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Removal of Sr^{2+} ions from simulated wastewater by electrodeionization

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ABSTRACT

Electrodeionization (EDI) was used for the removal of Sr^{2+} from simulated wastewater. The effects of several operational variables, including the flow rate, the initial pH, and the Sr^{2+} concentration, were investigated, respectively. The optimum operational parameters are as follows: the initial pH of feed solution is 7.0, the flow rate and the concentration of feed solution are $1.0\,L\,h^{-1}$ and $50\,mg\,L^{-1}$. Under these conditions, the residual Sr^{2+} concentration is as low as $0.0415\,mg\,L^{-1}$ after 200 min of EDI process, the energy consumption is $7.66\,kW\,h\,m^{-3}$, and the current efficiency 9.17%.

Keywords: Sr^{2+}; Electrodeionization; Removal percentage; Energy consumption; Current efficiency

1. Introduction

With the exhaustion of nonrenewable fossil resources, such as oil and coal, the nuclear energy has been drawn much attention as a novel efficient and green energy substitute. How to treat and dispose the radioactive wastes safely and economically has been one of the key problems for the sustainable development of nuclear industry, among which treatment of low-radioactive wastewater is of great importance [1].

Ion exchange is one of the most widely used treatment methods for low-radioactive wastewater because of its high efficiency. However, the conventional ion exchange consumes large amount of acid and base in order to regenerate ion-exchange resins, which increases overall operational cost. Besides, wastewater from the process of reactivating and washing ion-exchange resins also causes serious environmental pollution [2].

Electrodeionization (EDI) is a hybrid separation process of electrodialysis (ED) and conventional ion exchange. Compared with conventional ion exchange, regeneration of the ion-exchange resins is not required, which is generally labor-intensive and costly. Moreover, the EDI has the advantage that the conductivity in the dilute chamber filled with ion-exchange resins is increased by more than two orders of magnitude compared with the ED. Thus, the energy consumption is decreased greatly as expected [3,4].

Till now, the EDI has been widely used in the treatment of electroplating wastewater such as efficient removal and/or recovery of Ni^{2+} [5–8], Pb^{2+} [9], Cd^{2+} [10], and Cu^{2+} [11] ions. In addition, there are a few literatures about using EDI to treat low-radioactive wastewater. Liu et al. [12] used the continuous electrodeionization (CEDI) to treat the wastewater-containing Cs^{+}, Co^{2+}, and Sr^{2+}. It was shown that the CEDI has more continuous and effective operation performance compared with conventional ion-exchange processes, the removal efficiency of strontium was more than 95%,

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and nuclide removal percentage was $Cs^+ > Sr^{2+} > Co^{2+}$. Zhao et al. [13] studied the treatment of simulated wastewater containing Co^{2+}, Sr^{2+}, and Cs^+, respectively. The results demonstrated that the current should be greater than 0.1 A when treating the primary coolant with CEDI to reach 99% of removal efficiency. Yeon et al. [14] investigated the production of high-purity water from the primary coolant of a nuclear power plant via the CEDI process. The CEDI system was operated with a layered bed of cation-exchange resins (CERs), anion-exchange resins, and mixed-bed ion-exchange resins. With an inlet conductivity of 40 μS cm^{-1}, a linear velocity of 4.17 cm s^{-1} and an applied current density of 17 mA cm^{-2}, the CEDI process yielded an outlet conductivity of 0.5 μS cm^{-1}, thereby the precipitation of metal ions was prevented. These researches verify that the EDI technology is effective for low-radioactive wastewater treatment. However, how to control the operational condition to optimize the EDI performance and what are the energy consumption and the current efficiency for a specific nuclide removal have been still unknown so far, and more systematic studies on treating low-radioactive wastewater through EDI technology should be carried out.

Consequently, in this study, the wastewater-containing Sr^{2+} ions was chosen as a representative, the effects of several operational variables including the flow rate, the initial pH, and the initial Sr^{2+} concentration were studied in detail. The removal percentage of Sr^{2+}, the energy consumption, and the current efficiency were discussed, and the optimum operational parameters were obtained.

2. Experimental

2.1. Materials

Two cation-exchange membranes (CEMs) (Shanghai Shanghua Water Treatment Material Co. Ltd., China), two anion-exchange membranes (AEMs) (Shanghai Shanghua Water Treatment Material Co. Ltd., China) were used during all experiments, and their main characteristics are listed in Table 1. Strongly acidic styrene-type CER was supplied by Chengdu Kelong Co. Ltd., China, and its characteristics are illustrated in Table 2.

Table 1
Main characteristics of the AEM and CEM

Membrane	AEM	CEM
Resistance (Ω cm^2)	12	11
Exchange capacity (mol kg^{-1} dry)	≥1.8	≥2.0
Thickness (mm)	0.42	0.42
Transport number (%)	89	90
Water content (%)	30 ~ 45	35 ~ 55

Table 2
Main characteristics of the CER

Resin	001 × 7 (732)
Exchange capacity (mmol g^{-1} dry)	≥4.2
Water content (%)	45 ~ 55
Wet true specific gravity (%), 20℃	1.23 ~ 1.28
Wet density (g mL^{-1})	0.75 ~ 0.85
Wear rate (%)	≥93.0
Viscosity (%)	≥95

