The Development of Energy-Saving and Digital Intelligence Technologies for Primary Aluminium Industry in China

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Abstract

In the past 20 years, the Chinese primary aluminium industry faced new challenges, such as the stricter standards for both carbon emission and energy-saving, the impoverishment of bauxite resources, the deterioration of petroleum coke quality, the complexity of the spatial and temporal distribution characteristics of high/ultra-high amperage cells, and the shortage of labour resources. Therefore, the technical teams of Chinese aluminium industry, represented by experts from Aluminium Corporation of China and Central South University, developed a complete set of energy-saving, low-carbon and digital, intelligent aluminium electrolysis technology. This was a major breakthrough in energy conservation and carbon reduction and played a key role in maintaining the global leading position of energy consumption indicators for Chinese aluminium industry. A new method for online monitoring and regulation of the spatial and temporal distribution characteristics of high/ultra-high amperage aluminium electrolysis cells was proposed, and the key technology of intelligent optimization and manufacturing of aluminium electrolysis was developed. This technology is based on distributed monitoring and digital twin, resulting in "the digital intelligence of distribution parameters" for the control of aluminium electrolysis process, which opened new opportunities for energy saving, carbon emission reduction, and process efficiency improvement. The combination of innovative cathode design, and multi-field optimization improved magnetohydrodynamic stability of the cells. Energy saving technology, based on steady flow and heat preservation, was developed, which enabled the cell voltage reduction for a further energy saving in varying cell operation environment and production conditions of Chinese aluminium industry. The production and application of dust-free prebaked anodes solved technical problems caused by the quality deterioration of both anodes and alumina.

The application of these technologies reduced the cathode voltage drop by about 150 mV, increased the current efficiency by 0.5~1.5 %, reduced the amount of carbon dust by half, increased the labour productivity by more than 30 %, and reduced the energy consumption by 200 to 600 kWh/t Al. In 2023, the average overall AC power consumption of Chinese primary aluminium was 13 324 kWh/t Al, a decrease of 2 155 kWh/t Al compared with that of 20 years ago, which is absolutely a tremendous improvement in energy conservation and emission reduction.

Keywords: Aluminium electrolysis, Prebaked anodes, Magnetohydrodynamic stability, Energy saving, Digital intelligence.

1. Introduction

The aluminium electrolysis process is a high temperature electrochemical metallurgical process under the coupling of multi-fields (six kinds of physical fields, such as electric, magnetic, thermal, force, flow, concentration) and multiphase flow (gas, liquid and solid phase). The process mechanism and reaction characteristics of material and energy balance are complex, and energy saving and carbon footprint reduction has always been a worldwide technical problem.

Since the 1990s, Chinese aluminium electrolysis industry made a remarkable progress in energy conservation and emission reduction. But in the past 20 years, it faced many new challenges, such as stricter energy consumption and carbon emission standards, poor and inferior quality of bauxite and petroleum coke, complex spatial distribution of parameters in high/ultra-high amperage cells, labour shortage, and production and management concentration.

In particular, some of these factors also caused new problems that worsened the operation conditions of the cells, such as great length and high reaction area (> 110 m^2) in 600 kA electrolysis cels., due to increased magnitude of various physical fields and their coupling.

The degrading bauxites in alumina production accelerated the accumulation of impurities which form complex electrolyte in the cell. The inferior quality of petroleum coke for anode production led to the degradation of anode quality and excessive carbon dusting in the complex electrolyte, which worsened the dispersion and dissolution of alumina and increased the non-uniformity of the local distribution of alumina concentration. The joint effect of these factors deteriorated the MHD stability of the cell. The controllable domain of important state parameters was significantly narrowed. The key performance indicators (KPIs) of the cell were seriously affected and started to fluctuate easily in a wider range.

Facing above challenges, Chinese aluminium electrolysis research and development made great progress in energy saving and low-carbon aluminium production, using digital intelligence.

