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Upgrade Practice on 330 kA Aluminum Reduction Cell Line

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Abstract

China’s aluminum reduction industry faces strict energy consumption and environmental protection challenges. In response, an enterprise upgraded and optimized its 330 kA aluminum reduction cell, initially commissioned years ago. By analyzing issues related to magnetic field distribution, cathode structure, lining design, and upper cell structure, they proposed several enhancement measurements. Using new technologies to optimize the busbar magnetic field significantly improved the magnetohydrodynamic stability of the cells. The introduction of graphitized cathode blocks reduced cathode voltage drop and horizontal current in the aluminum liquid. Additionally, improvements in the cell lining insulation and gas collection efficiency of cell upper structure were made. The upgraded cell line now operates at a higher current and have significantly lower energy consumption, with a reduction of about 692 kWh per ton of aluminum. This results in an annual energy savings of approximately 187 million kWh and an increase in aluminum production by about 20,000 tons.

Keywords: aluminum reduction cell; cell lining; busbar magnetic field; cell upper structure; cell control system; energy conservation and consumption reduction; upgrade and optimization

Introduction

As energy costs continue to rise and national environmental policies tighten [1-3], some early-established aluminum reduction smelters are facing challenges in meeting energy consumption standards set by the latest regulations. This has led to a decline in their market competitiveness and put their survival at risk. However, these challenges also present an opportunity for technological and equipment upgrades [4-8]. On August 26, 2021, China issued the “Notice on Improving the Aluminum Reduction Industry’s Tiered Electricity Pricing Policy” by the National Development and Reform Commission [9]. In response, an aluminum reduction smelter swiftly upgraded its 330 kA reduction cells, aiming to reduce production costs and enhance profitability and market competitiveness. This article details the technical upgrade and optimization process of the company’s 330 kA reduction cell line.

Issues and Analysis Before the Upgrade

Before initiating the upgrade process, a thorough analysis was conducted to accurately identify the specific issues with the project in order to develop a scientifically sound upgrade strategy. This involved reviewing the original design data of the company's existing 330 kA reduction cells, along with key operational management data. By evaluating the technical characteristics and operational conditions of the reduction cells in relation to the actual site situation, a comprehensive understanding of the issues was achieved.

Overview of the Reduction Cells

This reduction cell series began construction in June 2007 and commenced trial production in May 2009, with a designed annual capacity of 250,000 tons. The cells were designed and operated at a current of 330 kA, with a total of 280 operational cells. Each cell includes 20 sets of anodes in a dual-anode configuration, with a designed anode current density of 0.737 A/cm^2. The cathode consists of 27 groups of carbon blocks made from 30% graphite material.

Key operational parameters for the reduction cells are summarized in Table 1. The cells exhibit high operating voltage and excessive aluminum energy consumption, significantly exceeding the industry average in energy inefficiency. Additionally, current efficiency is relatively low. After ruling out the effects of raw material quality—such as carbon anodes, alumina, and electrolyte composition—preliminary analysis identified an issue with the magnetic field distribution in the busbar system. Specifically, an uneven magnetic field distribution within the busbar system was found to be the primary cause of poor magnetohydrodynamic (MHD) stability, which negatively impacts efficient and stable production under lower energy input and reduced inter-electrode spacing [10]. A more detailed analysis of the busbar's magnetic field is required to address this issue effectively.

Items	***Parameters***
Current /kA	330.0
Current Efficiency /%	91.91
Average Voltage /V	4.066
DC Specific Energy Consumption /kWh·t-Al^{-1}	13182

Table 1: Key technical indicators of the 330 kA reduction cell.

Analysis of the Busbar Magnetic Field

Based on the original design drawings of the 330 kA reduction cell and busbar, along with on-site inspections, a single-line diagram of the 330 kA reduction cell's busbar system was created to verify its magnetic field. Table 2 presents the calculated magnetic field results in the X, Y, and Z directions across the four quadrants of the 330 kA reduction cell's busbar system.

