

Development of Ultra–Low Energy Consumption Technology in 500 kA Cells

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Abstract

Aluminium production is an energy-intensive process. On one hand, the country has imposed increasingly stringent requirements on the green and low-carbon development of the industry. On the other hand, energy conservation and consumption reduction are of critical importance to the sustainable development of smelters. Therefore, achieving ultra-low energy consumption in electrolytic cells has become a pressing priority. The solution proposed in this paper optimizes the lining and cathode collector bar structures of a 500 kA high amperage cell, reducing the cathode voltage drop by more than 100 mV, thereby enabling low-voltage, high-efficiency operation. Additionally, the solution integrates auxiliary energy-saving technologies, including energy-saving stubs, online busbar upgrades, anode block slotting, anti-oxidation coatings for anodes, and laser cleaning of anode rods. By employing these advanced technologies, the voltage drop across each conductor component can be further minimized. Complementary process management strategies have also been developed, forming a comprehensive ultra-low energy consumption technology framework for 500 kA cells, and achieving a reduction of energy consumption of 500 kWh/t Al. This approach not only facilitates technological upgrading and energy efficiency improvements but also supports the green and low-carbon transformation of the aluminium industry.

Keywords: Aluminium electrolysis, Lining design, Energy-saving technology, Ultra-low energy consumption, Cathode structure.

1. Introduction

As increasingly stricter regulatory control is imposed on the energy consumption and carbon emissions of the cells, China's aluminium electrolysis industry is facing huge challenges in saving energy and reducing consumption. Recent years have seen rapid advances in aluminium electrolysis technology in the country. According to statistics [1], China has reached the advanced level of aluminium electrolysis in the world, but it still lags behind in terms of energy cost, mainly due to high electricity price, as well as high electricity consumption in aluminium electrolysis, which accounts for 55–60 % of the total carbon emissions generated in the entire process [2]. Therefore, reducing the energy consumption associated with aluminium electrolysis, particularly electricity usage, has become a widely accepted objective within the industry. This paper examines the voltage components of the cell and investigates low-energy consumption technologies for its operation. Additionally, corresponding process technology management strategies are developed, leading to the establishment of a replicable and scalable low-energy consumption control framework for the cell.

2. Analysis of Energy Conservation and Reduction of Energy Consumption in Aluminium Electrolysis

To reduce the cell energy consumption, the first step is to lower the average voltage and improve current efficiency. In recent years, experts and scholars at home and abroad have undertaken extensive research and industrial trials to reduce cell operating voltage. Shuhong Song et al. [3] compared the applications of the graphitized cathode carbon block and the 50 % graphitic cathode carbon block, and the results showed that the voltage drop in the graphitized cathode blocks is, on average, 45.5 mV lower than in the 50 % graphitic cathode. In the study of the magnetic fluid stability characteristics of graphitized cathodes, Wei Tang et al. [4] confirmed that current efficiency of the graphitized cathode is 1.5 % higher than that of the graphitic cathode. It can be seen that the application of graphitized cathodes has become a hot topic of research, and graphitized cathodes are now widely used in the industry.

We have conducted measurements on the voltage distribution of various parts of the cells in a Chinese smelter, and the results are shown in Table 1.

Table 1. Summary of cell voltage balance in a Chinese smelter.

	Item	Voltage Drop (mV)	Percentage
Riser busbar	Vertical riser busbar	30.8	0.77 %
	Diagonal riser busbar	19.1	0.48 %
	Riser flexibles	38.6	0.97 %
	Junction surface	8.5	0.21 %
	Total anode riser voltage drop	97.1	2.43 %
Rim busbar	Busbar voltage drop around the cell	142.1	3.56 %
Anode busbar	Balance busbar	21.4	0.54 %
Anode assembly	Clamp voltage drop	13.7	0.34 %
	Aluminium conductor rod voltage drop	21.2	0.53 %
	Explosion weld voltage drop	8.3	0.21 %
	Anode voltage drop	339.8	8.50 %
	Sub-total	383.0	9.58 %
Cathode voltage drop		226.7	5.67 %
Anode-to-cathode voltage drop		3 126.8	78.23 %
Total		3 997.0	100 %

As shown in Table 1, in the cell voltage distribution, the total anode riser voltage drop accounts for 2.43 %, the voltage drop of the cathode ring busbar accounts for 3.56 %, the voltage drop of the anode busbar accounts for 0.54 %, the voltage drop of the anode assembly accounts for 8.50 %, the voltage drop of the cathode accounts for 5.67 %, and the anode-to-cathode voltage drop accounts for 78.23 %. Since the potline has been put into operation, the anode riser busbar and the cathode ring busbar no longer offer potential for improvement under the current production conditions. However, the voltage drop in the anode assembly, cathode and between anode and cathode can be further reduced through improvements in electrolysis cell lining design and the development of advanced process management technologies.

3. Cell Lining Design Optimization

As mentioned above, the fully graphitized cathode technology is now widely used in the industry to reduce cathode voltage drop and improve current efficiency. In the design of this study, copper is embedded into the cathode collector bar to increase its conductivity, and further lower cathode voltage drop and horizontal current. The simulation results of the horizontal current, cathode voltage drop, and thermal balance using copper-insert collector bars are shown in Figure 1.