An EDI system involves three processes simultaneously. First, the ion exchange, whereby ions dissolved in the feed solution passing through the ion-exchange resin layers are sorbed on the CERs according to the conditions of thermodynamic equilibrium and mass transfer. Second, the continuous transport of ions to the concentrate stream occurs through the ion exchangers and membrane layers. Third, the continuous regeneration of ion exchangers by hydrogen and hydroxyl ions produced as a result of electrolysis of water molecules under the action of a DC current. The initial Sr^{2+} concentration is very low (not higher than 75 mg L^{-1}) in this work, the volume of the solution containing Sr^{2+} is 1,000 mL, and the CER is 60.0 g. If the cation exchange is used as H form or Na form, the Sr^{2+} ions in the flow solution were experimentally observed to be exchanged with H^+ or Na^+ in the CER quickly under the drive of the large concentration difference, and the electric field does not work in the whole process. Consequently, to avoid the Sr^{2+} removal caused only by ion exchange, the CER was soaked in 0.5 mol L^{-1} NaOH and 1.0 mol L^{-1} HNO_3 for 6 h alternately and then converted from $R–SO_3H$ to $(R–SO_3)_2–Sr$ completely before EDI just like what was presented by Xing et al. [15].

In order to avoid the interference of other anions, $NaNO_3$ was used in the electrode chamber 1 and 5. Strontium nitrate, sodium nitrate, sodium hydroxide, etc. of AR grade were commercially obtained and used without further purification. Deionized water was used thoroughly.

2.2. Methods

In the EDI, the laboratory-scale installation was consisted of one anode, one cathode, two pieces of AEMs, as well as two pieces of CEMs inserted between them with the intermembrane distance of 10 mm. There were five chambers with the volume of

38.5 cm^3 from left to right: chamber 1 containing 0.5 mol L^{-1} of $NaNO_3$ solution, chambers 2–3 containing Sr^{2+} of a certain concentration, chamber 4 composed of 0.5 mol L^{-1} of $NaNO_3$ solution, and chamber 5 composed of 0.5 mol L^{-1} $NaNO_3$ solution. All chambers were connected to a separate external 1,000 mL beaker, allowing for continuous recirculation by five submerged pumps (AT-301, ATMAN) with the flow rate of 15.0 L h^{-1} (The flow rate of the electrolyte in chamber 2 can be changed). The size of ion-exchange membrane was 9 × 9 cm with an effective area of 38.5 cm^2. About 60.0 g of CER was filled in chamber 2. A DC power (DF1731SLL3A, Zhongce Electronics Co. Ltd., China) was used to apply constant current across the electrodes. The pH value of the solution was monitored by an acidity meter (PHS-2C, Shanghai Hongyi Instrumentation Co. Ltd., China). The concentration of Sr^{2+} was measured by an atomic absorption spectrophotometer (HITACHI-2300, Japan). The schematic diagram of the experimental apparatus was shown in Fig. 1.

With other conditions including the species, the concentration and the flow rate of solutions in chamber 1, 4, and 5 unchanged, effects of the initial pH, the flow rate, and the concentration ($C_{0,f}$) of the feed liquid were determined, respectively. The EDI experiments were carried out in the following order:

- The concentrations of the Sr^{2+} in chamber 2 and 3 are fixed as 50 mg L^{-1}. The flow rates of $Sr(NO_3)_2$ solution in chamber 2 and chamber 3 are 2.0 and 15.0 L h^{-1}, respectively. The variable is the initial pH of $Sr(NO_3)_2$ solution in chamber 2, which is adjusted from 3.0 to 11.0 by the addition of HNO_3 or NaOH solution.
- The concentrations of the Sr^{2+} in chamber 2 and 3 are fixed as 50 mg L^{-1}. The initial pH value of the solution in chamber 2 is fixed to be 7.0. The flow rate of the solution containing Sr^{2+} in chamber 3 is 15.0 L h^{-1}. The variable is the flow rate of the electrolyte in chamber 2, which is changed from 1.0 to 6.0 L h^{-1}.
- The flow rates of the solution containing Sr^{2+} in chamber 2 and chamber 3 are 2.0 and 15.0 L h^{-1}, respectively. The initial pH of $Sr(NO_3)_2$ solution in chamber 2 is fixed to be 7.0. The variable is the concentration of the Sr^{2+} $C_{0,f}$ in chamber 2 and 3, which is ranged from 10 to 75 mg L^{-1}, respectively.

All measurements were carried out for three times at constant temperature (20 ± 0.5℃), and their mean value was taken as the final result. The estimated error is about ±5%.

2.3. Calculations

Removal percentage of Sr^{2+} is one of the most important technical specifications to examine the practical feasibility in this work. In the EDI process, almost all Sr^{2+} ions from chamber 2 transfer across the CEM and concentrate in chamber 3. The removal percentage of Sr^{2+} can be calculated as R_e by Eq. (1):

