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Transport Characteristics of Co^{2+} Through an Ion Exchange Textile in a Continuous Electrodeionization (CEDI) System Under Electro-Regeneration

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ABSTRACT

The transport of cobalt ion in a continuous electrodeionization (CEDI) system was investigated in terms of electrochemical properties of ion exchange textile. The porous plug model and an extended Nernst-Plank equation were applied to describe the transport of Co^{2+} through an ion exchange textile. The transport characteristics of Co^{2+} during CEDI operation suggested the transport mechanism was due mainly to the increased current induced by the high conductivity in the ion exchange textile, not accelerated ionic mobility. This study suggested

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the important parameter for the high performance of the CEDI system is the conductivity of the ion exchange media.

Key Words: Continuous electrode ionization; Electroregeneration; Porous plug model.

INTRODUCTION

The CEDI process is a novel hybrid separation process consisting of electrodialysis (ED) and ion exchange (IX). The principle of CEDI system packed with cation exchange textile is illustrated in Fig. 1. Cation and anion exchange membranes are located between the electrodes like an ED system. The diluted compartment is filled with cation exchange textile that enhances the transport of cations under the driving force of direct current. Cations move to the concentrated compartment through cation exchange membrane and anions through anion exchange membrane under the DC electric field as shown in

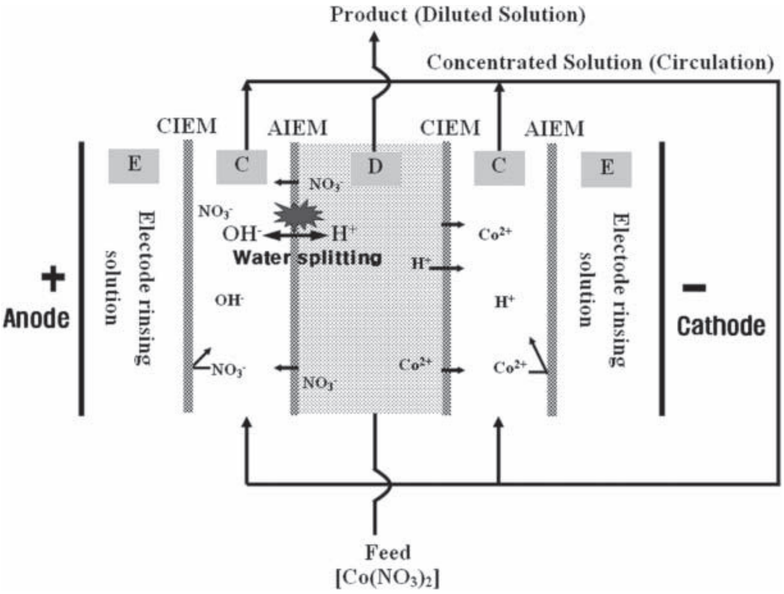

Figure 1. Principles of the CEDI system packed with cation exchange textile. CIEM: cation exchange membrane, AIEM: anion exchange membrane, CIET: cation exchange textile, C: concentrated compartment, D: diluted compartment, E: electrolyte compartment.

Fig. 1. Water splitting reaction during CEDI operation generates hydrogen ions and they enable to regenerate the cation exchange textile into hydrogen form.[1–3] Water splitting reaction in CEDI system causes the complicated phenomena such as changes in conductivity and pH. Also, electroregeneration by water splitting reaction make it difficult to describe transport mechanisms under the optimal operation of the CEDI system. Thus, the purpose of this study is to verify transport mechanisms of cobalt ion in a CEDI system under electroregeneration. For the verification of transport mechanisms, the porous plug model and extended Nernst-Plank equation were employed. Accordingly, the transport mechanism of cobalt ion in the CEDI was discussed based on the results of these models. Understanding of the mechanism would give useful guidelines for design and operation of CEDI systems.

THEORY

The current flowing through the diluted compartment in CEDI system is complex since it is composed of two phases with different properties: ion conducting media and interstitial liquid (Fig. 2). In the CEDI system, the second path (2 and *b* in Fig. 2) predominates because the resistance of the interstitial solution (white part in Fig. 2) is higher than the ion exchange media. Determination of the geometrical parameters (*a*, *b*, *c*, *d*, and *e* in Fig. 2) was suggested by Wyllie using the porous plug model.[4–6] Further, the transport of ions

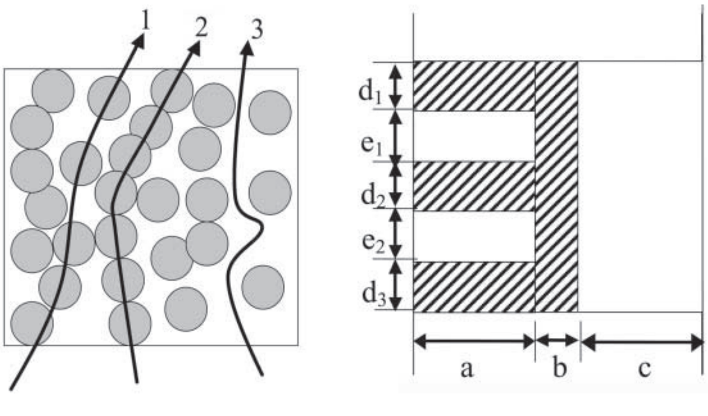

Figure 2. The “porous-plug” model. Left: schematic representation of the three paths which the current can take. Right: the simplified model consisting of three conductance elements in parallel. The geometrical parameters d and e are given by $d_1+d_2+d_3=d$, and $e_1+e_2=e$. From K. S. Spiegler, R. L. Yoest, and M. R. J. Myllie.

