Synergistic Effect of Mediated Electrochemical Reduction and Mediated Electrochemical Oxidation on NO Removal by Electro-Scrubbing

Muthuraman Govindan, Ramu Adam Gopal, Ho Geun Ahn, and Il Shik Moon*†

Department of Chemical Engineering, Sunchon National University, Jeollanam-do 57922, South Korea

A combined MER (mediated electrochemical reduction) and MEO (mediated electrochemical oxidation) approach was examined for the first time for the efficient removal of NO by electro-scrubbing. The generation of a mediator (Ni(I) from Ni(II)(CN)42− in 9 M KOH) by electrochemical reduction was identified by the changes in the ORP value and potentiometric titration. The Ni(I) formation found to be 9% (4.3 mM) in 2 h electrolysis, which is decreased to 1.83 mM (4%) during addition of NO demonstrates NO removal occurred. The MER of NO at the cathodic half-cell by electro-scrubbing revealed the formation of NH3 and N2. The reduction removal efficiency of NO was almost 100% up to a gas flow rate of 0.25 g min−1. At the anodic half-cell, the Co(III) mediator from Co(II)SO4 in 5 M H2SO4 was generated electrochemically with concomitant conversion of NO to NO3− in the solution phase with a removal efficiency of 28%. The combination of MEO and MER with electro-scrubbing demonstrates 97% removal efficiency of NO up to 0.5 g min−1. The combined removal approach is more suitable for high concentrated NO with energy efficiency of 0.99 g/kWh compared to the individual MEO (0.221 g/kWh) and MER (0.769 g/kWh) approaches.

Abundantly generated nitric oxide (NO) gas that includes power plant and steel plant etc., is decomposed by many technologies, such as wet scrubbing, catalytic oxidation, and selective catalytic reduction (SCR).1,4−6 The reduction of NO leads a combination of cationic intermediates and products, N2O, NH2OH, N2, and NH3, in the solution phase.4−6 The reduction products varied depending on the catalyst and experimental conditions: on TiO2 in the colloid solutions to produce NH3;4 in heterogeneous catalytic reduction process with NH3 as the product.1,13 Because of the catalytic reaction, NO is solubilized in an aqueous solution, otherwise it less soluble or insoluble in an aqueous solution.14 Using this approach, many oxidant11,15,16 and reductant11−13 containing wet-scrubbing processes have been adopted in NO removal. Note that the above methods require a continuous catalyst or reactant feed to make the process sustainable.

An electron considered to be a green catalyst and can be feed continuously to regenerate the spent catalyst sustainably. Using this approach, electrogenerated Ce(IV) and Mn(III) mediators have been continuously to regenerate the spent catalyst sustainably. Using this approach sustainable. methods require a continuous catalyst or reactant feed to make the process sustainable.

Published November 12, 2016.
was cooled slowly until a mass of thin orange platelets appeared. The resulting complex was filtered rapidly, washed with cold alcohol, recrystallized in ethanol, dried in a vacuum desiccator, and stored in an air-tight brown bottle.

**Ni(I) and Co(III) mediators generation and the electro-scrubbing setup.**—The electrolytic cell employed had a flow-through divided cell configuration, as reported elsewhere, with an additional scrubber column setup, as shown in Figure 1. The cell had cathode and anode areas of 50 cm² and an electrolyte volume of 500 ml. A scrubber column (40 cm high and 5.5 cm (i.d)) packed with 1 cm² of the Teflon tubes as packing material was attached to the top of the each anolyte and catholyte tanks, which is already attached with the flow through electrolytic divided cell. The scrubbing system was composed of an air supply system, a scrubbing solution (Ni(II)/Ni(I) in KOH solution), a scrubbing reactor column, and an FTIR gas analyzer system (MIDAC Corporation, USA) equipped with a data logger. The Ni(I) and Co(III) formation experiments were conducted using a catholyte containing 9 M KOH and 0.05 M Ni(II)(CN)₄²⁻; in a 1 L glass tank and an anolyte containing 5 M H₂SO₄ and 0.05 M Co(II)SO₄ in another 1 L glass tank, which were both connected to a flow through electrolytic divided (by Nafion 324 from DuPont, USA) cell membrane. The anolyte and catholyte were circulated continuously using magnetic pumps (Pan, World Co., Ltd, Taiwan) through the anode and cathode compartments, respectively, at a rate of 2 L min⁻¹. The electrolysis experiments were conducted using constant current mode by a constant current density to reach approximately 800 mV at the same time, the initial potential of Co(II) was around 1300 mV during electrolysis. The reduction and oxidation efficiencies are defined as follows:

