Effects of roasting and NH₄Cl catalysis on the direct electrotransformation products from an AlCl₃ solution

Xixiu Han, Ting-an Zhang, Guozhi Lv, Xijuan Pan and Daxue Fu

Key Laboratory of Ecological Metallurgy of Multi-metal Intergrown Ores of Ministry of Education, Special Metallurgy and Process Engineering Institute, Northeastern University, Shenyang 110819, Liaoning, People’s Republic of China

Abstract
Contemporary processes for extracting alumina from fly ash involve various disadvantages, including high-energy consumption, heavy slag discharge, and severe equipment corrosion, so a new method for extracting alumina via electrotransformation was developed in this work. This novel method reduced slag discharge, enabled recycling, and produced no acid or alkali waste. The theoretical solution pH associated with Al(OH)₃ precipitation and the actual solution pH during electrotransformation were also compared herein. Differential thermogravimetric analysis was performed for the direct electrotransformation products generated with and without NH₄Cl as a catalyst; the activation energy and reaction order of these reactions revealed large fluctuations. The effects of the roasting temperature on the phase, morphology, D(50), and D(90) of the roasting products were also studied. The results indicated that the solution reached the theoretical pH (4.7) of complete Al(OH)₃ precipitation in a short time when NH₄Cl was implemented as a catalyst. Additionally, the D(50) and D(90) of the roasting products were nearly ten times higher when NH₄Cl was used, relative to when it was not, reaching 227.1 and 519.6 μm, respectively. The activation energies of each reaction in the electrotransformation and roasting process were also reduced in the presence of the NH₄Cl catalyst. Between 100 °C–250 °C, the physical adsorption of water occurred, and some of the structural water of the electrotransformation products generated with NH₄Cl were removed in an endothermic reaction (reaction order, n₁ = 0.43; activation energy, E₁ = 2.13 J mol⁻¹). At temperatures between 250 °C–500 °C, the nitrogen-containing substances were removed in another endothermic reaction (reaction order, n₂ = 0.4697; activation energy, E₂ = 5.316 J mol⁻¹). Increasing the roasting temperature was beneficial for improving the crystal form of the roasting products, and the reduced electrotransformation products appeared more compact after roasting.

1. Introduction
In recent years, concerns regarding environmental problems have continued to grow around the world [1]. Coal fly ash is an industrial by-product of coal combustion, which is produced in high-temperature coal-fired thermal power plants, and it represents one of the most abundant incombustible solid wastes [2–7]. The global coal fly ash emissions reach about 780 million tons annually, and India alone contributes about 23% of that total [8–10]. Stockpiling of coal fly ash is irreversible, and storing such a huge quantity of coal fly ash would take up enormous land space. Meanwhile, the demand for electric power continues to increase all over the world, which raises much more serious problems in terms of fly ash disposal and environmental pollution [11, 12]. However, it is also considered to be the world’s fifth largest raw material resource [13].

Coal fly ash from parts of China’s Inner Mongolia and Shanxi provinces contains significant amounts of alumina (up to 40%–50% [14]), which is a promising secondary mineral resource (other than bauxite), and is therefore amenable to metallurgical and chemical recovery processes. As bauxite resources decrease and the
demand for alumina increases, fly ash with high alumina content can be used as a substitute for bauxite in alumina production [15, 16]. Considerable research efforts are currently aimed at determining potential applications for these solid waste materials; such studies have vital environmental significance in addition to their inherent scientific research and industrial value [17]. The rational and efficient utilization of fly ash not only alleviates environmental pollution, but also plays an important role in scientific advancements and sustainable development [18]. Currently, the extraction of aluminum and other valuable elements from fly ash has become a research hotspot worldwide [19–23].

The traditional Bayer process is suitable for recovering aluminum from bauxite resources with low silica content. Therefore, this process is not suitable for fly ash with high silica content, although alumina recovery from fly ash has been attempted using various approaches, including acid methods [24–29] and alkali methods [30, 31]. However, there are many shortcomings or deficiencies in these processes. Acid processes are the most commonly applied strategies for extracting alumina, and are accordingly the preferred methods for extracting alumina from fly ash. However, the acid-based process inevitably causes very serious equipment corrosion, so it requires highly acid-resistant and air-tight equipment, which increases investment costs; this process also produces acid smog, among other environmental problems [32]. The main steps of the alkaline process involves intering, dissolution, and separation, and its disadvantages mainly include high-energy consumption, large quantities of slag discharge, and lower alumina extraction rates [33].

