Analysis of the Main Technologies for the Utilization of High-Alumina Coal Fly Ash

Wei Cui[1], Yang Ni[2] and Lixuan Gu[3]
1, 2, 3. Senior Engineer
Guiyang Aluminium and Magnesium Design & Research Institute (GAMI), Guiyang, China
Corresponding author: yang_ni@chinalco.com.cn
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Abstract

The resource utilization of high-alumina coal fly ash has long been a focus of research. China's *Guiding Opinions on the Comprehensive Utilization of Bulk Solid Waste During the 14th Five-Year Plan Period* emphasizes that for bulk industrial solid wastes like coal fly ash, the fundamental principle is to combine large-scale and high-value utilization. The extraction and utilization of aluminium resources therefore represents an essential pathway to achieve its high-value application. Among China's technological routes for alumina resource recovery from high-alumina fly ash, the methods that have undergone pilot-scale or industrial production mainly include the one-step acid-leaching method, pre-desilication-soda-lime sintering process, and limestone sintering process. This paper summarizes these three technologies, analysing their technical characteristics, feasibility, advantages, and disadvantages. Meanwhile, based on the same fly ash composition, the consumption and production costs of these processes are calculated through equilibrium analysis and actual production data, followed by a comparative analysis. Additionally, the production costs of these processes are compared with those of the Bayer process using imported and domestic bauxite ores, respectively. The analysis determines the price range of bauxite at which the Bayer process becomes more cost-effective and, conversely, the conditions under which producing alumina from high-alumina fly ash proves economically advantageous.

Keywords: High-alumina coal fly ash, Bauxite, Alumina, Process comparison, Economic analysis.

1. Context and Present Situation

China is the world's largest producer and consumer of aluminium, yet it suffers from relatively scarce bauxite resources, predominantly consisting of low-grade diasporic and high-sulphur bauxite with high production costs [1]. Currently, China relies heavily on bauxite imports, being the world's top importer. In 2023, China imported 140 million tonnes of bauxite, a 12.7 % year-on-year increase; in 2024, imports reached 159 million tonnes, up 12.3 % year-on-year, with external dependence continuing to rise [2]. Excessive reliance on imports increases risks for the aluminium industry and threatens its development. For instance, from 2024 to 2025, due to policy changes in Guinea regarding bauxite mining and exports, imported bauxite prices surged, driving up alumina prices and severely impacting downstream industries such as electrolytic aluminium and aluminium alloys in China.

Fly ash typically refers to the fine particulates and residue generated by coal-fired power plants, as well as resource utilization power plants processing coal gangue and coal slurry. Generally, burning 1 tonne of coal produces 0.20–0.30 tonnes of fly ash [3, 4]. Currently, China's fly ash output accounts for approximately 50 % of the world's total production and continues to rise, with accumulated storage exceeding 3 billion tonnes. As the largest-volume industrial solid waste in China, its disposal has long been a major concern [5, 6]. Consequently, achieving high-valueadded recycling of fly ash to enable a green circular economy has become a prominent research focus in academia.

International research on the comprehensive utilization of fly ash began relatively early. Poland has conducted extensive exploration in fly ash utilization, with the Mineral and Energy Economy Research Institute of the Polish Academy of Sciences developing a sintering technology for mixed fly ash and bauxite residue to extract alumina, achieving an extraction rate of 75–80 %. The United States has carried out multiple technological developments for extracting aluminium, gallium, and rare earth elements from fly ash, though its fly ash utilization focuses more on the construction materials sector (e.g., as concrete admixtures), with relatively fewer studies on valuable metal extraction. Germany places greater emphasis on the application of fly ash in construction materials, ceramics, and other fields, with limited research on metal extraction.

The Siberian Branch of the Russian Academy of Sciences has developed a soda fusion-hydrothermal treatment process for high-alumina coal fly ash, achieving an aluminium recovery rate of over 80 %, though the process flow is relatively lengthy.

