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STUDY OF NOVEL MEASUREMENT INSTRUMENTATION INSPECTING THE STATE OF THE CELL DURING ELECTROLYTIC ROASTING PROCESS

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ABSTRACT

In the roasting process stage each component of the cell of aluminum performs unsteadily. Monitoring the currents of both anodes and cathodes of the cell at regular intervals is quite necessary. Rogowski coil is used to measure heavy direct currents (DC) of both anodes and cathodes of the cell. The paper introduces the principle of the current distribution characteristic of the cell and, introduces the principle of Rogowski coil used to measure DC and, analyzes the performances of the Rogowski coil. Some important considerations on improving the performance of Rogowski coil in DC measurement applications have been presented. The output variation with temperature and method of calibration of the instrumentation are presented as well. The experiment results are provided to confirm the validity of the proposed method for inspecting the state of the cell during the electrolytic roasting process.

Keywords: *State of cell, DC measurement, Novel measurement instrumentation*

I. INTRODUCTION

Electrolyzing alumina martial dissolved in cryolite-based melts: Na_3AlF_6-AlF_3-Al_2O_3 generally produces aluminum introduced in reference [1]. The roasting process of the aluminum cell is an important phase in the aluminum electrolysis process. A successful roasting process is not only beneficial to the quality of the electrolysis of aluminum, but also helpful to prolong the life span of the cell. With the continuous increasing of the DC, such

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heterogeneity will bring about serious results. For example, one part of the cell conducts current while the other doesn't. If there are some cracks in the bottom of the cell, the iron content in the aluminum electrolyte will increase. Aluminum electrolyte and other electrolytes will penetrate the cracks and gradually freeze. Thus, the conductivity around the anode will decrease, which would cause the cell to split introduced in reference [2].

In order to ensure the quality of roasting process, some practical solutions must be presented. However, the traditional adjustment is always based on experiences, such as observing the burning or the smoke from the anode by the naked eye, or touching it by hand to detect the temperature. However, these methods cannot determine the value of the current conducted in anodes. What's more, these methods have a common defect in that the quality of the electrolysis cannot be determined and predicted in advance. In other words, they belong to latter-wit examination methods, which may cause an overload of the anode and spoil it unless there is a prompt adjustment. Therefore, to overcome the shortcomings of the conventional ways, we need to look for new methods measuring the current of anodes effectively introduced in references [3-5]. The principle of adopting a Rogowski coil as a special sensor for measuring currents (i.e. pulse currents, alternating currents) has been known for some years. It has no core saturation effects and, has high frequency performances introduced in references [6-10].

The paper will introduce the principle of the DC measurement instrumentation based on Rogowski coil for inspecting the state of aluminum cell. Experiment results and performance of the coil are described respectively.

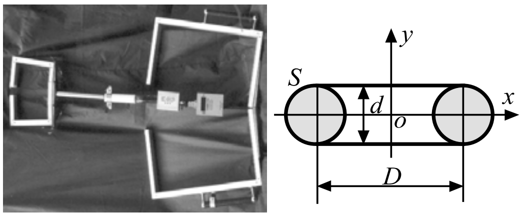
2. Principle of the current distribution characteristic of the cell

The primary cathodic reaction occurring at the surface of the molten aluminum cathode is the reduction of Al-containing species. Researchers [2] investigated mass transfer at the aluminum/melt interface. They came to the conclusion that the mass transfer in cryolite-based melts having an excess of AlF_3 is strongly influenced by interfacial convection caused by a gradient in the interfacial tension at the aluminum/melt interface. This so-called Marangoni effect is brought about by uneven current distribution at the cathode.

With the increasing of the contents of the mixture fluid: Al_2O_3, CaF_2, MgF_2 and AlF_3, the conductivity of the mixtures will be decrease distinctly more than 15~25%; the contents of the carbon and the electrolyzed aluminum will affect the conductivity of the mixtures. Some researches [1,2] indicate that these conditions will decrease the conductivity of the mixtures: the mean content of the carbon (whose diameter varies from 1 to 10 μm) is 0.04% in the mixtures, which make the carbonaceous material float on the surface of mixtures fluid; when the contents of the dissolved impurities go beyond the limit 0.04%, the conductivity of the mixtures will decrease 1%.

