

High-Efficiency Flue Gas Collection in Aluminium Reduction Cells

Peipei Song¹, Jian Lu², Zhongwei Qin³ and Likai Zhao⁴

1. Engineer, Smelter Design

2. Engineer in Charge

Guiyang Aluminium and Magnesium Design & Research Institute (GAMI), Guiyang, China

3. Senior Engineer

4. Engineer

Guangxi Longlin Baikuang Aluminium, Baise, China

Corresponding author: 874769214@qq.com

<https://doi.org/10.71659/icsoba2025-al057>

Abstract

With increasingly stringent environmental requirements and the ongoing pursuit of energy conservation and emission reduction, the effective collection of flue gas from aluminium reduction cells has become a critical issue in the aluminium electrolysis industry. This paper conducts an in-depth study on high-efficiency flue gas collection methods for aluminium reduction cells. Through an analysis of existing collection technologies, it is found that equipment renewal plays a significant role in improving flue gas collection efficiency. During the study, the flow mechanisms of flue gas were analysed to gain a deeper understanding of its movement characteristics in the cell, serving as a foundation for optimizing the collection process and ensuring better coordination between new equipment and collection strategies. The application of new equipment not only significantly improves flue gas collection efficiency but also contributes to energy savings. Taking the optimization of a 400 kA cell as an example, after the retrofit, the flue gas suction on the cell was reduced to 3022 m³/h, only one-fifth of the original value. This significantly lowers the required exhaust fan airflow and drastically reduces flue gas heat dissipation, thereby decreasing the energy input into the cell and improving its energy efficiency. It is estimated that the cell operating voltage will drop by 100–150 mV. Furthermore, after the implementation of this system, the flue gas concentration and temperature will increase substantially, providing a foundation for the development of subsequent technologies.

Keywords: Aluminium electrolysis, Aluminium electrolysis flue gas, Flue gas flow mechanism, Energy saving and consumption reduction.

1. Introduction

Under China's "carbon peak and carbon neutrality" goals, the domestic electrolytic aluminium industry is facing significant pressure to reduce energy consumption and emissions. As a highly energy-intensive and high carbon-emitting sector, aluminium electrolysis consumes enormous amounts of electricity per tonne of aluminium produced, with carbon emissions per tonne several times higher than those of the steel industry, exerting a substantial impact on the nation's overall energy consumption and carbon footprint [1]. Currently, some aluminium electrolysis capacities in China still operate above the benchmark energy efficiency level, with numerous outdated facilities offering considerable potential for energy saving and emission reduction. From a policy perspective, the National Development and Reform Commission (NDRC) and other departments have issued special action plans, stipulating that by the end of 2025, the proportion of production capacity reaching the advanced energy efficiency benchmark must exceed 30 %, while capacity above the baseline efficiency level must undergo technological upgrades or be phased out. Additionally, the industry's renewable energy utilization ratio must reach at least 25 % [2, 3]. Meanwhile, the Ministry of Ecology and Environment (MEE) plans to include the electrolytic aluminium industry in the national carbon emissions trading market, meaning smelters failing to

improve energy efficiency and reduce emissions promptly will face substantial carbon compliance costs. With the growing global emphasis on green development, international markets are increasingly imposing stricter carbon emission standards on aluminium products. If China's electrolytic aluminium industry fails to accelerate energy saving and emission reduction, it will be at a competitive disadvantage internationally and missed development opportunities. Substantial energy-saving, emission reduction, and technological advancements are among the primary means to enhance corporate competitiveness, which are critical to the survival and development of smelters [4].

The study on the high-efficiency flue gas collection method for aluminium reduction cells proposed in this paper aims to provide practical solutions and approaches for energy saving and consumption reduction in smelters, while also offering a better platform and space for further studies on waste heat utilization of flue gas [5].

2. Analysis of the Current Status of Flue Gas Collection in Aluminium Reduction Cells

2.1 Structure of Conventional Flue Gas Collection Systems

The flue gas collection system in traditional aluminium reduction cells is a critical component for environmental protection and process control in aluminium production. It is primarily used to capture hazardous emissions, including fluorides and particulate matter generated during the electrolysis process, while ensuring workplace safety and compliance with emission regulations [6].