Although China started research on fly ash comprehensive utilization later than the aforementioned countries, it has achieved global leadership in the field of extracting alumina from high-alumina fly ash. This is primarily because other countries lack high-alumina coal resources comparable to those in China's Inner Mongolia and Shanxi regions, resulting in generally lower alumina content in the fly ash and insufficient economic feasibility. In recent years, China has established a number of representative demonstration projects for alumina extraction from high-alumina fly ash, providing valuable industrial experience for further technological promotion. For example, Mengxi Group's "0.4 Mtpa alumina project", as China's first industrial-scale production line for alumina extraction from fly ash, has developed a set of industrial production technologies, including material proportioning, calcination, and clinker self-pulverization. Datang International's "0.24 Mtpa high-alumina fly ash to alumina multi-product project" introduced a pre-desilication process, further improving the A/S ratio of high-alumina fly ash and reducing residue volume. Shenhua Zhungeer's "0.3 Mtpa high-alumina fly ash comprehensive utilization project" has completed preliminary design work, with the government also allocating corresponding electrolytic aluminium production quotas in support.

The resource utilization of fly ash is a global challenge. China's *Guiding Opinions on the Comprehensive Utilization of Bulk Solid Waste During the 14th Five-Year Plan Period* emphasizes that for bulk industrial solid wastes like fly ash, the fundamental principle is to combine large-scale utilization with high-value utilization. The extraction and utilization of aluminium resources therefrom represents an essential pathway to achieve its high-value application [7]. After nearly two decades of scientific research, China has developed multiple technological routes for recovering alumina resources from fly ash, including the one-step acid leaching process for alumina production, the pre-desilication--soda-lime sintering process for alumina production, and the limestone sintering process for alumina production [2].

This paper summarizes the above-mentioned technologies, analysing their technical characteristics, feasibility, advantages, and disadvantages. Meanwhile, based on the same fly ash composition, the production costs of these processes are calculated through equilibrium analysis and actual production data, followed by a comparative analysis. Additionally, the production costs of these processes are compared with those of the Bayer process using imported and domestic bauxite ores, respectively. The analysis determines the price range of bauxite at which the Bayer process becomes more cost-effective and, conversely, the conditions under which producing alumina from high-alumina fly ash proves economically advantageous.

the relationship between the price of domestic diaspore and production cost is Y=2.46X+1074. This indicates that the production cost of alumina by the Bayer process is significantly influenced by bauxite prices.

Based on the above analysis, when bauxite prices are high, the use of high-alumina fly ash to produce alumina has certain advantages in terms of production costs. However, attention should be paid to its high construction investment, carbon emissions caused by high energy consumption, new and greater environmental problems caused by a large amount of residue, and market problems caused by a large amount of by-products.

6. Conclusion

The following conclusions have been derived from this study.

(1) All three processes and equipment for producing alumina from high-alumina fly ash have undergone pilot-scale or industrial verification, with their technologies being certified, and are technically feasible with low risks. Under identical boundary conditions, the limestone sintering process has the highest production cost, followed by the pre-desilication soda-lime sintering process, while the one-step acid leaching process has the lowest production cost.

(2) The main issues and challenges of the pre-desilication- soda-lime-sintering process and the limestone sintering process lie in the large volume of calcium silicate residue, significant environmental pressure, and high energy consumption, which are the primary factors restricting their further industrialization. The key problems and challenges of the one-step acid leaching process include the highly corrosive acidic environment, high capex, elevated impurity removal expenses, short equipment lifespan, high maintenance costs, and operational difficulties. These also constitute major obstacles to the industrialization of this process.

(3) Currently, the balance point in production costs between the Bayer process using bauxite and alumina production from high-alumina fly ash primarily lies in the bauxite cost, which is approximately 620–670 RMB/t (dry bauxite, approx. 87–94 USD/t). When the bauxite price falls below this price range, the Bayer process holds an economic advantage; conversely, alumina production from high-alumina fly ash becomes more cost-effective. Additionally, attention must be paid to the high capital investment and energy consumption (leading to carbon emissions) in the high-alumina fly ash, the large volume of residue posing greater environmental challenges, and the marketability issues arising from the substantial by-products.

(4) For the pre-desilication soda-lime sintering process and the limestone sintering process, further optimization is required to address existing challenges. Pretreating high-alumina fly ash to reduce its silica content and increase the A/S ratio represents a key research focus and trend, as well as an effective pathway toward industrialization. Regarding the one-step acid leaching process, process optimization, simplification of impurity removal steps, and exploration of more cost-effective acid-resistant materials are essential measures to accelerate its industrial application.

7. References

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