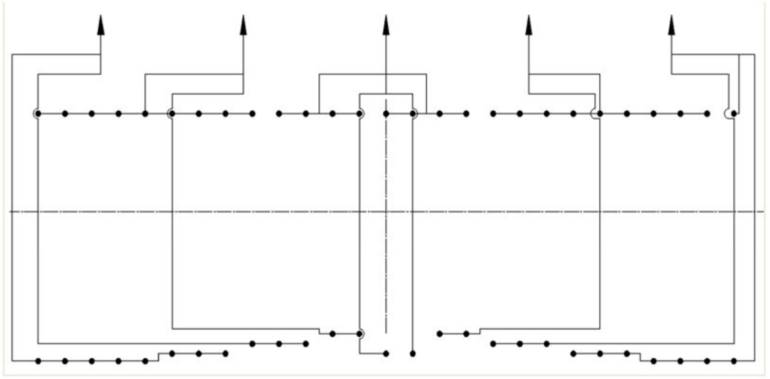


Figure 1: Single-line diagram of the 330 kA reduction cell busbar.

Based on the calculated vertical magnetic field (Bz) results for the 330 kA reduction cell, the average absolute magnetic field values in all four quadrants are significantly greater than 5 Gs, which clearly does not meet the current advanced magnetic field design standards for aluminum electrolysis cells. Among the data, the maximum value is 32.206 Gs, the minimum is less than 6.512 Gs, and the range exceeds 25.694 Gs, indicating poor uniformity in the distribution of the vertical magnetic field across the quadrants. This uneven magnetic field distribution, coupled with high values, can lead to excessive aluminum melt flow, increased interface fluctuations, reduced cell stability, and lower current efficiency [4, 11]. These findings align closely with actual on-site operational conditions, further confirming the existence and severity of the issue.

Unit:Gs	***1st quadrant***	***2nd quadrant***	***3rd quadrant***	***4th quadrant***	***Max***
Bx	45.391	46.142	76.896	77.534	-165.479
By	3.858	4.926	5.563	4.003	-23.750
Bz	7.184	15.687	14.806	6.512	32.206

Table 2: Calculation of the magnetic field for the 330 kA reduction cell busbar (average absolute value per quadrant).

The analysis of the simulation results for the original 330 kA reduction cell's magnetic field indicates that the key cause of instability in this reduction cell line is the uneven distribution of the vertical magnetic field.

Analysis of the Reduction Cell Cathode Structure

The design of the 330 kA reduction cell's cathode structure uses a traditional assembly method with small cross-section steel rods, as shown in Figure 4(a). Each cell has 27 sets of cathode carbon blocks, with dimensions of 515 mm (width) × 450 mm (height) for the carbon blocks and 70 mm (width) × 180 mm (height) for the steel rods. The steel rod slots are 200 mm high, with a gap of 20 mm on the narrow side and 12.5 mm on the wide side between the cathode carbon blocks and the steel rods. The effective height of the cathode carbon blocks is maintained at 250 mm, with a steel rod spacing of 202 mm, and a 150 mm gap between the steel rods at the center of the cathode carbon blocks.

The design of the cathode structure directly influences the horizontal current distribution in the aluminum melt, which is crucial for maintaining the electrolysis cell's magnetohydrodynamic stability. A simulation was conducted to review the horizontal current and cathode voltage drop, as shown in Figure 5.

The pre-optimization curve data indicates that the original 330 kA reduction cell's cathode voltage drop was designed at approximately 270 mV, with a maximum horizontal current in the aluminum melt of about 8233 A/m^2. This falls within the traditional cathode design range of high horizontal currents (7000–10000 A/m^2). In contrast, the current design standard for advanced energy-efficient large-capacity reduction cells is approximately 3000–5000 A/m^2, offering a reduction in horizontal current by 40–60% compared to traditional designs. Therefore, the original cathode structure of the 330 kA reduction cell can no longer meet the requirements for maintaining magnetohydrodynamic stability under reduced inter-electrode spacing [3].

