Current Status of Carbon Emissions in the Aluminium Electrolysis Industry and Analysis of Carbon Reduction Pathways

Jiao Qingguo[1], Wang Huaijiang[2], Zhang Yanan[3], Li Changlin[4] and Bao Shengzhong[5]
1,4. Second Level Researchers - Professor Level Senior Engineers
2.Vice General Manager - Professor Level Senior Engineer
3.Director - Professor Level Senior Engineer
5.Vice Director - Professor Level Senior Engineer
Zhengzhou Non-ferrous Metals Research Institute of Chalco (ZRI), Zhengzhou, China
Corresponding author: *qg_jiao@chinalco.com.cn*
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Abstract

Aluminium electrolysis is a highly energy-intensive and high-emission industry, generating substantial amounts of CO_2 greenhouse gases directly or indirectly during production, making it a key focus for global carbon emissions monitoring. In response to national carbon reduction requirements and targets for the aluminium industry, this paper analyses the mechanisms of greenhouse gas emissions in aluminium electrolysis, presents the current status of carbon emissions in the industry, and examines the technologies, approaches and potentials of greenhouse gas emission reduction from three key perspectives: power decarbonization, direct emission reduction, and PFC emission reduction, providing a reference for the aluminium industry to advance greenhouse gas emission reduction.

Keywords: Aluminium electrolysis, Carbon emission, Greenhouse gases, PFC, Anode effect.

1. Introduction

According to the Global Carbon Budget 2023 report released by the International Energy Agency (IEA) in March 2024, global energy-related carbon dioxide (CO_2) emissions increased by 410 million tonnes in 2023, rising by 1.1 % compared to 2022 and reaching a record high of 37.4 billion tonnes. China accounted for the largest share of global CO_2 emissions at 12.6 billion tonnes, representing approximately 34 % of the world's total [1]. As the world's leading producer in the aluminium industry, China's primary aluminium output reached 43.396 million tonnes in 2024, accounting for about 59.4 % of global output, according to International Aluminium Institute statistics. Estimates indicate that the total CO_2 emissions amounted to approximately 426 million tonnes, contributing roughly 5 % to the nation's net CO_2 emissions.

The aluminium electrolysis industry emits significant amounts of greenhouse gases due to the use of carbon anodes during production, while the substantial consumption of thermal power resources also indirectly generates considerable greenhouse gas emissions. As a result, the electrolytic aluminium industry has become one of China's key industries for carbon emissions control. On 22 September 2020, General Secretary Xi Jinping announced at the 75th General Assembly of the United Nations China's “dual carbon” goals: one to peak emissions before 2030, and the other to achieve carbon neutrality before 2060. This marks China's first explicit global announcement of the "carbon peak" and "carbon neutrality" targets, representing the most significant climate commitment by any nation to date in mitigating global warming [2–4]. In May 2024, the State Council issued a notice on the issuance of "2024–2025 Energy Conservation and Carbon Reduction Action Plan", requiring governments at all levels and ministries to implement energy conservation and carbon reduction initiatives by sector and industry. The electrolytic aluminium industry is required to strictly implement the replacement of production capacity quota.

By the end of 2025, the proportion of production capacity above the energy efficiency benchmark level in the electrolytic aluminium industry will reach 30 %, and the proportion of renewable energy use will reach more than 25 %. Therefore, gaining a comprehensive understanding of the carbon emission mechanism and the current situation of aluminium electrolysis industry, as well as applying new technologies and exploring innovative approaches for energy conservation and emission reduction, has become a critical task for the industry.

2. Mechanism of Carbon Emission in Aluminium Electrolysis

Carbon dioxide is referred to as a greenhouse gas due to its strong absorption and thermal insulation capacity. It can effectively absorb long-wave infrared radiation emitted from the earth's surface, thereby preventing the dissipation of heat and leading to a rise in earth's surface temperature. The greenhouse effect can trigger a series of environmental issues, such as rising sea levels, abnormal climate patterns, and increased extreme weather. Consequently, controlling greenhouse gas emissions has become a globally shared priority.