$$R_e(\%) = \left(1 - \frac{C_{t,f}}{C_{0,f}}\right) \times 100 \tag{1}$$

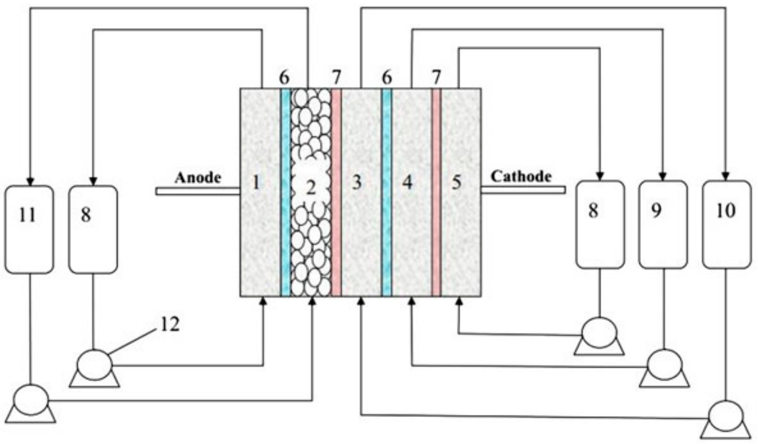

Fig. 1. Experimental set-up. (1) Anode chamber; (2) dilute chamber filled with CER; (3) concentrate chamber; (4) chamber 4 composed of 0.5 mol L^{-1} of $NaNO_3$ solution; (5) cathode chamber; (6) AEM; (7) CEM; (8) electrode solution reservoir; (9) $NaNO_3$ solution reservoir; (10) concentrated solution reservoir; (11) feed reservoir; and (12) pump.

where $C_{t,f}$ is the concentration of Sr^{2+} at any time in chamber 2 ($mg\,L^{-1}$); $C_{0,f}$ the initial concentration of Sr^{2+} in chamber 2 ($mg\,L^{-1}$).

Energy consumption (EC) and current efficiency (CE) are also important technical specifications of any electrochemical processes for their practical application. The energy consumption ($kW\ h\ m^{-3}$ of wastewater treated) is defined as Eq. (2):

$$\mathrm{EC}(\mathrm{kW\ h\ m^{-3}}) = \frac{\int_0^t \mathrm{IUdt}}{\mathrm{V}} \tag{2}$$

where V is the volume of treated wastewater (m^3); I the current (A); t the time (h) and U the voltage (V).

The overall current efficiency (CE) is defined as Eq. (3):

$$\mathrm{CE}(\%) = \frac{zF(n^{t_2} - n^{t_1})}{Q^{t_2} - Q^{t_1}} \times 100 \tag{3}$$

where z is the valence of ion; n^{t_2} is the total moles of Sr^{2+} removed from initial time to time t_2 (s), and n^{t_1} is the moles of Sr^{2+} removed from initial time to time t_1 (s). F is the Faraday constant ($96{,}500\,C\,mol^{-1}$), Q^{t_2} is the total applied charge (C) until time t_1, and Q^{t_1} is the total applied charge (C) until time t_2.

3. Results and discussion

3.1. I–V characteristic curve

Limiting current [16–18] is a very important performance variable for determining the operational current. Fig. 2 shows the variation of the current with different voltages in a classical EDI process, among which the concentrations of the Sr^{2+} in chamber 2 and 3 are fixed as 50 $mg\,L^{-1}$, the flow rate of the $Sr(NO_3)_2$ solution in chamber 2 is $2.0\,L\,h^{-1}$ and its initial pH is 7.0, the flow rates of chambers 1, 3–5 are $15.0\,L\,h^{-1}$. With the increase in voltage, the current increases slowly, and then, it rises sharply. The saltatorial current 125 mA is determined as the limiting current. At this point, the resistance in dilute chamber 2 increases significantly due to concentration polarization. Thus, the working current should be less than the limiting current, and 80% of limiting current, 100 mA is applied to the following EDI unit.

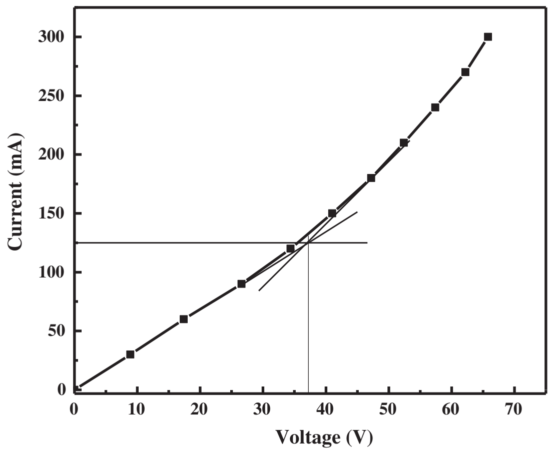

Fig. 2. *I-V* curve in the EDI process.

3.2. Effect of initial pH of feed solution

In order to investigate the effect of the initial pH of feed $Sr(NO_3)_2$ solution in chamber 2, initial pH of 3.0, 5.0, 7.0, and 11.0 were chosen as samples. The changes in removal percentage of Sr^{2+} and the voltage vs. time are shown in Figs. 3 and 4, respectively.

As shown in Fig. 3, at any initial pH, the removal percentage of Sr^{2+} in the dilute chamber is increased with time, and such a trend is analogous with that in Fig. 7. The residual nuclide concentration less than 0.05 $mg\,L^{-1}$ is acceptable [19]. The initial concentration of Sr^{2+} is 50 $mg\,L^{-1}$ herein, so the removal percentage of Sr^{2+} should be higher than 99.9%. When the initial pH is equal to 5.0 and 7.0, the largest removal percentage of Sr^{2+} can be achieved above 99.9%. However, when the initial pH is decreased to be 3.0, the largest removal ratio of Sr^{2+} is below 95.4%, namely too low initial pH of feed solution is disadvantageous to the Sr^{2+} removal. The reasons are as follows: When the initial pH is too low, lots of H^+ ions exist in the feed