Lining Structure and Thermal Balance Analysis

The lining structure of the 330 kA reduction cell, shown in Figure 2, employs a heat-dissipation design. The sidewalls are constructed with 90 mm thick silicon nitride combined with silicon carbide blocks, while the steel rod window area uses a single layer of diatomaceous earth bricks. The bottom insulation and anti-permeation layer have a total thickness of 372 mm, consisting of 65 mm calcium silicate board, two layers of insulation bricks, and 175 mm of dry anti-permeation material. This design significantly deviates from the current trend of insulation-based lining solutions, which prioritize low energy consumption and efficiency.

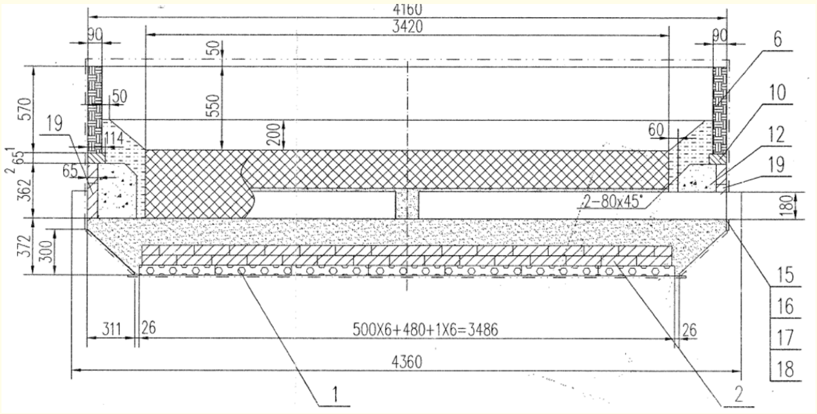


Figure 2: Previous scheme diagram of the 330 kA reduction cell lining.

Field tests and simulation analysis indicate that, in the 330 kA reduction cells, especially on the cathode side, the isotherms do not align vertically as expected. Notably, the 800°C isotherm exhibits an abnormal bulge at the upper part of the steel rod, where the cathode carbon blocks, carbon paste, and castable materials meet. This irregularity adversely affects the local thermal stress distribution and prevents the thermal balance from reaching the ideal state. Additionally, during production, the reduction cells often exhibit excessive leg extension, indicating that the cell's operating conditions are suboptimal, which negatively impacts the efficiency of the cell's operation.

Given the differences between the original 330 kA reduction cell's lining design and the latest lining design concepts, it is clear that improvements are needed to optimize the cell's thermal balance.

Analysis of the Upper Structure of the Reduction Cell

The original upper structure features a four-point spiral lifting system along the length of the reduction cell, with a large anode busbar on each side and five balance busbars. The traditional grouped pneumatic control method is used to regulate the shell formation and material discharge process. This approach negatively impacts the cell's thermal balance and heat buildup, as well as the uniformity of alumina distribution within the cell, which exacerbates local effects. Additionally, the traditional pneumatic control system is complex, making maintenance less efficient and posing safety risks, highlighting the need for improvement and optimization.

The original gas collection and exhaust system uses a combined design of a lower flue and a single smoke pipe. It incorporates a continuous chamber structure, with material discharge ports along the length of the cell. The system relies solely on the gas collection holes to regulate air intake during operation. However, this design has clear shortcomings: the long gas chamber creates significant variation in gas collection at both ends of the cell, and the high internal resistance reduces the overall collection efficiency, leading to higher purification energy consumption.

