Relationship Between Technical and Economic Indicators, Metal Level and Interpole Distance in an Aluminum Electrolyser

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Abstract: The article presents, in order of discussion, the mechanisms of the possible influence of the main technological parameters of the operation of electrolyzers for the production of aluminum - the metal level and the interpolar distance - on the technical and economic indicators of the process of electrolytic production of aluminu. The conclusions in the article are confirmed by practical measurements of process parameters in operating electrolyzers for aluminum production using statistical methods of data analysis and are in good agreement with literary sources. The negative impact of an increase in the height of the metal surface wave in the electrolyzer shaft due to a decrease in the metal level in the aluminum electrolyzer on the technical and economic indicators of the aluminum production process is shown. It is suggested that the technological violation "non-quenchable anode effect" is a consequence of the change in the electrolyte flow regime from laminar to turbulent. The theoretical inefficiency of the "slot" anode technology is shown, as well as the reason for the significant difference in the current output in electrolyzers with pre-baked and self-baking anodes.

1 INTRODUCTION

The electrolytic production of aluminum is try [1], [2]. one of the most energy-intensive and technologically demanding processes in contemporary metallurgy- Although process optimization and the introduction of new materials have led to a notable progress, the efficiency of the electrolyzes used in aluminum production is yet strongly impeded by various decisive operational parameters. The level of the metal in the electrolytic cell and in temporal distance are of particular importance as the principal factors that influence the technical and economical indicators of an aluminum plant [3], [4]. Thus, it is highly important to profoundly illuminate the correlation of these factors with production efficiency not only for scientific study but also for industrial application [5].

The metal level in an electrolyze is not only a geometric parameter, it influences the hydrodynamics of the electrolyte flow, the stability of electronic reactions and the amount of Joule losses [6]. A lower metal level will create a higher metal surface wave in the electrolyze shaft which in turn will make the process unstable and cause higher energy consumption [7]. Finally, such instability leads to technological disturbances, such as the non-quenchable anode effect that is the result of a transition in the electrolyte flow regime from laminar to turbulent [8]. Current efficiency is decreased and energy usage/operating costs is increased due to these disruptions [9].

The interpolar distance, which refers to the distance between the anode and the cathode, plays an important role on a voltage drop in the electrolytic cells [10]. Too large interpolar distance will bring unnecessary power consumption, whereas too small will result in cell short-circuit and instability [11]. Hence, the optimization of this parameter is important to attaining greatest current efficiency with least specific energy consumption [12].

It has also been previously established by others that another consideration for the synthetic anode technology, specifically the differentiation between

pre-baked and self-baking types, continues to have an impact on total cell current efficiency for aluminum electrolyzers [13]. In this sense, it is worth noting that technology of "slot" anode results theoretically not very reliable when used in practice, as it has its own serious limitations [14]. Furthermore, regarding to comparison, the comparison between the cells using a pre-baked anode and those using a self-baking anode was studied, and the former showed the superior and stable current output than the latter [15].

Based on the above, the objective of this paper is to analyze the impact mechanisms of the metal level and interpolar distance on both the technical and economic aspects of aluminum electrolyzers. Aasmundtveit et al. [16] combines hands-on experiments of process parameters in electrolysers in operation with statistical data analyses. The findings are critically assessed in light of the literature, yielding a holistic, solid, and scientifically sound insight into the correlation between crucial technological factors and efficiency of production [17].

The study further rationalizes the dependence of these parameters and sheds some new insight into aluminum electrolysis, which may provide important guidance for the more energy-efficient industrial practice as well as improved economic performance of aluminum production [18], [19].

It is known that the specific power consumption in the electrolytic production of aluminum depends on the metal level and the interpolar distance (hereinafter referred to as IPD). However, according to the authors, there are a number of poorly studied aspects that play an important role in this statement. Thus, to date, the nature of the dependence of power consumption W on the metal level in the electrolyzer is not reliably known. Is there a minimum on this curve, or does an increase in the metal level lead to a monotonic decrease in power consumption? The same question remains open with respect to the nature of the dependence of W on IPD. This article presents the results of the analysis of literary sources and conclusions on the essence of the above problems.