2. The Leap from the "Lumped Parameter Automation" to the "Distributed Parameter Intelligence"

The intelligent control technology of aluminium electrolysis developed and applied in China has contributed to energy-saving and emission reduction. However, with the upsizing of electrolysis cells and the consequently deteriorating operation conditions, the existing control technology, based on the online collection of two lumped parameters (cell voltage and current), is unable to process distributed online sensing and local control of the complex spatial and temporal distribution of high/ultra-high amperage cells. It was difficult to maximize the potential of energy saving, carbon reduction and process efficiency increase. It was also difficult to meet the new demand for more precise production control, let alone to support the construction of intelligent optimization manufacturing technology for aluminium electrolysis industry.

Chinese researchers developed a distributed-parameter accurate online monitoring, based on online distributed measurements and physical field modelling, and expanded the collection points of aluminium electrolysis cell online parameters from the traditional 2 types and 2 points to a maximum of 7 types and 297 points, with low-cost monitoring of individual anode current distribution and other distributed parameters, which had eluded the aluminium industry for a long time. A "dual-simulation" method was developed to extract the dynamic distribution of key parameters, such as local alumina concentration in the cell from the online monitoring of anode current distribution, and digital twin construction of aluminium electrolysis [1].

Based on data and process integration, a method of material balance, energy balance and stability monitoring and process adjustment for aluminium electrolysis was invented [2, 3]. An integrated intelligent control system [4], based on cell digital twin, was developed (Figure 1).

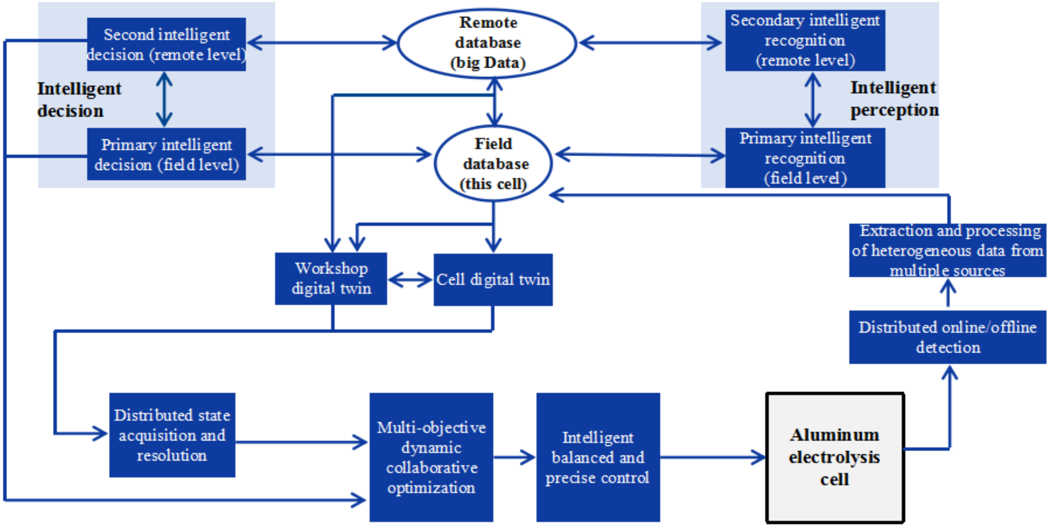


Figure 1. Principle of distributed monitoring - condition recognition - digital twin - partition control - intelligent decision.