\[
\text{Reduction efficiency} \ = \ \frac{[\text{Ni(I)}]}{[\text{Ni(II)}]} \times 100 \quad [1]
\]

\[
\text{Oxidation efficiency} \ = \ \frac{[\text{Co(III)}]}{[\text{Co(II)}]} \times 100 \quad [2]
\]

where Ni(I) and Co(III) are the concentrations of the electrolytically formed Ni(I) complex and Co(III) ion. Ni(II) and Co(II) are the initial concentrations of the Ni(II) complex and Co(II) ion precursor, respectively.

**Analysis.**—The aqueous reaction solution sample withdrawn at each defined interval during NO removal was analyzed by attenuated total reflectance – FTIR (ATR-FTIR, Thermo scientific, Nicolet iS5, USA) using a sapphire as the optical window. NO gases were introduced into the cell through a needle syringe. Gas chromatographic separations (Sigma Aldrich). The GC oven temperature was set constant at 250°C. Helium was used as carrier at a flow rate of 2 ml min⁻¹.

**Nitrate analysis by HACH.**—During the NO removal process, a 1 ml aliquot sample of the anolyte solution was drawn from the anode or catholyte chamber, in which the required amount of salicylic acid was added and heated at 80°C for 2 hours. The reaction mixture was cooled slowly until a mass of thin orange platelets appeared. The resulting complex was filtered rapidly, washed with cold alcohol, recrystallized in ethanol, dried in a vacuum desiccator, and stored in an air-tight brown bottle.

**Figure 1.** Schematic diagram setup for the electrochemical generation of Ni(I) and Co(III) and their application in NO removal by electro-scrubbing.
acid (0.2 ml reagent) was added and the solution was neutralized by adding NaOH (pH 6.8). The resulting amber color solution was then analyzed directly using a HACH colorimeter (DR-2800, U.S.A) using 410 nm.

Energy analysis.—The total energy that needs to generate Ni(I)(CN)₄³⁻ and Co(III), and NO removal were calculated based on the literature,²⁸ as given in Eq. 3, which is equal to total supplied energy to produce the Ni(I)(CN)₄³⁻ and Co(III), and NO removal processes.

\[
\text{Energy consumption} = V \times I \times t / V_e \text{ or } V_{NO} [3]
\]

Where V and I are the average cell voltage and current that used for electrolysis; t is the electrolysis time (h), Vₑ and V_NO are the volume of electrolyte and volume of NO gas treated, respectively. The energy consumption was reported in kWh m⁻³. In order to compare the present method of NO removal process with internationally accepted energy standard, the energy efficiency of NO removal was derived through a continuous flow operation process,²⁹ which was developed for NO removal using dielectric barrier discharge (DBD) method, as given in the Eq. 4.

\[
\text{Energy efficiency} = FR \times FC / 10^6 \times RE / 100 \times 30 / 22.4 \times I / W [4]
\]

Where FR is the gas flow rate (L/min) and FC is the initial feed concentration (ppm) used in the experiments and RE is removal efficiency of pollutant (NO). The gas constant for NO gas (30/22.4) at NTP (1 atm with 293 K) has been used to convert the gas mole into liquid.

