Technological Innovations and Practices of Carbon Roasting Furnaces for Aluminium Under the Demand of Large-Scale and High-Quality Production

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https://doi.org/10.71659/icsoba2025-el014

Abstract

The outdated ring-type baking furnaces for aluminium suffer from issues such as small product sizes, low production capacity, high energy consumption, and significant challenges in retrofitting, making them unable to meet the growing demand for larger-scale and higher-quality products. To address these issues, the team conducted a comprehensive technical upgrade of the baking furnaces. Initially, the operating conditions and baking results of the outdated baking furnaces were assessed through extensive testing. Numerical simulations were then employed to iteratively calculate the temperature, flow, and pressure fields, achieving the development of an optimal upgrade plan. The specific modifications included optimizing the baking furnace structure by adjusting the size and shape of the combustion chamber and altering the flue design, as well as innovatively using new thermal insulation materials. Following the upgrades, systematic testing and process optimization were conducted on the newly modified baking furnace. As a result, the first-grade rate of carbon products increased by 10 %, the baking furnace's energy consumption was reduced to 1.74 GJ per tonne, and the baking furnace now meets the requirements for producing prebaked anodes for 600 kA electrolytic cells. Ultimately, the upgraded baking furnace achieved both energy savings and quality improvement.

Keywords: Ring-type baking furnace, Structural optimization, Numerical simulation, Quality improvement, Energy saving.

1. Background and Current Situation

China accounts for over 60 % of global electrolytic aluminium production. With the increasing demand for large-scale and energy-efficient technologies in the aluminium sector, the trend towards larger and higher-quality anodes has become inevitable. Currently, there are over 100 carbon anode producers in China, with a total production capacity of around 30 million tonnes and an actual output of around 23.1 million tonnes. As a critical component in the anode production process, the predominant carbon baking furnaces for aluminium are still in small sizes, only capable of producing small anodes suitable for 300 kA electrolytic cells, making it difficult to meet the increasing demand for larger cells. Some baking furnaces have been in operation for 10 to 20 years, and the aging equipment has resulted in three major issues: limited production capacity, difficulty in improving product quality, and persistently high energy consumption. To address these challenges, systematic upgrades are essential, with a focus on three key areas: optimizing the furnace structure, precisely controlling baking process parameters, and applying new materials while improving maintenance systems. Notably, numerical simulation technology provides innovative solutions for these upgrades. By developing advanced computational models, it not only reduces trial-and-error costs but also allows for accurate prediction and optimized control of the production process. This "digital twin + physical upgrade" approach significantly enhances both the economic viability and efficiency of the upgrades, offering critical technical support for the industry's transformation.

We have systematically upgraded traditional, outdated baking furnaces using a comprehensive approach that combines performance diagnostics, design optimization, and numerical simulations. By innovatively optimizing the geometry of the combustion chamber, improving the flue structure, and adopting new high-performance thermal insulation materials, we significantly enhanced the operational performance of the outdated baking furnaces, confirming the effectiveness of the upgrade plan. This paper provides a reliable technical pathway and practical reference for the modernization of similar baking furnaces.

2. Operations and Baking Results of Outdated Small-scale Baking Furnaces

2.1 Operations

Take a 36-chamber baking furnace from a carbon plant as an example: with dimensions of 5246 × 773 × 5340 mm (L × W × H) for each pit, this baking furnace is capable of producing small-sized carbon anodes with specifications of 1560 × 660 × 620 mm. The baking furnace has been in operation for 17 years, but it is no longer compatible with the production needs for larger anodes required by modern electrolytic cell process.

(a) (b)

Figure 1. (a) Deformation and sagging of the flue. (b) Oxidation of baked products.

On-site inspection of the baking system revealed several issues, including sagging and deformation of the flue. Due to the extended operation time of the baking furnace, some areas experience rapid temperature increases in the carbon blocks during critical periods. Additionally, abnormal cooling at certain points in the flue and localized overheating have led to the sagging and deformation of the flue, as shown in Figure 1(a). Moreover, significant oxidation was observed in products from certain areas of the baking furnace, as shown in Figure 1(b). The oxidized products are no longer suitable for aluminium electrolysis.