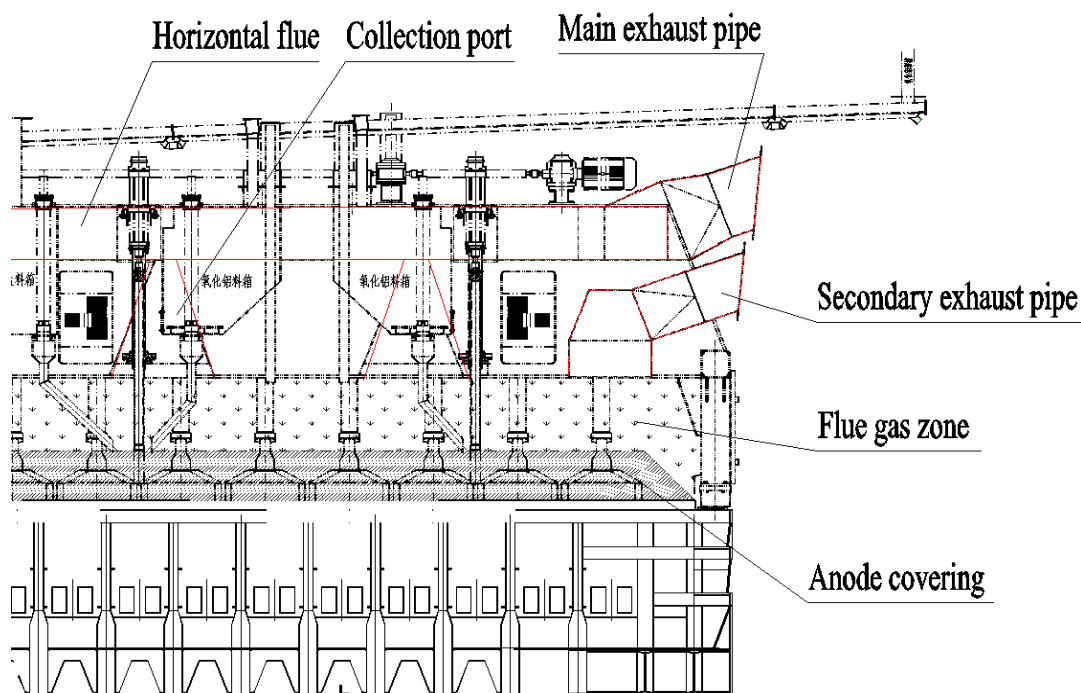


Figure 1. Partial schematic diagram of cell flue gas collection system.

Main components of the flue gas collection system in the cell and related details are as follows (Figure 1):

1) The cell sealing structure comprises the cell doors and hoods, sealing materials, and anode rod seal. The doors and hoods allow openings for tapping, feeding, and anode replacement. Sealing materials, such as asbestos rope or ceramic fibre, are used to fill gaps and edges around openings to prevent flue gas leakage. The anode rod seal employs sealing sleeves or covers around the anode rod to effectively reduce flue gas escape.

2) Flue gas collection system: The primary process involves installing a horizontal flue within or above the cell, with collection ports arranged along the flue. The flue gas is then discharged through the main exhaust pipe and eventually directed into the flue gas purification system. A butterfly valve is installed on the main exhaust pipe to regulate the negative pressure within the single cell collection system, typically maintained between 150–300 Pa. Flue gas collection systems mainly consist of two types: integrated and modular. The integrated horizontal flue covers the entire top of the cell and is commonly used in large prebaked anode cells, achieving a collection efficiency of over 90 %. The modular horizontal flue is installed in sections above the cell, facilitating anode replacement and other operations, though its sealing performance is slightly inferior. Structurally, both systems are made of high-temperature-resistant stainless or carbon steel, often lined with thermal insulation materials. They are equipped with flue gas outlets connected to the main exhaust pipe, which links to the subsequent flue gas purification system via ducts.