2 METHODS

The specific energy consumption in the production of aluminum by electrolytic means is determined by the ratio of the amount of energy consumed to the actual amount of aluminum obtained [20]:

$$W y\partial = \frac{W}{M} = \frac{Ucp}{k \cdot \eta}, \text{ kW*h/kg;} \quad (1)$$

where:

- W – amount of consumed electricity, kW·h;
- M – amount of aluminum produced per day; kg;
- Ucp – average voltage on the electrolyzer, V;
- k – electrochemical equivalent of aluminum, g/(A.h);
- η – current output, fractions of a unit.

The direct reaction that takes place in the electrolyzer:

$$Al_2O_3 + 1.5C + e = 2\ Al + 1.5\ CO_2 \quad (2)$$

And the reverse reaction:

$$2\ Al + 3\ CO_2 = Al_2O_3 + 3\ CO \quad (3)$$

Reaction (3) is multi-stage [21], [22], and consists of the following stages:

- Stage 1. Diffusion of metal from the metal phase into the electrolyte phase (with the formation of a true or colloidal solution, or with the formation of subions);
- Stage 2. Transfer of metal in the electrolyte phase from the catholyte to the anolyte;
- Stage 3. Chemical reaction between carbon dioxide and metal in the anolyte phase.

Stage 3 is not rate-limiting. As a result of this stage, aluminum remains in solution; only the oxidation state changes from 0 (+1 if aluminum is in the solution as a subion) to +3: $Al^0 \rightarrow Al^{3+}$. That is, this is the reverse process of the cathode part of the direct reaction (2). However, as is considered established [23] (based on the fact that the cathode overvoltage is extremely small), this reaction is fast and equilibrium.

This means that the rate of oxidation of the dissolved metal is a fast and equilibrium process.

Stage 2 is not limiting either. The evidence for this is as follows:

1) In the solidified electrolyte, which is taken for analysis by the diffractometric method, there are no particles of metallic alumina; these particles (if present) should be displayed on the diffractograms, which, however, is not observed. Literary data [24] are available only for laboratory conditions. The question for the conditions of industrial electrolytes is not closed, but can be verified by conducting an analysis by the gas-volumetric method (determining the volume of hydrogen released

during the reaction of the solid electrolyte with an alkaline solution).

2) It is believed that the "evolution of gas inclusions", i.e. the mixing of the electrolyte under the action of outgoing bubbles, is the main, if not the determining force, ensuring the circulation of the electrolyte [25]. Consequently, under conditions where stage 2 were the limiting stage, it would not make sense to carry out work related to the optimization of the busbar, since the result affects only the movement of the metal phase, and not the movement of the electrolyte.

   However, much attention is paid to such works and there is a positive result [26]. As a confirmation of the success of optimizing the influence of magnetic fields, one can cite the difference between the specific energy consumption in cases with longitudinally and transversely located electrolyzers (Table 1) [27].

3) The transfer of dissolved aluminum from the catholyte to the anolyte should mainly occur by the mechanism of convective diffusion (otherwise the meaning of the struggle to reduce the rate of circulation of the electrolyte is lost). In this regard, this process should be many orders of magnitude faster than diffusion transfer.

Table 1: Specific DC energy consumption for different electrolyzer arrangements.

Electrolyzer arrangement type	Specific energy consumption (kWh/t)
Longitudinal, double-row arrangement	15 056
Transverse, single-row arrangement	14 896
Difference	160
Relative difference (%)	1.06

Consequently, the rate-limiting stage of reaction (3) is, with a high degree of probability, the stage of diffusion of aluminum from the metal phase to the catholyte phase.

3 RESULTS

The rate of diffusion of the metal from the metal phase to the catholyte is the limiting stage of reaction (3). The rate of this reaction may depend on the contact area of the metal and electrolyte phases, as well as on the rate of movement of the electrolyte (namely the electrolyte, since the concentration of aluminum in the metal equals 1). Let's consider the first factor - the speed of movement of the electrolyte.

The dependence of the rate of metal diffusion into the electrolyte phase on the electrolyte velocity is estimated using the “diffusion boundary layer” model [28], which assumes the existence of a thin stationary boundary layer in which the transfer occurs by a diffusion mechanism. In this case, only the thickness of this layer depends on the electrolyte velocity. The rate of mass transfer per unit of interface surface is described by Fick’s first law [29]:

$$J = D\frac{\partial[Al]}{\partial x}; \quad (4)$$

where:

- D is the diffusion coefficient;
- J - diffusion flux through a unit surface area of the metal-electrolyte interface.