From analysis above, an important conclusion is that the conductivity of the mixtures will be influenced by a lot of factors, which will affect the current density of the mixtures. And the current along the anode varies accordingly. In this mixture system, with the increasing of the content of Al_2O_3 the electrical conductivity of the mixtures will be decreased distinctly.

3. Principle of the measurement instrumentation



(a) Manufactured coil

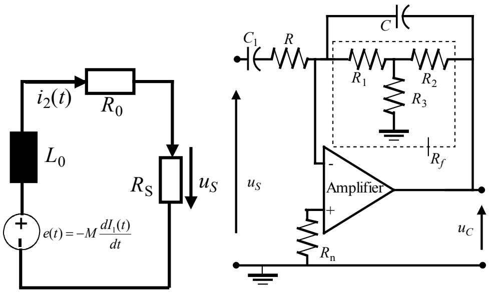
(b) Cross-section

Fig.1 Configuration of the novel instrumentation for DC measurement

A Rogowski coil briefly comprises a wire of length, cross-section area S m^2, wound onto a non-conducting, non-metallic, non-magnetic toroidal former of mean diameter D m. The instrumentation based on Rogowski coil is illustrated in Fig.1 (a) and (b). The coil is made of copper wire wound in plastic pipe and then returns through the center of the pipe to its point of origin. When the coil is uniformly wound with *N* turns/m, and formed into a close loop then the voltage *e* (*t*) induced in the coil is directly proportional to the rate of change of the measured current, I_1 (*t*), passing through the loop based on Eq. (1).

$$e(t) = -\mu_o NS\frac{dI_1(t)}{dt} = -M\frac{dI_1(t)}{dt} \tag{1}$$

Where *e* (*t*) is the EMF (electromotive force) voltage of the coil. μ_0 is the permeability of air (μ_0=4π×10^{-7} H/m). *M* is the mutual inductance of the coil, given $M=\mu_0 NS$.



(a) Equivalent circuit (b) Fig.3 Active integrator
Fig. 2 Equivalent circuit and an improved integrator circuit of Rogowski coil

The equivalent circuit of the Rogowski coil is illustrated in Fig.2 (a). When it is used to measure DC, *e* (*t*) can be expressed as Eq. (2)

$$e(t) = L_0\frac{i_2(t)}{dt} + (R_0 + R_S)i_2(t) \tag{2}$$

Where L_0 and R_0 represent the self-inductance and direct resistance of the coil respectively. The distribution capacitance of the coil is omitted in low frequency range. R_S is the terminating resistor (i.e. damping resistor). $i_2(t)$ is the induced current along the coil. Supposing

$$L_0\frac{i_2(t)}{dt} << (R_0 + R_S)i_2(t) \tag{3}$$

Based on equations (2) and (3), I_1 (*t*) can be expressed as Equations (4) and (5):

$$I_1(t) = -[(R_0 + R_S)/M]\int i_2(t)dt \tag{4}$$

$$I_1(t) = \frac{-R_0 + R_S}{MR_S}\int u_S dt \tag{5}$$

As the output voltage from Rogowski coil (i.e. u_S) is proportional to the time derivative of the measured DC current (i.e. I_1 (*t*)), an active integrator is needed to convert this back to the format I_1 (*t*). It is clear that the Rogowski coil is equivalent to a current differentiator. Mathematically, the output voltage of a Rogowski coil can be integrated:

$$u_C = -\frac{1}{RC}\int u_S dt \tag{6}$$

$$I_1(t) = \frac{R_0 + R_S}{MR_S}RCu_C \tag{7}$$

Where, u_C is the output voltage from the integrator. Eq. (7) indicates that voltage u_c is directly proportioned to the measured current. The improved integrator is illustrated in Fig.2 (b), where *R* and *C* represent the integrating resistor and capacitor respectively. C_1 is a coupling capacitor. Detail analysis of the integrator is omitted.

