Electrical Conductivity of Graphitized Cathode Carbon Block Based on Eddy Current Technology

Tong Liu[1] and Hongjie Yang[2]
1, 2. Senior Engineers
Zhengzhou Non-ferrous Metals Research Institute of Chalco (ZRI), Zhengzhou, China
Corresponding author: tongliu@chinalco.com.cn
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Abstract

With aluminium reduction cells evolving towards larger size, energy efficiency, and environmental sustainability, graphitized cathode carbon blocks have become the inevitable choice for large-scale aluminium reduction cells due to their excellent electrical conductivity and resistance to electrolyte corrosion. The cathode carbon block serves as the carrier of the cell current. If carbon blocks with significantly different electrical conductivities are combined and constructed in the same cell, it will inevitably hinder the uniform distribution of the cell current and the stable operation of the electrolytic cell during the electrolysis process. Resistivity is a key indicator for evaluating electrical conductivity. However, individually sampling and testing the resistivity of cathode carbon blocks, or passing a current through the blocks and measuring the voltage drop to calculate the resistivity, both suffer from the drawback of being unable to balance efficiency and reliability effectively. Eddy current is an electromagnetic induction phenomenon generated in a conductor by a changing magnetic field, where the distribution and magnitude of eddy currents are related to the conductor's electrical conductivity. This paper elaborates on a method for measuring the resistivity of graphitized cathode carbon blocks based on eddy current technology and introduces a novel detection device. Through test comparisons, it has been verified that this method can rapidly and non-destructively measure the resistivity of cathode carbon blocks, providing a novel method for detecting the resistivity of graphitized cathode carbon blocks.

Keywords: Graphitized cathode carbon block, Electrical conductivity, Eddy current, Detection, Resistivity.

1. Introduction

The cathode carbon block is a key component of the aluminium reduction cell's cathode lining. It serves as lining material to contain molten aluminium and electrolyte, and as a conductive material to transmit cell current. Its performance significantly impacts the energy consumption and operational stability of the electrolytic cell. Electrical conductivity - resistivity is a key performance indicator of cathode carbon blocks. Cathode carbon blocks with good electrical conductivity help reduce the voltage drop at the bottom of electrolytic cells, thereby saving energy consumption [1]. A large aluminium reduction cell typically requires the installation of approximately 20–30 cathode carbon blocks. If cathode blocks with significantly different electrical conductivity are installed in the same cell, it will adversely affect the stability and uniformity of cathode current distribution, increase horizontal currents in the molten bath region, and consequently impair cell operation stability and reduce current efficiency [2].

With aluminium electrolysis cells evolving toward larger capacity, higher current density, energy efficiency, and environmental sustainability, graphitized cathode carbon blocks have become the inevitable choice for modern large-scale aluminium reduction cells due to their superior performance in aluminium electrolysis, which reduces energy consumption, enhances production rate and current efficiency, while minimizing environmental pollution from spent cathode carbon blocks [3].

2. Electrical Conductivity of Graphitized Cathode Carbon Blocks

The graphitized cathode carbon block is a cathode carbon product manufactured using high-quality petroleum coke and artificial graphite fragments as aggregates, with coal tar pitch as the binder. It undergoes processes including mixing, shaping, roasting (or additional impregnation and roasting), and finally high-temperature graphitization. The graphitization process enhances the ordered arrangement of carbon atoms [4], thereby improving the electrical conductivity, thermal conductivity, thermal shock resistance, and sodium erosion resistance of the cathode carbon block, making it suitable for aluminium electrolysis production.

The resistivity of a conductor quantitatively characterizes its electrical conductivity, with lower resistivity indicating better electrical conductivity. Table 1 presents the resistivity indicators of cathode carbon blocks produced by selected international manufacturers, while Table 2 shows China's current resistivity indicators for cathode carbon blocks.

Table 1. Resistivity (μΩ·m) of cathode carbon blocks from selected international manufacturers for three kinds of grade [5].