2.2 Baking Results

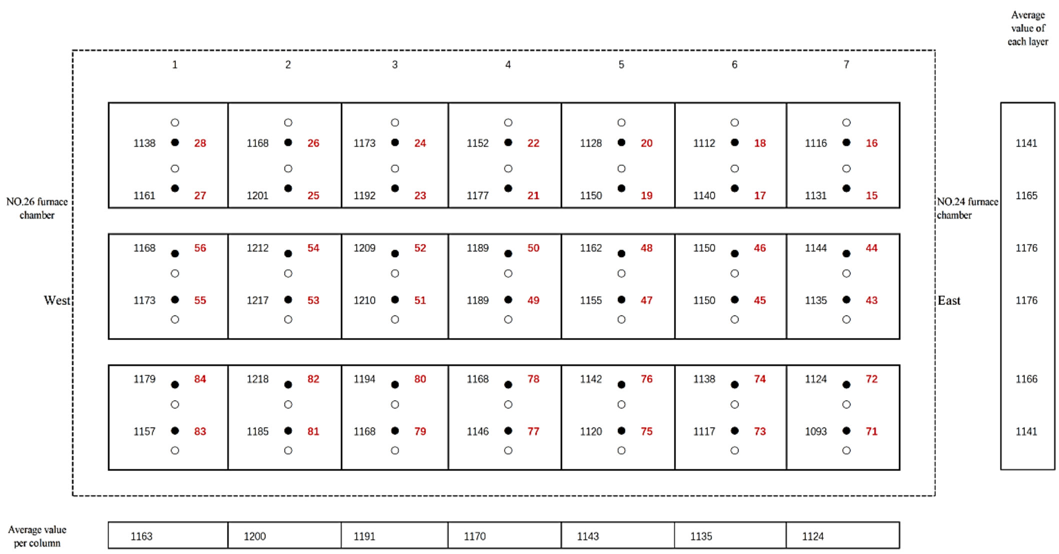
A comprehensive analysis was conducted on the dynamic temperature and baking results within the baking furnace's pit and flue. The results are presented below. Table 1 shows the final temperature at the side cross-section of the flue inside the pit. The measurements were taken at the upstream, midstream, and downstream sections across the upper, middle, and lower layers. The results indicate a temperature deviation of 47.8 ℃ at the cross-section, with significantly lower temperatures at the bottom layer and relatively higher temperatures in the middle section compared to both ends. The temperature variation across the section reached a maximum of 171 °C.

Table 1. Final temperature (°C) at the side cross-section of the flue inside the pit.

Location	Upstream	Midstream	Downstream	Average
Upper Layer	1081	1080	1069	1077
Middle Layer	1052	1127	1048	1076
Bottom Layer	990	1048	956	998
Average	1041	1085	1024	1050
Highest Temperature	1127			
Lowest Temperature	956			
Range	171			
Standard Deviation	47.8			

Equivalent baking temperature (EBT) is a physical quantity used to measure the degree of baking in a baking furnace. It is influenced not only by the final temperature but also by the heat retention time. Figure 2 shows the distribution of EBT inside the pit. The standard deviation inside the pit is 31.3 ºC, and the maximum variation in EBT across the upper, middle, and lower layers is 125 ºC. These significant temperature fluctuations affect the overall uniformity of the baking process.

Physicochemical index analysis of baked products. Samples were taken from the baked carbon blocks in the pit, specifically from Block 1 and Block 7 in the upper layer, Block 4 in the middle layer, and Block 1 and Block 7 in the bottom layer. Table 2 presents the physicochemical indexes of the samples. The average bulk density was approximately 1.575 g/cm^3, the electrical resistivity was 58.80 μΩ·m, and the air permeability was 2.90 nPm. Overall, the quality of the baked products before retrofitting exhibited noticeable fluctuations, and certain physicochemical indicators showed potential for further improvement.