Results and Discussion

Electrogeneration of Ni(I) and NO reductive removal optimization.—Fig. 2A shows ORP (oxidation/reduction potential) and reduction efficiency variation of Ni(II)(CN)₄²⁻ during electrolysis in a 9 M KOH solution. The ORP value reached ~800 mV in 120 min and increased steadily in further electrolysis times (Fig. 2A curve a) indicating the low oxidation state of Ni(II), in this case Ni(I) formation.²³ Ni(I) formation as a measure of the reduction efficiency, which was determined as mentioned in the Experimental section, increased with increasing electrolysis time to 9% (4.3 mM) for a 120 min duration (Fig. 2A curve b). Once the NO gas was introduced into the electrogenerated Ni(I)/Ni(II)-containing solution, the reduction efficiency of Ni(II) decreased to 1.83 mM (3%) and was varied slightly as long as NO was purged into the solution, which indicates that a reaction between Ni(I) and NO occurred, called mediated reduction. The Ni(II) reduction efficiency increased reached approximately 7% (3.4 mM) once the NO was stopped, showing that the process is sustainable.³⁴ and Ni(I) can be generated without additional chemicals. As reported in the literature, NO is relatively insoluble in water,¹⁴ but if scrubbed through a 9 M KOH solution, 100 ppm of the feed NO absorbed nearly 10 ppm in 15 min (Fig. 2B curve a) and decreased to 0 ppm in 20 min revealed absorption in a 9 M KOH solution. A similar trend was observed in a 9 M KOH solution with electrolysis (without 0.05 M Ni(II)(CN)₄²⁻) (Fig. 2B curve b) with a slight increase in absorption, 15 ppm in 5 min, followed by a decrease to 0 ppm in 15 min, indicating that the DER (direct electrochemical reduction) of NO occurred in a short time and a lower concentration of NO or no DER is occurred. At the same time, in the presence of 0.05 M Ni(II)(CN)₄²⁻ or electrogenerated Ni(I), the 0 ppm found in the outlet means 100% removal efficiency of NO (Fig. 2B curve c), which shows NO reduction follows the MER process.

In addition, the feed concentration variation of NO resulted in 100% removal efficiency at 100 ppm from the beginning of the NO feed to the studied time (Fig. 3A curve a). The NO removal efficiency decreased to 62% at the feed NO of 150 ppm (Fig. 3A curve b) and at feed of 200 ppm (Fig. 3A curve c) tells a saturation has been reached around 150 ppm feed concentration. Complete saturation occurred in the NO removal efficiency at a 200 ppm feed. This decrease in removal efficiency of NO at a high feed concentration might be due to the unavailability of Ni(I) in the electrolyte solution, which was confirmed by the Ni(I) concentration variation during NO removal at various feed NO concentrations, as shown in Fig. 3B. The Ni(I) concentration increased during 100 and 150 ppm of NO removal (Fig. 3B curve a and b). On the other hand, no change in Ni(I) concentration at 200 ppm feed of NO (Fig. 3B curve c). In addition, the effect of the gas flow rate was performed to understand the limit of the gas flow rate, which is depicted in Fig. 3C. At a low gas flow rate of 0.25 g min⁻¹, almost 100% NO removal efficiency was observed (Fig. 3C curve a). At the same time, the NO removal efficiency decreased to 75% at a 150 ppm feed (Fig. 3C curve b) and 50% at 200 ppm feed (Fig. 3C curve c) NO concentration, as expected, indicating the unavailability of Ni(I).

The online FTIR gas analyzer can monitor simultaneously whether additional gas coming from the scrubbing column during the reductive removal of NO, here NH₃ and N₂O gases, are produced along with NO based on the literature knowledge: the results are presented in Figs. 4A and 4B. In the case of N₂O, despite the variations in feed concentration of NO or gas flow rate, no N₂O was found at exit gas (Figs. 4A and 4B curve a), which means that NO reduction to N₂O.
Figure 3. (A) Effect of the feed concentration, and (C) gas flow rate (mentioned in the figure) on NO removal with time during electro-scrubbing. (B) Ni(I) concentration variation during reductive removal NO. Electrolysis and scrubbing conditions are same as in legend of Fig. 2.

(Reactions 5–8) did not occur under these reaction conditions.

\[ \text{NO} + 
H^+ + e^- \rightarrow \text{HNO} \rightarrow N_2O \]  
[5]

\[ \text{HNO} + 
H^+ + e^- \rightarrow \text{NH}_2O^* \]  
[6]

\[ \text{NH}_2O^- + 
H^+ + e^- \rightarrow \text{NH}_2OH \]  
[7]

Figure 4. Gas phase products (NH_3 and N_2) concentration variation on (A) feed concentration (B) gas flow rate (mentioned in the figure) during the removal of NO at cathodic half-cell by electro-scrubbing. Electrolysis and scrubbing conditions are the same as in the legend Fig. 2.