	Semi-graphitic (Graphite content > 50 %)	**Graphitic (Graphite content 100 %)**	**Graphitized**
Company A	24–32	18–23	11–13
Company B	15–30	12–18	8–14
Company C	23	16	14
Company D	28	13	11

Table 2. Resistivity of cathode carbon blocks in China [6, 7].

Grade	**Semi-graphitic(Graphite content > 50 %)**	**Graphitic (Graphite content 100 %)**	**Graphitized**
Resistivity, μΩ·m	< 30	< 21	< 12

Therefore, the resistivity of graphitized cathode carbon blocks is lower than that of semi-graphitic cathode carbon blocks. The use of graphitized cathode carbon blocks can reduce the bottom voltage drop of aluminium reduction cells by more than 90 mV compared to semi-graphitic cathode carbon blocks [8], demonstrating significant energy-saving effects.

3. Testing of Resistivity

The Chinese non-ferrous industry standard YS/T 63.2-2023 specifies the principle and method for measuring the resistivity of cathode carbon blocks [9]. This method is based on Ohm's law and the definition of resistivity of conductor, deriving the resistivity calculation equation:

$$\rho = \frac{U \cdot S}{I \cdot L} \tag{1}$$

where:

ρ Conductor resistivity, μΩ·m

U Voltage drop across the conductor, mV

I Current intensity flowing through the conductor, A

S Cross-sectional area of the conductor, mm^2

L Length of the conductor, mm

When measuring resistivity, samples are drilled from the unprocessed ends of cathode carbon blocks, as shown in Figure 1. The samples are processed into regular cylinders, and under a certain pressure, the current intensity and voltage drop through the samples are measured. The resistivity is then calculated using Equation (1). The detection process involves multiple steps, including sampling, processing, and measurement, resulting in a lengthy procedure. If detection of resistivity is conducted on every cathode carbon block, the workload would be excessive and impractical for operational implementation. Therefore, this method is used for sampling measurements of the resistivity of cathode carbon block.

Figure 1. Sampling for resistivity measurement of cathode carbon blocks.

Without sampling, a current is applied to the cathode carbon block, and the voltage drop is measured to calculate the resistivity. However, due to the machined cathode steel bar slot in the cathode carbon block, the current distribution becomes non-uniform, affecting the measurement accuracy. When measuring the cathode carbon block before machining, due to the large volume of the block, it is necessary to increase the current intensity and construct a dedicated device for current application and voltage acquisition, resulting in complex and bulky measurement device. Additionally, the cathode carbon blocks must be insulated from other conductors and hoisted into position before measurement. Consequently, this method for determining the resistivity of each cathode carbon block involves labour-intensive procedures.

4. Principle of Eddy Current Testing

Eddy current is an electromagnetic induction phenomenon. Its principle is as follows: When alternating current (magnitude and direction vary periodically with time) passes through a coil, an alternating magnetic field H1 is generated around the coil. Inside a conductor exposed to this magnetic field H1, an induced current is produced, which takes a vortex-like shape and is called eddy current (as shown in Figure 2). The distribution and magnitude of eddy currents are related to factors such as the shape and size of the coil, the magnitude and frequency of the alternating current, the electrical conductivity and magnetic permeability of the conductor, its shape and dimensions, the distance between the conductor and the coil, as well as the presence of surface cracks or defects in the conductor. According to Lenz's law, the eddy currents induced in the conductor generate a magnetic field H2, which opposes the original magnetic field H1. Due to the influence of H2, both the magnitude and frequency of the alternating current in the coil are affected. Different conductors will cause corresponding variations in the alternating current within the coil.