4. Practical considerations of the instrumentation

4.1 Relative error of self inductance δL0

Note preconditions**:** 1) the wire must be evenly twisted on the coil; 2) the parameter *S* is uniformly distributed; 3) the axis of *S* is tangent to the direction of DC flow (i.e. the direction of the DC transmission line). Only when all these conditions above are satisfied would the value of *M* become constant. In fact, the self-inductance of the coil is given by

$$n\phi = L_0 I_1(t) \tag{8}$$

The magnetic fluxφ was determined by integrating equation over the circular cross-section *S*. The co-ordinate system was illustrated in Fig.1 (b).

$$\left.\begin{aligned} \phi &= BS \\ B &= \mu_0\frac{I_1(t)}{2\pi r} \end{aligned}\right\} \tag{9}$$

Where *B* is magnetic flux density. Accordingly, self-inductance L_0 was calculated by:

$$L_0 = \frac{n^2\mu_0 S}{\pi D}\frac{2}{1+\sqrt{1-(d/D)^2}} \tag{10}$$

Therefore, the relative error of L_0 was calculated by:

$$\delta_{L_0} = \frac{2}{1+\sqrt{1-(d/D)^2}} - 1 \tag{11}$$

For the rectangular cross-section of width *b* and height *a*, the relative error of L_0 was calculated by:

$$\delta_{L_0} = \frac{D}{2b}\ln\frac{1+b/D}{1-b/D} - 1 \qquad (12)$$

Based on Eqs. (11) and (12), their relative errors of L_0, δ_{L0}, can be illustrated in Fig.3, which indicates that parameters of $x=d/D$ or $x=b/D$ will give direct influence to δ_{L0} value. Though there exists some difference of δ_{L0} between rectangular cross-section and circular cross-section, the choice of rectangular cross-section over circular cross-section is due to manufacturing constraints. Supposing *D*»*d* or *D*»*b* (at least 10 times), relative errorδ_{L0} can give satisfactory accuracy for measurement results.

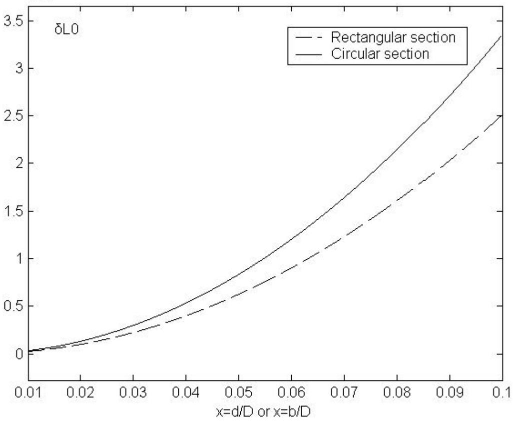


Fig.3 Comparison of the relative errorδ_{L0} of circular cross-section and rectangular cross-section

4.2 Shielded measures for measurement system

When the coil is adopted in strong interference surroundings, forcing anti-interference measures are needed to decrease the power supply ripple and reduce interference produced by the power supply system. A multilayer shielding structure is one character of this signal processing system. The schematic diagram is shown in Fig.4. The isolation transformer can reduce network voltage surges. The low pass filter with a high quality factor can cut down industrial frequency interference introduced by AC source. A shielded transformer isolates the primary and secondary from the transformer. The whole power supply system was covered with a shielding box.

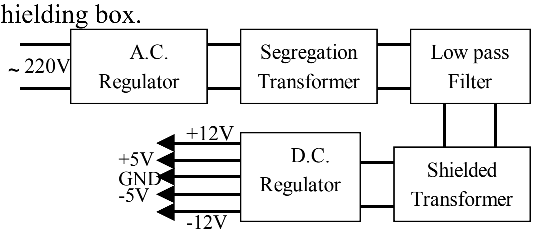


Fig.4 Volts. D.C. power supply system

In such special situation, some forcing, effective and easy-operated measures should be taken to guarantee that the coil fulfill its work introduced in references [3-5]. Firstly, a shielded box with an open slot is designed to shield from electrostatic interference. Secondly, the surface of the coil is covered with epoxy resin, which insulates the coil and reinforces its structure. Thirdly, the two ends of the coil are wrapped up with a sheet of silicon steel to shield magnetic interference and reduce the negative effect caused by unevenly distributed magnetic field near the joggling ends of the coil as well. It should be noted that a BNC connector jack would transmit the induced voltage signal to the voltage follower.