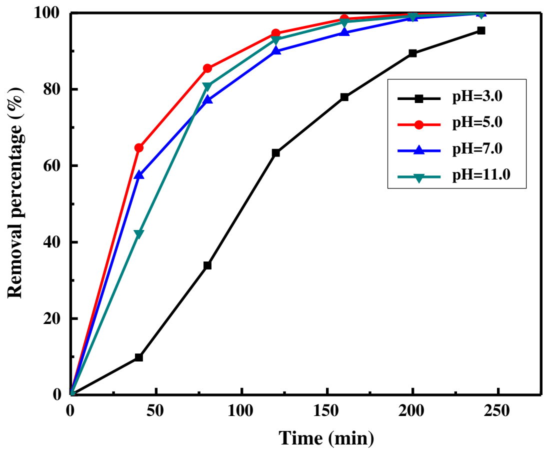

Fig. 3. Variation of removal percentage with time at different initial pHs. (Sr^{2+} concentration in the chambers 2 and 3: 50 $mg\,L^{-1}$; the flow rate of the feed $Sr(NO_3)_2$ solution in chamber 2: $2.0\,L\,h^{-1}$; operating current: 100 mA).

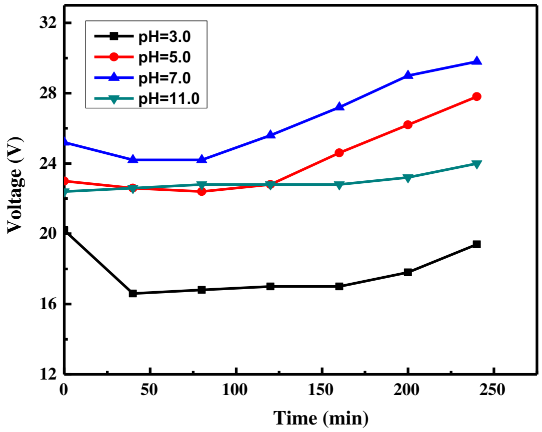

Fig. 4. Variation of voltage with time at different initial pHs. (Sr^{2+} concentration in the chambers 2 and 3: 50 mg L^{-1}; the flow rate of the feed $Sr(NO_3)_2$ solution in chamber 2: 2.0 L h^{-1}; operating current: 100 mA).

solution in chamber 2. It is worth mentioning that the CER was converted to be Sr^{2+} type before the EDI process as presented in the former experimental section 2.2. Therefore, the H^+ regeneration of the CER occurs after the feed solution is circulated through the dilute chamber 2 as the following Eq. (4):

$$R_2 - Sr + 2H^+ = 2R - H + Sr^{2+} \tag{4}$$

Such an H^+ regeneration allows a part of resin to be converted from R_2–Sr^{2+} to R–H, causing the concentration of Sr^{2+} in the chamber 2 increased unexpectedly. That is to say, this is actually a result of the release of Sr^{2+} from the CER that was saturated with Sr^{2+} previously.

Further, when the initial pH is raised to be 11.0, the largest removal percentage of Sr^{2+} is much higher than that at pH 3.0, but it is still slightly less than 99.9%. Different from most heavy metal ions, the removal percentage of Sr^{2+} decreases at high pH value herein cannot be assigned to the production of the sediment of $Sr(OH)_2$. Since $Sr(OH)_2$ is soluble in water, and the K_{sp} of $Sr(OH)_2$ at 25°C is around 10^{-3}. When the initial concentration of Sr^{2+} is 50 mg L^{-1}, $Sr(OH)_2$ cannot be formed as a sediment at pH 11.0. However, the initial pH value was adjusted to 11.0 by adding drops of NaOH solution. A little bit of Na^+ ion in chamber 2 may be transfer to chamber 3 under the electric power, and its competitive transference is disadvantageous to the removal percentage of Sr^{2+}.

The voltage decreases with time first, and then, it increases conversely at most pHs as shown in Fig. 4, and such a trend is always observed in all EDI processes in this study. Since the EDI was carried out at a constant current 100 mA, the decreased voltage means the decreased resistance and vice versa. When the EDI process starts, Sr^{2+} in chamber 2 is transferred to chamber 3 across the CEM, while NO_3^- transferred to chamber 1 across the AEM under the drive of electric power. As a result, the decrease in the electric resistance in chamber 3 and 1 causes the decline of voltage. With such a transport process going on, more and more Sr^{2+} and NO_3^- are transferred out of chamber 2, which results in the increase of the electrical resistance of the solution in chamber 2, and thus the sharp increase in the overall voltage. However, it can be noticed that the electrical potential at pH 11.0 is a little different from at other pHs especially at the beginning of the EDI process. Since the EDI experiments were carried out at constant current, low potential change at pH 11.0 in Fig. 4 means that the electrical resistance changes little. This unique phenomenon at pH 11.0 can be explained as follows: At the beginning of the EDI process, the Sr^{2+} transfer to chamber 3 leads to the decrease in the electric potential just like at other pHs. When the pH is 11.0, lots of OH^- and Na^+ ions exist in the feed solution in chamber 2, and these ions can offset the decrease in both Sr^{2+} and NO_3^-, which is also beneficial to the decrease in the potential. However, water is oxidized in the anode chamber, and H^+ is produced. Then, the H^+ leakage occurs across the AEM, and the leaked H^+ combine with OH^- to produce the chemically stable H_2O. And the electrical resistance in chamber 2 increases as a result. Above three adverse factors cause that the electrical potential at pH 11.0 does not decrease apparently as at other pHs. However, the electrical potential is also increased a little at later EDI process, and the reasons are similar with that at other pHs.