through a medium under an electrical field is expressed by the extended Nernst-Plank equation with geometrical parameters:

$$J_{\mathrm{i,tot}} = J_{\mathrm{i,diff}} + J_{\mathrm{i,el}} + J_{\mathrm{i,con}} = -\bar{D}_{\mathrm{i}} \frac{d\bar{c}_{\mathrm{i}}}{dx} - z_{\mathrm{i}}\bar{c}_{\mathrm{i}}\bar{u}_{\mathrm{i}}\, grad\,\varphi + \nu\bar{c}_{\mathrm{i}} \qquad (1)$$

where variables with over bar are the values within the ion exchanger. The first term on the right-hand side denotes the diffusion of ion i with concentration $\bar{c}_{\mathrm{i}}$ and diffusion coefficient $\bar{D}_{\mathrm{i}}$. The second term accounts for the migration of ion i with valence state z_{i} and mobility $\bar{u}_{\mathrm{i}}$ under the potential gradient φ. The third term describes the movement of the pore liquid within the ion exchanger and the convection rate of its center of gravity represented by ν. The convection rate can be expressed as (2):

$$\nu = \frac{wFX}{\rho_o\varepsilon}\, grad\,\varphi = w\bar{u}_o\, grad\,\varphi \qquad \left(\bar{u}_o \equiv \frac{FX}{\rho_o\varepsilon}\right) \qquad (2)$$

where ρ_{o} is the solvent flow resistance of the ion exchanger, X the concentration of fixed sites, w the charge of fixed sites, and ε the fractional pore volume in the ion exchanger. $\bar{u}_{\mathrm{o}}$ has the dimension of an electrochemical mobility, referred to as the "mobility" of the pore liquid. Substituting Eq. (2) with (1) gives the following simplified equation:

$$J_{\mathrm{i,tot}} = z_{\mathrm{i}}\bar{c}_{\mathrm{i}}\left(\bar{u}_{\mathrm{i}} + \frac{\bar{u}_o}{z_{\mathrm{i}}}\right) grad\,\varphi = z_{\mathrm{i}}\bar{c}_{\mathrm{i}}\bar{u}_{\mathrm{i}}^{*}\, grad\,\varphi \qquad \left(\bar{u}_{\mathrm{i}}^{*} \equiv \bar{u}_{\mathrm{i}} + \frac{\bar{u}_o}{z_{\mathrm{i}}}\right) \qquad (3)$$

where $\bar{u}_{\mathrm{i}}{}^{*}$ is the apparent mobility that includes the convection conductivity. From these relationships, apparent mobility through ion exchange textile $\bar{u}_{\mathrm{i}}^{*}$ can be determined from the relation between the potential drop ($grad\varphi$) and the effluent flux ($J_{\mathrm{i,tot}}$). The apparent mobility through the ion exchange textile depends on the physicochemical characteristics of ion exchangers including its capacity, degree of cross-linking, swelling ratio, osmotic pressure, valence of the counter ion, type of co-ion and solvent, and so on.[6–8]

EXPERIMENTS

Preparation and Characterizations of Cation Exchange Textile (CIET)

Figure 3 shows the schematic illustration of the synthesis of the ion exchange textile which would be packed in a CEDI system. Dried nonwoven polypropylene textile (3 mm, Jeonbang Co. Ltd., Korea) was coated with 3% BP (benzophenon, photo-initiator). The BP-coated textile was then irradiated

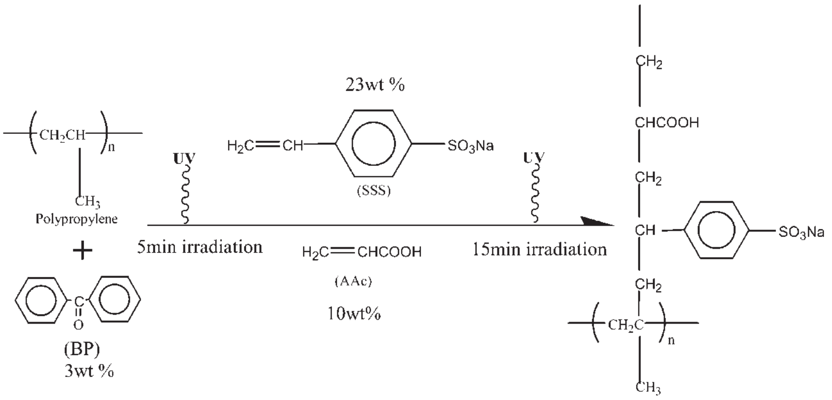

Figure 3. Synthesis of the cation-exchange textile.

with UV light (400 watts, wave length: 232–500 nm) for 5 min under nitrogen at ambient temperature. The irradiated polypropylene textile was then immersed in a solution containing monomer composed of styrenesulfonic salt (SSS, $CH_2 = CHC_6H_4SO_3Na$) and acrylic acid ($CH_2 = CHCOOH$). It was further irradiated for 15 min under the same conditions. After grafting, the textile was immersed in distilled water (80°C) to remove the residual monomer and homopolymer. The synthesized cation exchange textile is referred to as CIET. The reaction conditions are summarized in Table 1.

The ion exchange capacity of the synthesized ion exchange textile was determined using the titration method. Five grams of cation exchange textile was converted into the H^+ form and repeatedly washed with ultra pure water. The H^+ form sample was kept in a 2 M NaCl solution to exchange the protons with sodium ions. To ensure complete exchange, NaCl solution was refreshed two more times. The NaCl solution containing the released protons were titrated with NaOH.

Table 1. Reaction conditions for the preparation of cation exchange textile.

Photo initiator in methanol	3 wt % BP
Monomer concentration in water	25 wt % SSS 10 wt % AAc
Reaction temperature (°C)	80°C
Reaction time (hr)	6 hr

Abbreviations: SSS: sodium styrenesulfonate, AAc: acrylic acid, BP: benzophenon.