\[ \text{NH}_2OH + 2H^+ + 2e^- \rightarrow \text{NH}_3 + H_2O \]  
[8]

Instead, NH_3 was observed at the scrubber exit, as shown in Figs. 4A and 4B curves b–d. At a 100 ppm NO feed, 75 ppm of NH_3 was observed in 5 min, which was then reduced to 45 ppm in 20 min and became constant thereafter (Fig. 4A curve b). At a 150 ppm feed NO, the initial NH_3 concentration was 162 ppm, which reduced to almost 100 ppm in 30 min and remained constant thereafter (Fig. 4A curve c). Similarly, the initial NH_3 concentration found 200 ppm and was reduced during the removal time to 75 ppm in 60 min (Fig. 4A curve d). The decreasing trend of the formed NH_3 concentration with the removal time might be due to the additional reaction that forms an additional product. NH_3 and NO in the aqueous phase leads to the formation of N_2, as shown in Reaction 9.4, and an additional reaction might have started after certain level of NH_3 formation.

\[ 4\text{NO} + 4\text{NH}_3 + O_2 \rightarrow 4\text{N}_2 + 6H_2O \]  
[9]

This is what occurred in the present case. The initial NH_3 concentration was similar to the feed concentration of NO, and the NH_3 concentration began to decrease depending on the concentration of NH_3, which was further confirmed by the gas flow rate variation (Fig. 4B curve b–d). A difference in the initial NH_3 concentration was observed depending on the feed flow rate, but later, there was no change in the NH_3 concentration, which means no change in the feed NO concentration. To monitor for N_2, separate GC
experiments were performed during NO reduction, as shown in Fig. 4A curve e. In the case of 100 ppm feed NO, the N2 concentration increased to 45 ppm in 20 min and remained constant, which confirms the formation of N2 with NH3, as shown in Reaction 2. For confirmation, the gas phase FTIR were shown in Fig. 5A. The inbuilt (provided by the MIDAC instrument library) standard gas FTIR spectra for NO and NH3 shown in Fig. 5A curve a and b for comparison. The direct NO feed to the online FTIR shows two strong stretching peaks (1899.2–1905 cm$^{-1}$), which is the region fixed to monitor removal of NO, behavior of N-O along with moisture peaks (Fig. 5A curve c). Fig. 5A curve d shows outcome FTIR spectrum during removal of NO by MER, where N-H bending peaks (989.9–995 cm$^{-1}$), which is the region fixed to monitor NH3 gas, found that is similar to the Fig. 5A curve b spectrum along with moisture peaks confirms the NH3 formation. At the same time, the two strong stretching peaks for N-O completely vanished confirms the removal of NO. In addition, the solution phase ATR-FTIR of before and after the NO removal process revealed no change or an additional peak (Fig. 5B curve a and b) for N-O stretching region or N-H stretching region, which explains why the NH3 formed was not in solution due to the high pH (14) of 9 M KOH. Beyond pH 11, NH4OH becomes NH3 gas and escapes from solution.37

Electrogeneration of Co(III) and NO oxidative removal optimization.—Although NOx oxidation occurs by the MEO process, the use of Co(III) in a 5 M H2SO4 solution is new. Similar to NO reduction, oxidation was performed under different conditions and is presented in Fig. 6A. No absorption was observed except for 3 ppm in a short time at 5 to 20 min (Fig. 6A curve a). Similar behavior was found for the DEO (direct electrochemical oxidation) of NO (without 0.05 M Co(II)SO4 (Fig. 6A curve b) at 15 min and reached 0 ppm in 20 min, which confirms that no DEO of NO had occurred. Almost 28% of the NO was removed in the presence of electrogenerated Co(III) in 5 M H2SO4 (Fig. 6A curve c), which confirms that NO oxidation is influenced by MEO, as evidenced by the Co(III) concentration variations during the addition of NO. Fig. 6B shows 35% (18 mM) of Co(III) formed in 2 h electrolysis, which is decreased to 10 mM (20%) in 1 h after the NO was injected into the scrubbing column (Fig. 6B curve a) that confirms the reaction between Co(III) and NO gas.