In addition, with an unchanged time, the voltage is largest at pH of 7.0, and it is lowered when the initial pH is increased or decreased. Such a trend is understandable on account of the following reasons: the initial concentration of Sr^{2+} (50 mg L^{-1}) is very low, and any little change in the pH can affect the ionic concentration in the chamber 2 remarkably. For instance, when the initial pH is 3.0, the concentration of H^+ is 0.001 mol L^{-1}, which largely contributes to the increase in the ionic quantity. Besides the back diffusion of NO_3^- and leakage of H^+ occur from anode compartment to dilute compartment 2 especially at high pH as can be seen from Fig. 5. Such phenomena lead to the increase in the ion amount in chamber 2, which is beneficial to the decrease in operation voltage at

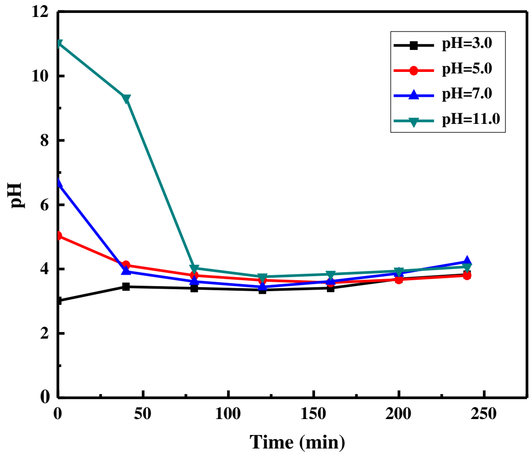

Fig. 5. Variation of pH of the feed solution in the dilute chamber 2 with time at different initial pHs. (Sr^{2+} oncentration in the chambers 2 and 3: 50 mg L^{-1}; the flow rate of the feed $Sr(NO_3)_2$ solution in chamber 2: 2.0 L h^{-1}; operating current: 100 mA).

most cases. Consequently, the resistance in chamber 2 is dropped sharply when the pH value is at high or low, causing the voltage decreased evidently.

Fig. 6 shows the energy consumption, and current efficiency varied with the different initial pH value of the feed solution in chamber 2 individually at the EDI time of 240 min. The order of energy consumption at different initial pH is 7.0 > 5.0 > 11.0 > 3.0. Since the EDI time is fixed as 240 min as mentioned previously, the energy consumption at a certain initial pH value of the feed solution is mainly dependent on the applied voltage as can be seen from Eq. (2). Obviously, the voltage at an equal time is lowest at pH 3.0 and highest at pH 7.0 as shown in Fig. 4, which verifies the energy consumption results. As for the current efficiency, the less the electrical resistance, the less the applied charge is, which is favorable to the current efficiency seen from Eq. (3). However, the EDI operation for long time may cause the lack of ions. And the dissociation of water at the CEM, AEM, and the CER may occur, causing the quick increase in membrane stack resistance [20], which is disadvantageous to the current efficiency. Therefore, whether the current efficiency is high or low lies on which one is preponderant among the advantageous and disadvantageous aspects. As for the initial pH of 3.0, the disadvantageous aspects apparently gain the upper hand, so the current efficiency is the lowest. As a matter of fact, in most cases, the increase in energy consumption is always in company with the decline of current efficiency [21]. However, the difference of current efficiency at various pHs is subtle, and all current efficiency are a little low as presented by Xing et al. [22]. As a result, how to improve the current efficiency of treating the wastewater-containing nuclide with EDI technique is urgent to be studied.

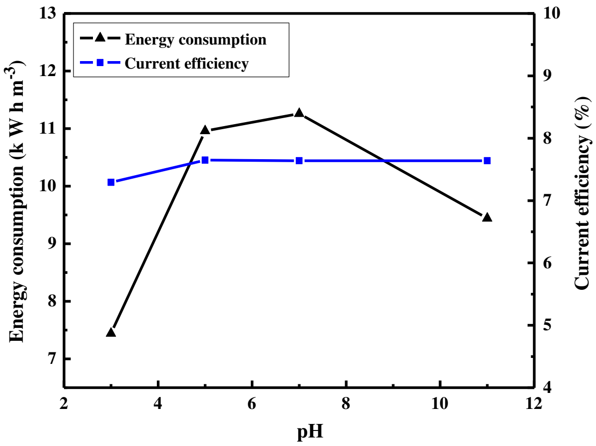

Fig. 6. Variation of energy consumption and current efficiency with different initial pHs. (Sr^{2+} concentration in the chambers 2 and 3: 50 mg L^{-1}; the flow rate of the feed $Sr(NO_3)_2$ solution in chamber 2: 2.0 L h^{-1}; operating current: 100 mA).

It is worth mentioning that only when the initial pH of feed $Sr(NO_3)_2$ solution in chamber 2 is 5.0 or 7.0 can the removal percentage of Sr^{2+} be achieved to be higher than 99.9% at the EDI time of 240 min as seen from Fig. 3. Taking the energy consumption and current efficiency results into consideration, the initial pH 5.0 seems the optimum value. However, a little of HNO_3 was added into the feed solution in chamber 2 to adjust its initial pH to be 5.0. The addition of another reagent to the feed solution leads to the increase in the overall operational cost. More seriously, the concentrated nuclide in chamber 3 is impure due to the competitive transport of H^+. As a consequence, considering the pH of pure $Sr(NO_3)_2$ solution is about 7.0, which is close to 5.0, the initial pH of feed solution in chamber 2 is suggested to be uncontrolled for a practical application in order to save the overall cost.

