Analysis of New Energy-Saving Technology 2.0 of Different Cathode Materials and Cell Types

Huaijiang Wang[1], Yanan Zhang[2], Qingguo Jiao[3], Yongfeng Cao[4], Guisheng Liang[5] and Bin Fang[6]
1. Vice General Manager - Professor Level Senior Engineer
2. Director - Professor Level Senior Engineer
3, 4, 6. Second Level Researcher - Professor Level Senior Engineers
5. Fourth Level Researcher - Engineer
Zhengzhou Non-ferrous Metals Research Institute of Chalco (ZRI), Zhengzhou, China
Corresponding author: zhangyanan828@163.com
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Abstract

As a high energy consumption industry, aluminium electrolysis has always pursued energy saving and consumption reduction as its goal. Zhengzhou Non-ferrous Metals Research Institute of Chalco has successfully developed the new energy-saving technology for current stabilization and thermal insulation of aluminium electrolysis cells, which effectively addresses technical challenges such as high energy consumption, low efficiency, and short service life of aluminium reduction cells, and achieves the goal of substantial energy saving and emission reduction. This paper provides a detailed analysis of the industrial application of the new energy-saving technology 2.0 across different cathode materials and cell types. Compared with the 1.0 version, this technology can further reduce DC power consumption by approximately 200 kWh/t Al, offering crucial technical support for achieving substantial energy-saving and carbon reduction in the aluminium industry.

Keywords: Aluminium electrolysis, Current stabilization and thermal insulation of cells, Energy consumption, Energy-saving.

1. Introduction

In 2024, China's primary aluminium production reached 43.396 million tonnes (data form International Aluminium Institute), accounting for 59.4 % of global production, maintaining its position as the world's largest producer for many years. To advance industrial structural upgrades and implement the "Dual Carbon Goals", the Chinese government has introduced multiple industrial policies to guide the aluminium industry in accelerating energy-saving and carbon reduction, thereby promoting low-carbon, and high-quality development of the aluminium industry.

Based on the physical field test data and system research of the cells in the past 30 years, through basic theory research, laboratory simulation, pilot and scale-up test verification, Zhengzhou Non-ferrous Metals Research Institute of Chalco has successfully developed the new energy-saving technology for current stabilization and thermal insulation of aluminium reduction cells. This innovative technology effectively addresses the technical challenges of high energy consumption, low efficiency, and short service life in aluminium reduction cells, achieving significant energy-saving and emission reduction. Building upon the accumulated expertise in the new energy-saving technology, the R&D team further integrated key technologies such as structural optimization of fully graphitized and fully graphitic cathode blocks and innovations in cast iron rodding, leading to the development of the new energy-saving technology 2.0 [1–3]. Through compatibility verification in mainstream domestic electrolytic cells ranging 200–500 kA, this technology has achieved large-scale application with diverse cathode material configurations, including fully graphitized cathodes and full graphitic cathodes, demonstrating significant energy-saving effects and providing an innovative solution for the industry's green transition.

2. Application Analysis of New Energy-Saving Technology 2.0

2.1 Performance of Cathode Materials

Chinese aluminium smelters predominantly use traditional carbon-based cathode materials such as GS-3 and GS-5 during cell relining, while fully graphitized or full graphitic cathode materials, despite their significant performance advantages, have not been widely used. This is primarily due to the long processing cycles and high costs associated with their complex forming processes. Table 1gives the physical characteristics of four types of cathode carbon block materials. It is evident that fully graphitized and full graphitic cathodes have significant advantages in three key indicators: electrical resistivity, thermal conductivity, and sodium expansion coefficient. Notably, their room temperature resistivity can be reduced by over 50 % compared to GS-3 and GS-5 carbon-based materials [4]. The simulation data indicate that the cathode voltage drop of fully graphitized and fully graphitic cathodes is the range of 180–220 mV, representing a reduction of 25–30 % compared to traditional cathode materials. This voltage drop advantage creates dual benefits for cell operation: it increases current efficiency while maintaining the same anode-to-cathode distance or enables further reduction in cell voltage while preserving the original current efficiency.

Table 1. Performance indicators of different cathode carbon block materials.