The transmission channel means that it can be employed for transmitting the voltage induced in the coil. In the system, both analog circuit and digital circuit are covered with a shielding box that depresses electromagnetic interference. The analog's ground is isolated from the digital ground by the voltage isolator to decrease common-mode interference. An ICL7135 chip, 4 ½ digital, dual-slope-integrator, analog-to-digital converter (ADC) is designed to provide interfaces to microprocessor and visual display. ICL7135 offers 50-ppm (one part in 20,000) resolution with a maximum linearity error of one count. Its zero error is less than 10 mV and zero drift is less than 0.5 mV/°C. Its source-impedance errors are minimized by low input current (less than 10 pA). And its rollover error is limited to ± 1 count. So ICL7135 can be adopted to reduce industrial frequency interference. Furthermore, an instrumentation amplifier INA103 chip can drive shielded twisted pair (STP).

5. Measurement Results

5.1 Temperature characteristic of the measurement system

When the measurement instrumentation is manufactured, we study its output characteristic with environmental temperature. The output voltage variation V_{drift} (unit: mV) with temperature is illustrated in Fig. 5. x axial represents environmental temperature (unit: ℃).

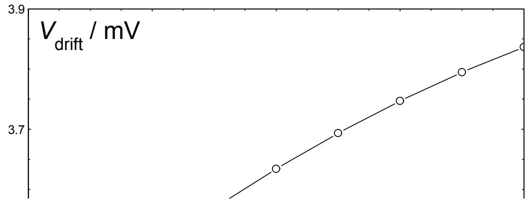


Fig. 5 Voltage variation V_{drift} with temperature

Based on analysis of Fig.5, the performance of the Rogowski coil output characteristic with temperature is excellent when it works at temperature 25~30℃ (the maximum voltage variation is approximately 3.5mV).

5.2 Degree of the linearity calibration

The significance of measuring the current of the anode in the cell is to estimate the difference of the current distributed between the front and back part of the anode of the cell, and to distinguish whether the current is evenly distributed or not. In the accuracy calibration diagram of Fig. 6, part 1 represents heavy DC generator whose stability is better than 0.03%/V. R_N is the standard resistor whose uncertainty is better than 0.01%. U_N is the potential of cross R_N. According to Ohm's law:

$$I_N = U_N / R_N \tag{13}$$

Given R_N=1Ω, the value of U_N is equal to that of I_N. The calibration data is omitted.

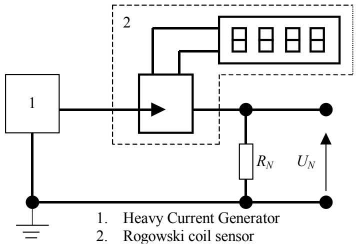


Fig.6 Rogowski coil accuracy calibration schematic diagram

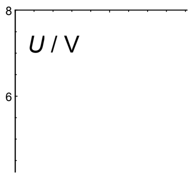


Fig. 7 Degree of linearity calibration of measurement instrumentation

The output voltage (i.e. U/V) as function of the measured DC (i.e. I/kA) is shown in Fig.7 at 20ºC room temperature. Fig.6 shows that the degree of linearity of the output voltage with measured DC is good over the wide range. This indicates that the relation of input with output signals of the instrumentation is linear.

5.3 Measurement results

The current of the anode doesn't distribute evenly during the pre-roasting stage of the cell. With the increasing of DC, the temperature in the terminal cell also increases tempestuously, which will stimulate materials such as carbon (C), silicon (Si) etc to carbonize. The resistance of carbon will increase tremendously also, which will cause the current to converge at one point of the cell. Therefore, measuring DC frequently with the coil becomes a practical method for monitoring the state of the anode.

The coil has been applied in measuring the current conducted by anode in the roasting process of aluminum electrolyzing in Sichuan province, Hubei province etc. The roasting process involves 3 phases: prophase, metaphase and anaphase, the data collected by the coil are formed in table 1~3 respectively, where F represents the front part of the anode; and B represents the back part of the anode. Photo of the cell is illustrated in Fig.8.

Fig.8 Photo of the cell during the roasting process

The practice shows this technology based on the coil is possible to distinguish the anode whose current is not evenly distributed, and after adjustment the current evenly distributes in each anode in time. For convenience, taking a newly built aluminum cell in Hubei province as example to discuss this key point.

From the data of date 7.26 and 7.27, some important conclusions can be drawn: in the early stage of the roasting process, the current of the anode isn't distributed evenly. To solve this problem, some measures must be taken to adjust the anode. Among these methods, shimming for anode joint is usually adopted. It includes adjusting slips of conductive gaskets on the joints of anodes and douching some aluminum gaskets into the cell. The essence of all these solutions is to change the resistance of conductors. From the collected data on the dates 7.28 and 7.30, the current of anodes is totally balanced after the adjustment.