3.3. *Effect of feed flow rate*

The feed flow rate plays a major role in the separation of Sr^{2+}. Herein, four different feed flow rates (1.0, 2.0, 4.0, and 6.0 L h^{-1}) were investigated, respectively.

Fig. 7 shows the removal percentage of Sr^{2+} changed with time at different flow rates. Obviously, the removal percentage of Sr^{2+} increases with time elapsed. With the same EDI time, the removal percent-

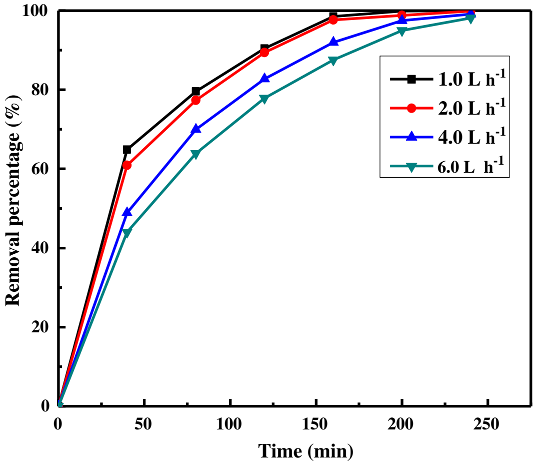

Fig. 7. Variation of removal percentage with time at different flow rates. (Sr^{2+} concentration in the chambers 2 and 3: 50 mg L^{-1}; initial pH of feed $Sr(NO_3)_2$ solution in chamber 2: pH 7.0; operating current: 100 mA).

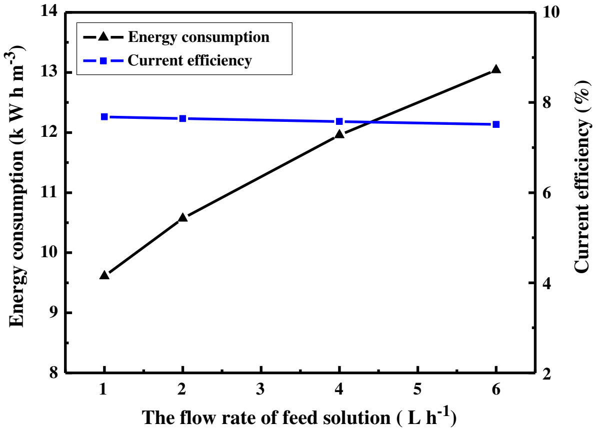

Fig. 8. Variation of energy consumption and current efficiency with different flow rates. (Sr^{2+} concentration in the chambers 2 and 3: 50 mg L^{-1}; initial pH of feed $Sr(NO_3)_2$ solution in chamber 2: pH 7.0; operating current: 100 mA).

age of Sr^{2+} decreases with the increase in flow rate. Since Sr^{2+} ions stay in chamber 2 for longer time at a slower flow rate, and thus, more Sr^{2+} ions are removed at an equal time. That is to say, decreasing the flow rate is advantageous to the removal percentage of Sr^{2+}. In this work, the largest removal percentage of Sr^{2+} can be achieved as 99.9% at 200 min when the flow rate is 1.0 L h^{-1}. Namely, the outlet concentration of Sr^{2+} is 0.0415 mg L^{-1}, which is quite satisfactory for a one-level EDI process for treating low radioactive wastewater. However, when the flow rate is raised to 4.0 or 6.0 L h^{-1}, the removal percentage of Sr^{2+} cannot reach 99.9% even after 240 min of EDI operation.

The energy consumption and current efficiency changed with different feed flow rates at 240 min of EDI operation are depicted in Fig. 8. Obviously, the energy consumption increases with rising feed flow rate. As a whole, the energy consumption follows such an order: 6.0 > 4.0 > 2.0 > 1.0 L h^{-1}. The reasons are considered as below: The overall stack resistance generally lies on that in dilute chamber 2. When the feed flow rate is smaller, more ions stay in chamber 2 at a constant time. The more the quantity of ions in chamber 2, the less the resistance is. Thus, the resistance of the EDI system is decreased with the decline of the feed flow rate, and the energy consumption is decreased as a result. When the removal percentage of Sr^{2+} reaches 99.9% at the feed flow rate of 1.0 L h^{-1}, the EDI time needed is 200 min, and the energy consumption is about 7.66 kW h m^{-3}, which is lower than that at 240 min of EDI operation as shown in Fig. 8. As for the current efficiency, it decreases with the flow rate rising. With the quantity of Sr^{2+} in chamber 2 decreased at high flow rate, a certain amount of water may be dissociated to transfer the current, causing the current efficiency lowered. In summary, the current efficiency in this work is a little low. As the removal percentage of Sr^{2+} is achieved to be 99.9% at the feed flow rate of 1.0 L h^{-1}, the current efficiency is less than 10%. However, such a result is still in agreement with that presented by Arar et al. [23]. And how to increase the current efficiency in using EDI technology to treating the low radioactive wastewater is a problem to be solved in the future.

Taking these three factors including removal percentage of Sr^{2+}, energy consumption and current efficiency into consideration, the feed flow rate of 1.0 L h^{-1} is the optimum one in this work.