2.2 Shortcomings of Traditional Flue Gas Collection Systems

The traditional cell flue gas collection system exhibits several notable issues in actual production:

- 1) Since the electrolytic flue gas first diffuses under the cell superstructure roof before being extracted through the flue gas collection system, flue gas persistently exists inside the flue gas zone (see Figure 1.). During operations such as crust breaking, anode replacement and aluminium tapping, the opened gaps allow flue gas to escape into the workshop, posing certain hazards.
- 2) Due to prolonged exposure to high temperatures during production, the sealing materials of the cell superstructure inevitably undergo aging and deformation, leading to inadequate sealing performance. This not only results in flue gas fugitive emissions but also reduces internal pressure in the flue gas zone, increasing the energy consumption of the negative pressure fans and ultimately raising the overall energy costs of electrolytic production.
- 3) Theoretically, aluminium electrolysis produces approximately 4000 m³ of flue gas per tonne of aluminium, with temperatures ranging from 100–200 °C and containing alumina dust, HF acid gas, and water vapor. However, practical measurements on a 400-kA cell show that to ensure complete flue gas capture, the negative pressure generated by the negative pressure fan must reach 200 Pa at the cell outlet (main exhaust pipe), resulting in a gas discharge volume of 12 000–14 000 m³/h, tens of times higher than the theoretical exhaust volume. This indicates significant air infiltration into the flue gas zone, leading to a relatively low flue gas collection efficiency, with a significant amount of heat being carried away by the flue gas, constituting unnecessary energy loss.

3. Analysis of Flue Gas Flow Mechanism in the Cells

The flow mechanism of flue gas within the cell is a complex process involving multi-physics coupling (e.g., thermal field, flow field). Its flow characteristics directly affect the efficiency, energy consumption, and pollutant emission control in aluminium electrolysis production. The following analysis is conducted from aspects such as flue gas sources, driving forces of flow, flow characteristics, and influencing factors:

3.1 Source of Flue Gas

The flue gas emissions from the cell primarily originate from the following chemical reactions and physical processes:

- 1) Anode reaction products: When alumina (Al₂O₃) is electrolyzed in the cryolite melt, the carbon anode (C) reacts with oxygen to generate carbon dioxide (CO₂). Anode air oxidation generates CO₂. The back reaction and Boudouard reaction generate carbon monoxide (CO).
- 2) Anode effect: When the alumina concentration in the electrolyte becomes too low, the anode

effect occurs, generating potent greenhouse gases such as CF_4 and C_2F_6 .

3) Fluoride hydrolysis and volatilization: Aluminium fluoride hydrolyzes to form HF gas, while the electrolyte volatilizes at high temperatures (approximately 950 °C), producing solid fluoride particles.

4) Reactions of other impurities: Sulphur, nitrogen, and other impurities in the anode carbon blocks burn to generate sulphur dioxide (SO_2) and nitrogen oxides (NO_x).

5) Air ingress: External air mixes with the flue gas due to negative pressure in the cell, significantly increasing the total flue gas volume (which accounts for over 95 % of the actual flue gas output).

3.2 Core Driving Force of Flue Gas

The flow of flue gas inside the cell is primarily driven by the following forces:

1) Buoyancy (thermal driving force): The electrolysis process releases a significant amount of heat, raising the flue gas temperature to 900–1000 °C. Its density becomes much lower than that of the surrounding cold air, creating a natural upward buoyant flow. This is the main force driving the upward movement of the flue gas.

2) Mechanical force (negative pressure suction): The flue gas collection applies negative pressure in the flue gas zone to forcibly extract flue gas into the purification system. The magnitude of negative pressure directly affects the flue gas collection efficiency and the amount of air entrainment.

3) Chemical reaction driving force: Local gas generation (e.g., CO_2/CO production) causes minor expansion, creating small momentum that drives flue gas dispersion.

3.3 Flow Characteristics of Flue Gas

The flow of flue gas inside the cell is primarily driven by the following parameters:

1) Flow path: After being generated at the bottom of the anode, the flue gas flows upward along the interface between the anode carbon block and the electrolyte, passes through the crust breaking holes and gaps between anodes into the cavity space of the cell, and is then collected by the hood and exhaust pipes before entering the purification system via the flue.

2) Flow regime: Laminar and turbulent flow: Within the narrow anode gaps, the flue gas is predominantly laminar, but transitions to turbulent flow upon entering the hood due to increased velocity or abrupt structural changes (e.g., bends and valves), which enhances gas mixing.

3) Multiphase flow characteristics: The flue gas is a gas-solid-liquid multiphase flow containing solid particles (alumina and carbon dust), droplets (condensate), and gases. Particle distribution and sedimentation affect flow resistance and purification efficiency.

4) Temperature and density variations: The initial flue gas temperature is approximately 900–1000 °C with low density. After mixing with cold air, the temperature drops sharply (to around 100–200 °C), density increases, and volumetric flow rate rises significantly (the theoretical flue gas volume can be diluted by air by more than 100 times).