Table 1: Current of anodes of the NO.1~8 cell in the forepart roasting

Date	July.26th		July.27th		July.28th		July.30th	
No.	F/kA	B/kA	F /kA	B/kA	F /kA	B/kA	F /kA	B/kA
1	11.16	12.97	9.61	9.91	5.94	6.83	2.20	2.07
2	6.28	12.77	7.92	12.43	3.55	7.86	4.40	4.16
3	7.19	10.13	10.78	10.35	7.65	6.48	4.04	4.25
4	0.25	0.00	8.11	8.37	5.06	7.84	3.87	4.97
5	0.00	0.00	1.20	0.20	7.72	7.52	3.55	4.64
6	0.00	0.03	0.00	0.12	5.45	5.81	6.06	5.42
7	7.36	0.13	1.22	0.00	0.94	0.42	4.91	5.40
8	12.37	0.88	10.18	0.48	2.63	0.00	0.95	3.08

After measuring the current of anodes of the cell No.1 during the metaphase of roasting, some important data are gathered in table 2. Obviously, it is evident that the current distributes evenly in the mass after the adjustment.

Table 2: Current of anodes of No.1 cell in the metaphase roasting

Anode number		1	2	3	4	5	6	7	8
Before adjustment	F/kA	0.13	4.62	7.45	1.60	6.08	9.20	7.57	6.70
	B/kA	0.08	3.16	4.26	0.24	6.99	12.36	0.87	0.36
After adjustment	F/kA	2.54	4.11	3.84	4.31	5.31	5.11	5.70	6.37
	B/kA	3.45	4.51	5.51	4.33	4.31	5.45	5.76	6.15

Table 3: Current of anodes of No.23cell in the anaphase roasting

Anode number		1	2	3	4	5	6	7	8
Before adjustment	F/kA	9.87	13.69	6.33	0.08	0.02	0.06	0.41	0.06
	B/kA	12.32	13.56	10.58	7.09	0.06	7.76	0.19	0.02
After adjustment	F/kA	4.85	5.64	7.51	4.30	6.29	4.97	5.61	5.10
	B/kA	5.39	4.39	5.41	4.96	2.39	5.98	5.99	5.06

The current of No.23 cell of aluminum during the anaphase of roasting is collected in table 3. From foregoing analysis, results have testified that the current distributes evenly in the mass after the adjustment.

For better comprehending the differences between the current data of the unaltered anode and the current data of the altered anode, the current curve can be drawn according to the data gathered by the coil. In the curve, X is the number of the measured anode; Y is the current (kA) of the corresponding anode. Taken the current of the front anode of table 3 as an example, the current curve can be drawn and shown in Fig.9. From the curve, the current changes more acutely before adjusting the anode than after doing so. The curve reflects the same distribution law of the current of the anode as that of the even-current coefficient, and it is apprehensible even to nonprofessional men.

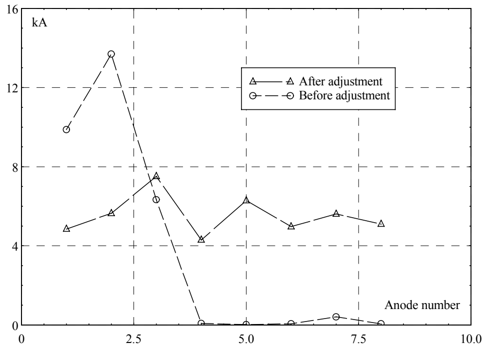


Fig .9 Current curves of No.23 cell in the anaphase of roasting process

6. Conclusions

Comparing with the traditional methods, the measuring instrumentation with Rogowski coil has advantages of small size, light weight, low cost, high reliability, simple operation, and easily popularized, which can save efforts of the researches on this aspect of the roasting process of cell. Based on the analysis above, some conclusions can be drawn: Rogowski coil is one kind of effective method for monitoring the state of the anode during the roasting process in the cell; Clamp-shape coil is applicable for the shape of the anode of the cell; Effective anti-interference technology should be adopted in the coil to improve its reliability.

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