NO2 is monitored simultaneously along with the NO concentration during oxidative removal, and N2O and N2O5 were monitored through the batch run mode (offline mode) after the NO removal experiments. Fig. 7 shows no N2O5, N2O, and NO2 during the NO removal process (Fig. 7 curve a–c). Previous studies of NO oxidative removal by

![Figure 5](image-url)  
Figure 5. (A) Online FTIR spectra during the reductive removal of NO at the cathodic half-cell by electro-scrubbing along with the inbuilt respective spectra ((a) NO and (b) NH3); (c) Spectrum for MER; (d) Spectrum for direct feed. (B) Solution phase ATR-FTIR spectra of (a) before and (b) after NO removal by electro-scrubbing of the catholyte solution. Electrolysis and scrubbing conditions are the same as in the legend Fig. 2.

![Figure 6](image-url)  
Figure 6. (A) Oxidative removal of NO under different conditions through anodic half-cell in 5 M H2SO4 solution by electro-scrubbing. (a) Absorption; (b) DEO (without 0.05 M Co(II)SO4); (c) MEO (with 0.05 M Co(II)SO4). (B) Effect of Co(III) formation on NO removal during the electrolysis and electro-scrubbing. Electrolysis and scrubbing conditions are the same as in the legend Fig. 2.
**Figure 7.** Gas phase (NO₂, N₂O₅, and N₂O) and liquid phase (NO₃⁻) product concentration variation with time during the removal of NO at anodic half-cell by electro-scrubbing. Electrolysis and scrubbing conditions are the same as in legend Fig. 2.

**Figure 8.** Removal efficiency of NO during a combination of MEO and MER processes using both half-cells by electro-scrubbing. Electrolysis and scrubbing conditions are the same as in legends of Fig. 2 and Fig. 6A.

Electrogeneated Ag(II) revealed 60 to 80% removal obtained depending on the conditions, but NO₂ was found as reaction product in first scrubber. In the present case, using electrogeneated Co(III), 28% removal efficiency was obtained with no NO₂ in the first scrubber exit. The solution was analyzed for NO₃⁻ using the HACH method and the results obtained showed an increase in the NO₃⁻ concentration from 62 ppm to 135 ppm with increasing oxidative removal time (Fig. 7 curve d) up to a 60 min duration. Although the oxidative removal efficiency of NO was 28% by electrogeneated Co(III) in a 5 M H₂SO₄ medium, there was no NO₃⁻ greenhouse gas generated, but NO₃⁻ was observed at the first stage electro-scrubber itself.

**NO removal by combined MEO and MER processes.—**As shown in the Fig. 3C curve a, 100% removal of NO was found until a 0.25 g min⁻¹ gas flow rate. To increase the removal efficiency of NO at a higher gas flow rate, a combined removal approach, a combination of MEO and MER processes was attempted and the obtained results were presented in Fig. 8. 100 ppm of NO with a 0.5 g min⁻¹ gas flow rate was injected into the bottom of the anolyte scrubber, which contained 30% Co(III) (15 mM) in a 4 M H₂SO₄ solution. The exit gas was injected sequentially into the bottom of the catholyte scrubber, where 3.8 mM (8%) of Ni(I) in 9 M KOH was generated at the time of gas injection. A 28% removal efficiency was observed using the Co(III) MEO of NO (Fig. 8 curve a) and the remaining 72% NO was removed completely by the Ni(I) mediator at the cathodic scrubber (Fig. 8 curve b). These results show that a combination of MEO and MER makes NO removal possible at a high gas flow rate due to the additional removal process.