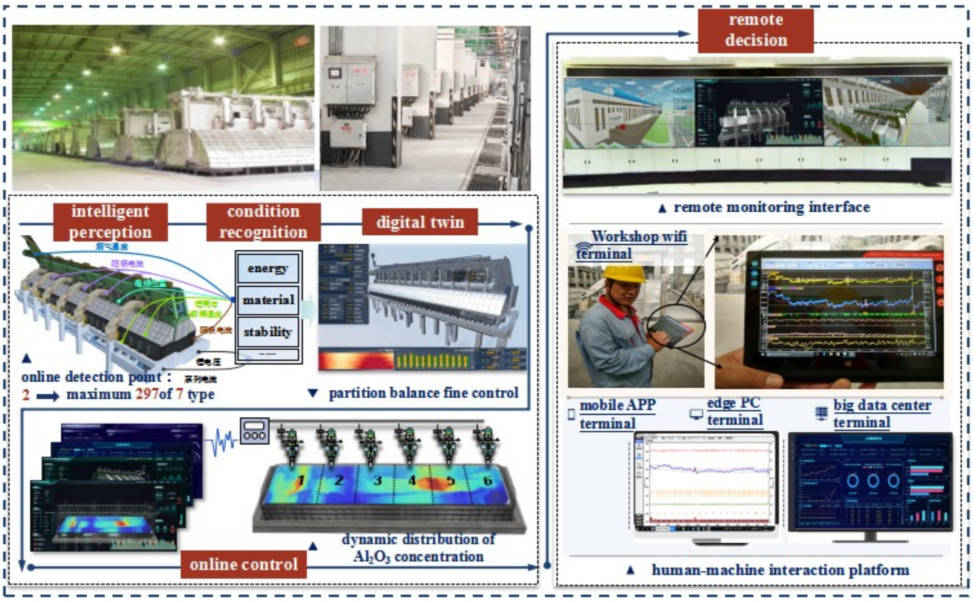


Figure 2. Comprehensive service platform and integrated technology of "intelligent monitoring - working condition recognition - digital twin - online control - remote decision" for aluminium electrolysis.

A complete set of key technologies and integrated service platform of "distributed monitoring - working condition recognition - digital twin - online control - remote decision" was formed (Figure 2). It integrated online sensing and localized control of spatial and temporal distribution of high/ultra-high amperage cells. The technology enables the aluminium electrolysis production control to upgrade from the "lumped parameter automation" era to the "distributed parameter intelligence" era. The large-scale application of more than three years showed that the local deviation of alumina concentration in the cell reduced by 80 % on average (in other words, the uniformity was increased by 80 %). The incidence of sick cells reduced by more than 50 %, the energy consumption decreased by more than 200 kWh/t Al, and the labour productivity of the aluminium smelter increased by 30 %.

3. Bottleneck to Increase Energy Saving by Reducing the Cell Voltage was Eliminated

Bath and metal flow, driven by electromagnetic forces (MHD), play a vital role in the operational stability and cell performance. The better the MHD, the lower the anode-cathode distance (ACD) can be set, and the lower the corresponding cell voltage can be reached, and finally, the lower the DC power consumption can be obtained. The Chinese aluminium industry achieved maximum low voltage energy saving by creating a new low voltage technology for aluminium electrolysis and by developing intelligent ACD control. However, with the upsizing of the cells and the adoption of more extreme operating conditions, the existing technologies have shown limits or deficiencies in MHD stability, Improvement of MHD to further reduce the cell voltage and increase energy savings, became a major industry goal in the new era.

Based on the study of the complex coupling relationship between multi-field and multiphase in high amperage cell, we put forward a new technical concept and method to increase the MHD stability. as well as to reduce the cathode voltage drop of the cathode by changing materials, structure and mode of the cathode collector bars and cathode carbon block [5]. A highly conductive cathode collector bar [6] was developed by the optimized combination of conductivity/permeability and structure/size matching. Graphitized cathode blocks with cast iron rodding were applied [7]. The energy balance strategy of the electrolysis cell was optimized to get good heat balance and minimize the stress in cathode lining. The application of these innovative technologies made the current distribution in liquid metal more uniform (Figure 3). The vertical current of the cathode carbon block increased by 2.9 % along the longitudinal axis and decreased by 32.7 % at downstream side, which reduced the fluctuation of liquid aluminium. The maximum deformation of the interface of liquid aluminium decreased by 0.3 cm or 11 % (Figure 4), which significantly increased MHD stability of the cells. At the same time, the bath flow velocity distribution was optimized to rapidly disperse and dissolve alumina. The isotherm distribution was also optimized (Figure 5) and heat loss in each area was reduced (Figure 6), creating positive conditions for low-voltage and energy-saving operation and extended cell life. It significantly reduced the cathode voltage drop, which contributed to energy saving. Industrial applications showed that the cathode voltage reduced by about 150 mV (reduction of about 50 %), energy consumption decreased by 200–600 kWh/t Al, while the current efficiency increased by 0.5–1.5 %.