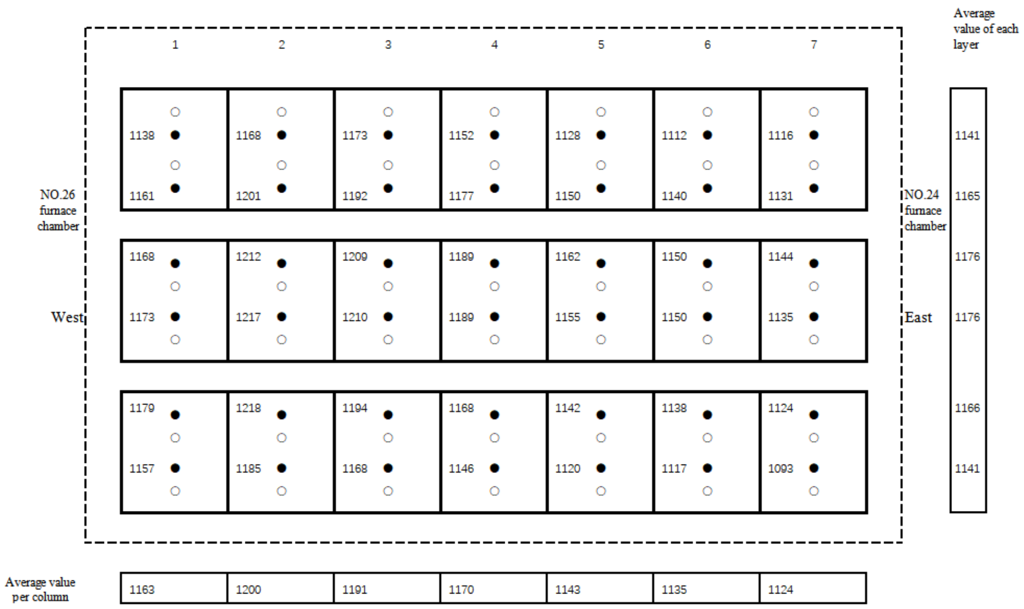


Figure 2. Equivalent temperature distribution in the pit before retrofit.

Table 2. Physicochemical indexes of the samples before retrofit.

Location	Bulk Density	Resistivity	Block Average	No.	Average Air Permeability
	g/cm3	μΩ·m			nPm
A112	1.593	56.86	57.02		
A114	1.592	57.18		A113	4.17
A172	1.588	57.34	58.58		
A174	1.590	59.82		A173	1.29
A242	1.572	58.02	58.77	A241	1.76
A244	1.565	59.51			
B312	1.557	62.35	59.66	A311	2.39
B313	1.552	56.96			
B371	1.574	56.21	59.98		
B374	1.565	63.75		A373	4.88
Average	1.575	58.80			2.90

2.3 Challenges During the Retrofitting

The retrofitting focuses on achieving the goals of improving product quality, reducing energy consumption, and maintaining production capacity at the current site. This requires a comprehensive consideration of the compatibility between the upstream and downstream equipment in the baking system to avoid operational bottlenecks. The main challenges are as follows:

(1) High technical and financial barriers: Baking furnaces face bottlenecks in terms of operational efficiency, eco-friendly performance, and product quality. As a result, both the research and development of retrofitting technologies and the implementation of these upgrades require significant technical and financial investment.

(2) Equipment compatibility challenges: The foundational structure of outdated baking furnaces, such as materials and spatial layout, is not directly compatible with modern technologies. Therefore, the retrofitting must consider multiple factors, including production capacity and structural adjustments, to improve the overall compatibility of the baking system with upstream and downstream production processes.

(3) Production disruption during retrofitting: The retrofitting process requires a furnace shutdown, which disrupts continuous production and places economic pressure on the enterprise.
(4) Upskilling of operators: The implementation of new technologies demands that operators acquire skills in managing intelligent equipment and conducting data analysis. However, traditional workers lack the necessary training in these areas.

3. Solutions

Using the aforementioned baking furnace as a case study, a structural redesign was carried out. A digital model of the upgraded structure was created, and optimization calculations based on simulation were performed. A pilot baking furnace was then constructed according to the redesigned plan and put into trial operation.

3.1 Expanding the Pit for Higher Production Capacity

New thermal insulation materials were used to reduce the thickness of the lateral walls, allowing for an expansion of the pit size while accommodating changes in product specifications. After the modification, the pit size was increased to 5246 × 830 × 6040 mm (L × W × H), enabling the production of carbon anodes with dimensions of 1750 × 750 × 710 mm. The upgraded furnace has a production capacity of 145 kt/y.

3.2 Optimizing the Insulation of Lateral Walls and Connecting Flue

Due to limitations of the original furnace shell size and the new product specifications, the width of the pit needed to be increased during the retrofitting. To this end, the insulation thickness of the lateral walls was reduced from 692 mm to 447 mm. Traditional clay insulating bricks were replaced with prefabricated insulation blocks made from new fibre materials, with a thermal conductivity of 0.153 W/m·K. The expansion of the pit led to a shift in the centreline of the flue. To maintain the original flue centreline position, the original brick-built connecting flue was dismantled. A new lightweight connecting flue was designed and rebuilt using the same fibre-based insulation material. This redesign reduces heat and negative pressure losses in the "bypass furnace chamber", ensuring even temperature distribution in the flue.

3.3 Optimization and Improvement through Numerical Simulation

Software tools such as ANSYS, FLUENT, and CFX were employed to establish a simulation model of the industrial baking furnace flue. The model enabled simulations and computing of fuel combustion, flue gas flow, temperature distribution, and stress distribution. The simulation results validated the structural feasibility of the modified flue wall and were used to optimize the dimensions and layout of the tie bricks and custom-shaped refractory bricks. Figures 4 and 5 show structural diagrams of the flue before and after the retrofit. The main differences are: the internal width of the flue was increased from 310 mm to 330 mm, and the design of baffle walls was improved by narrowing the upper flue outlet and extending the baffle walls between ports 1 & 2 and ports 3 & 4 downward by 103 mm.