Analysis of the Cell Control System

In the aluminum reduction industry, the cell control system is a core component, and its technological advancement is crucial for improving production efficiency and product quality. The old cell control system used a traditional large mainboard design, with low hardware integration, complicated maintenance, and inefficiency. Due to the limitations of simple control algorithms, the system struggled to handle the nonlinearity and lag characteristics of the reduction cells, resulting in poor control precision and stability. This posed challenges to production stability and efficiency. Additionally, the user interface was rudimentary, making operation inconvenient and further hindering production efficiency. In the context of modern industry's urgent demand for automation and intelligence, the old system's limited capabilities in data processing, fault diagnosis, and remote monitoring made it insufficient to meet the company's development needs. Therefore, a technological upgrade and optimization of the cell control system are necessary.

Upgrade and Optimization Plan

Given that the original 330 kA reduction cell design is quite dated and involves numerous issues, a comprehensive upgrade and optimization will be carried out on the reduction cell . This will include improvements to the busbar structure, cathode materials and structure, cell lining, upper structure, and the cell control system.

Busbar Magnetic Field Optimization

Based on a thorough evaluation of the current busbar system's performance and the reduction cell's magnetohydrodynamic stability, a completely new busbar system design will replace the original one, aiming to optimize the magnetic field and significantly improve the cell's magnetohydrodynamic stability.

Using the latest busbar magnetic field design technology from SAMI [3, 4, 12], an electromagnetic simulation model was developed for the optimized 330 kA reduction cell busbar. Based on this model, a magnetic field optimization design was implemented. Table 3 presents the distribution of the magnetic field in the X, Y, and Z directions after optimization.

Unit:Gs	***1st quadrant***	***2nd quadrant***	***3rd quadrant***	***4th quadrant***	***Max***
Bx	40.782	44.625	77.636	77.349	-167.263
By	4.716	5.150	3.902	5.004	-23.087
Bz	2.878	3.698	4.509	4.139	23.854

Table 3: Magnetic field calculation for the upgraded 330 kA reduction cell (average absolute value per quadrant).

As shown in Figure 3, the magnetic field distribution in the Z direction has significantly improved after the upgrade. Not only have the average absolute values in each quadrant decreased, but they have also been successfully controlled within 5 Gs, achieving a more uniform distribution and a significantly improved gradient. In the reduction cell's molten zone, the average vertical magnetic field has decreased from 11.047 Gs to 3.806 Gs, representing a 65.5% reduction. Additionally, the maximum vertical magnetic field, which previously occurred at the corners of the reduction cell, has dropped from 32.206 Gs to 23.854 Gs, marking a 25.9% reduction. The optimized magnetic field will significantly enhance the overall operational stability of the reduction cell.

Cathode Structure Optimization

Compared to conventional graphite cathode carbon blocks, graphitized carbon blocks exhibit superior thermal and electrical conductivity, enabling them to withstand higher current loads [13]. Their sodium expansion rate is significantly lower than that of graphite cathode carbon blocks, making them more resistant to sodium corrosion, which helps extend the cathode's lifespan [14]. Additionally, due to the higher volumetric density of graphitized carbon blocks, the absorption and diffusion of sodium are greatly reduced, enhancing the material's stability. This results in a more uniform cathode current distribution, promoting stable and efficient operation of the reduction cell [15, 16]. Given these advantages, replacing traditional graphite cathode carbon blocks with graphitized ones is a key strategy in this reduction cell upgrade.

Building on the properties of graphitized cathode carbon blocks, the upgrade not only focuses on improving conductivity and thermal performance but also considers mechanical properties, cell lifespan, and safety/economic factors. The size of the graphitized carbon blocks has been adjusted and optimized. In addition, the supporting improvements include changing the traditional small-section double steel rod structure (Figure 4a) to a large-section single steel rod design (Figure 4b), and replacing the traditional carbon paste bonding method with phosphoric iron casting for connections. These optimizations effectively reduce horizontal current and cathode voltage drop in the aluminum melt, improving the overall advantages of the new cathode structure in reducing voltage drop, lowering horizontal current, and extending the reduction cell's lifespan, thus achieving energy savings, reduced consumption, and improved efficiency [17, 18].