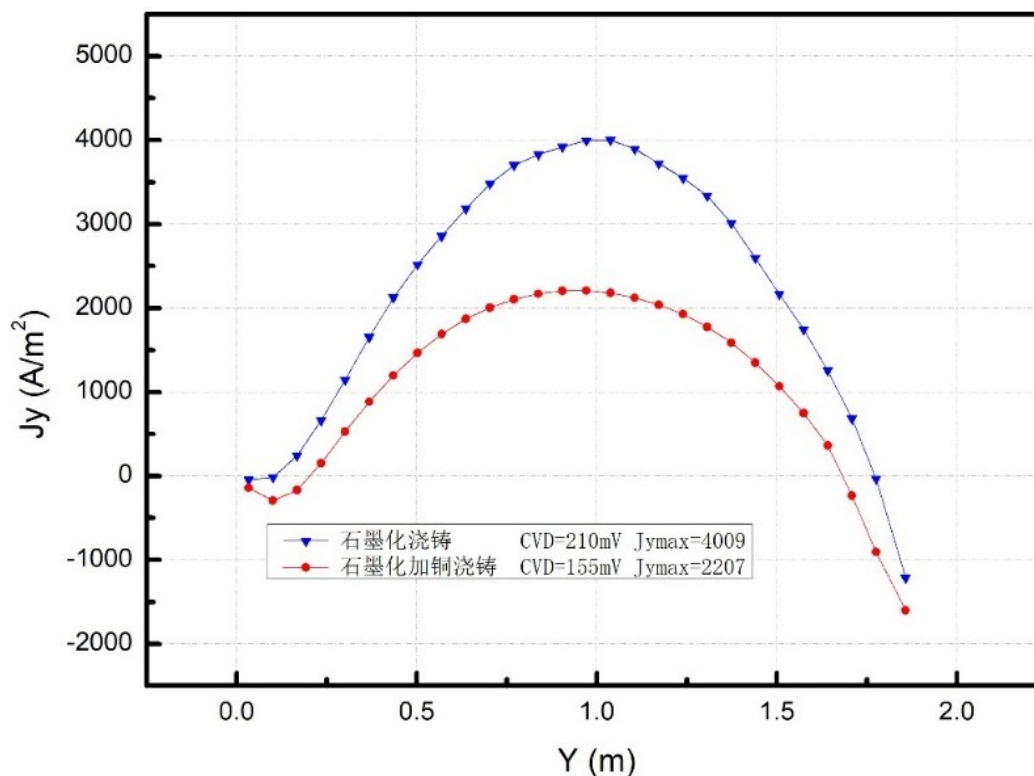


Figure 1. Comparison of horizontal current (pot transversal section) and cathode voltage drop.

Legend: Blue triangle-curve: Graphitized cathode with steel collector bars, for which CVD = 210 mV and maximal $J_y = 4009 \text{ A/m}^2$; Red circle-curve: Graphitized cathode with copper in the collecting bars, for which CVD = 155 mV and maximal $J_y = 2207 \text{ A/m}^2$.

The research indicates that the cathode voltage drop with copper-insert collector bars is 155 mV, with a horizontal current of 2 207 A/m². Compared to the scenario without copper embedding, the horizontal current decreased by 45 %, while the cathode voltage drop was reduced by 26 %.

The calculation results (Figure 2) indicate that under the traditional application of vermiculite insulation bricks, with 500 kA current and an average voltage of 3.854 V, the anode-to-cathode distance (ACD) is 4.0 cm, and the cathode voltage drop is 0.163 V. The average bath temperature is 958 °C, with a superheat of 8 °C. The thinnest section of the cell top ledge measures 17.4 cm, and the bottom ledge is 7.2 cm, indicating a favourable cavity condition. The isothermal line distribution at the bottom of the cell is uniform and within normal range. The average potshell temperature of the sidewall melting zone is 262 °C, with the peak temperature of 279 °C. Due to the limited extension of the copper bar, without reaching the end of the collector bar, the temperature at the end of the collector bars reaches approximately 330 °C. The average temperature of the cell bottom is 62 °C, with a bottom heat dissipation ratio of 6.8 %, indicating a good thermal balance.