Considering the aforementioned aspects and available techniques, developing a new method for extracting alumina from fly ash is crucial to overcome the deficiencies in the conventional fly ash processing treatments and to ease the current environmental burden [33]. In this paper, a novel approach for alumina preparation via electrotransformation of fly ash using an AlCl₃ solution is proposed (figure 1). This method has various advantages, including slag reduction, recycling, and no acid or alkali waste. The theoretical solution pH value related to Al(OH)₃ precipitation and the actual solution pH value during electrotransformation were compared and analyzed. Additionally, the differential scanning calorimetry thermogravimetric analysis (TG-DSC) of direct electrotransformation products and electrotransformation products catalyzed by NH₄Cl was studied. The endothermic and exothermic peaks with large fluctuations in their differential scanning calorimetry (DSC) curves were fitted, and the activation energy and reaction order of the corresponding chemical reactions were calculated. The effects of roasting temperature on the phase, morphology, D(50)(the average particle size), and D(90)(the cumulative particle distribution is 90% particle size) of the roasting products were also investigated.

2. Experimental section

2.1. Materials and equipment

Currently, the application of electrolysis for alumina extraction from fly ash is still a new research direction, so such experiments are in the basic research stage. Therefore, fly ash was not used as the raw material in the
experiments described in this article; instead, the main reagent used in the experiments was pure AlCl$_3$·6H$_2$O (Sinopharm Group Co. Ltd, Shanghai, China; analytical grade, used as received without further processing). The main equipment used for the experiments were a plexiglass electrolyzer (Dongling Plexiglass Factory, Shenyang, China), and a DC power supply (eTM-L305SPL, Dong guan Tong men Electronic Technology Co. Ltd, China), etc. The main testing instrumentation were an x-ray diffractometer (Bruker D8, Bruker Corp., Billerica, MA, USA), a simultaneous thermal analyzer (STA449F3, NETZSCH company, Germany), a scanning electron microscope (SU-8010, Hitachi High-Technologies Corp., Tokyo, Japan), and a laser particle size tester (Dandong Baxter Instrument Co., Ltd, Liaoning, China) etc.

2.2. Experimental process

The specific experimental conditions for the electrotransformation process are as follows: current intensity = 2A; electrotransformation time = 3 h; electrode spacing = 2 cm; AlCl$_3$ solution concentration in the anodic chamber and cathodic chamber = 100 and 0 g l$^{-1}$, respectively; NH$_4$Cl solution concentration in the anodic chamber and cathodic chamber = 0 and 60 g l$^{-1}$, respectively.

The main steps in this experimental process included weighing reagents, preparing solutions, electrolysis, filtering products, drying, and roasting, among other operations. The specific procedure was as follows: first, the cation exchange membrane (CJMC-3, Hefei Ke jia Polymer Material Technology Co., Ltd, China) was installed, and the power was switched on and the current value set to 2A (according to the experimental scheme for conducting electrotransformation experiments). Simultaneously, the solution pH in the cathodic chamber was recorded (and monitored during the experiment). After the experiment was completed, the power was turned off, and the solution in the cathodic chamber was poured out for filtration. Next, the products that precipitated after filtration were isolated and dried, and the dried products were analyzed and roasted to ultimately obtain the desired alumina products. The schematic diagram illustrating the electrotransformation using AlCl$_3$ solution is shown in figure 2.

2.3. Determining the pH value of the Al(OH)$_3$ solution at the beginning and after completing precipitation

Al(OH)$_3$ is an insoluble electrolyte, and its dissolution and formation are reversible. When the dissolution rate and formation rate of Al(OH)$_3$ are equal, the concentration of each ion in solution does not change, and the precipitation dissolution equilibrium between solid Al(OH)$_3$ and hydrated ions in the solution is established. The specific equilibrium is shown in equation (1):

$$\text{Al(OH)}_3 \rightleftharpoons \text{Al}^{3+} (\text{aq}) + 3\text{OH}^- (\text{aq})$$

The solubility product ($K_{sp}$) expression for Al(OH)$_3$ is shown in equation (2),

$$K_{sp}(\text{Al(OH)}_3) = [C(\text{Al}^{3+})][C(\text{OH}^-)]^3$$

where $C(\text{Al}^{3+})$ is the concentration of Al$^{3+}$, $C(\text{OH}^-)$ is the concentration of OH$, C$ is the standard concentration (generally defined as 1 mol L$^{-1}$, and is used to cancel the units of the $K_{sp}$ calculation), and $K_{sp}(\text{Al(OH)}_3)$ is the solubility product constant of Al(OH)$_3$. 