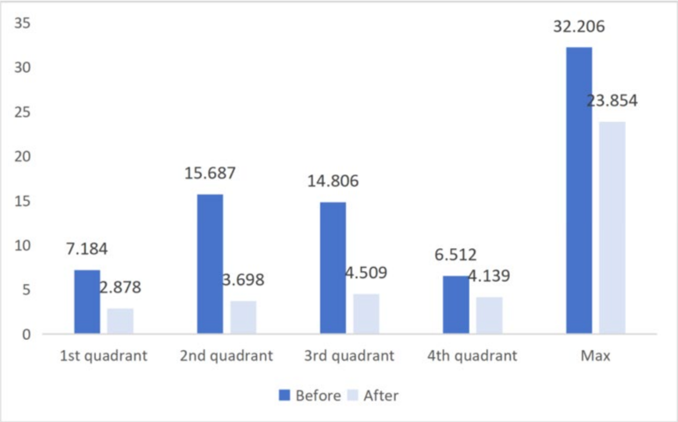
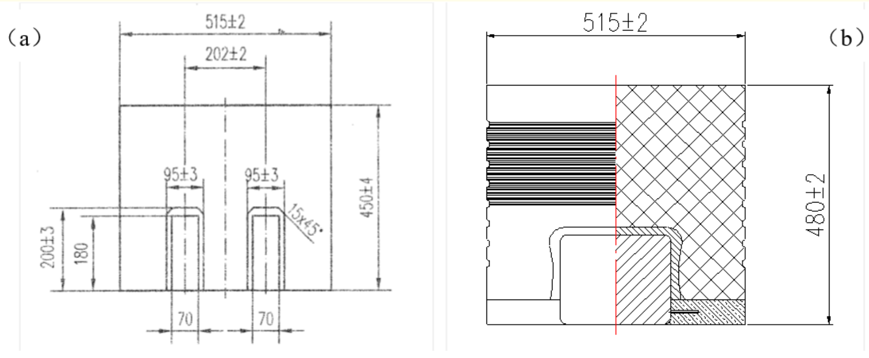


Figure 3: Comparison of average magnetic flux density values per quadrant before and after the magnetic field upgrade in the 330 kA reduction cell (Unit:Gs).



（a）Before；（b）After

Figure 4: Comparison of cathode optimization for the 330 kA reduction cell (cross-sectional view).

Before optimization, the original design had a maximum horizontal current of approximately 8223 A/m^2 and a cathode voltage drop of about 270 mV. As the cell's operating life increased, the voltage drop in the original graphite cathode design rose significantly, with the average series cathode voltage drop reaching approximately 317 mV. After optimization, the simulated maximum horizontal current in the aluminum melt dropped to 4979 A/m^2, and the simulated cathode voltage drop decreased to around 210 mV, a reduction of about 107 mV compared to the pre-optimization actual operating voltage drop. The simulated results for horizontal current and cathode voltage drop before and after the optimization of the 330 kA reduction cell are shown in Figure 5.

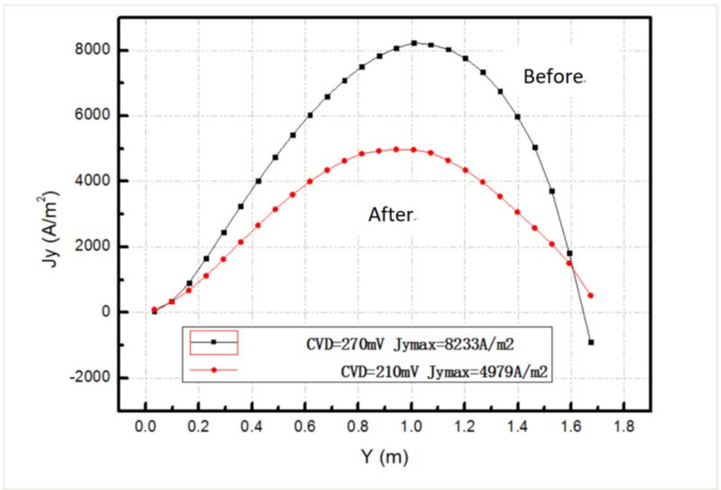


Figure 5: Simulation results of horizontal current and cathode voltage drop before and after the optimization of the 330 kA reduction cell.