Material	Real density g/cm^3	Room temperature resistivity μΩ·m	Compressive strength, Mpa	Bending strength Mpa	Young's modulus GPa	Sodium expansion %	Thermal conductivity W/m·K
	≥	≤	≥	≥	≤	≤	≥
GS-3	1.95	35	24	7	7	0.8	8–16
GS-5	1.99	30	24	7	7	0.7	12–25
Full graphitic cathode	2.08	21	26	7.5	7.5	0.5	20–35
Fully graphitized cathode	2.18	12	20	7	2.8	0.35	120

2.2 Characteristics of Cell Type

Aluminium electrolysis is a molten salt electrolysis process at 940–960 °C. This temperature range is critical for cell stability and efficiency, but has energy consumption challenges. An effective approach for energy saving is improving the utilization efficiency of electrical energy and reducing reactive power loss. Notably, due to the quadratic relationship between Joule heat and current, the heat generation is nonlinear [5]. As can be seen from Table 2, the unit heat flux density of the 500 kA large-scale cell is reduced by 14.1 % compared with the 200 kA cell type. Therefore, based on the thermo-electric coupling characteristics of the cells with different amperages, the new energy-saving technology 2.0 uses different cathode configurations.

Table 2. Comparison of cell capacity and heat dissipation area per unit capacity.

Cell amperage, kA	Total heat dissipation area, m^2	Heat dissipation area per kA, m^2/kA
200	42–46	0.21–0.23
300	58–63	0.193–0.21
400	76–82	0.19–0.205
500	92–98	0.184–0.196

2.3 Cast Iron RoddingTechnology

In the cathode rodding, cathode carbon blocks, and collector bars are connected primarily in two ways: paste ramming and cast iron. While the traditional paste ramming can achieve initial low contact resistance, under high-temperature operating conditions, the contact between carbon and collector bars drives a carburization rate of steel as high as 0.8–1.2 mm/year. This carbon penetration changes the microstructure of the collector bars, causing the contact voltage drop to increase at an annual rate of 15–20 mV. The relationship between carbon content and collector bar resistivity is presented in Table 3. In comparison, the cast iron achieves metallurgical bonding between molten cast iron and the cathode collector bar, forming a transition layer with controllable thickness that significantly slows down the carburization cycle. Meanwhile, this process optimizes the cast iron composition to create a self-expansion effect, effectively stabilizing contact voltage drop and making an equivalent wide-collector-bar structure, which reduces the horizontal current density of the metal pad by over 35 %.

Table 3. Relationship between carbon content and resistivity of sealing cast iron at room temperature.

Item	Units	Data						
Carbon content	(%)	0.1	0.3	0.4	0.55	0.7	0.8	0.95
Electrical resistivity	μΩ·m	0.15	0.18	0.19	0.21	0.226	0.236	0.26

3. Design of New Energy-Saving Technology 2.0 for Current Stabilization and Thermal Insulation Aluminium Reduction Cells

Zhengzhou Non-ferrous Metals Research Institute of Chalco has established a differentiated cathode technology approach based on thermo-electric coupling simulation and material property research: fully graphitic cathodes are used for cells with amperage ≤ 300 kA, while fully graphitized cathodes are used for cells with amperage > 300 kA. By coupling the energy balance optimization and voltage balance control, a multi-dimensional parameter collaborative model of the cell was developed, and industrial tests of the new energy-saving technology 2.0 for the current stabilization and thermal insulation aluminium reduction cells were carried out on 200 kA, 300 kA, 400 kA, and 500 kA cells.

3.1 Voltage Balance Design

The energy-saving technology 2.0 uses full graphitic or fully graphitized cathode blocks and cast iron rodding, which can reduce the cathode voltage drop to less than 220 mV. By integrating technologies such as aluminium-steel direct welding, low-resistance anode stubs, and slotted anodes, the anode voltage drop is lower than 320 mV, enabling a target cell voltage of 3.84 V. The specific voltage balance and distribution are detailed in Table 4.

Table 4. Cell voltage balance of the new energy-saving technology 2.0.

Item	Fully graphitic cathode, mV	Fully graphitized cathode, mV
Anode rod contact	10	10
Anode rod	20	20
Anode stubs	35	35
Anode block with stub-carbon contact	255	255
External busbar voltage drop	220	220
Electrolyte voltage drop	1380	1380
Back EMF	1700	1700
Cathode voltage drop	220	200
Cell voltage	3840	3820

3.2 Energy Balance Design

The sidewall design of the new energy-saving technology 2.0 is upgraded from high heat loss to good thermal insulation, and silicon carbide-silicon nitride side wall with vermiculite thermal insulation brick. The cathode bottom uses nano hard calcium silicate insulation boards and nano microporous insulation panels to increase thermal insulation. The optimized energy balance enables the cell total heat loss below 1.62 V equivalent, with bottom heat loss reduced to less than 6 %. The electrolyte liquidus isotherm in the barrier material is controlled, ensuring the cathode thermal stability of the cathode materials [6]. The energy balance design is detailed in Table 5.