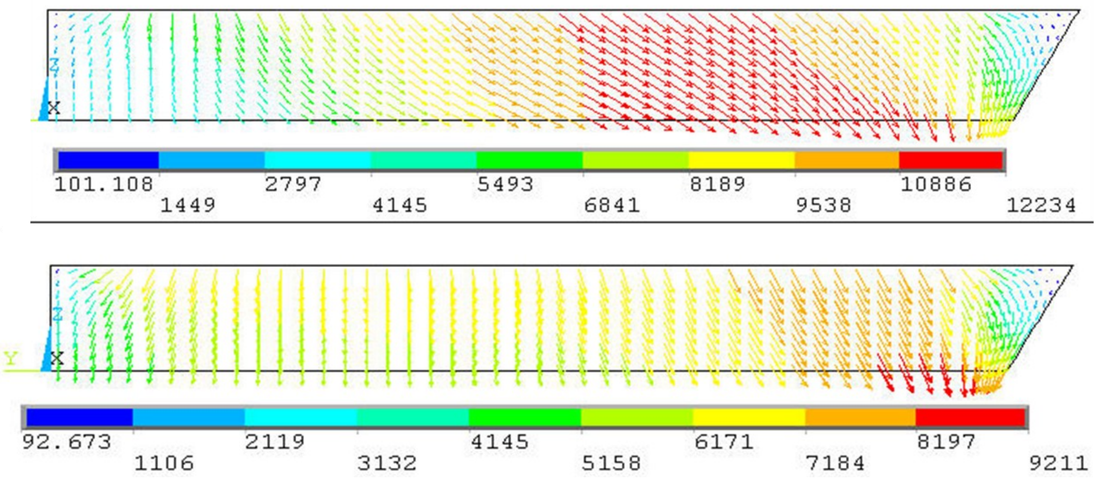


Figure 3. Current distribution in liquid aluminium. Top: before optimization, Bottom: after optimization.

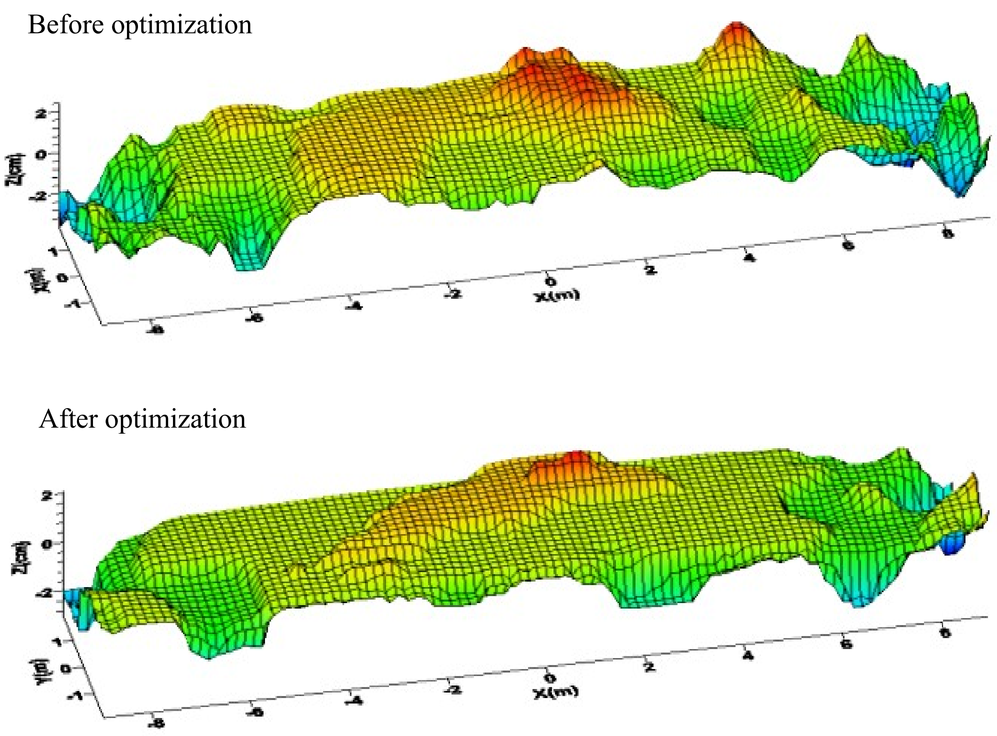


Figure 4. Deformation of the metal-bath interface in the cell.

