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# EFFICIENCY ANALYSIS OF THE USE OF HIGHLY GRAPHITIZED BOTTOM BLOCKS IN 156 – 160 kA ALUMINUM ELECTROLYZERS

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A comprehensive efficiency analysis of the energy consumption is carried out for two types of aluminum electrolyzers using graphitized bottom blocks available from the Ukrainian Graphite JSC. The use of bottom blocks high in graphite (50 and 70%) leads to economic consumption of electric power, increased output, and extended service life of the electrolyzers.

## INTRODUCTION

A challenge in the world aluminum industry is reduction of the specific consumption of electric energy, increase in the unit power of electrolyzers, and extension of their service life.

Specific consumption of electric energy is an important characteristic of the energy efficiency of an aluminum electrolyzer. The specific consumption is a function of the electrolysis process parameters such as current efficiency and working voltage of the electrolyzer. Part of this voltage is spent usefully on heating, dissolution, electrochemical decomposition of alumina etc., whereas the other part (about 50%) is dissipated into the environment as heat losses. Therefore an issue of major concern in the aluminum electrolysis is the decrease in working voltage and, consequently, reduction of heat losses. The specific consumption of electric energy can be decreased by increasing the current efficiency and by decreasing the working voltage. The working voltage can be economically decreased using: (i) proper refractory materials (for example, bottom or cathode blocks with a high concentration of graphite) and heat insulators for the cathode unit; (ii) automatically controlled feed of alumina; (iii) automatically controlled interelectrode spacing (IES), or (iv) electrolyte composition variation. Most economical in the production of aluminum are electrolyzers operating at low working voltage, high current efficiency, and high current loading.

As is known, increasing the concentration of graphite improves strength characteristics, resistance to corrosive attack of molten media, heat conductivity, and electric resistivity of cathode blocks [1]. However, despite these advantages, the replacement of amorphous blocks by graphitized blocks may incur damage to the refractory lining — for example, the early leakage in the bottom lining, increased scull buildup, and, as a consequence, decreased current efficiency, etc. To obtain a positive effect from this replacement, judicious design of the cathode lining and properly controlled operating parameters of the electrolyzer are needed.

Using bottom blocks high in graphite causes a voltage drop, which makes it possible to increase the current strength on condition that the cathode lining has been modified properly. The decreased concentration of metal and increased current strength make it possible to optimize the workspace configuration (WSC), in particular, to decrease slag scull buildup in the anode compartment. In turn, this leads to the increase in current efficiency owing to the decrease in horizontal current components.

Thus, a comprehensive approach makes it possible to implement modernization of the aluminum productions in all aforementioned aspects, namely, reduction of the specific consumption of energy, increasing the output, and extending the service life of the electrolyzer.

A scheme for evaluating the efficiency of cathode blocks high in graphite should involve the following steps:

– choice of the base types (prototypes) of electrolyzers intended for use of graphitized bottom blocks;

– survey of technical documentation, performance parameters, and experimental data (temperature regimes for cathode casings, workspace configuration, etc.) on the prototypes chosen;

– development of the refractory lining for cathodes;

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– development of numerical models for analysis of the thermal and electric fields in electrolyzers;

– feasibility analysis of the efficiency of engineering solutions for graphitized bottom blocks using computer-aided simulation data;

– analysis of the data obtained, suggested recommendations, and conclusions.

## BASIC AND UPDATED DESIGN OF THE ALUMINUM ELECTROLYZER CATHODES

Two types of electrolyzers have been considered as basic designs (prototypes):

S-8BM type — an electrolyzer with a self-baking anode (SBA) and an upper current lead (UCL), for a current strength of 156 kA;

S-160 type — an electrolyzer with baked electrodes (BE), for a current strength of 161 kA.

*S-8BM Electrolyzer*. SBA has dimensions of 8400 × 2850 × 1650 mm and is fitted with 72 anode pins. The cathode cap insulation consists of several layers (bottom upwards): (i) a thin levelling layer (about 10 mm) of chamotte powder (filler); (ii) three rows of foamed diatomite components and one row of chamotte components; (iii) a layer of dry barrier mixture (DBM, about 110 mm). The heat insulation of the cap sidewalls (35 – 50 mm) consists of chamotte powder; the heat insulation of the sidewall blocks (35 – 50 mm) is composite: in the lower section, it is chamotte powder, and in the upper section, it is carbon-containing gunning mix No. 2.