**Energy for mediator generation and NO removal.—**Energy consumption for Ni(I)(CN)₄³⁻ and Co(III) generation, and NO removal were calculated using the Eq. 3 and presented in Table I. As shown in Table I, generation of only Ni(I)(CN)₄³⁻ needs 0.121 kWh m⁻³, but the both Co(III)(18 mM) and Ni(I)(CN)₄³⁻ (4.3 mM) mediators can be generated by the same energy when operate the both half-cells together. The NO removal by using only MER (cathodic half-cell) is 0.060 kWh m⁻³, but more than a half of the energy (0.031 kWh m⁻³) is reduced if use the MEO (anodic half-cell) with MER (cathodic half-cell). Table I also contains the energy efficiencies of Ni(I)(CN)₄³⁻ and Co(III) generation, and NO removal processes that are calculated using the Eq. 4. The energy needed to remove NO through individual MEO and MER processes found to be 0.221 g kWh⁻¹ and 0.769 g kWh⁻¹ respectively (Table I middle column). At the same time, the NO removal energy efficiency become higher 0.99 g kWh⁻¹ (Table I middle column) when combined the MEO & MER processes, which is almost 10 times lower than the energy efficiency obtained for NO removal by nanosecond pulsed discharge (12 g kWh⁻¹) and non-thermal discharge (~20 g kWh⁻¹) methods. Noteworthy here that the high installation cost of nanosecond pulsed discharge and non-thermal discharge methods makes the present electrochemical (installation cost is very less) approach more economical. Moreover, no electrochemical methods reported for energy efficiency of NO removal explains the present attempt is a comparatively efficient method in concerning the energy efficiency.

**Conclusions**

The MEO and MER combined removal of NO by electro-scrubbing process is very efficient. The electrogeneation of Ni(I) from Ni(II)(CN)₄²⁻ was sustainable and was used for NO reduction for the first time by electro-scrubbing. The reduction of NO using

**Table I. Energy consumption (kWh m⁻³) and energy efficiency (g/kWh) during mediator generation and NO removal by electro-scrubbing.**

| Conditions                        | Energy consumption (kWh m⁻³) | Energy efficiency (g/kWh)⁸ | Removal efficiency (%) |
|-----------------------------------|-----------------------------|----------------------------|------------------------|
| Generation of Ni(I)(CN)₄³⁻         | 0.121                       | 0.015                      |                        |
| NO removal only by MER using Ni(I)(CN)₄³⁻ | 0.060                       | 0.769                      | 100                    |
| Generation of Co(III)             | 0.121                       | 0.075                      |                        |
| NO removal only by MEO using Co(III) | 0.060                       | 0.221                      | 28                     |
| NO removal by MER & MEO           | 0.031                       | 0.990                      | 97.3                   |

*Average cell voltage = 4.5; Current density = 25 mA cm⁻²; Electrolyte volume = 1.2 L; Gas volume = 91 L for MER; 182 L for MEO & MER.

⁸Energy efficiency calculated using Equation 4.
Ni(I) leads to the formation of NH$_3$ and N$_2$ products. Simultaneously, Co(III) was generated at the anodic half-cell in the 5 M H$_2$SO$_4$ solution and was used to oxidize NO by electro-scrubbing. The oxidative removal of NO leads to the formation of NO$_3^-$ in solution. Almost 100% NO removal efficiency by MER was observed up to a gas flow rate of 0.25 g min$^{-1}$. The combined MEO and MER process revealed 97% removal efficiency at a higher gas flow rate of 0.5 g min$^{-1}$, which confirms the efficient removal of NO. Moreover, the energy efficiency for NO removal becomes higher (0.99 g/kWh) than the individual MEO (0.221 g/kWh) and MER (0.769 g/kWh) processes.

Acknowledgment
This study was supported by the National Research Foundation of Korea (NRF) funded by Ministry of Engineering Science and Technology (MEST) from the Korean government (grant No. 2014R1A2A1A01001974).