3.4 Key Factors Influencing Flue Gas Flow

During electrolysis production, the flow characteristics of flue gas are affected by multiple factors, including the cell structure, process control parameters, and material properties. Below is a detailed explanation:

1) Cell superstructure design;

– Anode arrangement: A smaller anode spacing increases the resistance to flue gas rise, potentially causing localized turbulence or leakage.

- Sealing performance of the hood: Poor sealing allows excessive air ingress, diluting flue gas concentration and reducing purification efficiency (e.g., low HF concentration may hinder effective absorption).
 - Flue duct layout: Pipe diameter, elbow angle, and flow velocity (typically controlled at 10–15 m/s to prevent particle sedimentation) affect flow resistance and energy consumption.
- 2) Operational parameters;
- Cell current and anode-to-cathode distance (ACD): Higher current generates more heat, enhancing the buoyancy-driven flow of flue gas; changes in ACD affect electrolyte flow, indirectly altering the flue gas path.
 - Negative pressure: Excessively high negative pressure draws in excessive air, increasing the load on downstream treatment systems, while insufficient negative pressure leads to fugitive emissions (e.g., flue gas escaping from cell openings).
- 3) Material properties;
- Electrolyte composition: The viscosity and surface tension of the cryolite-alumina molten electrolyte affect the generation and detachment rate of flue gas bubbles.
 - Moisture content in raw materials: Higher moisture levels lead to increased generation of HF and water vapor, which may exacerbate pipeline corrosion and condensation.

3.5 Application Example of Traditional Flue Gas Collection Systems

A 400 kA cell was used as an example. This cell type uses an integrated flue gas collection system design. Specifically, a flue gas collection port is arranged above each feeding point, and a horizontal flue duct is installed inside the cell superstructure to converge the flue gas into the main exhaust pipe, which is then connected to the purification system. After collecting field data, simulation calculations were performed. The measured negative pressure at the outlet of the cell main exhaust pipe was 200 Pa. The flue gas flow model is illustrated in Figure 2.

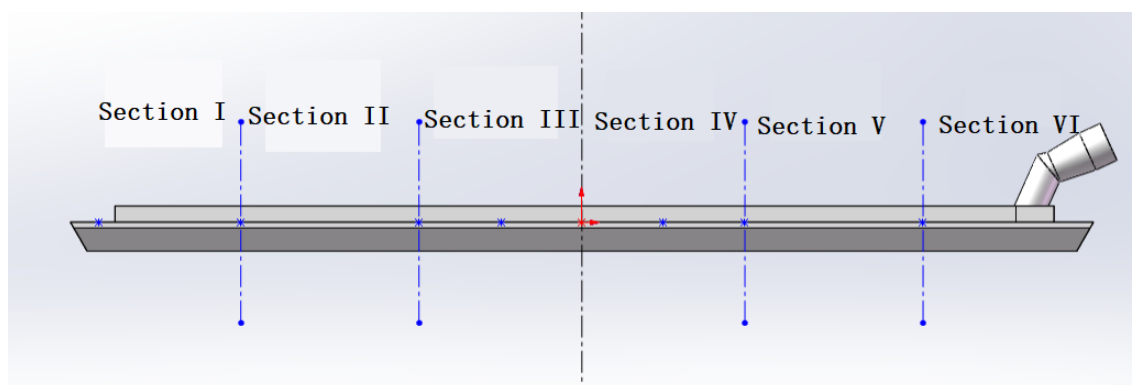


Figure 2. Flue gas model diagram of 400 kA cell's flue gas collection system.

The flue gas volumes at different sections along with the total flue gas volume are listed in Table 1.

According to the simulation results, the traditional flue gas collection system of a 400 kA cell requires a minimum air volume of 14 726 m³/h to completely extract the electrolytic flue gas. This substantial airflow results in over 90 % of the extracted gas being entrained air, indicating extremely high heat loss due to the flue gas extraction.

Table 1. Flue gas flow distribution of a 400 kA cell.

Flue inlet	Mass flow rate (kg/s)	Volumetric flow rate (m ³ /h)	Average flow rate (m ³ /h)	Deviation (%)
Section I	0.5643	2379	2454	-3.1
Section II	0.5761	2429		-1.1
Section III	0.5822	2454		0.0
Section IV	0.5743	2421		-1.4
Section V	0.6	2529		3.1
Section VI	0.5968	2516		2.5
Total flow volume	3.4933	14726		

Note: Flue inlets are numbered starting from the tapping end, with an outlet pressure of 200 Pa (negative pressure).