*S-160 Electrolyzer*. The anode array accommodates 22 three-nipple baked anodes with dimensions of 1450 × 700 × 600 mm. The cathode cap insulation consists of several layers ((bottom upwards): (i) a thin levelling layer (about 10 mm) of chamotte powder (filler); (ii) three rows of foamed diatomite components and two rows of chamotte components; (iii) a cushion (about 40 mm) of bottom mix. The heat insulation of the cap sidewalls (35 mm) consists of chamotte powder; the heat insulation of the sidewall blocks (35 mm) is composite: in the lower section, it is chamotte powder, and in the upper section, it is carbon-containing gunning mix No. 2.

The bottom in these electolyzers is made up from 30 bottom blocks with dimensions: a long block, 2200 × 550 × 400 mm, and a short block, 1600 × 550 × 400 mm. The graphite concentration in the amorphous material of bottom blocks is 30%. The depth of the cathode shaft is 550 mm. The cathode casings are counterfort type structures.

The updated cathode lining based on heavily graphitized blocks (50 and 70% graphite) is capable of sustaining heavy currents; to that effect, “heat-dissipating” sidewalls were used; the cathode shaft depth was lowered to about 450 mm to allow operation with a low-level metal; the refractory section of the cathode cap was reinforced with a row of chamotte components. For heat insulation of the cap sidewalls in the lower section, calcium silicate components, rather than foamed diatomite components and chamotte powder, were used. The cathode casings were of frame type. The newly designed cap lining was intended for a longer service life of the electrolyzer.

## MATHEMATICAL MODELS OF PHYSICAL FIELDS IN ALUMINUM ELECTROLYSIS CELLS

### An Electric Potential Problem for the Bottom of the Electrolysis Cell

We consider a three-dimensional ($3D$) problem for a half-bottom of the electrolysis cell. The electric potential field is described by Laplace’s equation

$$\Delta u = 0, \tag{1}$$

where $u$ is the electric potential, V, and $\Delta$ is the Laplace operator.

For $3D$ (or $R^3$) problems, one has $\Delta = \frac{\partial}{\partial x^2} + \frac{\partial}{\partial y^2} + \frac{\partial}{\partial z^2}$, $X(x, y, z) \in R^3$.

The boundary conditions for Eq. (1) as applied to the bottom of an aluminum electrolysis cell take the form:

the zero electric potential at the ends of a bloom is (Dirichlet condition):

$$u|_{\Gamma} = u(x, y, z) = 0, \tag{2}$$

where the subscript $\Gamma$ refers to a boundary (the surface of a structural element of the electrolysis cell);

the anode current density projected on the liquid metal surface is (Neumann conditions):

$$-\chi \left.\frac{\partial u}{\partial n}\right|_{\Gamma} = j(x, y, z), \tag{3}$$

where $\chi$ the electric conductivity, $(\Omega \cdot \text{m})^{-1}$ (or $\chi = 1/\rho$, $\rho$ being electric resistivity, $\Omega \cdot$ m); $j$ is the normal current density, A/m$^2$. On the other hand, $j = I/S_{\text{anode}}$ ($I$ is the current passing through the electrolysis cell), A; $S_{\text{anode}}$ is the cross-sectional area at the bottom of the baked anode (or, alternatively, of the composite anode array), m$^2$; conditions for the boundary joining of structural elements (at absolute contact) are

$$\begin{cases} u|_{\Gamma-} = u|_{\Gamma+} \\ -\chi_{-} \left.\frac{\partial u}{\partial n}\right|_{\Gamma-} = \chi_{+} \left.\frac{\partial u}{\partial n}\right|_{\Gamma+} \end{cases}, \tag{4}$$

where symbols ± denote positions on the left and on the right of the contact boundary; $n$ is the normal to the external surface;