3.4. Effect of Sr^{2+} concentration

In this part, the effect of Sr^{2+} concentration was investigated. Herein, the initial concentration of Sr^{2+} in chamber 2 is different. Even if the removal percentage of Sr^{2+} is equal to each other, a more important parameter in practice, the residual concentration of Sr^{2+} still makes a difference. Therefore, the changes of the concentration of residual Sr^{2+} in the dilute chamber 2 with the EDI time were depicted in Fig. 9. The lowest residual Sr^{2+} concentration and the time needed to reach the lowest Sr^{2+} concentration are shown in Table 3.

Considering that the residual nuclide concentration less than 0.05 mg L^{-1} is acceptable [19], the energy consumption and the current efficiency at the lowest

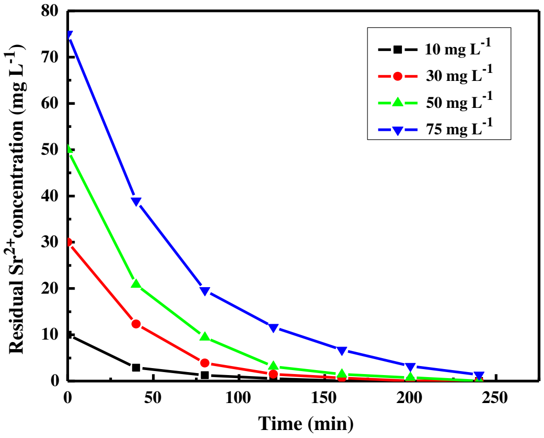

Fig. 9. Variation of the concentration of residual Sr^{2+} with time at different concentrations of Sr^{2+} in chamber 2 and 3. (the flow rate of the feed $Sr(NO_3)_2$ solution in chamber 2: 2.0 L h^{-1}; initial pH of feed $Sr(NO_3)_2$ solution in chamber 2: pH 7.0; operating current: 100 mA).

Table 3
The lowest residual Sr^{2+} concentration at different initial Sr^{2+} concentrations

Initial Sr^{2+}concentration (mg L^{-1})	10	30	50	75
The lowest residual Sr^{2+} concentration (mg L^{-1})	0.040	0.042	0.043	1.375
The EDI time (min)	160	200	240	240

residual concentration were shown in Fig. 10. Apparently, the residual concentration of Sr^{2+} at all feed concentrations except 75 mg L^{-1} is less than 0.05 mg L^{-1}, meaning that the EDI technology is effective for the wastewater-containing Sr^{2+} with its concentration of no higher than 50 mg L^{-1}.

The order of energy consumption at different Sr^{2+} concentration is as following: 50 > 75 > 30 > 10 mg L^{-1}. When the Sr^{2+} concentration is 75 mg L^{-1}, the energy consumption is a little lower, and the current efficiency is the highest, which seems plausible. However, the residual Sr^{2+} concentration is 1.375 mg L^{-1}, which is higher than the acceptable value. As can be seen for Fig. 10, when the initial Sr^{2+} concentration is too low, the current efficiency is too low as well. That is to say, too low Sr^{2+} concentration is also no desirable for practical application. As a consequence, taking the residual Sr^{2+} concentration, the energy consumption and current efficiency into a comprehensive concern, the Sr^{2+} concentration of 50 mg L^{-1} is the optimum value.

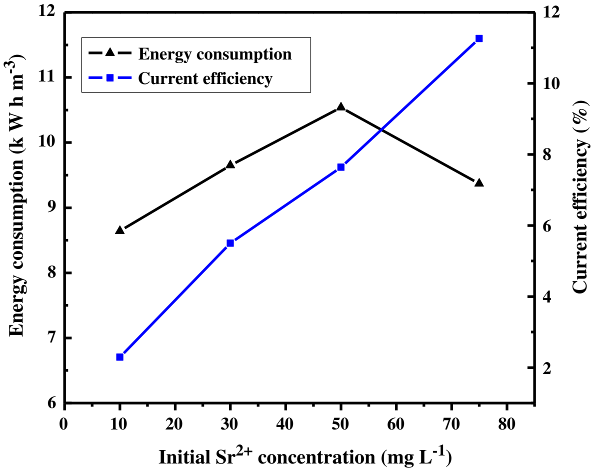

Fig. 10. Variation of energy consumption and current efficiency with Sr^{2+} concentrations. (the flow rate of the feed $Sr(NO_3)_2$ solution in chamber 2: 2.0 L h^{-1}; initial pH of feed $Sr(NO_3)_2$ solution: pH 7.0; operating current: 100 mA).

4. Conclusions

The CEDI process with five chambers was verified to be successful in removal of Sr^{2+} from synthetic wastewater. The optimum operational parameters are as follows: the initial pH of feed $Sr(NO_3)_2$ solution in chamber 2 is 7.0, the flow rate of feed $Sr(NO_3)_2$ solution in chamber 2 is 1.0 L h^{-1}, and the initial Sr^{2+} concentration in chamber 2 and 3 is 50 mg L^{-1}. Under these conditions, the residual Sr^{2+} concentration in chamber 2 is as low as 0.0415 mg L^{-1} after 200 min of EDI operation, when the energy consumption is 7.66 kW h m^{-3}, and the current efficiency 9.17%. Further, the effects of membrane configuration, the species of the ion-exchange resin and the nuclide, and the arrangement of the ion-exchange resin on the EDI performance are our work under way.