Characterization of the Ion Conducting Media

A flow cell was used to measure the electrical conductivity of cobalt–saturated ion exchange textile. Composed of various types of cobalt conductivity, the feed solution circulated in the flow cell apparatus until it reached an equilibrium with the ion exchange textile. Each solution conductivity and textile conductivity were measured using an LCZ meter (model 2321, NF electronics, Japan) at a linear velocity of $1.5\,\mathrm{cm}\cdot\mathrm{sec}^{-1}$.[4]

A clip cell with electrode area of $0.196\,\mathrm{cm}^2$ and thickness of 0.6 cm was used to measure the resistance of cobalt and nitrate-saturated ion exchange membranes using LCZ meter at 1000 Hz.[9] The electrical conductivity measured by the clip cell and flow cell, k, was determined from Eq. (4):

$$R = \frac{1}{k}\frac{l}{A} \tag{4}$$

where l = distance between the electrodes; A = area of the electrode.

CEDI Operation

A CEDI system with an effective membrane area of 5 cm × 10 cm was used. The thickness of the diluted compartment was 10 mm. The prepared cation exchange textile was used as the ion conducting spacer in the diluted compartment. CMX—strong acidic cation exchange membrane and AMX—strong basic anion exchange membrane (Tokuyama Soda Co. Ltd., Japan) were used for the compartment. The CEDI experiments were carried out with a cell consisting of three compartments (C, D, and E compartments as shown in Fig. 1). Cathode and anode made of Pt plate were installed at the end of the system sized with 5 cm × 10 cm. One molar H_2SO_4 solution was used as the concentrated solution and high resistivity water ($18.2\,\mathrm{M\Omega\,cm}$) as the diluted solution to investigate the effects of electroregeneration in the CEDI system. Na_2SO_4 solution of $500\,\mu\mathrm{s}^{-1}$ conductivity was circulated as electrode rinsing solution during CEDI operation. In this configuration, protons transport through the anion exchange membrane for cathode by proton leakage from sulfuric acid or water splitting reaction between anion exchange membrane and cation exchange textile. This can regenerate the cation exchange textile with hydrogen form, causing the transport of cobalt ion into the concentrated compartment through cation exchange membrane. The stack configuration is shown in Fig. 4. The cobalt concentrations during a CEDI operation were analyzed using an inductively coupled plasma spectrophotometer (Model- Thermo Jarrel ash IRIS/AP).

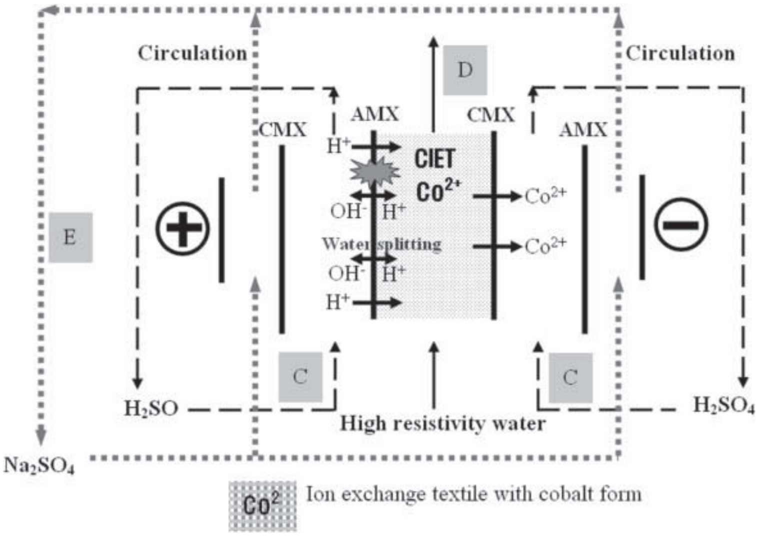

Figure 4. Stack configuration of the CEDI system for the electro-migration experiments. CMX: cation exchange membrane, AMX: anion exchange membrane, C: concentrated solution, D: diluted solution, E: electrode rinse solution.

RESULTS AND DISCUSSIONS

Characterization of the Ion Exchange Textile and Membranes

Ion exchange capacity was measured to determine the concentration of cobalt ion in the ion exchange textile. The ion exchange capacity of the prepared textile was found to be $2.267\,\text{meq}\,\text{g}^{-1}$, and its density $1.3\,\text{g}\,\text{cm}^{-3}$. The total cobalt concentration of ion exchange textiles was calculated from the determined parameters using the following Eq. (5):

$$\bar{c}^{\mathrm{t}}_{\mathrm{co}}(\text{mmol cm}^{-3}) = \frac{\begin{array}{c}\text{Ion exchange capacity (meq g}^{-1}) \times \text{Density of}\\ \text{ion exchange textile (g cm}^{-3})\end{array}}{\text{Charge valence (z)}} \tag{5}$$

The total cobalt concentration in the ion exchange textile ($\bar{c}^{\mathrm{t}}_{\mathrm{co}}$) was found to be $1.472\,\text{mmole}\,\text{cm}^{-3}$.

Electrical resistance in the CEDI system was estimated from the electrical conductivity of ion exchange textile and membranes. The resistance of the diluted compartment of the CEDI system consisted of two parts: the resistance of the ion exchange membranes (R_m) and that of the cation exchange textile (R_t). Figure 5 shows the electrical conductivity of the ion exchange textile with various Co^{2+} concentration. The conductivity equation of the ion exchange textile was λ_b $[\mu s\,cm^{-1}] = 121.24 + 11.6266\ \lambda_f^{0.6490}$ ($R^2 = 0.998$). Therefore, the conductivity of the ion exchange textile in the diluted compartment (thickness: 1 cm) was found to be 121.21 μs when the feed was infinitely diluted. Compared with the textile resistance under infinitely diluted solution, the membrane resistance measured using a clip cell was negligible because a thin membrane has a relatively high conductivity. Thus, the potential drop in the diluted compartment of the CEDI system was estimated by multiplying the textile resistance (R_t) by the stack current (I_{stack}).