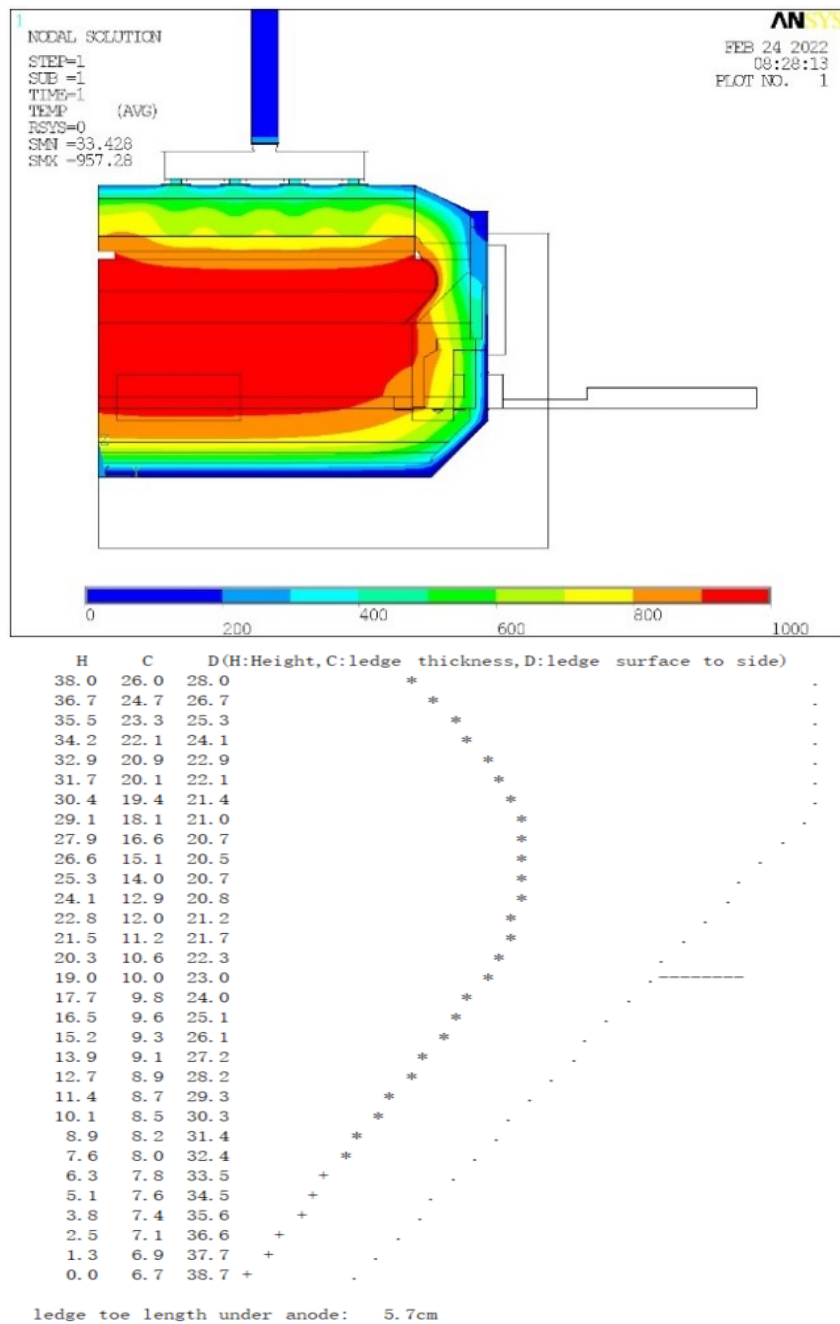


Figure 2. Top: Temperature distribution (scale range 0-1000 °C) in the cell cross section, Bottom: Ledge profile (curved line) in relation to the side lining (straight lines) – positions in cm, thickness in column C.

Through optimization, the cathode voltage drop was reduced by 71 mV compared to that of the 50 % graphitic cathode and by 53 mV relative to the graphitized cathode. The results are summarized in Table 2.

Table 2. Cathode voltage drop statistics.

Cathode material	50 % graphitic cathode	Graphitized cathode	Copper-insert collector bar + graphitized cathode
Cathode voltage drop (mV)	226	208	155

4. Process Technology Control Optimization

For the upgraded and optimized cells, process management technologies were developed based on exploratory tests conducted during three key stages: cell preheat, startup, early operation, and normal operation. During the early operation phase, a "3+1" management model was implemented, under which the first three months were designated as the non-standard period. Aluminium fluoride was introduced after 90 days, with the dosage increased by 7 kg per week. The cell entered normal operation period after the 120th day. During the initial three months, the cell cavity was established following the "three highs and one low" principle, which includes a high molar ratio, high bath height, high temperature, and low metal height.

The process parameters during the early operation are maintained according to Table 3.

Table 3. Process parameters during the early operation period.

Item	Week 1	Week 2	Week 3	Week 4	Month 2	Month 3
Metal height (cm)	18–20	18–21	18–22	19–22	19–22	20–22
Bath height (cm)	25–32	24–32	23–32	23–32	18–25	18–20
Bath temperature (°C)	970–990	970–985	965–980	965–980	960–975	955–970
Molar ratio	≥ 3.0	≥ 2.9	≥ 2.8	≥ 2.8	≥ 2.7	≥ 2.6
Cathode voltage drop (mV)	≤180	≤180	≤180	≤180	≤180	≤180

During normal operation, the process technology management adhered to the principle of "stability and order as core objectives" for test cells. Operation management emphasized the key elements of "stability, accuracy, flexibility, meticulousness and practicality", with particular attention given to the "Three Checking and One Scraping" (checking the cathode, checking the neighbouring anode, checking the ledge and scraping the sludge) for anode replacement operations, as well as ensuring a compact and level anode cover.

The process parameters during the normal operation are maintained according to Table 4.

Table 4. Process parameters during the normal operation.

Cell Age	91 days – year 1	Year 1 to year 3	Year 3 to year 4	Year 4 to year 6	> 6 years
Set voltage (V)	3.84–3.88	3.84–3.88	3.85–3.89	3.86–3.90	3.88–3.92
Bath height (cm)	18–22	17–20	17–19	17–19	17–19
Metal height (cm)	20–23	20–23	21–24	22–25	22–25
Molar ratio	2.40–2.60	2.35–2.50	2.35–2.50	2.35–2.50	2.35–2.50
Bath temperature (°C)	950–967	945–958	945–958	945–958	945–958

5. Application and Management Optimization of Auxiliary Energy-Saving Technologies

5.1 Application of Networked Busbar, MHD Stability, In-Situ Upgrade Technology

The networked self-balancing busbar, through a non-blocking configuration approach, effectively corrects current distribution deviations caused by the metal pad, prevents mutual interference between upstream and downstream cells, and reduces imbalances in current distribution between the anode and cathode under unstable operating conditions (such as during cell shutdown, anode effects, and cell instabilities). This design addresses the issue of anode effect and abnormal oscillation transmission between the cells during potline production. Additionally, it significantly enhances the MHD stability, operational performance, and anti-interference capability of the cell.