the conditions for the joining of structural elements with allowance for a jump in potential (contact resistance) at the boundary between structural elements are

$$\begin{cases} u_- - u_+ = -r_{e+}\,\chi_+ \left.\dfrac{\partial u}{\partial n}\right|_+ \\ -\chi_- \left.\dfrac{\partial u}{\partial n}\right|_- = \chi_+ \left.\dfrac{\partial u}{\partial n}\right|_+ \end{cases},$$

$$\text{or} \begin{cases} u_- - u_+ = -r_{e+}\, j_+ \\ j_- = -j_+ \end{cases}, \qquad (5)$$

where $r_e$ is the contact resistance (for example, at the contact boundary metal – bottom, or bottom block – iron casting), $\Omega \cdot m^2$.

The condition for the rest of surfaces is

$$\frac{\partial u}{\partial n} = 0. \qquad (6)$$

**Problem for the Thermal State of an Electrolysis Cell**

We consider half of the transverse or longitudinal section of an electrolysis cell (2*D* problem). The mathematical description of the temperature field in this case is given by a nonlinear heat conduction equation of the type

$$[\operatorname{div} \lambda_i(t)\nabla t(X)] + q_{vi}(X) = 0, \quad X(x, y) \in \Omega, \qquad (7)$$

where $\lambda_i(t)$ defines the temperature dependence for heat conductivity of the *i*th structural element, $W/(m \cdot K)$; $\nabla = \dfrac{\partial}{\partial x} + \dfrac{\partial}{\partial y}$; $t$ is the temperature, °C; $q_{vi}$ is the internal source of heat generated by the passage of current in the *i*th structural element, $W/m^3$; $X(x, y) \in \Omega$ are the Cartesian coordinates, m.

The boundary conditions for Eq. (7) are: for axes of symmetry, these are adiabatic conditions; at the outer boundaries in contact with air these are conditions of the convective type; at the contact boundaries of structural elements, these are the boundary joining conditions for perfect contact.

In a generalized statement, the heat conductivity of materials is given as a function dependent on temperature:

for uniform regions, a linear relationship $\lambda(t) = a_0 + a_1 t$ is given, where the coefficients $a_0$ and $a_1$ are determined from literature data by linear approximations [2];

for composite regions with a boundary not necessarily known beforehand (anode – liquid anodic mass, electrolyte – protective slag, metal – crust, or material impregnated – not impregnated with fluoride salts), it is

$$\begin{cases} \lambda(t) = \lambda_1, \quad t < t_m - \dfrac{\Delta t}{2}, \\ \lambda(t) = \lambda_1 + \dfrac{\lambda_2 - \lambda_1}{\Delta t}\, t,\ t_m - \dfrac{\Delta t}{2} \le t \le t_m + \dfrac{\Delta t}{2}, \lambda_2 > \lambda_1, \\ \lambda(t) = \lambda_2, \quad t > t_m + \dfrac{\Delta t}{2}, \end{cases} \qquad (8)$$

**TABLE 1.** Voltage Drop across the Electrolyzer's Bottom

| Crust size | Voltage drop across the bottom, mV, for different graphite concentrations in the bottom blocks, % | | |
|---|---|---|---|
| | 30 ($\rho = 32\ \mu\Omega \cdot m$) | 50 ($\rho = 28\ \mu\Omega \cdot m$) | 70 ($\rho = 20\ \mu\Omega \cdot m$) |
| *S-8BM electrolyzer* | | | |
| Beneath the anode projection, cm: | | | |
| 40 | 391.26 (391.0)* | 375.05 | 341.23 |
| 20 | 369.49 | 355.65 | 326.68 |
| 0 | 357.25 | 345.08 | 319.51 |
| *S-160 electrolyzer* | | | |
| Beneath the anode array projection, cm: | | | |
| 10 | 343.26 (343.0)* | 331.44 | 306.65 |
| 5 | 340.84 | 329.35 | 305.21 |
| 0 | 337.64 | 326.64 | 303.52 |

* Shown in brackets are experimental values.

where $\lambda_1$ and $\lambda_2$ are heat conductivities of different parts of the composite region; $t_m$ is the phase boundary temperature; $\Delta t$ is the smoothing interval. The heat conductivities $\lambda_1$ and $\lambda_2$ can be defined as $\lambda = a_0$ or $\lambda = a_0 + a_1 t_{av}$, where $t_{av} = \dfrac{1}{2}(t_m \pm \delta t)$, $\delta t$ being the temperature variation interval in a part of the composite region.