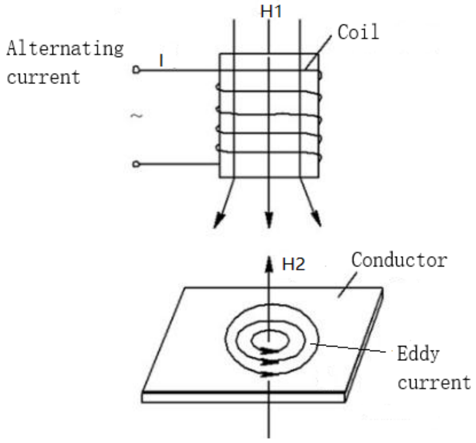


Figure 2. Schematic diagram of eddy current.

The eddy current phenomenon is represented by an equivalent circuit, as shown in Figure 3[10].

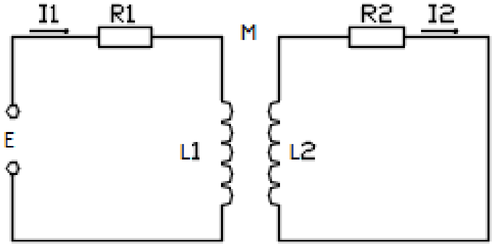


Figure 3. Equivalent circuit diagram of eddy current.

According to Kirchhoff's laws, the equivalent circuit equations are:

$$R1 \cdot I1 + j\omega L1 \cdot I1 - j\omega M \cdot I2 = E \tag{2}$$

$$R2 \cdot I2 + j\omega L2 \cdot I2 - j\omega M \cdot I1 = 0 \tag{3}$$

where:

R1	Coil resistance, Ω
L1	Coil inductance, H
I1	Current through the coil, A
R2	Conductor resistance, Ω
L2	Conductor inductance, H
I2	Eddy current, A
E	Excitation voltage, V
M	Mutual inductance between the coil and conductor, H
ω	Angular frequency, rad/s
j	Imaginary unit

According to equations (2) and (3), the equivalent impedance Z of the coil is obtained as:

$$Z = R1 + \frac{R2 \cdot \omega^2 \cdot M^2}{R2^2 + \omega^2 \cdot L2^2} + j\left(\omega \cdot L1 - \frac{\omega \cdot L2 \cdot \omega^2 \cdot M^2}{R2^2 + \omega^2 \cdot L2^2}\right) \tag{4}$$

where:

Z Coil impedance, Ω

The impedance of the coil changes from R1 + jωL1 to Equation (4). Therefore, when eddy currents are generated, the coil impedance depends not only on its own resistance R1 and inductance L1, but also on the conductor's resistance R2, inductance L2, angular frequency ω, and the mutual inductance M between the coil and the conductor. The conductor resistance R2 is related to its resistivity. If the variation in the coil's equivalent impedance can be detected and correlated with the conductor's resistivity, the resistivity of the conductor can be derived.

5. Relationship Between Coil Voltage and resistivity of Cathode Carbon Blocks

Enamelled copper wire is wound around an insulator to form a coil, which is connected in parallel with capacitor C to form the circuit, as shown in Figure 4. The coil is equivalently modelled as an inductor in series with a resistor, where R represents the external line resistance. An excitation voltage is applied across the circuit, and its frequency is adjusted to achieve resonance, at which point the voltage U across the coil reaches its maximum. When the coil approaches a conductor, its equivalent impedance changes, causing the circuit to detune and the coil voltage to decrease. Thus, the voltage across the coil reflects variations in its equivalent impedance. The voltage waveform across the coil is recorded using an oscilloscope, as shown in Figure 5.