![Figure 2. Schematic diagram of electrotransformation using AlCl$_3$ solution.](image-url)
The formula for calculating the solution pH is presented in equation (3):

$$\text{pH} = -\log\left(\frac{[\text{H}^+]}{[\text{H}^+]}\right)$$

According to literature reports, the $K_{sp}$ of amorphous Al(OH)$_3$ at room temperature, is $1.3 \times 10^{-33}$. Based on calculations, when the mass concentration of AlCl$_3$ solution is 100 g l$^{-1}$ (equivalent to a molar concentration of 0.75 mol l$^{-1}$), the solution pH when Al$^{3+}$ begins to precipitate is 3.08. When the Al$^{3+}$ is completely precipitated (i.e., when the Al$^{3+}$ concentration is lower than $1 \times 10^{-5}$ mol l$^{-1}$), the solution pH value is 4.7.

3. Results and discussion

3.1. Direct electrotransformation of the AlCl$_3$ solution

The actual solution pH value during direct electrotransformation was compared with the theoretical pH value of Al(OH)$_3$ precipitation. The TG–DSC analysis of direct electrotransformation products, and the DSC curve fitting of the absorption and exothermic peaks were investigated. Additionally, the effects of roasting temperature on the phase, morphology, D(50), and D(90) of the roasting products were studied.

Figure 3 shows the actual solution pH value during direct electrotransformation and the theoretical pH of Al(OH)$_3$ precipitation. As the direct electrotransformation proceeded, the actual solution pH value increased gradually as H$^+$ ions in the cathodic chamber were continuously reduced to H$_2$. Simultaneously, Al(OH)$_3$ precipitation was observed. In the anodic chamber, Cl$^-$ ions were continuously oxidized to Cl$_2$. After approx. 150 min, the actual solution pH value exceeded 3.08, where Al$^{3+}$ began to precipitate; however, in reality, Al(OH)$_3$ precipitation began before that time. This was mainly because the actual local solution pH value near the electrode had reached the theoretical pH value of Al(OH)$_3$ precipitation before 150 min. When the electrotransformation experiment finished, the actual solution pH value was 3.13, which was lower than the theoretical solution pH value(4.7) when Al(OH)$_3$ was completely precipitated.

Figure 4 presents the differential thermogravimetric analysis(TG–DSC) of electrotransformation products obtained via direct electrotransformation of an AlCl$_3$ solution. The weightlessness temperature of the first stage was between 100 $^\circ$C–350 $^\circ$C. Within this temperature range, the physical adsorption water occurred and some of the structural water for the direct electrotransformation products was removed. The discharge of structural water was an endothermic reaction, so a more intense endothermic peak appeared in this region. The weightlessness temperature of the second stage was between 350 $^\circ$C–800 $^\circ$C. Within this temperature range, a series of crystalline transformations took place, resulting in small endothermic peaks. The weightlessness temperature of the third stage was between 800 $^\circ$C–860 $^\circ$C. Within this temperature range, the alumina underwent a crystal line transformation, thus generating an exothermic peak. As the temperature gradually increased from 1000 to 1200 $^\circ$C, there was no detectable weight loss phenomenon (i.e., exothermic peak), indicating that alumina had good thermal stability in this temperature range.
Figures 5(a) and (b) respectively show the DSC analysis and curve fitting of endothermic and exothermic peaks, revealing large fluctuations in the DSC curves of the direct electrotransformation products. Based on the fitting data shown in figure 5(a), a linear fit (slope = −0.15139; intercept = 0.73537) could be obtained. This enabled calculation of the reaction order \( n_1 = 0.74 \) and the activation energy \( E_1 = 2.90 \text{kJ mol}^{-1} \) of the endothermic reaction. According to the fitting data shown in figure 5(b), a linear fit (slope = −1.0033; intercept = 0.0744) was obtained, and the reaction order \( n_2 = 0.07 \) and activation energy \( E_2 = 19.21 \text{kJ mol}^{-1} \) of the exothermic reaction were calculated. In this linear fitting process, the degree of fitting was not fully clear because of some data distortion, which led to some potential calculation errors.