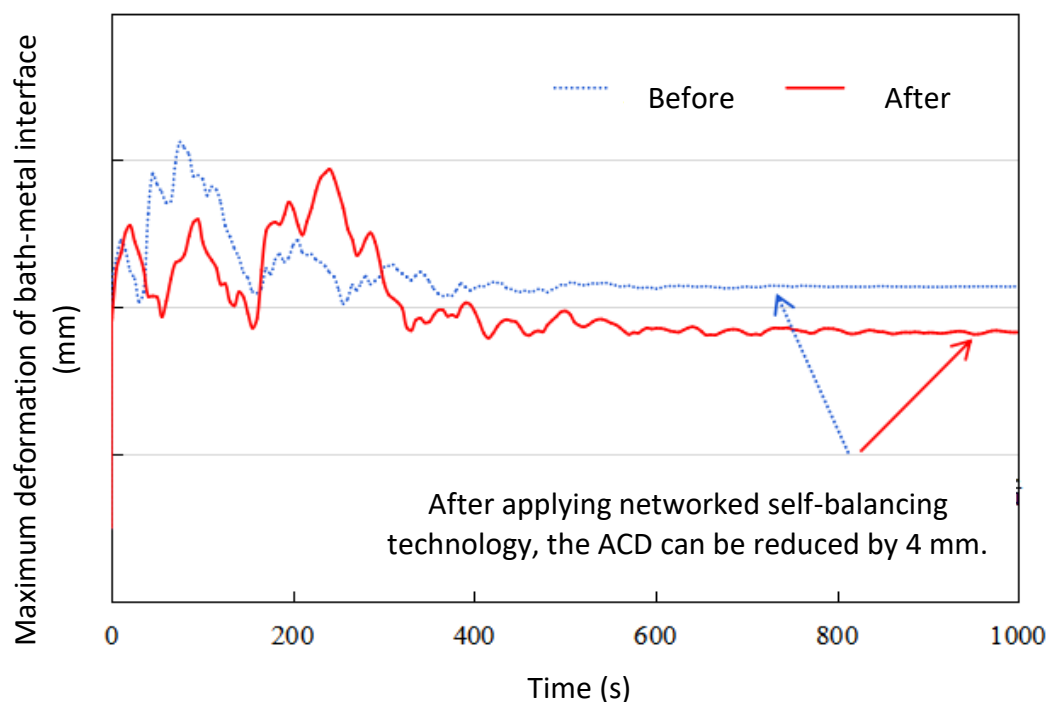


Figure 3. Comparison of ACD changes of the cells before and after application of the “self-balancing networked busbar technology” (equalizing connections between collecting busbars).

The results of the addition of copper inserts are shown in Table 5.

Table 5. Comparison before and after implementation of copper inserts.

Cell No.	Current efficiency (%)		Voltage (V)		Energy consumption (kWh/t Al)	
	Before	After	Before	After	Before	After
1433	93.18	93.2	3.972	3.958	12 703	12 655
1434	92.59	93.25	3.954	3.963	12 726	12 665
Mean	92.88	93.22	3.963	3.960	12 714	12 660
Difference	0.34		-0.002		-54	

DC energy consumption before implementation of copper inserts was 12 714 kWh/t Al, and 12 665 kWh/t Al after, representing a decrease of 54 kWh/t Al.

The research conducted by Ye Kong et al. [5] demonstrates that the implementation of self-balancing networked busbar technology can significantly enhance the cell stability. This technology exhibits strong self-balancing and anti-oscillation capabilities, thereby improving system robustness. Furthermore, Jian Zhang et al. [6] confirmed that self-balancing busbar technology effectively interrupts the transmission of fluctuating currents within the potline during unstable operating conditions.

5.2 Application of Energy-Saving Anode Stubs and Aluminium-Titanium-Steel Welding Technology

By developing new alloy materials and optimizing the overall structure of the stubs, the strength and stiffness of the stubs were significantly improved, thereby meeting the requirements for energy consumption reduction without compromising their service life. The implementation of the energy-saving stubs resulted in a 21 mV reduction in voltage drop compared to existing anode stubs, corresponding to 67 kWh/t Al (Table 6). Simultaneously, the material properties and structure of aluminium-titanium-steel tri-metal explosion welds were studied, clarifying the chemical compositions (including impurities) and structural requirements of each constituent material. The voltage drop of the new design is 5 mV lower than that of the current aluminium-steel explosion welding technology used by the company, corresponding to 16 kWh/t Al (Table 7).

Table 6. Comparison of voltage drop tests between energy-saving stubs and traditional stubs (unit: mV).

Cell No.	Anode No.	Measurement Point 1	Measurement Point 2	Measurement Point 3	Measurement Point 4	4-point average	Current Distribution	Corrected Value
#122 (test cell)	B1	42	30	31	40	36	2.3	31
	B2	60	29	33	50	43	2.3	37
	A19	51	27	36	42	39	2.6	30
	A20	50	30	30	51	40	2.6	31
	B1	41	28	30	46	36	2.4	30
	B2	47	35	40	60	46	2.4	38
	A19	47	32	32	42	38	2.6	29
	A20	No data	32	33	48	38	2.3	33
	B1	43	33	30	42	37	2.2	34
	B2	46	38	40	45	42	2.3	37
	A19	44	37	41	48	43	2.4	35
	A20	No data	30	28	43	34	2.2	31
						Mean value		33
419# (reference cell)	A1	83	51	52	No data	62	2.1	59
	A2	50	32	30	38	50	2.0	50
	B21	72	46	42	63	56	2.2	51
	B22	67	50	44	76	59	2.1	56
							Mean value	

The average voltage drop difference between energy-saving stubs and traditional stubs is 54 – 33 = 21 mV, which indicates a significant energy saving of 67 kWh/t Al.