Thus, in a numerical analysis of the temperature field of an electrolysis cell three boundaries can be determined simultaneously: baked anode – liquid anodic mass, electrolyte – protective slag, and metal – crust.

## NUMERICAL ANALYSIS RESULTS

Numerical analysis of the thermal state and energy balance of electrolyzers were carried out using software in [2 – 4] and experimental data and performance parameters of aluminum electrolyzes reported from aluminum manufacturers. Electric potential fields for the bottom of electrolyzers were calculated using a standard CAD (Computer Aided Design) program package.

Relevant data are summarized in Table 1 and Fig. 1. The electric resistivities for cathode blocks were those as given in a certificate from the Ukrainian Graphite JSC; electric contact resistivities for the bottom were borrowed from [1].

Calculated data from Table 1 show that the voltage drop across the bottom is controlled by the bottom block resistance and the size (length) of the crust (measured as a projection of the anodic array). Calculated and experimental data are compared in Table 2.

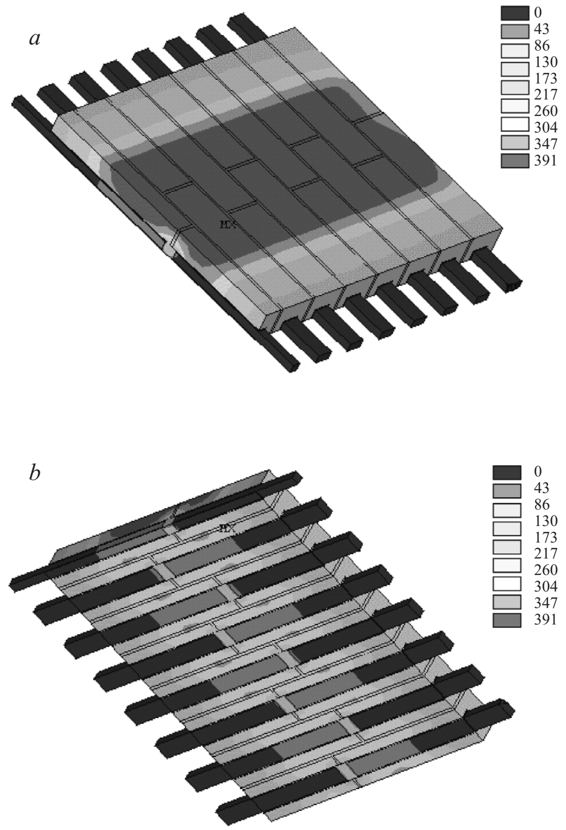


**Fig. 1.** Electric potential field (mV) for half of the bottom of an S-8BM electrolyzer composed of cathode blocks (30% graphite). The crust extends to 40 cm beneath the anode array projection lengthwise. Cathode blocks are composite: long blocks with dimensions of 2200 × 550 × 400 mm and short blocks with dimensions of 1600 × 550 × 400 mm; *a*) top view; *b* ) bottom view.

As can be seen, the calculated results are in agreement with the field test data (Table 2). One will infer therefore that numerical thermal-state models are suitable for comparative performance analysis of updated cathode linings in S-8BM and S-160-type electrolyzers using cathode blocks high in graphite.