Figure 6 presents the phases of roasting products generated by roasting the direct electrotransformation products at different temperatures. As the roasting temperature increased, the diffraction peak strength of the roasting products also increased. When the roasting temperature was 500 °C, the roasting products were all amorphous. In contrast, when the roasting temperature was between 700 °C–900 °C, the roasting products were ‘steamed bread’ alumina with a cubic crystal system and a P space group. Then, when the roasting temperature was between 1100 °C–1300 °C, the roasting products were alumina with a rhombohedral crystal system and an R-3c space group. Therefore, it was concluded that the roasting temperature had a significant impact on the crystallization state of roasting products; the higher the roasting temperature, the better the crystallization state.

Figure 7 shows the scanning electron microscopy (SEM) images (i.e., the morphology) of roasting products obtained after roasting the direct electrotransformation products at different temperatures. When the roasting temperature was 1300 °C, the roasting products all adopted honeycomb-like appearances, and as the roasting temperatures decreased, their appearance became denser. When the roasting temperature was 300 °C, all of the
roasting products appeared flakey. These results indicated that the roasting temperature could influence the morphology of roasting products.

Figure 8 shows the D(50) and D(90) of roasting products prepared by roasting direct electrotransformation products at various temperatures. The D(50) and D(90) of the roasting products obtained in these experimental conditions were between 14–17 and 39–47 μm, respectively, and importantly, both were within one order magnitude. This result indicated that the roasting temperature did not have an appreciable effect on the D(50) or D(90) of the roasting products obtained in this study.

3.2. Electrotransformation of the AlCl₃ solution catalyzed by NH₄Cl

The actual solution pH during the electrotransformation of the AlCl₃ solution catalyzed by NH₄Cl was compared with the theoretical pH value of Al(OH)₃ precipitation. Additionally, the TG–DSC analysis of the electrotransformation products obtained following the electrotransformation of the AlCl₃ solution catalyzed by NH₄Cl was performed, and the DSC curve fitting of the absorption and exothermic peaks for these products were investigated. Simultaneously, the effects of the roasting temperature on the phase, morphology, D(50), and D(90) of the roasting products were also studied.
Figure 9 shows the actual solution pH values during the electrotransformation of the AlCl₃ solution catalyzed by NH₄Cl and the theoretical pH of Al(OH)₃ precipitation. Within a short time (approx. 5 min), the actual solution pH value reached the theoretical pH (4.7) where Al(OH)₃ was completely precipitated. The solution pH value increased as the electrotransformation process proceeded over time, and the local solution pH reached 9.5 by the end of the experiment. This was mainly due to the continuous oxidation of Cl⁻ to Cl₂ in the anodic chamber. Accordingly, the H⁺ in the cathodic chamber was continuously reduced to H₂. To achieve a charge balance of cations and anions in the electrolyte, Al³⁺ ions in the anodic chamber were constantly transferred to the cathodic chamber during the electrotransformation process. When the actual solution pH reached the Al³⁺ precipitate range, Al³⁺ ions combined with OH⁻ ions to form an Al(OH)₃ precipitate in the cathodic chamber. This occurred simultaneously with NH₃ formation, leading to the high pH value observed in the cathodic chamber.

Figure 10 presents the TG–DSC analysis of the electrotransformation products obtained using NH₄Cl catalytic conditions. The weightlessness temperature of the first stage was between 100 °C–250 °C. Within this temperature range, the physical adsorption of water occurred and some of the structural water for the
electrotransformation products prepared via NH₄Cl catalysis was removed. The discharge of structural water was associated with an endothermic reaction, so a more intense endothermic peak appeared in this region. The weightlessness temperature of the second stage was between 250 °C–500 °C. Within this temperature range, nitrogen-containing substances were removed, and this nitrogen removal reaction was also an endothermic reaction, thus, a very intense endothermic peak was observed. As the temperature gradually increased from 500 to 1000 °C, there was no clear weight loss phenomenon (i.e., neither endothermic nor exothermic peaks appeared), indicating that alumina had good thermal stability in this temperature range.