Table 7. Comparison of voltage drop tests between aluminium-steel-titanium tri-metal welding block and aluminium-steel bimetallic welding block.

Cell No	Anode No.	Clad voltage drop (mV)	Date
#122 Test cell with aluminium-titanium-steel explosion welding clad	A1	5	2024/5/21
	A23	5	2024/5/21
	A24	5	2024/5/21
	A21	4	2024/5/23
	B22	5	2024/5/23
	B23	5	2024/5/23
	B24	5	2024/5/23
	Mean value	5	
#419 Reference cell (with aluminium-steel explosion welding clad)	A3	11	2024/5/23
	A4	9	2024/5/23
	B4	11	2024/5/23
	B5	10	2024/5/23
	B6	7	2024/5/23
	B16	12	2024/5/23
	B17	10	2024/5/23
	Mean value	10	

The voltage drop of the aluminium-titanium-steel clad is $10 - 5 = 5$ mV lower than that of the aluminium-steel clad, corresponding to 16 kWh/t Al.

The combined effect of the aforementioned two measures has resulted in voltage drop reduction of 26 mV corresponds to energy consumption decrease of 83 kWh/t Al.

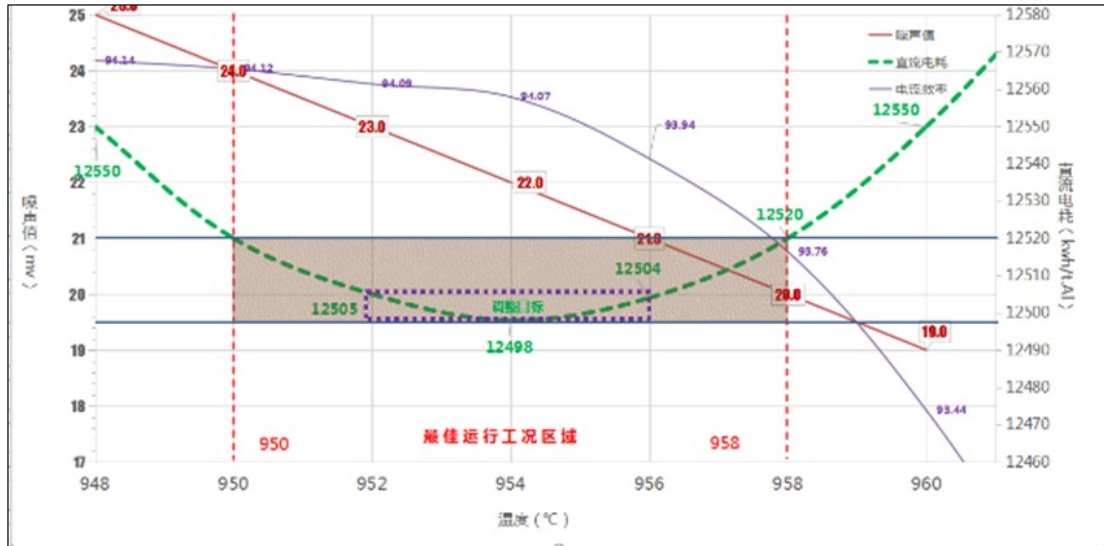
5.3 Application of Other Energy-Saving Technologies

Anode slotting can improve the current efficiency of aluminium production by 0.44 % and reduce anode voltage drop by about 10 mV, corresponding to a reduction of 60–80 kWh/t Al in DC energy consumption. The point feed technology can achieve feeding control at individual points, reducing the impact on the alumina concentration in the bath to ensure a more even alumina distribution, and thus mitigating manual labour intensity. Anode anti-oxidation coating technology uses nano coating material to reduce oxidation caused by air contact with the anode. This technology can extend the anode replacement cycle by 1 day and reduce the anode gross consumption by 4.7 kg C/t Al. Anode rod laser cleaning technology can reduce the voltage drop of the rod by approximately 2.3 mV, saving about 7.4 kWh/t Al. Many other energy-saving technologies are available, but they will not be covered here. These technologies have been widely applied in the industry. However, the combined effectiveness of the above technologies is not just a straightforward sum of their individual effects.