Table 5. Energy balance of the new energy-saving technology 2.0 (equivalent voltage).

Heat dissipation zone		Fully graphitic cathode		Fully graphitized cathode	
		Heat dissipation (V)	Proportion (%)	Heat dissipation (V)	Proportion (%)
Anode zone	Large side cover plate	0.252	15.8	0.249	15.5
	Cell ledge cover	0.055	3.4	0.05	3.1
	End face cover plate	0.01	0.6	0.01	0.6
	Cell top	0.164	10.3	0.156	9.7
	Anode rod	0.045	2.8	0.045	2.8
	Fume	0.358	22.4	0.358	22.2
	Sub-total	0.884	55.4	0.868	53.9
Cathode zone	Molten zone	0.323	20.2	0.315	19.6
	Cathode block zone	0.124	7.8	0.132	8.2
	Refractory zone	0.04	2.5	0.04	2.5
	Cathode collector bars	0.075	4.7	0.08	5.0
	Side cradle	0.025	1.6	0.03	1.9
	Cell bottom	0.095	6.0	0.095	5.9
	Bottom cradle	0.03	1.9	0.05	3.1
	Sub-total	0.712	44.6	0.742	46.1
Total		1.596	100.0	1.61	100.0

3.3 Design of Process Technical Parameters

After adopting fully graphitic or fully graphitized cathodes in the new energy-saving technology 2.0, the voltage drop of the molten electrolyte decreases. Without altering the current, the heat input of the cell is significantly reduced, while the heat loss in the cathode zone increases markedly. To maintain the thermal balance of the cell, it is necessary to increase the upper insulation, increase the particle size and thickness of the anode cover material, reduce heat loss from the molten bath zone, and lower the metal height [7]. The design of the main technical parameters is shown in Table 6.

Table 6. Main technical parameters of new energy-saving technology 2.0.

Technical parameters	Units	Full graphitic cathode	Fully graphitized cathode
Cavity depth	mm	550–580	550–580
Metal height	cm	22–24	20–22
Bath height	cm	18–20	18–20
Molecular ratio		2.3–2.5	2.3–2.5
Superheat	°C	8–12	8–15
Alumina concentration	%	1.8–2.8	1.8–2.8
Anode-to-cathode distance	cm	4.0–4.2	4.0–4.2
Anode cover thickness	cm	20–25	20–25
Particle size of anode cover	mm	0.5–2	0.5–2

4. Industrial Test

In 2022, Zhengzhou Non-ferrous Metals Research Institute of Chalco initiated industrialized tests of its new energy-saving technology 2.0. Different cell types used different cathode materials to ensure voltage and energy balance, with all test cells achieving DC power consumption below 12 300 kWh/t Al. The technology was validated for industrial implementation in 2023.

4.1 Management During Cell Early Operation

The new energy-saving technology 2.0 uses a "3+1" management model during early operation, consisting of 3 months of target changes, followed by 1 month of adjustment. The voltage was gradually decreased to the designed range of 3.82–3.84 V in approximately 45–50 days, as shown in Figure 1. The metal height reached the long-term target range in 50–80 days, and the cryolite ratio reached the long-term target in 4 months. During this 4-month transition period, the test cell was in good condition, maintained excellent thermal balance, had low noise, and clean cathode surface [11].

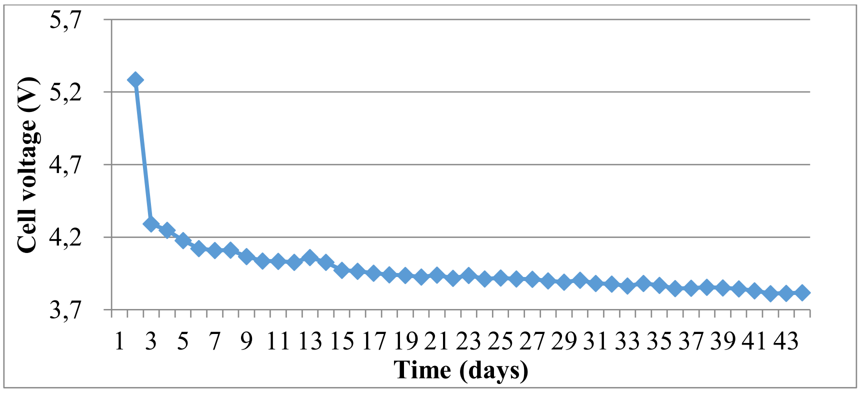

Figure 1. Voltage management of the test cell during early operation.