Figures 11 (a) and (b) respectively show the DSC analysis and curve fitting of the two endothermic peaks, which showed large fluctuations in the case of electrotransformation products prepared under NH₄Cl catalytic conditions. According to the fitting data shown in figure 11(a), a linear fit (slope = −0.11115; intercept = 0.42512) was obtained. The reaction order (n1 = 0.43) and the activation energy (E1 = 2.13 kJ mol⁻¹) of the corresponding endothermic reaction were calculated. Based on the fitting data shown in figure 11(b), a linear fit (slope = −0.27766; intercept = 0.4697) was obtained. The reaction order (n2 = 0.4697) and the activation energy (E2 = 5.316 kJ mol⁻¹) of this endothermic reaction were also calculated. As expected, the activation energy was lower in these cases than in experiments without the NH₄Cl catalyst, thus confirming that the NH₄Cl catalyst reduced the activation energy of each reaction in the roasting process of electrotransformation.

Figure 12 shows the phases of the products obtained via electrotransformation catalyzed by NH₄Cl and roasting at different roasting temperatures. As the roasting temperature increased, the diffraction peak intensity of the roasting products increased. At roasting temperatures of 500, 700, and 900 °C, the roasting products were all ‘steamed bread’ alumina with a cubic crystal system, an Fd–3m space group, and 227 space group numbers. When the roasting temperature was 1100 °C–1300 °C, the roasting products were alumina with a rhomboid
crystal system, an R–3c space group, and 167 space group numbers, and the number of diffraction peaks increased substantially. Therefore, the roasting temperature had a significant impact on the crystallization state of the roasting products, such that the crystallization state was better when the roasting temperature was higher than 1100 °C.

Figure 13 shows the morphology (SEM images) of the roasting products following electrotransformation catalyzed by NH₄Cl and roasting at various temperatures. Han Xiuxiu et al (2019a; 2019b) found that additives (e.g., HCl, Na₂CO₃, NaHCO₃), the current intensity, the electrotransformation duration, and the initial electrotransformation temperature, among other parameters, all had no clear effect on the morphology of roasting products, and all products adopted an irregular sheet structure. However, from figure 13, it is clear that in this study, both NH₄Cl and the roasting temperature influenced the morphology of the roasting products. When the roasting temperature was 1300 °C, the roasting products had regular, angular, and smooth block structural morphologies. When the roasting temperature was less than 1300 °C, the apparent morphology of the roasting products were all massive structures with rough surfaces, and the microstructure did not change significantly with the roasting temperature decreased further. Therefore, when the roasting temperature was higher than 1300 °C, the morphology of the roasting products could effectively be controlled.
Figure 14 displays the D(50) and D(90) values of the roasting products obtained following electrotransformation catalyzed by NH₄Cl and roasting at various temperatures. Han Xiuxiu et al determined that the particle size of the roasting products did not change significantly in the presence of certain additives (e.g., HCl, Na₂CO₃, NaHCO₃), and they were all small. However, from figure 14, it is clear that D(50) and D(90) of the roasting products obtained in this study under the described conditions were all larger, with values ranging from 101–227.1 μm and 371.5–519.6 μm, respectively. Additionally, the D(50) and D(90) of the roasting products first increased and then decreased as the roasting temperature increased. When the roasting temperature was 900 °C, the D(50) and D(90) of the roasting products both reached their maxima (227.1 and 519.6 μm, respectively). These results indicated that it was possible to effectively control the D(50) and D(90) of the roasting products prepared under the applied conditions by controlling the roasting temperature.

4. Conclusions

The study presented in this paper led to the following key results:

(1) The solution reached the theoretical pH value (4.7) associated with complete Al(OH)₃ precipitation in a short time when using a NH₄Cl catalyst.

(2) For the non-catalyzed reaction, between 100 °C–350 °C, the physical adsorption of water occurred, and some of the structural water of the direct electrotransformation products were removed in an endothermic reaction with a reaction order of n₁ = 0.74 and an activation energy of E₁ = 2.90 J mol⁻¹. At temperatures between 800 °C–860 °C, crystal transformation of alumina occurred in an exothermic reaction with a reaction order of n₂ = 0.07 and an activation energy of E₂ = 19.21 kJ mol⁻¹. The law of fitting was not entirely clear because of some data distortion.

(3) Between 100 °C–250 °C, the physical adsorption of water occurred, and some of the structural water of the electrotransformation products obtained via NH₄Cl catalysis were removed in an endothermic reaction with a reaction order of n₁ = 0.43 and an activation energy of E₁ = 2.13 J mol⁻¹. At temperatures between 250 °C–500 °C, the nitrogen-containing substances were removed in another endothermic reaction with a reaction order of n₂ = 0.4697 and an activation energy of E₂ = 5.316 J mol⁻¹. These results confirmed that the NH₄Cl catalyst reduced the activation energy of each reaction in the electrotransformation products’ roasting process.