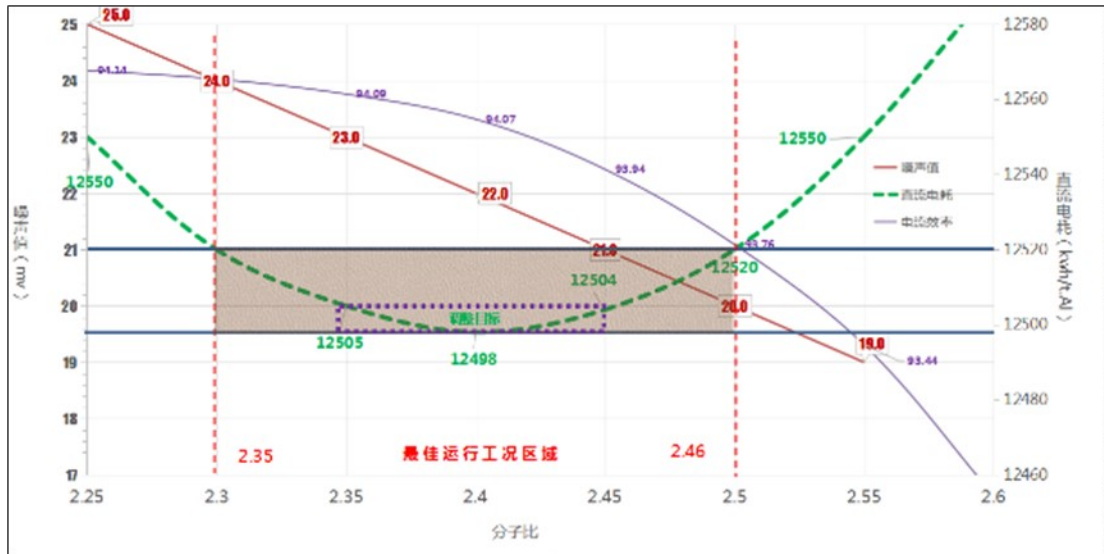
5.4 Management Technology Optimization

It is worth mentioning that most smelters have overlooked one important aspect of aluminium production: management technique innovation, which is also an essential task for energy conservation and consumption reduction. The "horizontal-vertical dual-directional and cross-connected" management model proposed by Lunshou Xie et al. [7] has demonstrated effective practical application in this study through refined management of aluminium electrolysis, the establishment of low-energy consumption control models, and health status monitoring models for the cells (Figures 4 and 5).

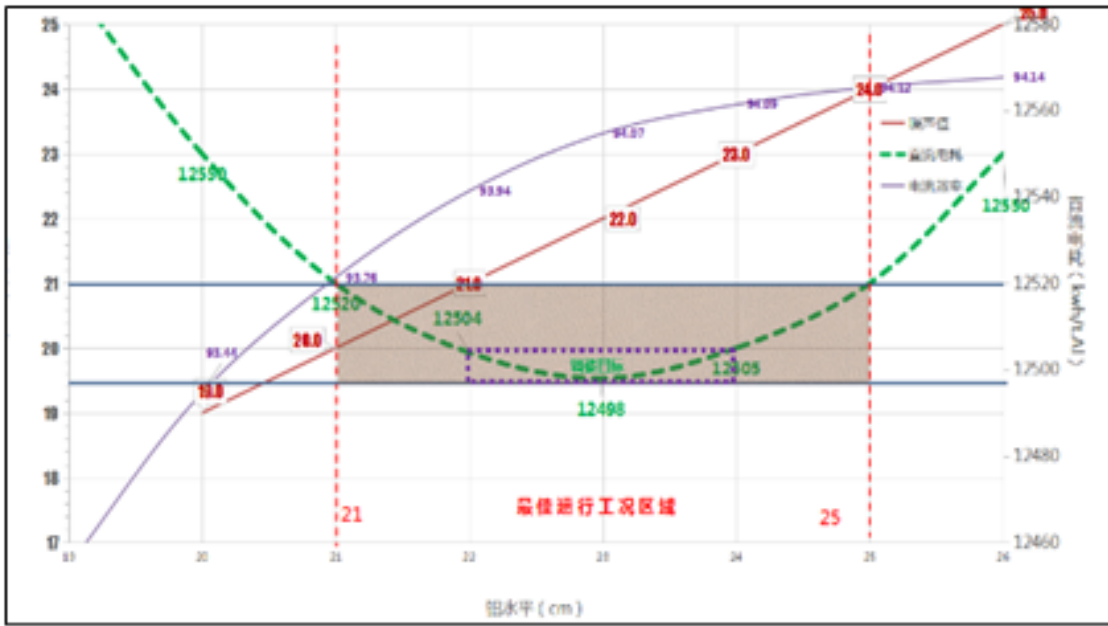
In order to achieve the dual objective of balancing cell stability and efficiency, specifically, maintaining the noise below 21 mV and direct current (DC) energy consumption below 12 520 kWh/t Al, an optimal control model for key process parameters, including bath temperature, molecular ratio, cell voltage, and metal height, was developed through analysis. The model specifies the following control ranges: bath temperature should be maintained at 950–958 °C, molecular ratio at 2.35–2.48, metal height at 21–25 cm; and cell voltage at 3.939–3.954 V.