Porous-Plug Model

Predetermined concentration ($\bar{c}^{t}_{co}$) in CIET Co was related with the total conductivity by ion exchange media (total gray blocks in Fig. 2). However,

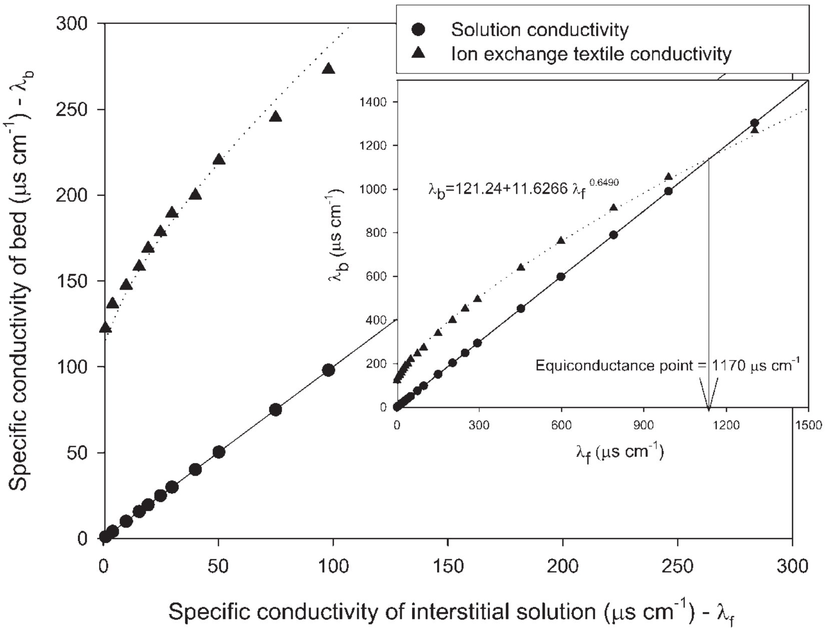

Figure 5. Electrical conductivity of the ion exchange textile fully loaded with cobalt form.

Co^{2+} must move through only pathway *b*, not *a* and *c* in Fig. 2 because all experiments in this study were carried out with high-resistivity water. For this reason, the total cobalt concentration ($\bar{c}^{t}_{co}$) determined previously could not be applied into the Eq. (3) directly. To overcome these problems, effective concentration ($\bar{c}^{eff}_{co}$) was introduced and the concentration was calculated with the geometrical parameters in the porous plug model. It has been known that the conducting fraction and the electrochemical properties of ion conducting media can be determined using geometrical parameters in the porous plug model.[4−6] The geometrical parameters in the CIET were determined from the electrical conductivity plotted in Fig. 5, and presented according to the porous plug model in Fig. 6. The white block represents the conducting regions through the interstitial solution and the gray block the ion exchange textile in the CEDI system. From the above geometrical parameters, the effective concentration of ion exchange textile ($\bar{c}^{eff}_{co}$) was determined with following Eq. (6).

$$\bar{c}^{eff}_{co} = \bar{c}^{o}_{co} = \bar{c}^{t}_{co} \times \frac{\text{Total area of } b \text{ in Fig 6}}{\text{Total area of gray block in Fig 6}} \tag{6}$$

Conducting pathway *b* in this study was found to be 0.10 and this value was applied in Eq. (6). The total area of gray block was found to be 0.58. Consequently, the initial mole concentration of cobalt ($\bar{c}^{0}_{Co}$) in the second pathway was determined as $0.25\,\text{mmol}\,\text{cm}^{-3}$, which was used as the effective mole concentration in Eq. (3).

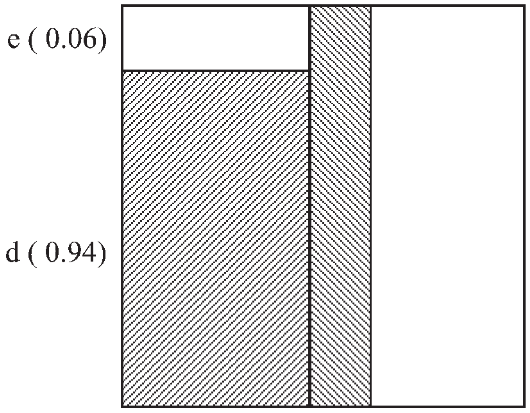

Figure 6. Configuration of the ratio between the solid and solution phases; Gray blocks are solid phases and white blocks solution phases.

Effect of Potential Drop in the Diluted Compartment on the Cobalt Flux

Figure 7 shows the relationships between the operating time and the number of moles of cobalt transported into the concentrated compartment under various potential drops. The cell potential drop in the diluted compartment ($\Delta E_{\mathrm{diluted}}$) was calculated using the stack current (I_{stack}) and the diluted compartment resistance (R_{diluted}) of Eq. (7):

$$\Delta E_{\mathrm{diluted}} = I_{\mathrm{stack}} R_{\mathrm{diluted}} = I_{\mathrm{stack}}(R_{\mathrm{m}} + R_{\mathrm{t}}) \approx I_{\mathrm{stack}} R_{\mathrm{t}} \quad (R_{\mathrm{m}} \langle\langle R_{\mathrm{t}}) \tag{7}$$

In Fig. 7, the slopes in each graph represent the flux change in the CEDI system with an effective membrane area of $50\,\mathrm{cm}^2$. The curves show linear relations at the initial operating time. The Nernst-Plank equation is known to be applicable under a homogeneous state, representing a constant flux in a constant current mode as suggested in Eq. (8). Further, Fig. 7 shows linear slopes only at the initial operating periods. This result implies that homogeneity was not developed within the time period; such nonhomogeinity may be induced by the concentration change in the textile. The hydrogen ion