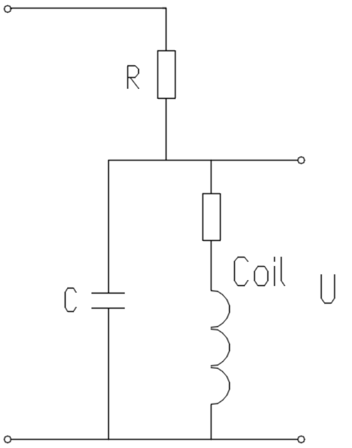
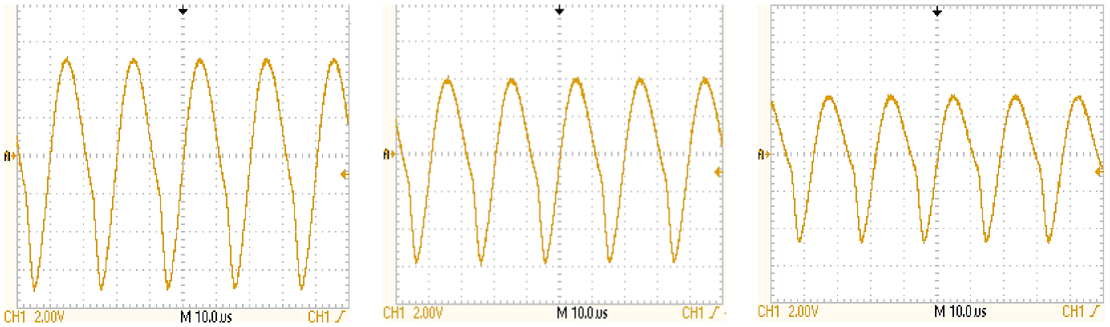


Figure 4. Resonant current of coil.



(a) **(b)** **(c)**

Figure 5. Voltage waveform across coil. (a) Resonance. (b) Cathode carbon block A. (c) Cathode carbon block B.

Figure 5(a) displays the voltage waveform across the coil during circuit resonance, Figure 5(b) displays the coil voltage waveform when placed on the surface of cathode carbon block A, and Figure 5(c) displays the corresponding waveform when the coil is placed on cathode carbon block B. From the waveforms, it can be observed that the voltage amplitude across the coil reaches its maximum at circuit resonance. The voltage amplitude measured at position A is greater than that at position B. According to the YS/T 63.2-2023 standard testing, the resistivity at position A is higher than that at position B. The coil is placed on cathode carbon blocks with different electrical resistivities, and the corresponding voltage values across the coil are recorded. Through mathematical analysis, the relationship between the voltage variation across the coil and the resistivity is determined. Table 3 presents the resistivity of cathode carbon block samples tested according to the YS/T 63.2-2023 standard and the corresponding voltage variation of the coil placed on the samples. Based on Table 3, the relationship between resistivity and coil voltage variation is illustrated in Figure 6.

Table 3. Relationship between carbon block resistivity and coil voltage variation.

Sample	Resistivity (μΩ·m)	Coil voltage (V)
1	6.35	0.857
2	7.31	0.838
3	10.29	0.780
4	13.10	0.728
5	14.74	0.698
6	19.80	0.601
7	23.55	0.524
8	29.97	0.404

