$$E = \frac{\bar{U}It}{V_1 - V_2} \quad (11)$$

$$R = \frac{V_1 - V_2}{V_1} \times 100\% \quad (12)$$

$$D = \frac{C_1 - C_2}{C_1} \times 100\% \quad (13)$$

where  $E$  is the energy consumption, kWh/m<sup>3</sup>;  $\bar{U}$  is the average regeneration voltage, V;  $I$  is the current, A;  $t$  is the regeneration time, h;  $V_1$  is the total volume of purified water, L;  $V_2$  is the volume consumed for regeneration, L;  $R$  is the water recovery, %;  $D$  is the desalination rate, %;  $C_1$  is the influent conductivity, μS/cm; and  $C_2$  is the purified water

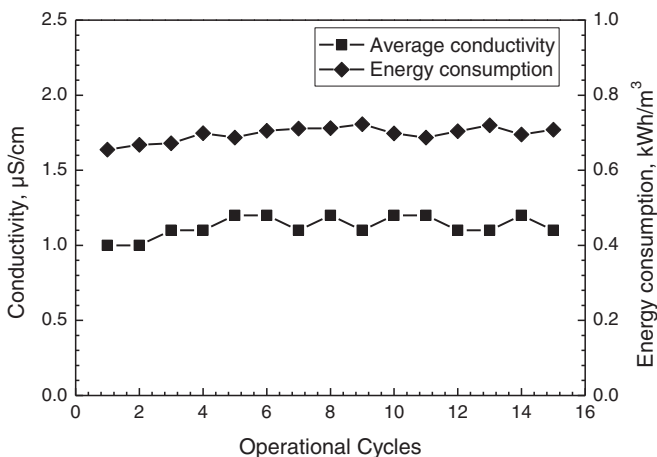


Fig. 11. Purified water conductivity and energy consumption variations in 15 operational cycles.

Table 2

Performance of CFIE for purifying the synthetic desalinated seawater with different conductivities.

Influent conductivity (μS/cm)	20	30	40	50	60	70
Purified water conductivity (μS/cm)	0.8	0.9	1.0	1.2	1.3	1.5
Energy consumption (kWh/m <sup>3</sup> )	0.29	0.43	0.57	0.70	0.85	1.04
Water recovery (%)	94.7	92.1	89.7	86.9	83.7	81.8
Desalination rate (%)	96.0	97.0	97.5	97.6	97.8	97.9

conductivity, μS/cm. In this work,  $\bar{U} = 350$  V,  $I = 0.142$  A,  $t = 0.5$  h,  $V_1 = 40.5$  L,  $V_2 = 5.3$  L,  $C_1 = 50$  μS/cm, and  $C_2 = 1.2$  μS/cm. Using Eqs. (11) to (13), the energy consumption ( $E$ ), the water recovery ( $R$ ) and the desalination rate ( $D$ ) were calculated to be 0.7 kWh/m<sup>3</sup> water, 86.9% and 97.6%, respectively.

To produce purified water from 50 μS/cm NaCl solution, the regeneration costs of the CFIE process and the conventional TBIE process were estimated to be about 0.058 dollars/m<sup>3</sup> water and 0.032 dollars/m<sup>3</sup> water, respectively, based on the electricity price, 0.083 dollars/kWh, the regenerant consumption, 1.8 times theoretical quantity, and the chemical prices, 630 dollars/t NaOH and 158 dollars/t HCl solutions in China [29]. Obviously, CFIE costs more than TBIE in regeneration. Despite of slightly lower purification efficiency and higher regeneration cost, CFIE is superior to TBIE in many other aspects. First, CFIE does not use chemicals for resin regeneration, and thus a series of facilities corresponding to chemical storage, transportation, metering, as well as wastewater treatment are not needed anymore. This helps to save the investment and wastewater treatment cost significantly. Secondly, labor cost can also be reduced dramatically due to the easy operation of CFIE. In addition, as mentioned before, the regenerating wastewater of CFIE can be returned directly to RO for reuse. In contrast, it seems impractical to return the regenerating wastewater of TBIE to RO for reuse even after neutralization because of its overly high electrolyte concentration. The relatively low investment, easy operation and easy wastewater recovery will allow CFIE to be a promising secondary desalination alternative to the conventional TBIE process.

### 3.6. Operation stability and adaptability of CFIE

In order to know if frequent regeneration could cause a deterioration in the CFIE system performance, the average conductivity of the purified water and the energy consumption variations were investigated for a total of 15 operational cycles, and the results are shown in Fig. 11. The average conductivity of the purified water was found to be only 1.1–1.2 μS/cm, with the desalination rates being 97.6–97.8%. There was no deterioration tendency in the purified water quality after 15 operational cycles. Furthermore, it was noticed that the energy consumption fluctuated in the range of 0.68–0.72 kWh/m<sup>3</sup>, and yet no increase in energy consumption appeared in these operational cycles. The results above demonstrate the good purification performance and high stability of the CFIE system.

In order to evaluate the adaptability of the CFIE system, investigation on the purification of the synthetic desalinated seawater with different conductivities was carried out, and the results are shown in Table 2. It was found that the CFIE system was able to reduce the conductivity from original 20–70 μS/cm to 0.8–1.5 μS/cm, indicating its good adaptability for purifying different desalinated seawater. The regeneration energy consumption and water recovery were 0.29–1.04 kWh/m<sup>3</sup> water and 81.8–94.7%, respectively, depending on the conductivity of the desalinated seawater purified.

## 4. Conclusions

CFIE is a promising process that can be used to replace the conventional two-bed (cation–anion) ion exchange for further purifying

desalinated seawater. Good purification and effective regeneration were achieved. After treatment, the conductivities of the synthetic desalinated seawater were reduced from original 20–70  $\mu\text{S}/\text{cm}$  to 0.8–1.5  $\mu\text{S}/\text{cm}$ . The regeneration energy consumption and water recovery were 0.29–1.04  $\text{kWh}/\text{m}^3$  water and 81.8–94.7%, respectively, depending on the conductivity of the desalinated seawater purified. The concentrate produced during regeneration can be returned to RO for reuse. No wastewater was produced. Repetitive experimental results showed that the CFIE system could run steadily, without any performance decay detected after long-term frequent regeneration.

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