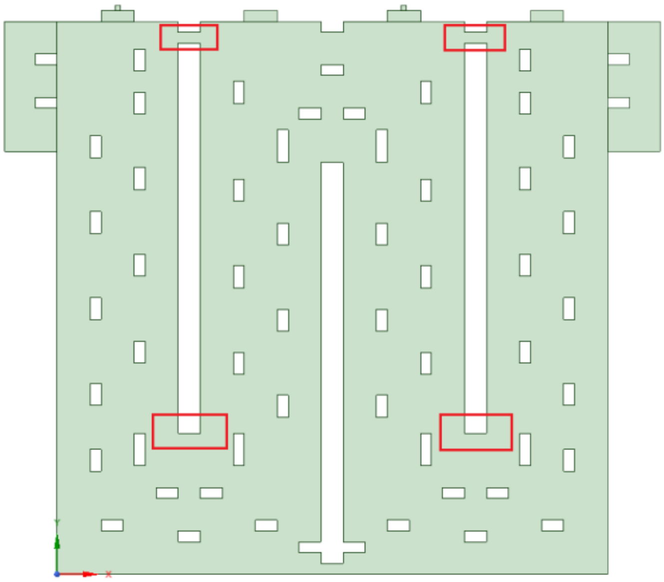


Figure 4. Cross-sectional view of the flue layout before the retrofit.

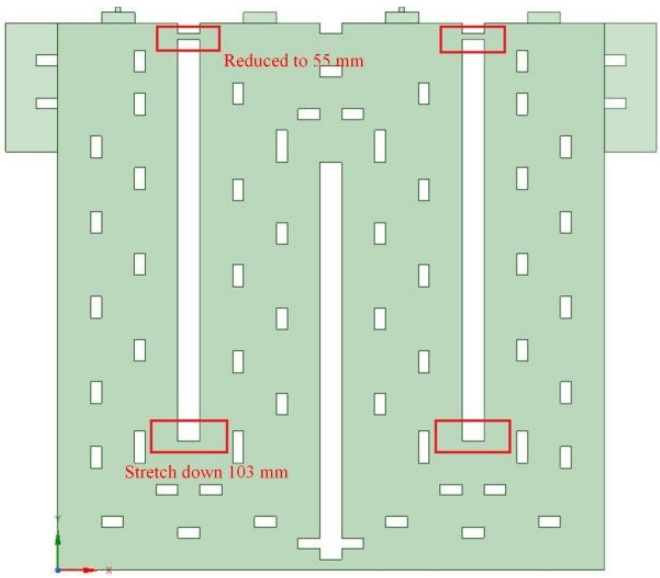


Figure 5. Cross-sectional view of the flue layout after the retrofit.

3.3.1 Structural Optimization

The following assumptions were made for the simulation calculations to simplify the model: The pressure at the inlet and outlet cross-sections was assumed to be uniformly distributed. The fuel and oxidizer were controlled using a time-sharing and zoning strategy, allowing independent regulation across different zones and stages. The gas medium was treated as an incompressible fluid. The system was modelled under steady-state conditions. The velocity inlet boundary condition was set to a steady flow rate of 2.91 m/s, with an accompanying high temperature of 1100 °C. A static pressure of 2500 Pa was applied at the pressure inlet boundary, while the natural gas inlet was maintained at ambient temperature (27 °C). The pressure outlet was set to a gauge pressure of -8 Pa to establish a reasonable pressure gradient.

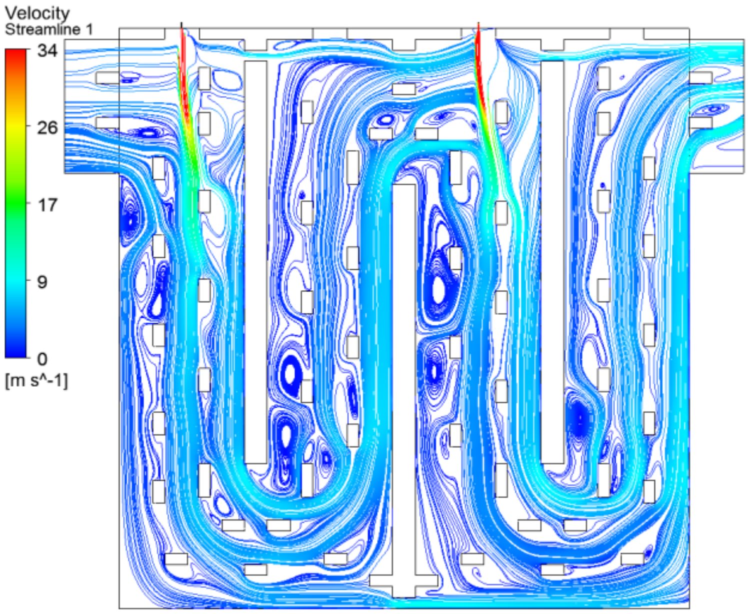


Figure 6. Streamline distribution on the central plane of the flue before the retrofit.