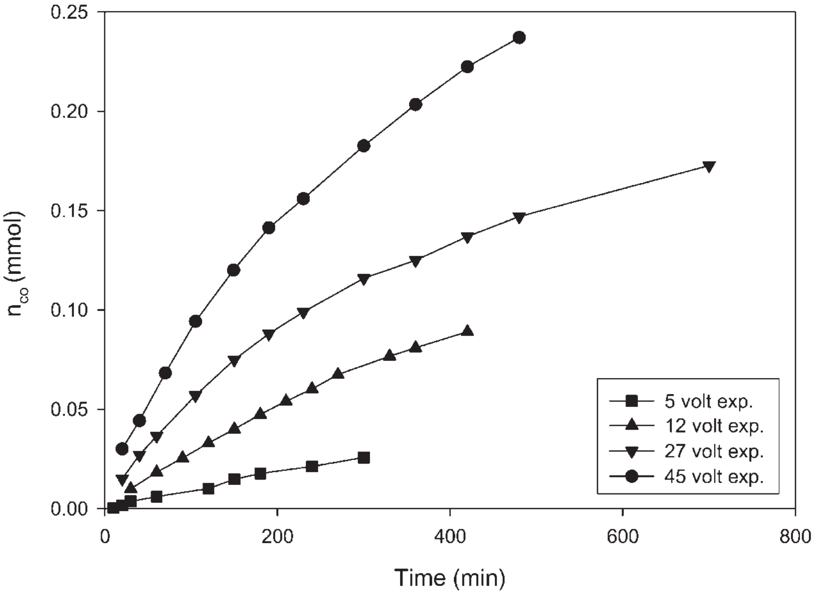

Figure 7. Comparison of the cobalt concentration with the potential drop in dilute compartment.

produced by water dissociation or proton leakage through an anion membrane can be transported into the ion exchange textile. This transport can change the cobalt concentration in the textile, increasing the concentration of hydrogen ion. In turn, this change disrupted the homogeneity of the ion exchange textile and made it difficult to apply the Nernst-Plank equation to the system. To confirm the quantitative changes in the ion exchange textile, current efficiency (η_{Co}) was calculated using the following Eq. (8):

$$\eta_{\mathrm{Co}} = \frac{2F(n_{\mathrm{Co,c}}^{t_2} - n_{\mathrm{Co,c}}^{t_1})}{Q^{t_2} - Q^{t_1}} \tag{8}$$

where F is the Faraday constant, Q^{t_2} the accumulated charge until time t_2 (columb), Q^{t_1} the total applied charge until time t_2 (columb), $n_{\mathrm{Co,c}}^{t_2}$ the moles of cobalt in the concentrated compartment until time t_2, and $n_{\mathrm{Co,c}}^{t_1}$ the moles of cobalt in the concentrated compartment until time t_1.

Figure 8 shows the time profiles of current efficiency in terms of transport number for cobalt ion. The transport number of cobalt decreased with time, although it was close to 1.0 under the initial operating condition. This result indicates that the initially applied current was used for the transport of cobalt ions but

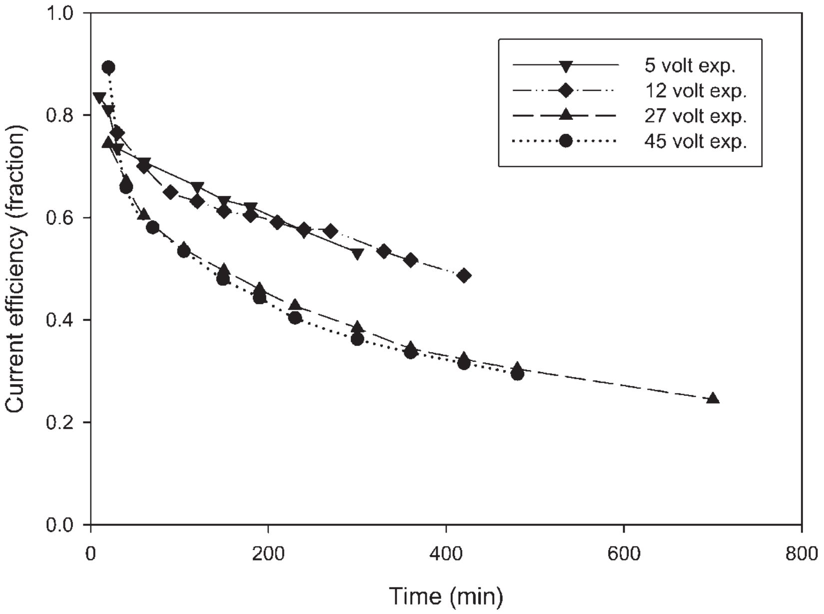

Figure 8. Change in the current efficiency according to operating time.

later for the transport of hydrogen ions. Figures 7 and 8 imply that the Nernst-Plank equation can be applied during the initial CEDI stage only.

Figure 9 presents the amount of the cobalt ion transported into the concentrated compartment according to the applied charge. Results show that the relationship between the transported cobalt ion and the applied charge did not depend on the potential drop in the diluted compartment; thus indicating that the transported cobalt is a function of the applied charge. Deviations may also occur due to the electrochemical reactions in the cobalt ion, including metallic cobalt generation.[7] Thus, assuming that no electrochemical reaction occurred, the amount of charge flux into the diluted compartment must be equal to the charge efflux from the diluted compartment. The charge influx is expressed by the hydrogen ion ($Q_{\mathrm{H}^+_{\mathrm{in}}}$), and the charge efflux by both the cobalt ion ($Q_{\mathrm{Co}^{2+}_{\mathrm{out}}}$) and hydrogen ion ($Q_{\mathrm{H}^+_{\mathrm{out}}}$) as shown in Fig. 4.