Reduction Cell Lining Optimization

The application of the new energy-efficient cathode structure significantly reduces the cathode voltage drop [19, 20]. However, due to the higher heat dissipation of graphitized cathodes [21], it is necessary to upgrade the cell lining design to maintain thermal balance in the cathode region [22-25]. This involves selecting materials with excellent thermal insulation properties that can withstand high-temperature electrolytes and vapor corrosion [26]. The design must ensure that, despite a significant reduction in cell voltage (overall energy input), cathode voltage (heat generation), and horizontal current, both regional and overall thermal balance are maintained without excessive additional energy consumption. This solution also addresses the impact of climate variations on the reduction cell [27].

In the lining design, particular attention is given to the cathode steel rod window area, which experiences high heat dissipation [9]. Traditional designs tend to result in excessive leg extension under low-energy input and low-voltage operation. To address this, upgrades to materials, structure, and construction processes have been implemented to enhance the sidewall's anti-permeation capability. Additionally, the cell's insulation is strengthened to create a well-structured furnace lining that extends the cell's lifespan. The design also includes providing sufficient compression space around the cathode carbon blocks to absorb thermal expansion and reduce cracking. Furthermore, dry anti-permeation material and a physical anti-permeation layer are used to prevent corrosion from the electrolyte and sodium vapor, ensuring proper thermal balance and temperature distribution [23].

Finally, new insulation materials, such as ceramic perlite insulation boards, are used to further enhance thermal insulation, control leg extension length, and meet the requirements for low aluminum levels in operation [28].

Upper Structure Optimization

As national energy consumption and environmental regulations become increasingly strict, improving the efficiency of gas collection, reducing uncontrolled emissions, minimizing exhaust resistance, and lowering the energy consumption of the purification system are key future objectives [29, 30]. Additionally, aluminum reduction cells require substantial energy to heat alumina to electrolysis temperatures and dissolve it. By implementing precise control over alumina feeding and dissolution, and homogenizing the alumina concentration within the cell to reduce local effects, significant energy savings can be achieved.

The 330 kA reduction cell's upper structure, designed in 2007, has become outdated. Since its commissioning in 2009, it has been in operation for 12 years. Therefore, under the current stringent energy-saving and environmental requirements, the original upper structure of the 330 kA reduction cell needs to be upgraded. This includes replacing the original lower flue with an upper flue, positioning the smoke pipes within the main beams, and optimizing the flue structure to improve gas collection efficiency. These changes will reduce the uncontrolled emission of fluoride compounds, lower the reduction cell's purification energy consumption, and maintain accessibility and safety for equipment maintenance in the upper structure.

Using Fluent software for modeling and simulation, the gas collection system in the upper structure was fully upgraded to achieve uniform gas collection along the length of the cell. This optimization significantly reduced pressure loss in the gas collection flue and system airflow while successfully lowering energy consumption in the purification system. Additionally, the new design effectively addresses the issue of dust deposition in the exhaust gases, ensuring minimal resistance in the gas collection system while maintaining uniform collection efficiency.

In terms of the shell formation and material discharge system upgrade, the transition from pneumatic to electric control using cylinders significantly improved system responsiveness and precision. The air supply piping in the upper structure was simplified, reducing leakage risks and air consumption, which greatly facilitates future maintenance. Furthermore, the new system includes an automated exhaust gas treatment device, which reduces the noise generated by exhaust emissions, creating a better working environment for employees [31].

Cell Control System Optimization

The cell control system functions as the "brain" of the reduction cell. Achieving efficient and stable production relies on an effective "brain." The role of the cell control system is to ensure precise control, improve production stability and efficiency, and guarantee the safe and efficient operation of the reduction process. By continuously monitoring and adjusting parameters such as alumina concentration and cell voltage, the control system keeps the reduction cell operating at optimal conditions, improving production metrics and extending equipment life.