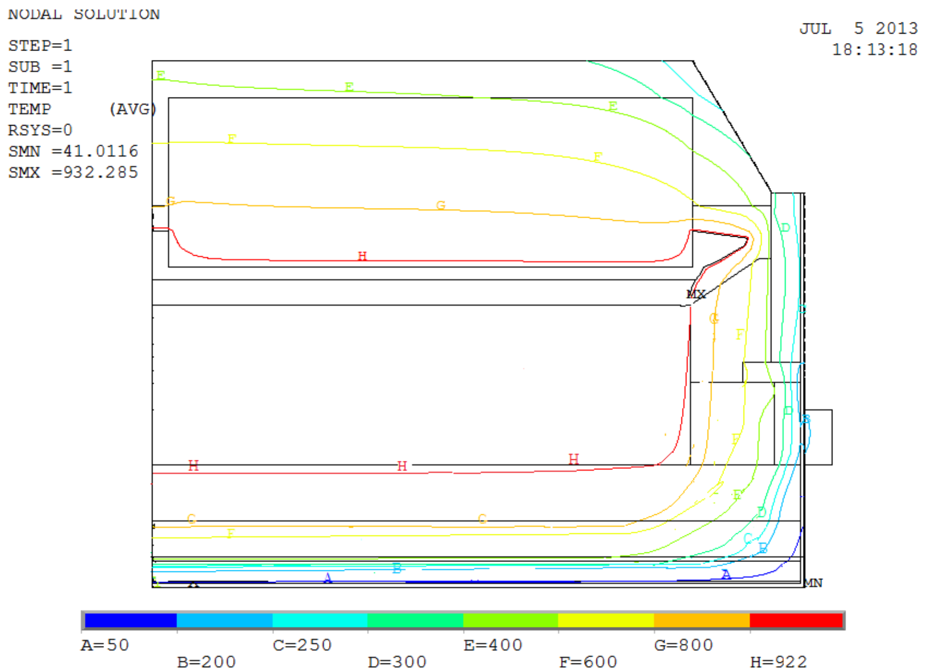


Figure 5. Optimization of isotherm distribution.

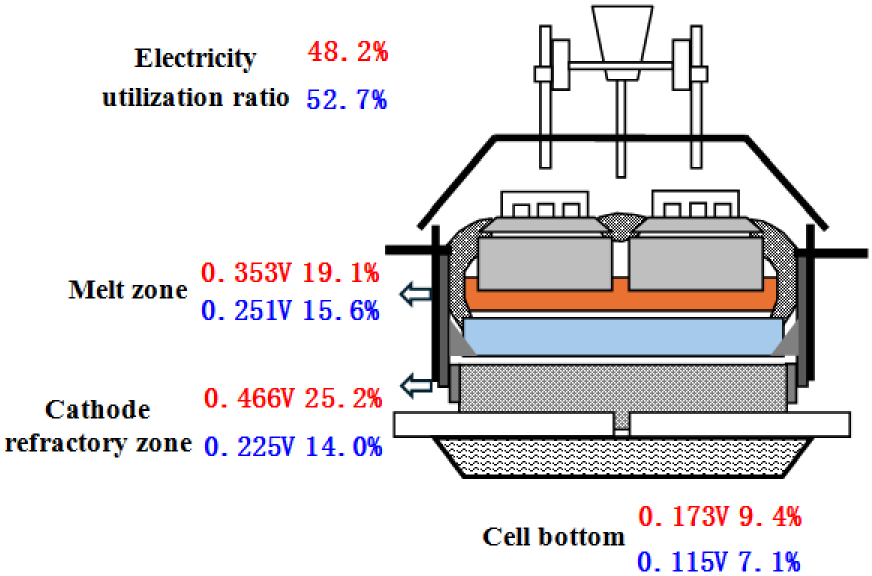


Figure 6. Distribution of heat dissipation before and after optimization. Number before optimization in red, number after optimization in blue.