(4) The D(50) and D(90) of the roasting products obtained using the catalyst were nearly ten times higher than those generated without NH₄Cl, reaching 227.1 and 519.6 μm, respectively.

(5) Increasing the roasting temperature helped improve the crystal form of the roasting products, and the reduced products appeared relatively compact after roasting the direct electrotransformation products; however, the roasting temperature had no appreciable effect on the D(50) and D(90) of the roasting products.
Acknowledgments

We acknowledge the National Natural Science Foundation of China (Nos. U1710257, 51874078, U1508217); the State Key Laboratory of Pressure Hydrometallurgical Technology of Associated Nonferrous Metal Resources (YY2016060); the Fundamental Research Funds for the Central Universities (N182505038); and the Shenyang Science and Technology Project (17–500–8–01, Z18-5-022).

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

ORCID iDs

Ting-an Zhang  https://orcid.org/0000-0002-9778-5259

References

[1] Dong Y C, Hampshire S, Zhou J E, Ji Z L, Wang J D and Meng G Y 2011 Sintering and characterization of flyash-based mullite with MgO addition J. Eur. Ceram. Soc. 31 667–95
[2] Sun L Y, Luo K, Fan J R and Lu H L 2017 Experimental study of extracting alumina from coal fly ash using fluidized beds at high temperature Fuel 199 22–7
[3] Yao Z T, Ji X S, Sarker P K, Tang J H, Ge L Q, Xia M S and Xi Y Q 2015 A comprehensive review on the applications of coal Fly Ash Earth-Sci. Rev. 141 105–21
[4] Guo Y X, Li Y Y, Cheng F Q, Wang M and Wang X M 2013 Role of additives in improved thermal activation of coal fly ash for alumina extraction Fuel Process. Technol. 110 114–21
[5] Yao Z T, Xia M S, Sarker P K and Chen T 2014 A review of the alumina recovery from coal fly ash, with a focus in China Fuel 120 74–85
[6] Guo Y X, Zhao Z S, Zhao Q and Cheng F Q 2017 Novel process of alumina extraction from coal fly ash by pre-desilicating-Na2CO3 activation-Acid leaching technique Hydrometallurgy 169 418–25
[7] Meng F Q, Liu W Z, Chu G R, Yue H R, Liang B, Wang L M and Li C 2019 Phase Diagrams of (NH4)2SO4–Al2(SO4)3–H2O ternary system: effect of sulfuric acid and its application in recovery of aluminum from coal Fly Ash J. Chem. Eng. Data 64 557–66
[8] Ahmed S, Saurikia A, Haleem A and Gangopadhyay S 2016 Geographical spread of fly ash generation and residual potential for its utilization in India Int. J. Innov. Res. Dev. 4 8–19 (www.researchgate.net/publication/312198237_GEOGRAPHICAL_SPREAD_OF_FLY_ASH_GENERATION_AND_RESIDUAL_POTENTIAL_FOR_ITS_UTILIZATION_IN_INDIA)
[9] Surabhi S 2017 Fly ash in India: generation vis-a-vis utilization and global perspective Int. J. Appl. Chem. 13 29–32 (www.researchgate.net/publication/337562728_Fly_ash_in_India_Generation_vis-a-vis_Utilization_and_Global_perspective)
[10] Tomiolo N and Boccaccini A R 2017 Fly ash-based geopolymers containing added silicate waste a review Ceram. Int. 43 14545–51
[11] Shenm A, Mpana R N, Ndlovu S, van Dyk L D, Shibanda V and Scepe L 2012 Alternative techniques for extracting alumina from coal fly ash Miner. Eng. 34 30–7
[12] Tian Q Z, Guo B L, Nakama S and Sasaki K 2018 Distributions and leaching behaviors of toxic elements in Fly Ash ACS Omega 3 13055–64
[13] Mukherjee A B, Zevenhoven R, Bhattacharya P, Sajwan K S and Kikuchi R 2008 Mercury flow via coal and coal utilization by-products: a global perspective Resour. Conserv. Recycl. 52 571–91