Based on the charge conservation law,

$$Q_{\mathrm{H}^+_{\mathrm{in}}} = Q_{\mathrm{Co}^{2+}_{\mathrm{out}}} + Q_{\mathrm{H}^+_{\mathrm{out}}} \tag{9}$$

From the Nernst Eq., Eq. (9) becomes:

$$n_{\mathrm{H}^+_{\mathrm{in}}} = \frac{1}{2} n_{\mathrm{Co}^{2+}_{\mathrm{out}}} + n_{\mathrm{H}^+_{\mathrm{out}}} \tag{10}$$

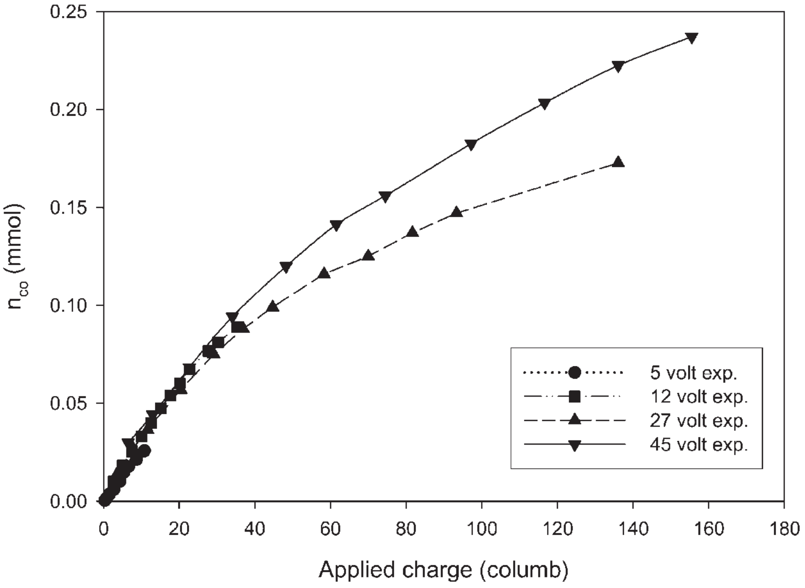

Figure 9. Amount of cobalt ion according to the applied current.

where $n_{\mathrm{H}^{+}_{\mathrm{in}}}$ is the number of moles of hydrogen ion in the diluted compartment, $n_{\mathrm{Co}^{2+}_{\mathrm{out}}}$ the number of moles of cobalt ion out of the diluted compartment, and $n_{\mathrm{H}^{+}_{\mathrm{out}}}$ the number of moles of hydrogen ion out of the diluted compartment.

Then, the amount of regenerated hydrogen ion in the CEDI system can be expressed as:

$$n_{\mathrm{H}^{+}_{\mathrm{diluted\,compartment}}} = n_{\mathrm{H}^{+}_{\mathrm{in}}} - n_{\mathrm{H}^{+}_{\mathrm{out}}} \tag{11}$$

where $n_{\mathrm{H}^{+}_{\mathrm{diluted\,compartment}}}$ is the number of moles of hydrogen ion in the diluted compartment. Based on Eq. (10) and (11), the number of moles of hydrogen ion in the diluted compartment ($n_{\mathrm{H}^{+}_{\mathrm{diluted\,compartmet}}}$) should be half the number of moles of cobalt in effluent ($1/2n_{\mathrm{Co}^{2+}_{\mathrm{out}}}$). Therefore, the slopes in Fig. 7 also enable to predict the regeneration velocity with time. In this system, the regeneration velocity decreased with time due to the transport of hydrogen ion into the concentrated solution. Figure 10 shows the flux change of cobalt ion in the CEDI system according to the potential drop in the diluted compartment. A large potential drop in the diluted compartment resulted in a high flux of cobalt. Nonetheless, the flux decreased over time by the transport of hydrogen ions into the concentrated compartment.

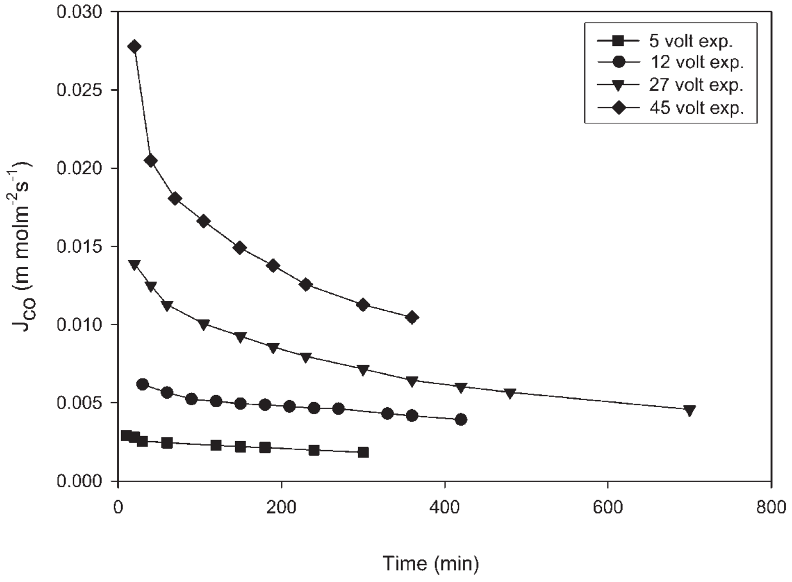

Figure 10. Flux change, according to the operating time, in the concentrated compartment.