4.2 Cathode Voltage Drop (CVD)

The new energy-saving technology 2.0 has maintained a furnace bottom voltage drop of less than 220 mV throughout more than one year of industrial trials. Compared with the GS-5 reference cell started at the same time, the CVD of this cell was by 60–80 mV lower than the G-5 cells. The CVD of the four tested cells are shown in Figure 2.

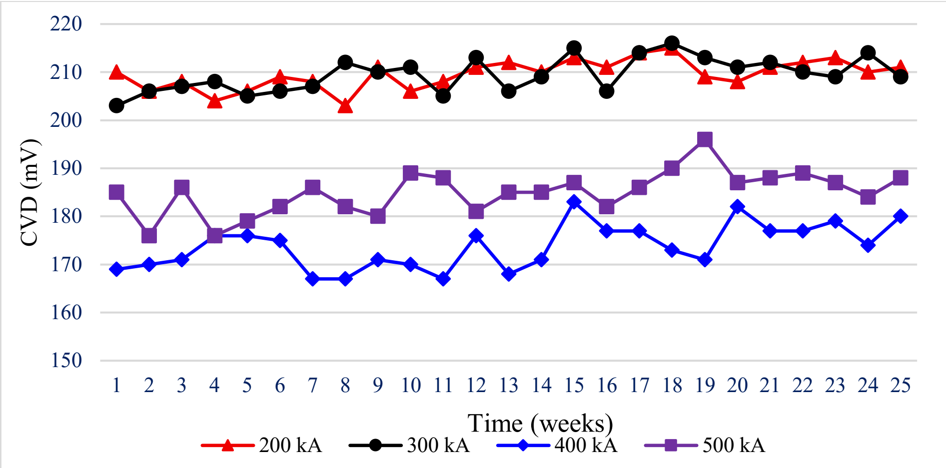

Figure 2. CVD of the test cell (black and red curves are graphitic cells).

4.3 Ledge Thickness

The formation of a certain ledge thickness is the essential for maintaining stable operation, prolonging service life, and keeping cell energy balance. New energy-saving technology 2.0 uses fully graphitic and fully graphitized cathodes, which have excellent thermal conductivity to facilitate the formation of side ledge. The ledge thickness of different cell types is greater than 15 cm, which is 4–8 cm thicker than that of ordinary cells, and the potshell window temperature is lower than 300 °C, which is 30–50 °C lower than that of ordinary cells. The detailed measurement results are presented in Table 7.

Table 7. Ledge thickness and steel window temperature of different cells.

Item	Units	200 kA	300 kA	400 kA	500 kA
Ledge thickness	cm	18	16	17	16
Potshell window temperature	°C	286	291	288	297

4.4 DC Specific Energy Consumption

The new energy-saving technology 2.0, which has undergone over one year of industrial testing across four cell types (200 kA, 300 kA, 400 kA and 500 kA), demonstrates significant performance improvements. For the full graphitic cathode test cells, the average voltage was 3.855 V, with a current efficiency of 93.46 %, and the overall DC power consumption was 12 292 kWh/t Al. For the fully graphitized cathode test cells, the average voltage was 3.832 V, with a current efficiency of 93.38 %, and the overall DC power consumption was 12 229 kWh/t Al. Compared to the previous version 1.0 technology, this new version reduced energy consumption by more than 200 kWh/t Al, achieving benchmark level within the industry. Detailed key performance indicators are presented in Table 8.

Table 8. Average voltage, current efficiency, and DC power consumption of different cell types.

Item	Units	200 kA	300 kA	Avg.	400 kA	500 kA	Avg.
Average voltage	V	3.864	3.846	3.855	3.848	3.816	3.832
Current efficiency	%	93.64	93.28	93.46	93.53	93.23	93.38
DC power consumption	kWh/t Al	12 297	12 287	12 292	12 260	12 197	12 229

5. Conclusions

The new energy-saving technology 2.0 for current stabilization and thermal insulation aluminium reduction cells, developed by Zhengzhou Non-ferrous Metals Research Institute of Chalco, is well aligned with national energy policies. By fully implementing all graphitic or all graphitized cathodes and cast iron rodding of cathode blocks, the technology enables significant reduction of specific energy consumption. Industrial tests demonstrate that the cathode voltage drop remains below 220 mV, with the overall average DC power consumption of 12 261 kWh/t Al. Compared to the previous version of the technology, this upgraded solution reduced specific energy consumption by more than 200 kWh/t Al, attaining benchmark level within the industry.

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