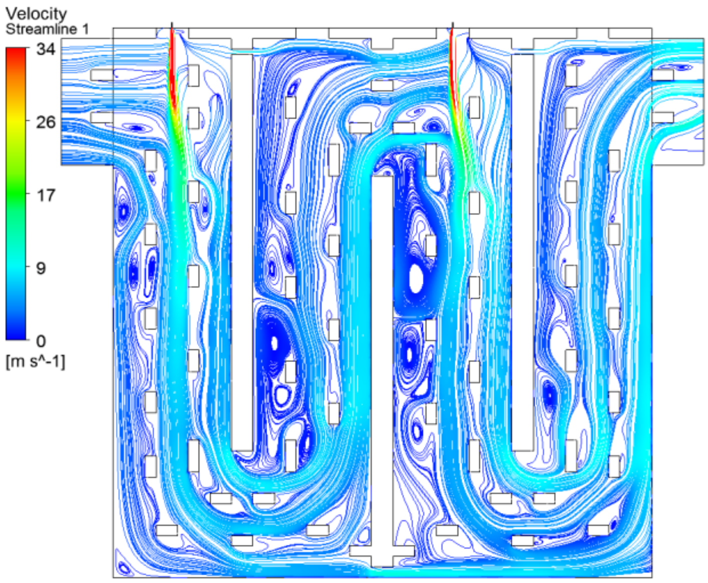


Figure 7. Streamline distribution on the central plane of the flue after the retrofit.

Figures 6 and 7 show the distribution of flue gas flow on the centre plane of the flue before and after the retrofit. These diagrams clearly and intuitively display the gas flow velocity, flow patterns, and the uniformity of distribution within the flue. Compared to the original design, the new structure features a reduced opening above the baffle wall, near the natural gas nozzle. This reduction in the upper passage causes a decrease in airflow through that section, while increasing the gas flow velocity around the bottom and front of the baffle wall.

The temperature distribution inside the flue is closely influenced by the gas flow pattern. Under the above-mentioned gas flow conditions, compared to the original design, the high-temperature zone near the No.1 natural gas nozzle in the new structure shifts downward, and the high-temperature zone in front of the third baffle wall expands. Additionally, temperatures rise at the bottom of the flue, in front of the central baffle wall, and near the wall close to the flue gas outlet, resulting in an enlarged high-temperature zone.

3.4 Implementation of the Upgrade

In 2021, a diagnostic assessment was conducted on the outdated baking furnace to identify key areas for improvement in preparation for the upgrade. Based on structural optimization of the baking furnace, the upgrade was completed in 2023. In 2024, the upgraded baking furnace successfully passed capacity and quality acceptance tests, followed by performance verification.

4. Testing on the Upgraded Baking System

After the upgrade, each furnace chamber was equipped with seven pits and eight flues. The heating curve was set to 216 hours. Chamber #30 underwent dynamic temperature testing, equivalent temperature analysis, negative pressure measurement, volatile content, production capacity, product quality, and energy consumption tests. The results are as follows.

4.1 Dynamic Temperature Distribution Testing

Testing was conducted on Pits 1 and 3 and Flues 1 and 3 of the upgraded Chamber #30, with the results compared to the data obtained under the same conditions before the upgrade. Two measuring points were set in each flue and five in each pit, totalling 14 measuring points. The temperature variations at each point were recorded in real time throughout a complete baking cycle. Figures 8 and 9 show the dynamic temperature data of Flue 3 at Hole #4, and Pit 3 at Measuring Point #1, respectively. The data are analysed as follows.

The temperature differences between the top, middle, and bottom at the same measuring point in the flue were relatively small. From stage 2P to 6P of the baking cycle, 42.8 % of the data showed a temperature difference of ≤ 40 °C, 49.3 % showed a difference between 40–80 °C, and only 7.9 % showed a difference of ≥ 80 °C, with the maximum recorded difference being 133 °C. The heating rate inside the pit was generally steady, with temperatures at different depths showing good consistency. The maximum temperature difference at varying depths within the same location was less than 55 °C. Compared to the pre-retrofit data, the maximum temperature difference decreased by 38 °C, indicating more uniform temperature distribution and a smoother heating rate in both the pits and flues after the retrofit.