4. Optimization of High-Efficiency Flue Gas Collection Methods

4.1 Development of Novel Collection Equipment

Through analysing the mechanism of flue gas generation and flow in cells, it is found that collection can be performed at the source of flue gas generation. An independent flue gas collection system is designed, consisting of collection ports, horizontal flues, and a main exhaust pipe. The key distinction lies in the collection ports, which are not used to capture flue gas from the cell flue gas zone but are instead inserted directly into the anode cover, fully enclosing the feeding point. This allows the flue gas to be immediately extracted through the collection system upon generation. The structure is illustrated in Figure 3.

The main R&D challenges of this flue gas collection system are as follows:

- 1) The upper structure of the cell is relatively complex, with limited internal space, making the installation of a new flue gas collection system spatially constrained and technically demanding.
- 2) The cell body has stringent insulation requirements. Since the equipment is fully inserted into the anode covering, unresolved insulation issues could pose significant safety hazards.
- 3) The production process of the cell is highly intricate. Modifying its flue gas collection system necessitates simultaneous optimization of process control; otherwise, excessive cell temperature may occur, compromising production stability and even risking cell leakage.
- 4) It requires multi-disciplinary collaboration and extensive production data support, resulting in a relatively long project cycle.

4.2 Simulation Analysis of Novel Flue Gas Collection System

Taking a 400 kA cell as an example, the 3D model is established as shown in Figure 4. The entire flue gas collection system is equipped with six collection ports, corresponding to the six feeding points.

Since the collection ports fully cover the feeding points, the generated flue gas possesses an upward thrust of its own. Therefore, in the numerical simulation, a negative pressure of 100 Pa is applied at the exhaust outlet. The flue gas flow rates at different sections and the total flue gas volume are listed in Table 2, and the velocity distribution is shown in Figure 5.

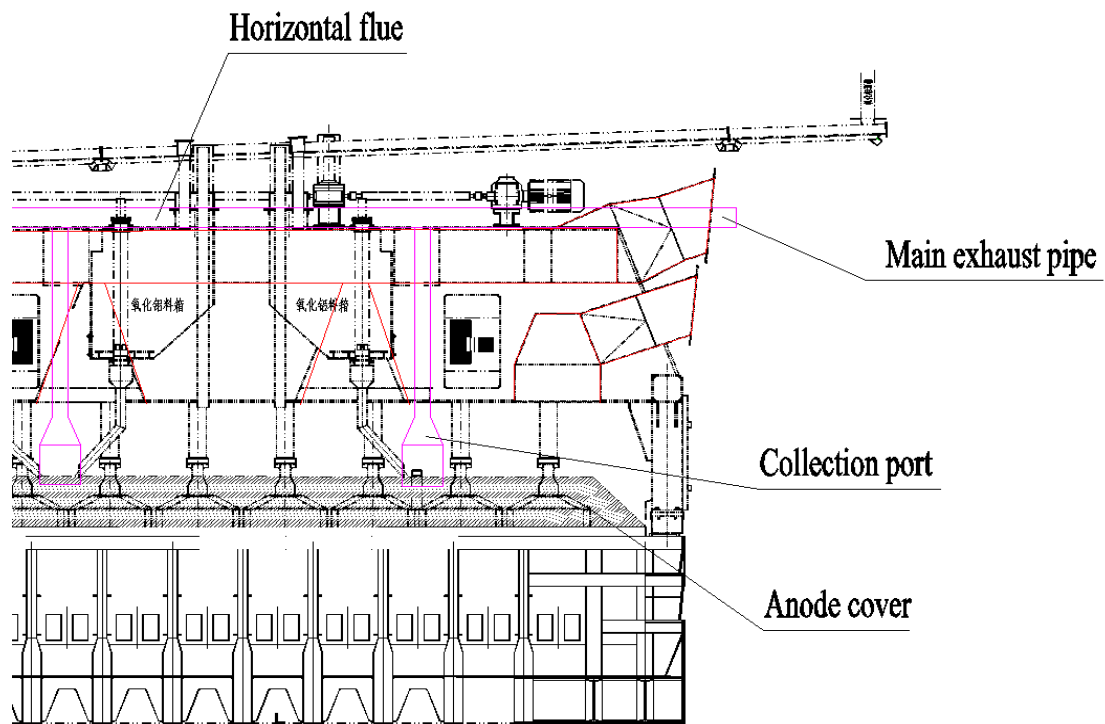


Figure 3. Schematic diagram of novel flue gas collection system.