Removal Mechanism of Cobalt Ion Through the Ion Exchange Textile

Figure 11 shows the relationship between the initial cobalt flux and the potential drop within the diluted compartment. The initial cobalt flux was determined by extrapolating the initial time in Fig. 10. Figure 11 shows a linear relation between the potential drop and the initial cobalt flux. In this case, the apparent mobility of cobalt in the CEDI system can be calculated using Eq. (12) as derived in Eq. (3):

$$J^0_{Co} = z_{Co}\bar{C}^0_{Co}\bar{u}^0_{Co}grad\varphi \tag{12}$$

where 0 denotes the initial conditions in the CEDI system. The equation gives the apparent mobility of cobalt ion through textile $\bar{u}^0_{Co}$ using the values for the flux, potential gradient, and initial ionic concentration in the ion exchange textile. Equation (12) was rearranged to calculate the diffusion coefficient as following:

$$\bar{u}^0_{Co} = \frac{J^0_{Co}}{z_{Co}\bar{C}^0_{Co}grad\varphi} = \frac{1}{z_{Co}\bar{C}^0_{Co}}\frac{J^0_{Co}}{\Delta E/\Delta x} \tag{13}$$

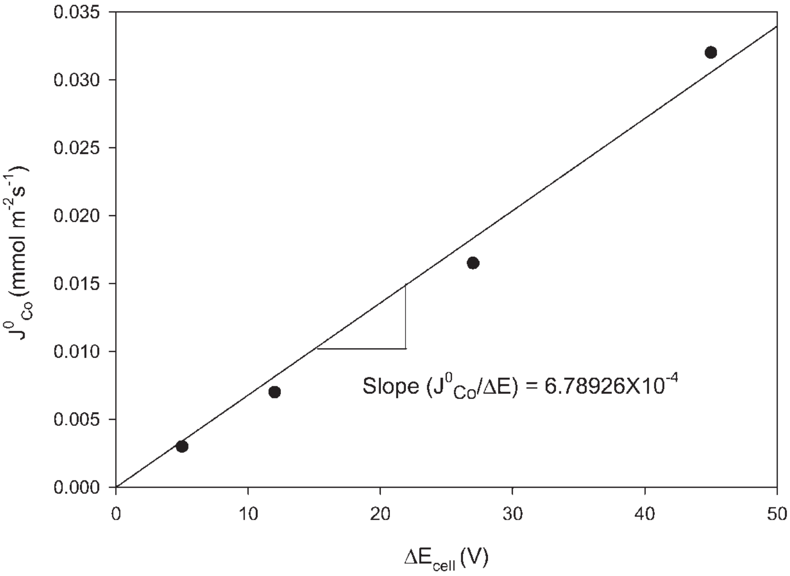

Figure 11. Initial cobalt flux with respect to the potential drop in the diluted compartment.

where ΔE is the potential changes in the diluted compartment and Δx the thickness of the diluted compartment in the CEDI system.

From Fig. 11, the slope was found to be 6.78926×10^{-4} (mmol $m^{-2}\,s^{-1}\,V^{-1}$), and this was used in Equation (13) instead of $J^0_{Co}/\Delta E$. Therefore, the apparent mobility of the cobalt ion through the ion exchange textile was calculated as 1.36×10^{-11} ($m^2\,s^{-1}\,V^{-1}$) when the ion exchange textile was fully saturated with cobalt ion. To compare the mobility to the solution, the mobility of cobalt ions in a solution was calculated from the limiting equivalent conductivity. The mobility in the limiting diluted solution was observed to be 10^2–10^3 times higher than the mobility through the ion exchange textile. Spoor et al. studied the mobility of nickel ion whose transport mechanism is the same as that of cobalt ion.[6] They reported that the ionic mobility of nickel ion through *Amberlyst 15* ion exchange beds was within the range of 10^{-11}–10^{-12} ($m^2\,s^{-1}\,V^{-1}$) of the concentration change and concluded that the mobility of nickel ions in an aqueous solution was approximately 10^3 times higher than the mobility of the ion exchange resins. These results showed that the removal mechanism of ions in the CEDI system was not mainly dependent on the ionic mobility but on other electrical properties. To determine the transport mechanism of cobalt ion through the ion exchange textile, microscopic equations are applied. For a strong electrolyte in concentration c under electric field ($\vec{F}$) to give rise to cations with charge z_+ and mobility u_+ and anions with charge z_- and mobility u_-, the relation between current density (i) and conductivity (k_c) is expressed by the following Eq. (14):

$$i = i_+ + i_- = cF\vec{F}(v_+u_+z_+ + v_-u_-z_-) = k_c\vec{F} \tag{14}$$

where i_+, i_- are the current density contribution from cation and anion and v_+, v_- the number of moles of cations and anions, respectively. From Eq. (11), the current density in the CEDI system with textile packing can be described by the following Eq. (15):

$$i(\text{with textile}) = k_{\text{textile}}\vec{F}. \tag{15}$$

Without ion exchange textiles, the current density can be described by the following Eq. (16):

$$i(\text{without textile}) = k_{\text{solution}}\vec{F} \tag{16}$$

If the system is under the same electric field, the ratio of the current density with textile to that without textile can be expressed as the ratio of conductivity (17):

$$\textit{Ratio of current density } (x) = \frac{k_{\text{textile}}}{k_{\text{solution}}} \tag{17}$$

Figure 12 shows the predicted ratio of current density with textile to that without textile in the CEDI system for cobalt nitrate solution. This ratio was much greater under textile packing at a low solution conductivity, because the CEDI system with textile packing induced a higher current than that without packing due to the self-conductivity of polyelectrolyte. Moreover, these results imply that the ability of the ion exchange media to absorb is also an important parameter because most of the current pass through ion exchange media.