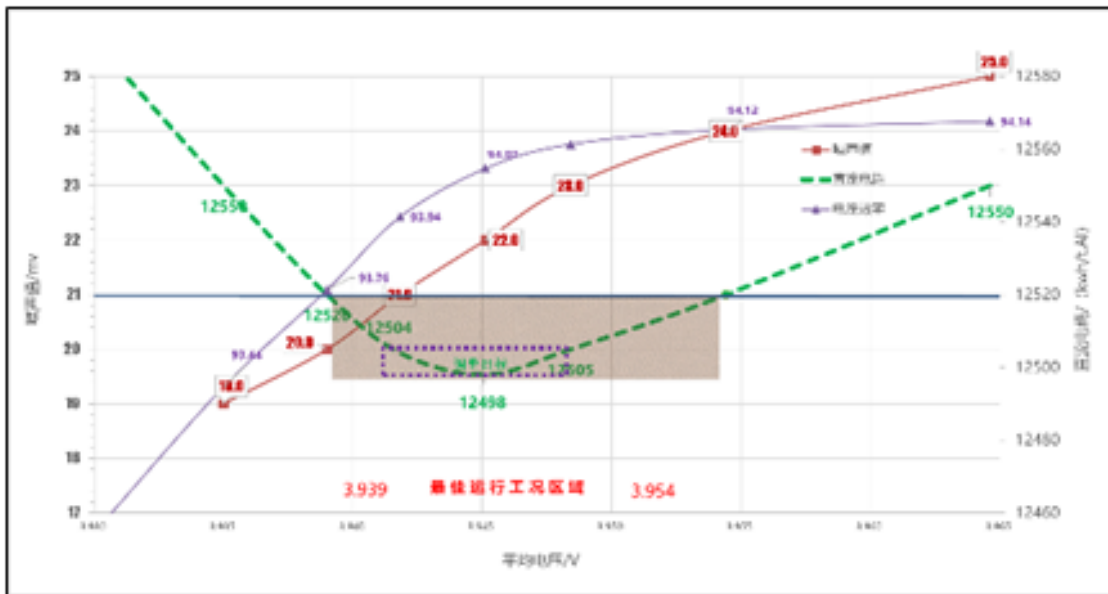
(a) Bath temperature control model. Where: x-axis = Bath temperature (range 948–965 °C); left y-axis = noise (range 17–25 mV); right y-axis = specific power consumption (range 12460–12580 kWh/t Al); Green dot line = correlation line with specific power consumption; Violet line = correlation with current efficiency (%); Red line = correlation with noise (mV); Dark area: Optimal working conditions zone = 950–958 °C for bath temperature (red dot lines), below 21 mV for noise and 12 520 kWh/t Al for specific consumption.



(b) Molar ratio control model. Where: x-axis = Molar ratio (range 2.25–2.6); left y-axis = noise (range 17–25 mV); right y-axis = specific power consumption (range 12460–12580 kWh/t Al); Green dot line = correlation line with specific power consumption; Violet line = correlation with current efficiency (%); Red line = correlation with noise (mV); Dark area: Optimal working conditions zone = 2.35–2.48 for molar ratio (red dot lines), below 21 mV for noise and below 12 520 kWh/t Al for specific consumption.



(c) Metal height control model. Where: x-axis = Metal height (range 19–26 cm); left y-axis = noise (range 17–25 mV); right y-axis = specific power consumption (range 12460–12580 kWh/t Al); Green dot line = correlation line with specific power consumption Violet line = correlation with current efficiency (%) Red line = correlation with noise (mV); Dark area: Optimal working conditions zone = 21–25 cm for metal height (red dot lines), below 21 mV for noise and below 12 520 kWh/t Al for specific consumption.



(a) Average voltage control model. Where: x-axis = Voltage (range 3.930–3.965 V); left y-axis = noise (range 17–25 mV); right y-axis = specific power consumption (range 12460 – 12580 kWh/t Al); Green dot line = correlation line with specific power consumption; Violet line = correlation with Current Efficiency (%); Red line = correlation with noise (mV); Dark area: Optimal working conditions zone = 3.939–3.954V for voltage, below 21 mV for noise and below 12 520 kWh/t Al for specific consumption.

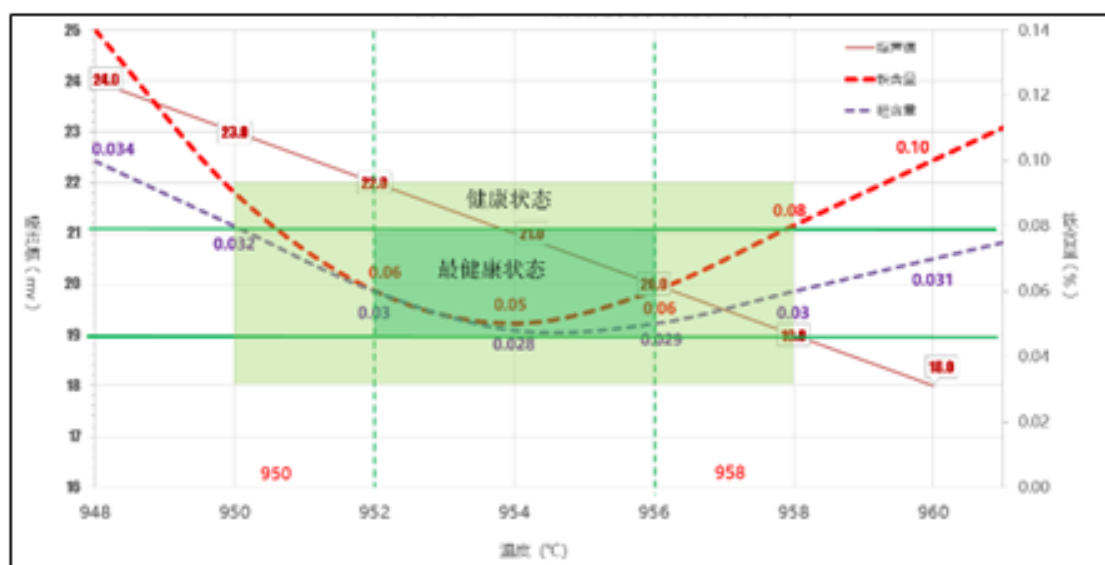
Figure 4 (a)(b)(c)(d). Low energy consumption control models for the cell.