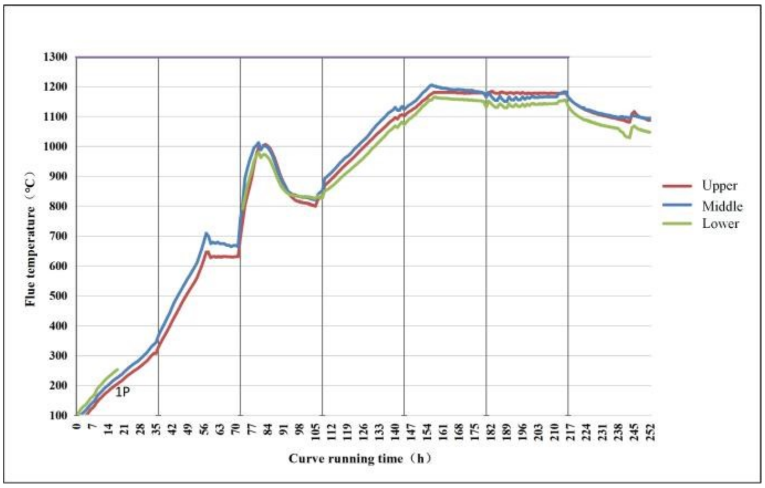


Figure 8. Temperature rise curve for Flue 3 at Hole #4.

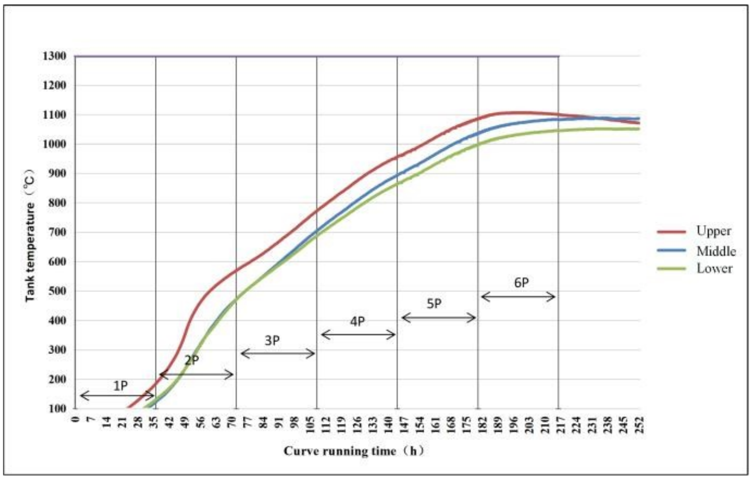


Figure 9. Temperature rise curve of Pit 3 at Measuring Point #1.

4.2 Equivalent Temperature Testing

The acceptable range for equivalent baking temperature is 1160–1320 ºC. Equivalent temperature tests were conducted on Pits #1 and #3 of the upgraded Chamber #30. Figures 10 and 11 show the test results for Pits #1 and #3, respectively. In these figures, yellow indicates that the temperature is within the acceptable range, green indicates it is below the acceptable range, and the intensity of the colour represents how far the temperature deviates from the normal value.

The results show that the equivalent temperatures at most measuring points within the pits were within the acceptable range, with 80 % of the equivalent temperatures exceeding 1160 ºC. The equivalent temperature for Pit #1 (edge position) was 1194 ºC, and for Pit #3 (centre position), the average was 1213 ºC, indicating sufficient baking. Compared to the pre-retrofit data, the overall temperature inside the pits increased, temperature fluctuations at the same locations decreased, and temperature uniformity improved, leading to better baking of the carbon blocks.

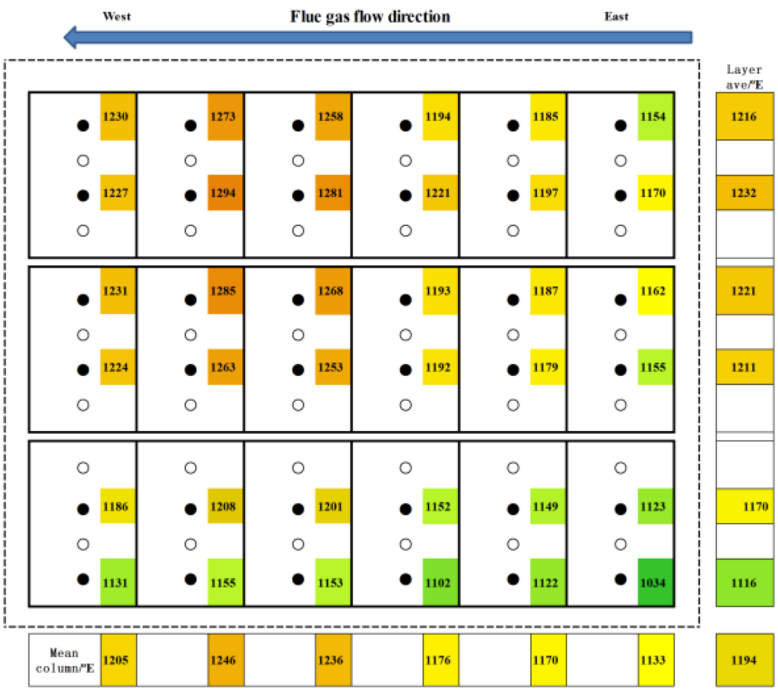


Figure 10. Equivalent temperature distribution in Pit 1.