In this upgrade, the new cell control system replaces the traditional mainboard design with a blade-style modular integrated architecture and a server-like multi-processor control CPU array. This significantly enhances real-time data processing and analysis capabilities, as well as system safety and reliability. The new system can accommodate different current intensity requirements, reduce construction complexity, and simplify future maintenance tasks. Additionally, it offers features such as flexible modular plug-and-play functionality, strong resistance to interference, high execution speed, and stability. It also incorporates fuzzy adaptive control to improve the system's robustness against disturbances in the reduction production process.

Optimization Results

After completing the infrastructure for all the upgrade projects, the reduction cells gradually entered production. The company's technical team, closely working on-site, explored new processes under the "Four New" conditions (new materials, new designs, new equipment, and new systems). Over the course of more than a year of technical exploration and practice, the operating current of the reduction cells was enhanced from 330 kA to 350 kA, increasing the anode current density by 0.045 A/cm^2 and reducing the molecular ratio by approximately 0.2, Seen Table 4.

Items	***Before***	***After***
Current /kA	330.0	350.0
Current Efficiency /%	91.91	94.0
Average Voltage /V	4.066	3.940
DC Specific Energy Consumption /kWh·t-Al^{-1}	13182	12490
Temperature/°C	950~960	950~960
Metal Level/cm	28~30	20~23
Bath Level/cm	18~20	18~20
Ratio	2.45~2.55	2.28~2.33
Anode Current Density/ A/cm^2	0.737	0.782

Table 4: Main technical parameters before and after upgrading 330 kA reduction cells.

As a result of these improvements, comprehensive calculations show that compared to the original series, DC electricity consumption was reduced by about 692 kWh·t-Al-1, leading to an annual energy savings of approximately 187 million kWh. Additionally, the annual production of aluminum increased by over 20,000 tons. The calculation process is as follows.

Calculation of Annual Aluminum Production Increase

The increase in annual production is calculated as follows:

Annual production increase $=0.3355\times10^{-6}\times24\times280\times365\times(350\times10^{3}\times94\%-330\times10^{3}\times91.91\%)$

Where:

0.3355×10^{-6}: is the coefficient that converts energy to aluminum production.

24×280×365: represents the number of hours in a year, the number of reduction cells, and the number of production days per year.

Annual production increase=21,146 tons of aluminum.

Calculation of Annual Energy Savings

Annual energy savings$=0.3355\times10^{-6}\times24\times280\times365\times350\times10^{3}\times94\%\times692=1.87\times10^{8}$ kWh.

Conclusion

The upgrade and optimization of the 330 kA reduction cell line led to the following conclusions:

The introduction of new technologies significantly enhanced the magnetohydrodynamic stability of the reduction cells, reduced cathode voltage drop, optimized thermal balance, and improved gas collection efficiency. These results fully demonstrate the importance and effectiveness of the technological upgrades. The measures implemented are widely applicable and provide strong support for similar reduction cell upgrades.

While the upgrade results are significant, attention must still be given to the adaptability and optimization of the "Four New" technologies (new materials, new designs, new equipment, and new systems) under different operating conditions to ensure optimal performance. Further exploration in this area will continue in the future.

The upgrade not only aligns with national energy-saving and environmental protection policies but also directly improves the company's economic performance. It achieves the goals of energy savings, reduced consumption, and enhanced quality, laying a solid foundation for the company's high-quality development and economic success.

It is recommended that the industry actively respond to national policy initiatives, seize the opportunities presented by digitalized equipment upgrades, and accelerate technological innovations under new operating conditions. This will promote the sustainable development of the aluminum reduction industry. Additionally, continuous attention should be given to the application of new technologies and materials, further optimizing reduction cell performance and contributing valuable experience and technical support to the industry's growth.

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