4. The Problem of Low-Quality Anodes and Complex Bath Composition Was Solved

In the past, high-quality anodes with selected petroleum coke were used in China. For the last ten years, the output of Chinese prebaked anodes increased greatly with the rapid development of aluminium industry, while the increase of petroleum coke output was not following. In China, more than 60 % of the world's prebaked anode output was supported by about 30 % of the world's petroleum coke output. The structural shortage of petroleum coke and the increasingly inferior quality of petroleum coke had adverse effects on anode quality.

More than 10 years ago, alumina with low impurity content was used in Chinese smelters in order to keep pure electrolytes without LiF and KF. Since then, about 40 % of Chinese alumina was produced with domestic poor low-grade bauxite through enhanced dissolution process. The content of lithium, potassium and other impurities in alumina was high, which finally accumulated in the electrolysis cell as LiF and KF and resulted in a complex electrolyte.

The above two negative factors, poor anode quality and complex electrolyte composition, caused the increase of carbon dusting and anode burn-offs, which was hard to remove from the electrolyte. Moreover, the dispersion and dissolution of alumina in the electrolyte got worse, which seriously affected the operational stability of the cell and the KPIs, such as current efficiency and power consumption.

Dust-free prebaked anode technology was developed and applied in China, which was a combination of an innovated anode process with an optimized electrolysis process. For anode production process, the mechanism of defects in the anodes due to mismatched coke calcination temperature was found (Figure 7).

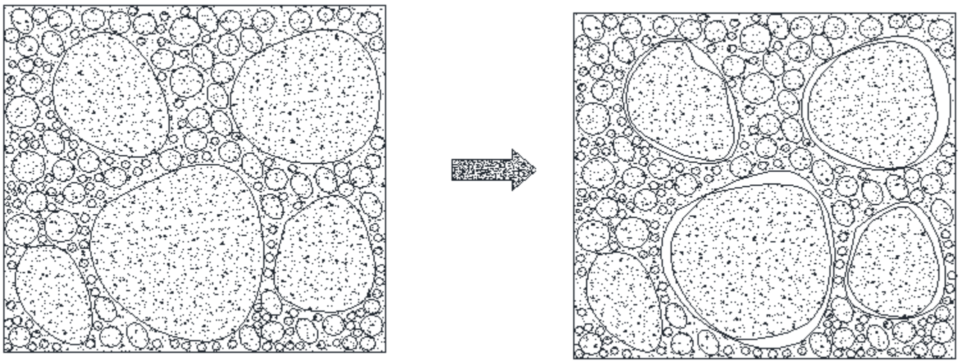


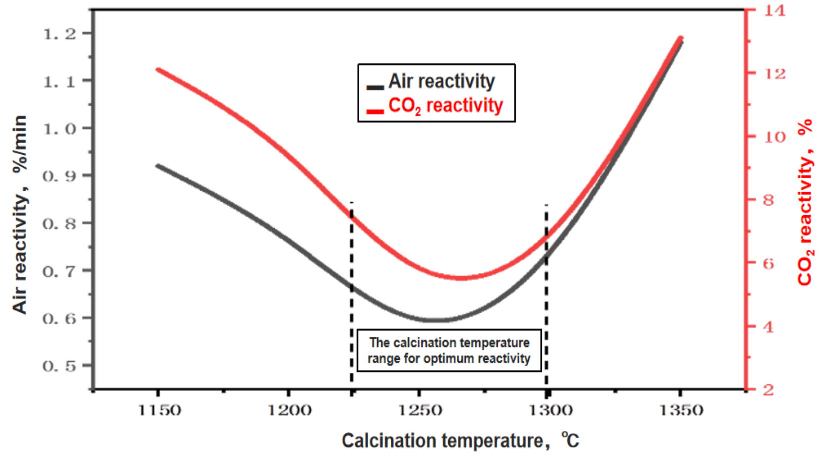
Figure 7. Internal anode defects caused by low-temperature calcination and high-temperature calcination.