The carbon dioxide emissions in the aluminium electrolysis process primarily consist of three categories:
1) Direct CO_2 emissions from carbon anode consumption;
2) PFC greenhouse gas emissions generated during anode effects in the electrolysis process, expressed as CO_2 equivalent; and
3) Indirect CO_2 emissions from electricity consumption [5].

2.1 Carbon Emission Mechanism of Anode Consumption

The cryolite-alumina molten salt electrolysis process is adopted for aluminium electrolysis production. Both the anode and cathode materials need to possess properties such as high-temperature resistance, immunity to molten salt corrosion, and high electrical conductivity, typically fulfilled by carbon materials. When direct current is applied, electrochemical reactions occur at both anode and cathode, with the process described as follows [6]:

$$2Al_2O_3 + 3C \rightarrow 4Al + 3CO_2 \quad (1)$$

The above reaction Equation (1) indicates that the carbon anode not only serves as a conductive material but also participates in the electrochemical reaction, generating carbon dioxide with oxygen. According to the calculation of the reaction Equation (1), the theoretical carbon consumption per tonne of primary aluminium produced is 333.867 kg/t Al, corresponding to CO_2 emissions of 1223.331 kg CO_2/t Al. Currently, the actual net carbon anode consumption in domestic aluminium production in well operated cells is around 400 kg C/t Al, resulting in CO_2 emissions of approximately 1467 kg CO_2/t Al, assuming no influence from other impurities.

2.2 Formation Mechanism of PFC

The primary components of PFC are tetrafluoromethane (CF_4) and hexafluoroethane (C_2F_6). The formation mechanism of PFC primarily occurs during aluminium electrolysis when the alumina (Al_2O_3) mass fraction in the electrolyte is below 1 %. At this point, the mass fraction of oxygen ions on the anode surface decreases rapidly, leading to an increase in anode overvoltage and cell voltage (typically reaching 25–35 V). This phenomenon is termed as "anode effect". The occurrence of anode effects causes carbon from the anode to react with fluoride ions in the cryolite bath, generating CF_4 and C_2F_6 through the following chemical reactions [7–8].

area between the anode and electrolyte, lowers the actual current density of anode, and decreases the frequency of anode effects or localized effects, thereby reducing perfluorocarbon (PFC) emissions during production.
2) Aluminium electrolysis intelligent crust breaking and feeding control system. This system can detect and preprocess material blockages during feeding, prevent hammerhead clogging, and ensure a crust hole opening rate of over 90 %, thereby reducing anode effect occurrence [28].
3) Anode current online monitoring technology. This technology enables real-time online monitoring of anode current in aluminium cells, effectively eliminating the data delay inherent in manual measurements. It allows prompt adjustment upon detecting current imbalance, thereby mitigating various issues caused by anode current deviation and ensuring stable and efficient aluminium cell operation [29].

4. Conclusions

By analysing the carbon reduction potential and technology path of aluminium industry, the author believes that the development and industrialization of carbon-free aluminium technology (inert anode electrolysis and aluminium chloride electrolysis) should be the important direction of carbon reduction in aluminium industry in the future, and complete replacement with non-carbon anode will avoid direct emission of carbon dioxide; Focusing on developing more energy-efficient process technologies (copper-embedded cathode steel bars, full-copper cathode bars, and alumina preheating technology) as key carbon reduction measures, to further reduce electricity consumption by 300 kWh/t Al, achieving carbon emission reductions per tonne of aluminium of over 180 kg CO_2/t Al.

The dedicated PFC emission reduction technology should be based on further optimization of the alumina feeding control system to ensure the stability and uniformity of alumina concentration in the electrolytic cells, thereby reducing the occurrence of anode effects. Simultaneously, it is essential to develop and enhance PFC process monitoring technologies and further investigate their generation mechanisms and patterns to provide improved methods and measures for comprehensive PFC emission reduction.

5. References

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