References
1. J. Zhang, R. Zhang, X. Chen, M. Tong, W. Kang, S. Guo, Y. Zhou, and J. Lu, Ind. Eng. Chem. Res., 53, 6450 (2014).
2. M. Sarma and B. Mondal, Inorg. Chem., 50, 3206 (2011).
3. P. Fang, C. Cen, Z. Tang, P. Zhong, D. Chen, and Z. Chen, Chem. Eng. J. (Amsterdam, Neth.), 168, 52 (2011).
4. S. Goldstein, D. Behar, T. Rajh, and J. Rabani, J. Phys. Chem. A, 119, 2760 (2015).
5. M. T. De Groot, M. Merks, and M. T. M. Koper, J. Am. Chem. Soc., 127, 16224 (2005).
6. S. M. Park, H.-G. Jang, E. S. Kim, H.-S. Han, and G. Seo, Appl. Catal., A, 427–428, 155 (2012).
7. R. Rota, D. Antos, E. F. Zanoelo, and S. Carra, Combust. Sci. Technol., 163, 25 (2001).
8. S. Ogriscek and G. P. G. Vanegas, Chem. Eng. J. (Amsterdam, Neth.), 160, 641 (2010).
9. V. Cantatore and I. Panas, J. Chem. Phys., 144, 151102/1 (2016).
10. Z. Zhang, J. D. Atkinson, B. Jiang, M. J. Rood, and Z. Yan, Appl. Catal., B, 148–149, 573 (2014).
11. K. Skabka, J. S. Miller, and S. Ledakowicz, Chem. Pap., 64, 269 (2010).
12. Z. Ren, Y. Guo, Z. Zhang, C. Liu, and P.-X. Gao, J. Mater. Chem. A, 1, 9897 (2013).
13. T. Kameda, A. Kodama, and T. Yoshioka, Chemosphere, 120, 378 (2015).
14. I. G. Zacharia and W. M. Deen, Ann. Biomed. Eng., 33, 214 (2005).
15. S. Zhou, J. Zhou, Y. Feng, and Y. Zhu, Ind. Eng. Chem. Res., 55, 5825 (2016).
16. N. D. Hutson, R. Krzyzynska, and R. K. Srivastava, Ind. Eng. Chem. Res., 47, 5825 (2008).
17. Y. Zhou, L. Gao, Y.-F. Xia, and W. Li, Environ. Sci. Technol., 46, 12640 (2012).
18. M. Aurousseau, F. Lapicque, and A. Storck, Ind. Eng. Chem. Res., 33, 191 (1994).
19. J. Bringmann, K. Ebert, U. Galla and H. Schmieder J Appl. Electrochem, 27, 870 (1997).
20. S. J. Chung, K. C. Pillai, and I. S. Moon, Sep. Purif. Technol., 65, 156 (2009).
21. T. Raju, S. J. Chung, and I. S. Moon, Environ. Sci. Technol., 42, 7464 (2008).
22. K. Chandrasekara Pillai, S. J. Chung, and I.-S. Moon, Chemosphere, 73, 1505 (2008).
23. M. Govindan, S. J. Chung, and I.-S. Moon, Ind. Eng. Chem. Res., 51, 2697 (2012).
24. A. C. A. de Voors, M. T. M. Koper, R. A. van Santen, and J. A. R. van Veen, Electrochim. Acta, 46, 923 (2001).
25. V. Kosca, G. L. Beltrozo, and M. T. M. Koper, Langmuir, 21, 1448 (2005).
26. S. Suzuki, T. Nakato, H. Hattori, and H. Kita, J Electroanal. Chem., 396, 143 (1995).
27. A. Kudo, K. Watanabe, Y. Minakata, and A. Mine, Chem. Lett., 391 (1998).
28. S.-H. Cheng and Y. O. Su, Inorg. Chem., 33, 5847 (1994).
29. K. H. Kleifges, G. Kreysa, and K. Juttner, J. Appl. Electrochem., 27, 1012 (1997).
30. G. I. Miltzarek, C. H. Sampaio, and J. L. Cortina, Minerals Eng., 15, 75 (2002).
31. W.C. Fernelius, J.J. Burbage, and N.E. Ballou, Potassium Tetracyanonickelate(II), in: Inorganic Syntheses, p. 227, John Wiley & Sons, Inc., New York (2007).
32. A. K. Chopra, Ind. Eng. Chem. Res., 33, 191 (1994).
33. K. Yukimura, K. Kawamura, S. Kambara, H. Moritomi, and T. Yamashita, Chem. Pap., 427–428, 155 (2005).
34. G. Muthuraman and I. S. Moon, Sep. Purif. Technol., 64, 641 (2008).
35. M. Brass, T. Pritzel, E. Schulte, and J. U. Keller, Int. J. Thermophys., 21, 883 (2000).
36. T. Matsumoto, D. Wang, T. Namihira, and H. Akiyama, Langmuir, 33, 6410 (2011).
37. M. T. Izquierdo and B. Rubio, J. Adv. Oxid. Technol., 14, E390-E396 (2016).
38. T. Kameda, A. Kodama, and T. Yoshioka, Chem. Pap., 64, 269 (2010).