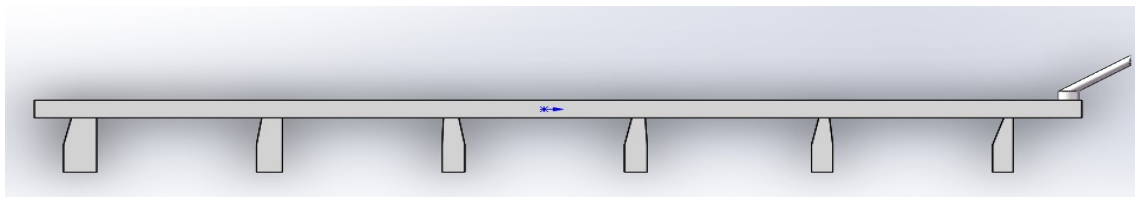


Figure 4. Flue gas flow model diagram of novel flue gas collection system.

Table 2. Flue gas volume distribution in novel flue gas collection system.

Flue inlet	Mass flow rate (kg/s)	Volumetric flow rate (m ³ /h)	Average flow rate (m ³ /h)	Deviation (%)
Section I	0.1223	516	503.75	2.3
Section II	0.1222	515		2.3
Section III	0.1177	496		-1.5
Section IV	0.1217	513		1.8
Section V	0.1173	494		-1.8
Section VI	0.1157	488		-3.2
Total flow volume	0.717	3022		

Note: Flue inlets are numbered starting from the tapping end, with an outlet pressure of 100 Pa (negative pressure).

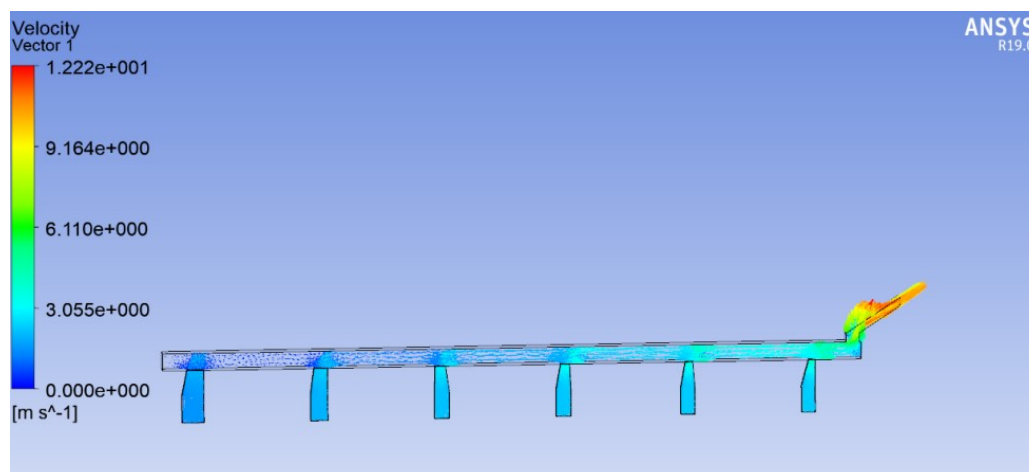


Figure 5. Flue gas velocity contour plot of novel flue gas collection system.

According to the simulation results, the novel flue gas collection system for the 400 kA cell requires only 3022 m³/h of air flow to completely extract the electrolytic flue gas, merely one-fifth of the air flow needed by traditional systems. This also implies a significant reduction in heat loss carried away by the flue gas. Furthermore, as shown in Figure 5, the flow velocity at each collection port of the system remains below 3 m/s, while the main exhaust pipe maintains a flow velocity of approximately 6 m/s. Typically, to prevent excessive entrainment of alumina particles in the flue gas, the flow velocity in the flue gas collection system should be kept below 6 m/s. At this level, the flow velocity is lower than the settling velocity of dust particles, effectively avoiding excessive dust carryover into the main exhaust pipe. This ensures an unobstructed cross-sectional area of the main exhaust pipe and maintains long-term flue gas collection efficiency.