The thermal state of S-8BM and S-160 electrolyzers with updated cathode linings composed of 50% and 70% graphitized bottom blocks was analyzed under the following conditions:

the heat conductivities of graphitized bottom blocks were those as recommended in a certified document from the Ukrainian Graphite Joint-Stock Co.;

the current strength was 162 kA in S-8BM and 166 kA in S-160;

the cathode shaft depth was 455 mm, and the decrease in metal level and increase in current strength provided grounds to believe that the crust size beneath the anode array could be decreased by a factor of 2;

owing to the optimized workspace configuration, the current efficiency could be increased by 0.5 – 1%;

**TABLE 2.** Calculated Results (numerals above the bar) and Field Test Data (numerals below the bar) Compared[*1]

| Parameter | Electrolyzer | |
|---|---|---|
| | S-8BM (IPS = 52.0 mm, $t_{\text{air zero}} = -2$°C) | S-160 (IPS = 54.5 mm, $t_{\text{air zero}} = -13$°C) |
| Working voltage, V | 4.55 / 4.54 | 4.51 / 4.5 |
| Electrolyte temperature, °C | 952.8 / 953.3 | 961.3 / 960.9 |
| Workspace configuration (WSP): | | |
| longitudinal side, cm: | | |
| scull thickness | 6.3 / 0 – 17 (6.7) | 9.14 / 6 – 10 (8) |
| crust length[*2] | −30.0 / −(40 – 92) (−65.8) | −9.15 / −(0 – 10) (−5) |
| longitudinal side, cm: | | |
| scull thickness | 3.74 / (−1) – 9 (4.5) | 7.45 / – |
| crust length[*2] | −20.2 / −(0 – 53) (−38) | +16.5 / – |
| Sintering cone height on the anode axis, cm | 126 / 125 | – |
| Cathode casing temperature, °C: | | |
| at upper belt at longitudinal side | 288 / 235 – 334 (266) | 305 / 204 – 314 (279) |
| at middle belt at longitudinal side | 223 / 171 – 247 (204) | 239 / 126 – 307 (213) |
| at lower belt at longitudinal side | 55 / 37 – 63 (53) | 87 / 63 – 82 (72) |
| at bottom | 64 / 28 – 130 (61) | 69 / 51 – 110 (75) |
| at lower belt (end face) | 72 / 62 – 118 (87) | 80 / – |
| Current efficiency, % | 89 | 92 |
| Electric energy consumption, kW · h/ton Al | 15,531 / 15,400 | 14,886 / 14,800 |
| Total heat loss, kW | 346.58[*3] | 384.815 |
| Heat loss, kW: | | |
| anodic | 154.5 | 108.268 |
| cathodic | 192.08 | 276.548 |

[*1] Shown in brackets are average values based on field test data.

[*2] The crust length is measured with respect to the projection of the anode array: the minus (plus) sign signifies that the crust extends (does not extend) to beneath the anode array.

[*3] Data based on energy balance analysis.

the voltage drop across the electrolyzer's bottom was that as given in Table 1.

Using 50% and 70% graphitized cathode blocks, improvements in the performance characteristics of updated S-8BM and S-160 electrolyzers were obtained:

the electric power consumption per ton of aluminum could be decreased to 95 – 138 kW · h on S-8BM electrolyzer and to 313 – 331 kW · h on S-160 electrolyzer;

increasing the current strength by 5 kA allowed the metal output to be increased to 36.22 kg/day (S-8BM) and 37.23 kg/day (S-160);

using the advanced cathode lining makes it possible to extend the electrolyzer's service life by a further 6 months.

Thus, decreasing the resistance of cathode blocks (by increasing the graphite concentration to 50 and 70%), decreasing the interelectrode distance (IES) (by increasing the current strength), and increasing the current efficiency (by optimizing the workspace configuration) leads to economical use of electric power in the updated electrolyzers.

Results of numerical analysis and field tests are compared in Table 2.

## CONCLUSIONS

Using bottom blocks high in graphite (50 and 70%) and leaving the design of cathode lining and the current strength unchanged allows one to save electric power consumption by decreasing the voltage drop across the electrolyzer's bottom:

in an S-8BM electrolyzer, decreasing the voltage drop by 16 – 50 mV gives an economy of electric power of 54 – 168 kW · h per ton Al;

in an S-160 electrolyzer, these characteristics are 12 – 37 mV and 39 – 120 kW · h.

A comprehensive approach to the use of bottom blocks high in graphite (50 and 70%) available from the Ukrainian Graphite JSC provides a means for saving electric power consumption and increasing the output and service life of aluminum electrolyzers.

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