[14] Zhang Z J 2007 Research on extraction of alumina and other useful resources from high aluminum fly ash doctoral dissertation of Northwestern University China (kns.cnki.net/kcms/detail/detail.aspx?dbcode=CJFD&dbname=CJFD2000&filename=2007129549.nhbkw=0016c4af7d4fLmt4X7TF9Wkld%25mdz3fQpck95Um4DKKU96FPQ4YIoOvdQYMKXneYuQyQ)
[15] Guo C B, Zou J J, Jiang Y S, Huang T P, Cheng Y and Wei C D 2014 Thermal activation of coal fly ash by sodium hydrogen sulfate for alumina extraction Chin. J. Aeronaut. 49 4315–22
[16] Ma Z B, Zhang X L, Guo Y X and Cheng F Q 2020 Extraction of valuable metals and preparation of mesoporous materials from circulating fluidized bed–Derived Fly Ash via an Acid–alkali–Based alternate method ACS Omega 5 31295–305
[17] Ahmaruzzaman M 2010 A review on the utilization of fly ash Prog. Energ. Combust 36 327–63
[18] Wu Y S, Xu P, Chen J, Li L S and Li M C 2014 Effect of temperature on phase and alumina extraction efficiency of the product from sintering coal fly ash with ammonium sulfate Chin J. Chem. Eng. 22 1563–7
[19] Matjie R H, Bunt J R and van Heerden J H P 2005 Extraction of alumina from coal fly ash generated from a selected low rank bituminous south african coal Miner. Eng. 18 299–310
[20] Ji H M, Lu H X, Hao X G and Wu P 2007 High purity alumina powders extracted from fly ash by the calcining-leaching process J. Clin. Ceram. Soc. 36 1565–70
[21] Cobo M, Gallar Z A, Conesa J A and Correa C M D 2009 Characterization of fly ash from a hazardous waste incinerator in Medellin Colombia, J. Hazard. Mater. 168 1223–32
[22] Yang J L, Lin Y, Sun J H and Peng T J 2017 Research progress on alumina extraction technology from fly ash B. Chin Ceram. Soc. 36 485–90
[23] Jiang J and Zhao Y C 2008 Current research situation of Al extraction from fly ash Nonferrous Met. Eng. Res. 24 40–3
[24] Wu Y, Zhai Y C, Yi Z and Ji F 2009 Research on mechanical grinding activation of alumina extraction process by acid method from fly ash Min. Metall. Eng. 29 71–3
[25] Li L S, Wu Y S, Liu Y Y and Zhai Y C 2011 Extraction of alumina from coal fly ash with sulphuric acid leaching method Chin J. Process Eng. 11 234–8
[26] Wu C Y, Yu H F and Zhang H F 2012 Extraction of alumina by pressure acid leaching method from coal fly ash T Nonfer. Metal. Soc. 22 2282–322
[27] Yakaboylu G A, Baker D, Wayda B, Sabolsky K, Zondlo J W, Shekhawat D, Wildfire C and Sabolsky E M 2019 Microwave-Assisted Pretreatment of Coal Fly Ash for Enrichment and Enhanced Extraction of Rare-Earth Elements Energy & Fuels 33 12083–95
[28] Han X X, Zhang T A, Lv G Z, Pan X J and Fu D X 2019a Investigation of alumina preparation from aluminum chloride aqueous solution by electrical transformation Hydrometallurgy 185 30–7
[29] Han X X, Zhang T A, Lv G Z, Pan X J and Fu D X 2019b Effects of additives on alumina preparation from aluminum chloride solution by electrolytic transformation JOM 71 1574–80
[30] Rattanasak U and Chindaprasirt P 2009 Influence of NaOH solution on the synthesis of fly ash geopolymers Miner. Eng. 22 1073–8
[31] Wang T F, Zhang J S, Li X, Li Y X and Xue Z M 2019 Research progress on alumina extraction by alkali method from high-alumina fly ash Multipurpose Util. Miner. Resour 315 16–21
[32] Ding J, Ma S H, Zheng S L, Zhang Y, Xie Z L, Shen S and Liu Z K 2016 Study of extracting alumina from high-alumina PC fly ash by a hydro-chemical process Hydrometallurgy 161 58–64
[33] Wang L, Zhang T A, Lv G Z, Dou Z H, Zhang W G, Zhang J Z, Niu L P and Liu Y 2019 Carbochlorination of alumina and silica from high-alumina fly ash Miner. Eng. 130 85–91