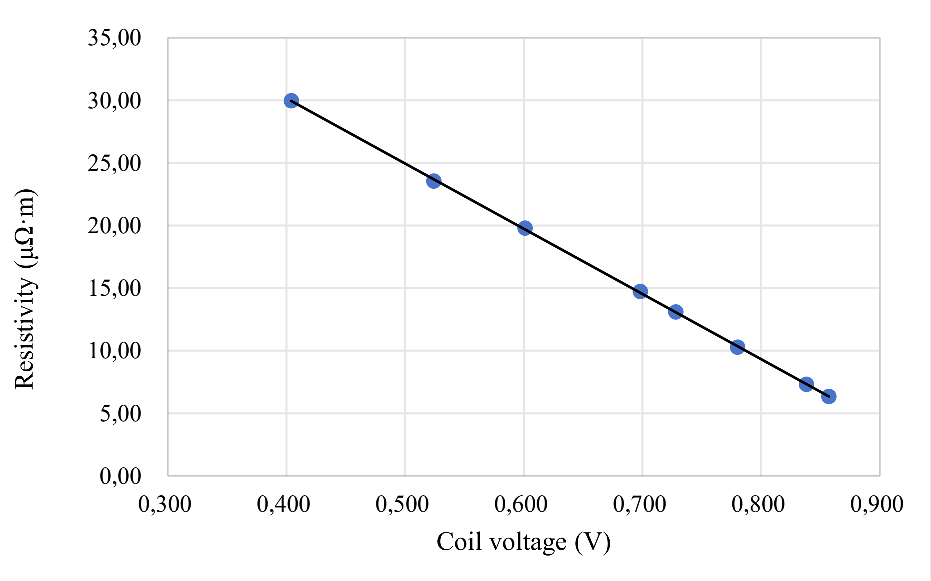


Figure 6. Relationship between coil voltage and resistivity.

In Figure 6, the vertical axis represents resistivity, while the horizontal axis denotes the variation in voltage across the coil. It can be observed that higher resistivity values correspond to lower voltages, exhibiting an approximately linear relationship, expressed as:

$$\rho \propto f\left(\frac{1}{\Delta U}\right) \tag{5}$$

where:

ρ	Resistivity of carbon block, μΩ·m
ΔU	Voltage variation across the coil, V

6. Experiment

The measuring instrument developed based on the eddy current principle consists of a measurement probe, an oscillation excitation circuit, an acquisition circuit, measurement software, and a display screen, as shown in Figure 7. The measurement probe is made of a coil and insulating material. When the probe is placed on the surface of the cathode carbon block, the measurement software automatically collects the voltage value across the coil and calculates the resistivity using Equation (5), then displays and records the result.

Figure 7. Measuring instrument.

According to YS/T 63.2-2023, the resistivity of graphitized and graphitic cathode carbon block samples was measured by sampling, and the same samples were measured using the eddy current method. A comparison of the measurement results between the two methods is shown in Table 4. The maximum difference between the two methods was 0.15 μΩ·m, the minimum difference was 0.01 μΩ·m, the average absolute difference was 0.07 μΩ·m, and the percentage difference was less than 1.0 %.

Figure 8 shows the measurement results of carbon blocks with different electrical resistivities using two methods. The filled bars represent the eddy current measurement results, while the unfilled bars indicate the standard measurement results. The numerical values within the elliptical boxes denote the differences between the two measurement methods. The results obtained by both methods are in close agreement and exhibit consistent variation trends.

Therefore, instruments developed using the eddy current method can measure the resistivity of graphitized cathode carbon blocks, enabling rapid measurements.

Table 4. Results of standard measurement and eddy current measurement.

YS/T 63.2-2023 standard measurement (μΩ·m)	**Eddy current measurement (μΩ·m)**	**Absolute difference (μΩ·m)**	**Percentage difference**
6.34	6.35	0.01	0.20 %
7.31	7.34	0.03	0.45 %
10.29	10.36	0.07	0.72 %
13.10	13.07	0.03	0.21 %
14.74	14.64	0.10	0.71 %
19.80	19.69	0.11	0.56 %
23.55	23.70	0.15	0.64 %
29.97	29.95	0.02	0.06 %
Average absolute difference (μΩ·m)		0.07	0.44 %