According to the optimal model of process parameters, the safe, stable, and efficient parameter control range for the cell is as follows: the bath temperature should be maintained at 950–958 °C, the molecular ratio should be controlled within the range of 2.30–2.50, the metal height should be maintained at 20–24 cm; and the cell voltage should be kept within 3.939–3.945 V. However, conventional process technology typically adjusts only three parameters: aluminium tapping mass, aluminium fluoride content and set voltage.

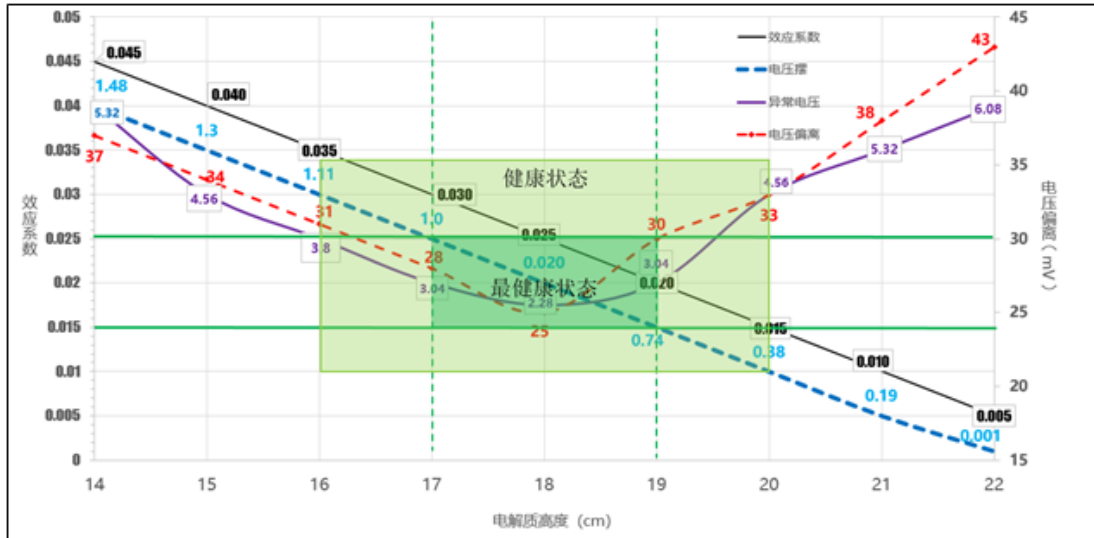
According to the optimal model of process parameters, the safe, stable, and efficient parameter control range for the cell is as follows (the process indicators and operational indicators): noise is within 18–22 mV, the cell temperature ranges 950–958 °C, the molar ratio falls 2.35–2.45; the anode effect frequency is ≤ 0.025 ; the voltage swing is ≤ 1 minute; the duration of abnormal voltage is ≤ 3 minutes, with a voltage deviation of 25–30 mV; and the bath height is within 17–19 cm.

Through the above practice, the relevant indicators of this batch of cells have been optimized as shown in Table 8.

Following the implementation of the technology, DC energy consumption decreased by 628 kWh/t Al, and key consumption indicators, including anode gross consumption and specific alumina consumption, were all significantly reduced.



(a) Bath temperature health model. Where: x-axis = Bath temperature (range 948–965 °C); left y-axis = Noise (range 16–25 mV); right y-axis = (range 0–14); Red line = correlation with noise (mV); Light-Green area: Healthy zone = 950–958 °C for bath temperature, below 22 mV for noise; Dark-Green area: Optimal Health zone = 952–956 °C for bath temperature (green dot lines), below 21 mV for noise.



(b) Operational indicator health model. Where: x-axis = Bath height (range 14–22 cm); left y-axis = Anode Effect frequency (range 0–0.05 AE/cell·day); right y-axis = Overtoltage (range 15–45 mV); Black line = correlation with Anode Effect Rate; Red dot line = correlation with overvoltage; Violet line = correlation with overvoltage duration (min); Light-Green area: Healthy zone = 16–20 cm for bath level, below 0.034 AE/cell.day and below 36 mV of overvoltage; Dark-Green area: Optimal Health zone = 17–19 cm for bath level (green dot lines), below 0.025 AE/cell.day and below 30 mV of overvoltage.

Figure 5 (a)(b). Health control model for the cell.

Table 8. Comparison of technical indicators.

No.	Description	Unit	Before	After
1	Current	kA	500	500
2	Average cell voltage	V	3.980	3.886
3	Current efficiency	%	91.75	94.16
4	DC energy consumption	kWh/t Al	12 926	12 298
5	Anode effect frequency	AE/cell·day	0.049	0.019
6	Anode gross consumption	kg C/t Al	482	456
7	Specific alumina consumption	kg Al ₂ O ₃ /t Al	1 915	1 908

6. Conclusions

The project team has conducted tests and analysis on the overall cell voltage drop to identify directions for technology improvement. By optimizing the cathode lining and cathode collector bar structure, the cathode voltage drop was reduced, creating conditions for low-voltage operation of the cells. At the same time, by developing process technology management for early operation and steady-state operation of the cell, stable operation under low cell voltage was also achieved. The application of auxiliary energy-saving technologies has further enhanced cell MHD stability and current efficiency, laying the foundation for low-voltage and high-efficiency operations. All these measures reduced DC energy consumption by 628 kWh/t Al. This technological route provides a reference for the low energy-consuming development of the industry. By optimizing the lining design and the design of the cathode collector bars, the cathode voltage drop was reduced, thereby enabling low-voltage operation of the cells. This technical approach serves as a valuable reference for advancing energy efficiency across the industry.

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