Calcination temperature optimization based on gas reactivity, kneading temperature optimization based on pitch rheological properties and baking temperature optimization based on heat treatment effect equivalence were developed (Figure 8). A rapid control system for the key process parameters of anode production was established, which was suitable for the complex and variable quality of petroleum coke. The anode production process of "precise dosing - pitch optimization - high-density homogenization - three-temperature quantization optimization" was developed, and the double goals of improving anode quality and reducing anode production energy consumption was achieved. Based on the research results, China's national standard "*Energy consumption limit per unit product of carbon for aluminium use*" [8] was formulated. The mechanism of selective oxidation resulting in carbon dusting was found, and efficient antioxidants were developed. The particle size dosing technology [9] and zoned dosing technology [10] of raw materials with different qualities were invented. The "*activity inhibition - matrix modification*" technology was integrated and comprehensively improved the anode oxidation resistance. The residual ratio of air reactivity of prebaked anodes produced with low quality petroleum coke with high vanadium nickel, was increased from 60 % to more than 90 %. Based on the above research, a complete quality index system of dust free anodes was formulated (Table 1).

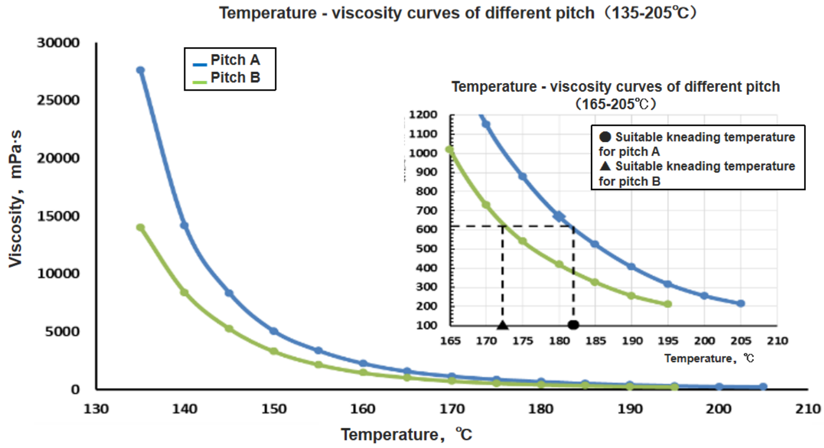
On the other hand, for the aluminium electrolysis process, the influence of lithium and potassium content, superheat, electrolyte temperature and molecular ratio of complex electrolytes on the wettability of carbon materials and carbon content in electrolytes was found. The key technology of carbon dust-free aluminium electrolysis production with the coupling matching of "lithium and potassium content - superheat - electrolyte temperature - molecular ratio" was established.

The application of this technology solved the problem of serious carbon dusting while using the anode produced with low-quality petroleum coke. The carbon dust in the cell reduced by more than 7 kg/t Al (about 50 %).

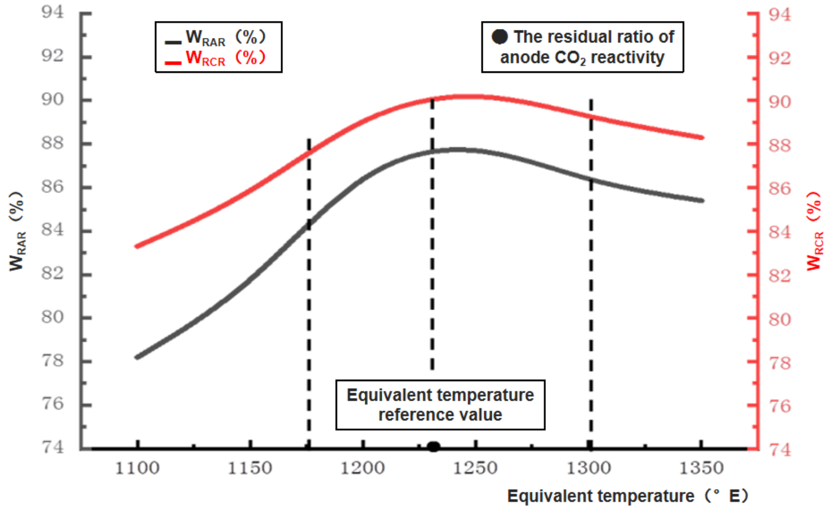
The technical teams of Chinese aluminium industry revealed the influence of deterioration of petroleum coke resources on anode oxidation activity and microstructure defects, the internal mechanism of the increase of anode dust caused by the comprehensive effect of microstructure defects and the complex electrolyte formed by high impurity alumina, and created the production and application technology of dust-free prebaked anode. It has overcome the major problem that the deterioration of aluminium smelting resources and the serious impact on the operation of aluminium electrolysis.



a. Calcination temperature optimization.



b. Kneading temperature optimization.



c. Baking temperature optimization.