5. Conclusions and Outlook

5.1 Conclusions

This paper summarizes the current status and shortcomings of traditional flue gas collection systems in cells. Based on an analysis of the mechanism of flue gas flow within the cell, a novel high-efficiency flue gas collection device is proposed. This innovation fundamentally transforms the conventional electrolytic flue gas collection structure by capturing and treating flue gas directly at the source. The system achieves highly efficient flue gas collection, requiring only 1/5 of the airflow volume of traditional collection systems to ensure complete capture and discharge of reaction gases. This breakthrough significantly reduces the energy consumption of purification system fans and minimizes heat loss caused by flue gas extraction. The implementation of this equipment is expected to deliver the following benefits:

- 1) Taking the optimization of a 400 kA cell as an example, the existing flue gas emission requires the negative pressure generated by the exhaust fan to be set at 300 Pa, with a flue gas volume of approximately 14 726 m³/h. After the modification, the negative pressure generated by the exhaust fan can be reduced to 100 Pa, and the cell hooding flue gas emission volume drops to 3022 m³/h, only one-fifth of the original value, significantly reducing the air flow.
- 2) After optimization, the heat dissipation of flue gas will be significantly reduced, thereby lowering the energy input of the cell and improving its energy efficiency. The working voltage of the cell is expected to decrease by 100–150 mV.
- 3) Based on the existing purification system, the power consumption is approximately 120 kWh/t Al. After optimization, efficient flue gas treatment can be achieved, reducing purification power consumption by 50 %, i.e., to 60 kWh/t Al.
- 4) After the implementation of this system, the concentration and temperature of the flue gas will increase significantly, providing a foundation for the development of subsequent technologies.

5.2 Prospects

The newly designed high-efficiency flue gas collection equipment presented in this study represents a disruptive innovation over the traditional electrolytic flue gas collection system. By capturing and treating flue gas directly at its source, it achieves highly efficient collection of electrolytic flue gas. Centred on energy conservation and equipment renewal, this technology provides smelters with a new development direction, promoting the transformation of the electrolytic aluminium industry toward greater efficiency, intelligence, and sustainability. Moreover, this equipment significantly increases flue gas concentration while reducing heat loss from cells, laying the foundation for further optimization and upgrading of electrolytic processes. This enhances energy utilization efficiency, thereby lowering energy consumption for both smelters and society as a whole. For smelters, reduced energy costs translate to improved economic benefits. For society, reduced energy dependence enhances the security and stability of energy supply while mitigating economic risks caused by energy price fluctuations. This technology has promising industrial implementation prospects.

6. References

1. Yanbin Wang, Current Status of Carbon Emissions in the Electrolytic Aluminium Industry and Pathways for Energy Conservation and Carbon Reduction, *Resources Economization & Environmental Protection*, 2025, (02), 14–19, DOI:10.16317/j.cnki.12-1377/x.2025.02.027 (in Chinese).
2. Improvement of Step Tariff Policy for Electrolytic Aluminium Industry by the National Development and Reform Commission, *The Chinese Journal of Nonferrous Metals*, 2021(18), 24 (in Chinese).
3. Xuan Wang, Lisong Xu, Current Situation and Trend Analysis of Carbon Emission in the Electrolytic Aluminium Industry, *Energy Saving of Nonferrous Metallurgy*, 2022, 38(04), 1–6, DOI: 10.19610/j.cnki.cn11-4011/tf.2022.04.001 <https://qikan.cqvip.com/Qikan/Article/Detail?id=7107943512> (in Chinese).
4. Zhenjun Cui, et al., Research on Energy Saving and Consumption Reduction Technology of 500 kA Aluminium Reduction Cell, *Gansu Metallurgy*, 2024, 46(03), 85–89, DOI: 10.16042/j.cnki.cn62-1053/tf.2024.03.018 (in Chinese).
5. Jie Kou, Research on the Treatment of Electrolytic Aluminum Production Flue Gas and Waste Heat Utilization, *World Nonferrous Metals*, 2022, (12), 12–14 (in Chinese).
6. Wenbo Wang, et al., Research on the Advanced Treatment Technology to Reduce Fugitive Emission of Flue Gas Generated during Aluminum Electrolysis, *Light Metals*, 2022, (08), 60–62, DOI:10.13662/j.cnki.qjs.2022.08.013 (in Chinese).