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References

[1] Y.C. He, Y.Q. Gao, H.J. Wang, J.M. Ola, L. Yu, Transport of nuclear leakage from Fukushima nuclear power plant in the north pacific, Acta Oceanol. Sin. 34 (2012) 12–20 (in Chinese).

[2] Ö. Arar, Ü. Yüksel, N. Kabay, M. Yüksel, Demineralization of geothermal water reverse osmosis (RO) permeate by electrodeionization (EDI) with layered bed configuration, Desalination 317 (2013) 48–54.

[3] A.S. Kurup, T. Ho, J.A. Hestekin, Simulation and optimal design of electrodeionization process: Separation of multicomponent electrolyte solution, Ind. Eng. Chem. Res. 48 (2009) 9268–9277.

[4] L. Alvarado, I.R. Torres, A. Chen, Integration of ion exchange and electrodeionization as a new approach for the continuous treatment of hexavalent chromium wastewater, Sep. Purif. Technol. 105 (2013) 55–62.

[5] Y.S. Dzyazko, V.N. Belyakov, Purification of a diluted nickel solution containing nickel by a process combining ion exchange and electrodialysis, Desalination 162 (2004) 179–189.

[6] P.B. Spoor, L. Grabovska, L. Koene, L.J.J. Janssen, W.R. ter Veen, Pilot scale deionization of a galvanic nickel solution using a hybrid ion-exchange/electrodialysis system, Chem. Eng. J. 89 (2002) 193–202.

[7] A.J. Ren, J.Y. Wang, H.X. Lu, Y.L. Su, Study on synchronous purification and concentration of dilute solution containing nickel ion by electrodeionization, Mod. Chem. Ind. 29 (2009) 55–58 (in Chinese).

[8] J.Y. Wang, H.X. Lu, B. Yan, L. Fu, X.Q. Fu, Dilute nickel wastewater treatment by improved electrodeionization technology, Environ. Sci. Technol. 32 (2009) 132–136 (in Chinese).

[9] K. Basta, A. Aliane, A. Lounis, R. Sandeaux, J. Sandeaux, C. Gavach, Electroextraction of Pb^{2+} ions from diluted solutions by a process combining ion-exchange textiles and membranes, Desalination 120 (1998) 175–184.

[10] A. Smara, R. Delimi, E. Chainet, J. Sandeaux, Removal of heavy metals from diluted mixtures by a hybrid ion-exchange/electrodialysis process, Sep. Purif. Technol. 57 (2007) 103–110.

[11] A. Mahmoud, A.F.A. Hoadley, An evaluation of a hybrid ion exchange electrodialysis process in the recovery of heavy metals from simulated dilute industrial wastewater, Water Res. 46 (2012) 3364–3376.

[12] L.J. Liu, F.Z. Li, X. Zhao, G. Zhao, Low-level radioactive wastewater treatment by continuous electrodeionization, J. Tsinghua Univ. (Sci. Tech. Version) 48 (2008) 1012–1014 (in Chinese).

[13] X. Zhao, T. Hou, Nuclide removal from the primary coolant of a nuclear power plant by continuous electrodeionization, J. Tsinghua Univ. (Sci. Tech. Version) 50 (2009) 1429–1431 (in Chinese).

[14] K.H. Yeon, J.H. Song, S.H. Moon, A study on stack configuration of continuous electrodeionization for removal of heavy metal ions from the primary coolant of a nuclear power plant, Water Res. 38 (2004) 1911–1921.

[15] Y.Q. Xing, X.M. Chen, D.H. Wang, Variable effects on the performance of continuous electrodeionization for the removal of Cr (VI) from wastewater, Sep. Purif. Technol. 68 (2009) 357–362.

[16] J.H. Song, K.H. Yeon, S.H. Moon, Effect of current density on ionic transport and water dissociation phenomena in a continuous electrodeionization (CEDI), J. Membr. Sci. 291 (2007) 165–171.

[17] R.Q. Fu, T.W. Xu, W.H. Yang, Z.X. Pan, A new derivation and numerical analysis of current-voltage characteristics for an ion-exchange membrane under limiting current density, Desalination 173 (2005) 143–155.

[18] R.V. Pérez, J.A.I. Mengual, Current-voltage curves for an electrodialysis reversal pilot plant: Determination of limiting currents, Desalination 141 (2001) 23–37.

[19] X.L. Duan, B.B. Chen, Q.C. Li, Treatment of uranium-bearing wastewater by vacuum membrane distillation, J. Nucl. Radiochem. 28 (2006) 220–224 (in Chinese).

[20] X.Y. Zhang, W.H. Lu, H.Y. Ren, W. Cong, Recovery of glutamic acid from isoelectric supernatant using electrodialysis, Sep. Purif. Technol. 55 (2007) 274–280.

[21] Y.P. Zhang, Y. Chen, M.Z. Yue, W.L. Ji, Recovery of L-lysine from L-lysine monohydrochloride by ion substitution using ion-exchange membrane, Desalination 271 (2011) 163–168.

[22] Y.Q. Xing, X.M. Chen, P.D. Yao, D.H. Wang, Continuous electrodeionization for removal and recovery of Cr(VI) from wastewater, Sep. Purif. Technol. 67 (2009) 123–126.

[23] Ö. Arar, Ü. Yüksel, N. Kabay, M. Yüksel, Removal of Cu^{2+} ions by a micro-flow electrodeionization (EDI) system, Desalination 277 (2011) 296–300.