Figure 8. Three temperature optimization technologies for "calcination-kneading-baking" key parameters of anode production

Table 1. Technical specifications of dust-free prebaked anode.

No.	Item	Unit	Indicator guarantee	No.	Item		Unit	Indicator guarantee
1	Ash content	%	≤ 0.5	11	CO_2 reactivity residual		%	≥ 90
2	Sulphur content	%	≤ 2.7		CO_2 reactivity loss		%	≤ 3
3	Apparent density	g/cm^3	≥ 1.57	12	Air reactivity residual		%	≥ 85
4	Real density	g/cm^3	≥ 2.07		Air reactivity loss		%	≤ 4
5	Electrical resistivity	μΩ·m	≤ 56	13	Content	Si	×10^{-6}	≤ 300
6	Compressive strength	MPa	≥ 35			Fe		≤ 500
7	Flexural strength	MPa	9.5–14			Ca		≤ 300
8	Coefficient thermal expansion	×10^{-6}/°C	≤ 4.5			V		≤ 200
9	Air permeability	nPm	≤ 2.5			Na		≤ 200
10	Thermal conductivity (20–60 °C)	W/m·K	≤ 4.5			Ni		≤ 230

5. Conclusions

The new technology application led to the following observations:

The main technical performance and technical and economic indicators of the energy-saving and low-carbon digital intelligent technology for aluminium electrolysis are at the leading level in the world. According to more than three years of large-scale application, current efficiency increased by 0.5–1.45 %, DC power consumption was reduced by 200-623 kWh/t Al. In addition, after application of the digital smart technology, the labour intensity of workers was significantly reduced, the incidence of abnormal cells was reduced by 50 %, and the labour productivity of the electrolysis plant increased by 30 %.

The research and development of this new technology played a leading and supporting role for Chinese aluminium electrolysis industry to continuously maintain and expand the global leading advantage of energy consumption, even in the case of deterioration of aluminium smelting resources (Figure 9). According to the statistics of the International Aluminium Association, the average comprehensive power consumption of China in 2022 was 1 560 kWh/t Al lower than that abroad (11.6 %). It is of great value and significance for Chinese aluminium electrolysis industry to implement a dual-carbon strategy, ensure resource security, accelerate the construction of digital and smart factories, and solve the problem of labour shortage.

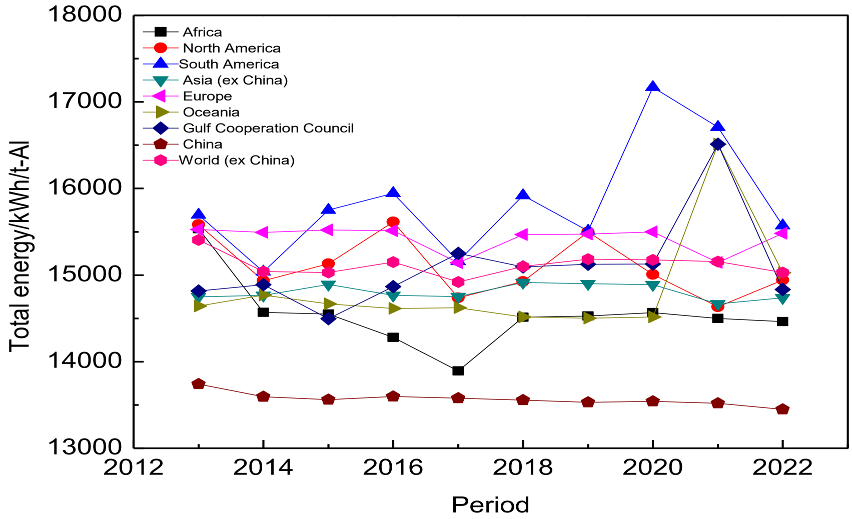


Figure 9. Specific energy consumption in China compared to the rest of the world.

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