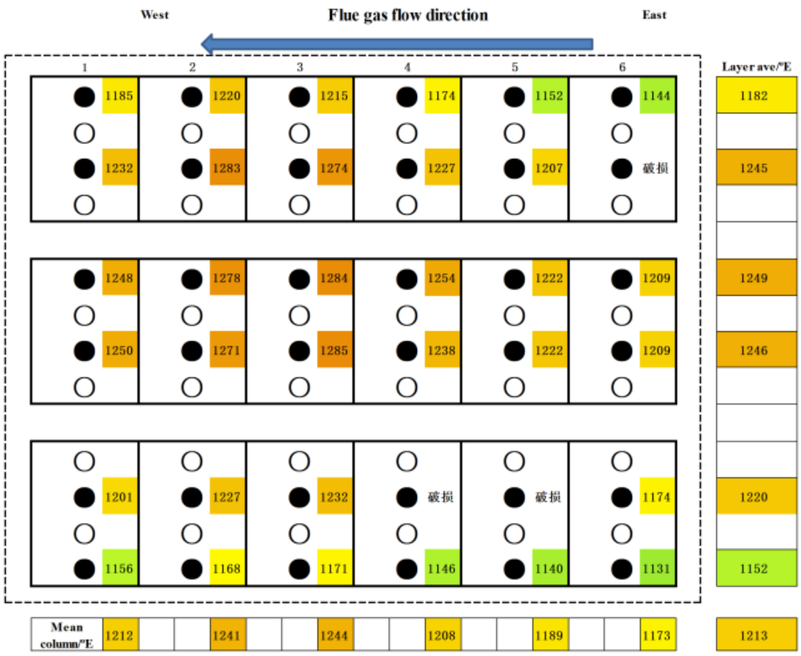


Figure 11. Equivalent temperature distribution in Pit 3.

4.3 Negative Pressure Testing

After the retrofit, negative pressure testing was conducted on the baking furnace. On the one hand, the above simulation results were compared; on the other hand, the resistance loss of the flue gas in the modified baking furnace was reflected. The test data are presented in Table 3, where 18# and 19# refer to the bypass chambers. The results indicate that the industrial test data closely matched the simulation results, following the same trend. The retrofit effectively reduced the flue gas resistance inside the baking furnace.

Table 3. Negative pressure test results of the upgraded baking furnace.

Flue No.	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**Negative pressure at the exhaust ramp**	**Temperature at the exhaust ramp**
22#	88	83	85	88	83	81	94	115	82
19#	63	64	61	63	61	62	64		
18#	54	56	56	55	56	56	56		
Static pressure difference between inlet and outlet	10	9	8	7	9	6	8		

4.4 Combustion of Volatile Matter

A key factor in reducing energy consumption in the baking furnace is effectively utilizing the volatile matter released during the anode baking process. By analysing the release and combustion of volatile matter at different stages and times, adjustments to the baking furnace temperature can be made, and energy saving potentials can be discovered. The test was conducted in Chamber 30#, with timing starting when the material entered the baking system. The release and combustion of volatile matter were recorded every 12 hours after the 24th hour. Figure 12 shows the results at hour 48 and hour 84, corresponding to periods of significant volatile matter release and sufficient combustion, respectively. In the figure, blue text indicates the release of volatile matter, yellow shading indicates the temperature reaching the ignition point for the volatile matter, and brown shading marks the temperature for sufficient combustion.