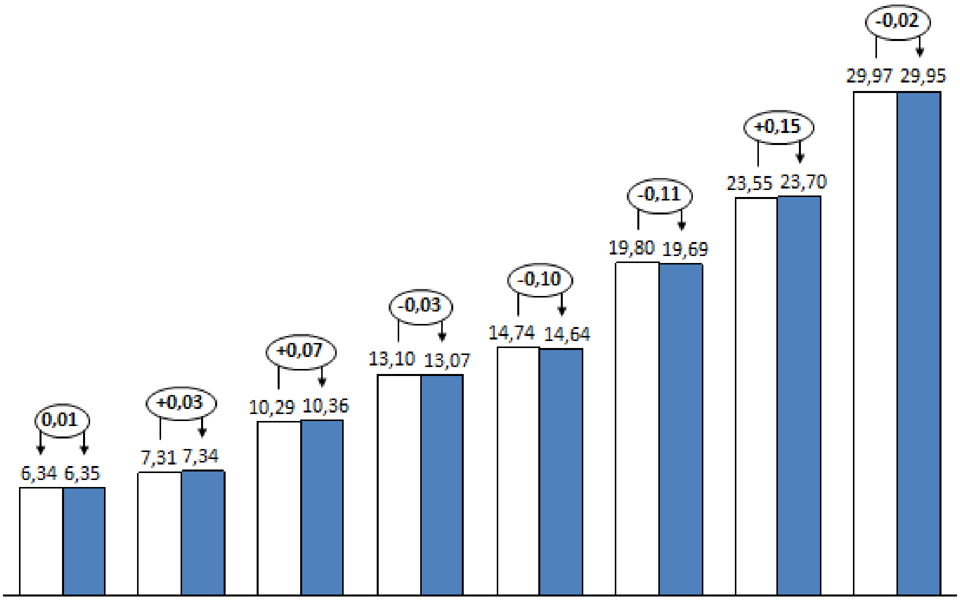


Figure 8. Comparison between standard measurement and eddy current measurement.

7. Conclusion

With the trend of aluminium reduction cells moving toward larger capacity and energy efficiency, graphitized cathode carbon blocks have become the inevitable choice for modern large-scale aluminium reduction cells due to their superior performance indicators such as excellent electrical conductivity. The resistivity indicator characterizes the conductive performance of graphitized cathode carbon blocks. The eddy current principle is employed to measure the resistivity of graphitized cathode carbon blocks without the need for drilling or processing samples, thereby reducing measurement steps. This method is unaffected by cathode steel bar slots, enables rapid resistivity measurement, and facilitates accurate assessment of each cathode carbon block's electrical conductivity, thus providing better guidance for practical applications.

8. References

1. Yanfeng Lu, et al., Application of graphitized cathode carbon blocks in 400 kA energy-saving aluminum reduction cells, *Energy Saving of Non-Ferrous Metallurgy*, 2017(6), 31–34 (in Chinese).
2. Feiya Yan, Analysis on the importance of cathode current distribution in aluminum reduction cells, *Light Metals*, 2013(4), 34–40 (in Chinese).
3. Yanning Wu, Application and production practice of new cathode steel bar technology in 330 kA potline, *Light Metals*, 2016(7), 30–32 (in Chinese).
4. H. MARSH AND J. GRIFFITHS, A high resolution electron microscopy study of graphitizable carbon, International Symposium on Carbon, Toyohashi, Japan, 1981:81–85.
5. Shihuan Yao, Selection of graphitized and fully graphitized cathode carbon blocks for aluminum production, Chinalco, 2009(11), 5–17 (in Chinese).
6. Ministry of Industry and Information Technology of the People's Republic of China, *Graphite Cathode Carbon Blocks for Aluminum Electrolysis - YS/T 623-2021*, Nonferrous Metals Industry Standard of the People's Republic of China, 2021 (7) (in Chinese).
7. Ministry of Industry and Information Technology of the People's Republic of China, *Graphitized Cathode Carbon Blocks for Aluminum Electrolysis YS/T 699-2018*, Nonferrous Metals Industry Standard of the People's Republic of China, 2019 (4) (in Chinese).
8. Xi Cao, et al., Performance analysis and application of cathode carbon blocks for aluminum reduction cells, *Light Metals*, 2019(2), 37–41 (in Chinese).
9. Ministry of Industry and Information Technology of the People's Republic of China, *Carbonaceous Materials Used for the Production of Aluminium - Part 2: Determination of Electrical Resistivity at Ambient Temperature - YS/T 63.2-2023,* Nonferrous Metals Industry Standard of the People's Republic of China, 2023 (11) (in Chinese).
10. Huaxiang Wang, et al., *Principles and applications of sensors*, 1st ed., Tianjin, Tianjin University Press, 1988, 151–153 (in Chinese).