The above results on transport characteristics of cobalt ion in CEDI system suggested the important understandings for CEDI system design. Firstly, the each cell pair in a CEDI system must be as thin as possible because the ionic mobility through the ion exchange textile is much slower than that through solution. Secondly, ion exchange textile with high conductivity must be used in the diluted compartment for the high performances of CEDI system to induce high current density during the operation. Consequently the sizing parameter was not the volume capacity (thickness of diluted compartment) but the conductivity of ion exchange textile in a CEDI system.

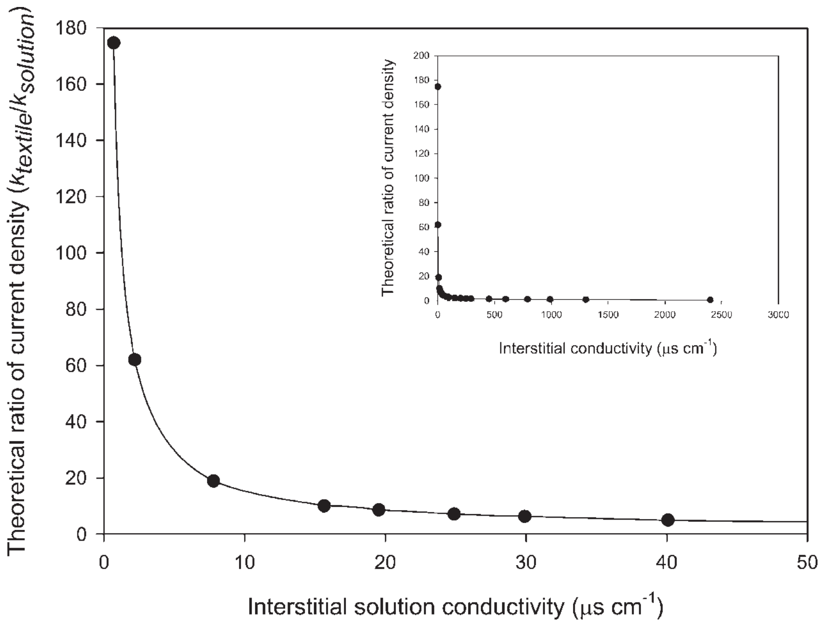

Figure 12. Theoretical ratio of current density for the textile packing to that of solution in the CEDI system.

CONCLUSIONS

The apparent mobility of cobalt ions in the CEDI system under regeneration was determined using the porous plug model and the extended Nernst-Plank equation. The current distribution and potential drop in the diluted compartment were determined using electrical conductivity. The Nernst-Plank equation was valid at the initial operating period only. Likewise, the cobalt flux was a function of the applied charge rather than the potential drop under nonelectrochemical reaction. The apparent mobility of the ion exchange textile proved that the removal mechanism of the CEDI system is not due to the accelerated ionic mobility but due to the induced current in the ion exchange textile. Moreover, the ratio of flux for the textile packing to that of solution shows a high value at a low interstitial solution conductivity; thus indicating that the CEDI enhanced the transport of ions more effectively at a low feed concentration. This study also suggested that the sizing factor for CEDI design is not the volume capacity but the conductivity of ion exchange textile for high CEDI performance.

LIST OF SYMBOLS

$J_{i,tot}$	Total flux of ions through a homogeneous ion exchanger (mole $m^{-2}\,sec^{-1}$)
$J_{i,diffusion}$	Diffusion flux of ion i through a homogeneous ion exchanger
$J_{i,con}$	Convection flux of ion i through a homogeneous ion exchanger
$\bar{D}_i$	Diffusion coefficient of ion i in the ion exchanger ($m^2\,sec^{-1}$)
$\bar{c}_i$	Concentration of ion i in the ion exchanger (mol m^{-3})
$\bar{u}_i$	Mobility of ion i through the ion exchanger ($m_2\,sec^{-1}\,V^{-1}$)
$grad\ \varphi$	Electrical potential gradient in the ion exchanger ($V\,m^{-1}$)
ν	Convection rate of the pore liquid's center of gravity ($m\,sec^{-1}$)
z_i	Valence state of ion i
w	Charge of fixed sites in the ion exchangers
F	Faraday constant (96485C mol^{-1})
X	Concentration of fixed sites (mole m^{-3})
ε	Fractional pore volume in the ion exchanger
$\bar{u}_o$	Mobility of the pore liquid in the ion exchanger ($m^2\,sec^{-1}\,V^{-1}$)

$\bar{u}_{\mathrm{i}}^*$	Apparent mobility of ion i in the ion exchanger ($\mathrm{m^2\,sec^{-1}\,V^{-1}}$)
$\bar{D}_{\mathrm{i}}^*$	Apparent diffusion coefficient of ion i in the ion exchanger ($\mathrm{m^2\,sec^{-1}}$)
W	Weight of the ion exchange textile (g)
$\bar{c}_{\mathrm{Co}}$	Cobalt concentration in the ion exchange textile ($\mathrm{mole\,m^{-3}}$)
λ_{f}	Conductivity of the feed solution in the CEDI system ($\mathrm{\mu s\,cm^{-1}}$)
λ_{b}	Conductivity of the diluted compartment in the CEDI system ($\mathrm{\mu s\,cm^{-1}}$)
$\Delta E_{\mathrm{diluted}}$	Potential drop in the diluted compartment (V)
I_{stack}	Stack current ($\mathrm{C\,sec^{-1}}$)
R_{diluted}	Resistance of the diluted compartment (Ω)
R_{a}	Resistance of the anion exchange membrane (Ω)
R_{c}	Resistance of the cation exchange membrane (Ω)
R_{t}	Resistance of the ion exchange textile (Ω)
η_{Co}	Fraction of current efficiency of the cobalt ion
Q	Applied charge in the system (Columb)
n_{i}	Number of moles of ion i (mole)
Δx	Thickness of the diluted compartment (cm)

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