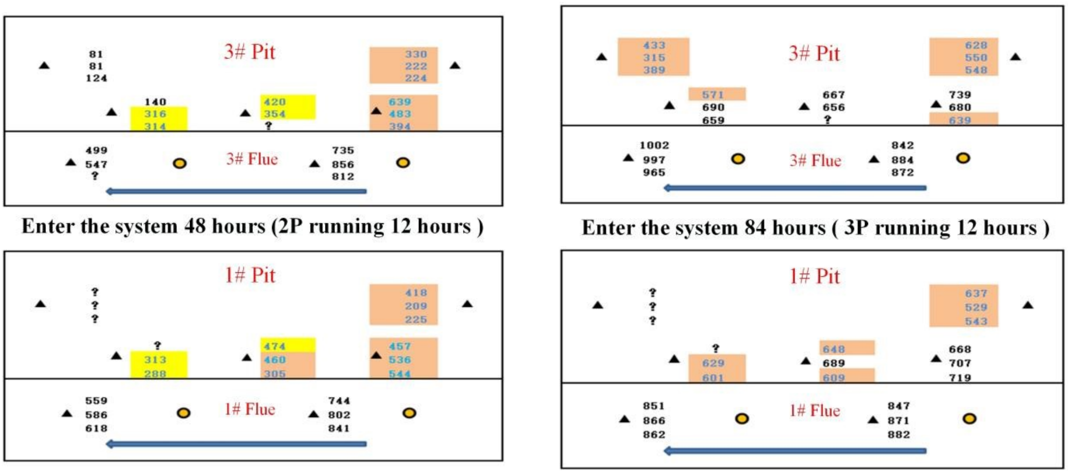


Figure 12. Release and combustion of volatile matter at different time intervals. Left: hour 48, Right: hour 84.

The temperature data shows that the combustion of volatile matter primarily occurred between the mid-stage of 2P and the early stage of 4P, with the combustion duration lasting around 50 hours at most measuring points. Compared to the pre-retrofit test data, only 7.9 % of the measuring points showed a temperature difference of ≥ 80 °C. The temperature difference between the upper, middle, and lower parts of same measuring point was generally small, indicating better temperature uniformity. As a result, the volatile matter was more easily burned completely in the flue.

4.5 Product Quality and Energy Consumption

The physicochemical indicators of the sample products after the retrofit are shown in Table 4. Compared to the data in Table 2 (before the retrofit), the average resistivity of the anode products decreased by 2.8 μΩ·m, bulk density increased by 0.002 g/m^3, and air permeability decreased by 1.26 nPm. After the retrofit, the products exhibited better indicators in bulk density, resistivity, and other key parameters, reflecting enhanced product quality.

Table 4. Physicochemical indicators of the samples after the retrofit.

Location	Bulk Density	Resistivity	Block Average	No.	Average Air Permeability
	g/cm^3	μΩ·m			nPm
B1	1.592	54.32	53.02	B1	1.92
B2	1.589	51.72			
B3	1.573	56.61	57.21		
B4	1.576	57.81		B4	1.58
B5	1.580	55.80	56.11	B5	1.50
B6	1.570	56.41			
B7	1.571	58.08	57.65	B7	1.57
B8	1.584	57.22			
Average	1.579	56.0			1.64

In terms of energy consumption, the comparison focused on natural gas usage during the same production cycle before and after the retrofit. After the retrofit, the average natural gas consumption per tonne of anodes was 50 m^3, which represents a saving of 18 m^3 per tonne compared to pre-retrofit levels.

5. Conclusions and Application Prospects

To address the limitations of traditional ring-type baking furnaces, such as constraints on product specifications, low production capacity, high energy consumption, and the technical challenges of retrofitting, this study integrates diagnostic testing, structural optimization, and numerical simulation to develop an efficient upgrade solution for aging baking furnaces. After applying this solution, the baking furnace of a carbon enterprise was able to meet the conditions for large-scale anode baking. The average natural gas consumption per tonne of anodes was reduced by 18 m^3, and the anode resistivity was lowered by 2.80 μΩ·m.

1. In line with the demand for high-efficiency, low-carbon, and intelligent industrial upgrades, the airflow distribution within the baking furnace was significantly improved by redesigning the structure size of combustion chamber and flue shape. The innovative use of new insulating materials reduced both renovation and operational costs while improving the quality of carbon anodes. These upgrades offer a practical solution for revamping small-sized baking furnaces and for replacing or repairing flue systems in aging serving equipment, both domestically and internationally.

2. A coordinated optimization model integrating process, design, and simulation was established. Based on dynamic alignment between fuel characteristics and product quality requirements, CFD simulations guided the optimization of key structural parameters. This approach resulted in a comprehensive energy-saving and quality improvement solution that covers the entire cycle of design, operation, and retrofit of baking furnaces.

3. Energy-saving diagnostic and optimization techniques were implemented on both existing and upgraded baking systems. The furnace structure was optimized to better align with the baking process, resulting in a 10 % increase in the yield of first-grade anode blocks and a reduction in energy consumption to 1.74 GJ/t, successfully achieving the goals of quality improvement and energy efficiency.

Through the above measures, large-scale and high-quality products were produced while reducing both energy consumption and investments. During the implementation, challenges emerged due to the limitations of the flue gas purification system and the reused combustion control system. Although the technical team successfully addressed the issues, the experience highlights the importance of thoroughly evaluating the process coordination and the compatibility with existing facilities in such upgrading projects.

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