To assess the significance of this effect, it should be taken into account that an increase in the mixing speed leads to a linear increase in flow only up to a certain speed, until the liquid flow regime changes from laminar to turbulent.

To assess the flow regime of a liquid, the Reynolds criterion is used [30], which is defined as follows:

$$\mathrm{Re} = \frac{\rho \nu L}{\eta}; \quad (5)$$

where:

- Re is the Reynolds number, if it is greater than a certain critical value, then the mode currents are turbulent, if less – laminar;
- ρ is the density of the electrolyte;
- ν is the speed of movement of the electrolyte;
- η - dynamic viscosity of electrolyte;
- L - characteristic size, i.e. a factor describing the shape of the vessel.

Thus, the rate of dissolution of the metal, and, accordingly, the rate of the reverse reaction (3) will increase slightly, but only up to a certain limit; after that, the rate of dissolution will increase sharply and many times over.

This phenomenon can explain the appearance of the "unquenchable anode effect" - a phenomenon that is quite rare, but does not have sufficient theoretical justification. From the point of view of the transition from laminar to turbulent flow, this is explained logically.

However, under normal conditions with a laminar flow pattern, another factor that influences the rate of metal dissolution is more significant – the surface area of the "metal-electrolyte" interface.

With an already constructed electrolyzer, the area of the interface between the metal and the electrolyte depends on the thickness of the deposit in the area of this interface, which is obvious, and the presence of waves at the phase boundary.

The increase in the area of the section in the presence of waves can be multiple. Table 2 shows the value of the area of the section assuming a sinusoidal plane wave with different frequency and amplitude [31]:

Table 2: Interface area for a sinusoidal metal–electrolyte wave at different frequencies and amplitudes.

Frequency, ω	Amplitude, α	Area, S
0	0	π
1	1	1.22π
1	2	1.68π
2	1	1.68π
2	2	2.81π
3	3	5.81π
4	3	7.78π
10	3	19.16π

That is, the area of the interphase boundary can increase many times and even by orders of magnitude.

The waves are obviously caused by interaction with the magnetic field. Moreover, the more energy is required to excite the wave, the more stable such a boundary is to disturbances from external influences and the smaller the area of the boundary will be.

Here we will consider an approach that considers not the force of external influence from the magnetic field, as is traditionally accepted, but the actual energy of the wave.

It is believed [32], [33] that the magnetic field interacts with currents inside the metal, which causes the formation of waves. Thus, the analogy of this process cannot be the process of formation of wind waves on the surface of water (in this case, the effect of the wind is only on the surface layers of water), but can be the process of formation of tsunamis.

When a tsunami is formed, the entire thickness of water rises (for example, as a result of an earthquake). This is very similar to the process of interaction between a metal and a magnetic field: the magnetic field affects the entire layer of metal.

The properties of tsunami waves are well known: in deep water they are characterized by high speed and low amplitude; on the other hand, when moving to shallow water, the speed decreases and the amplitude, accordingly (the law of conservation of energy), increases. In relation to the electrolyzer, this means that when the metal level decreases, we should expect an increase in amplitude (an increase in the area of the metal and electrolyte interface) and a slowdown in the circulation of the metal.

In wave theory [11]-[20] it has been proven that the total energy (vertical plus horizontal component) of the energy of an internal gravitational wave at the interface between a metal and an electrolyte is equal to:

$$\varepsilon_{\Sigma} = \tfrac{1}{2}([(\rho_{Al} - \rho_{Et})/(\rho_{Al} + \rho_{Et})]\, g + [\gamma/(\rho_{Al} + \rho_{Et})]\kappa^2)\alpha^2, \quad (6)$$

where:

- ε_{Σ} - average total wave energy per unit surface J/m^2;
- ρ_{Al} - density of aluminum;
- ρ_{Et} - electrolyte density;
- g - acceleration of gravity;
- γ - surface tension at the metal/electrolyte interface;
- κ is the wave number, i.e. the number of wave periods in a segment of length 2 π ($\kappa=2\pi/\lambda$), λ – wavelength;
- α - amplitude.

From (6) it follows directly that an increase in surface tension will increase the wave energy, which, with the same disturbing effect, will lead to a decrease in the wave amplitude and, consequently, a decrease in the surface area of the "metal-electrolyte" interface, which will reduce the rate of the reverse reaction (3) and will, thereby, lead to an increase in the current efficiency.

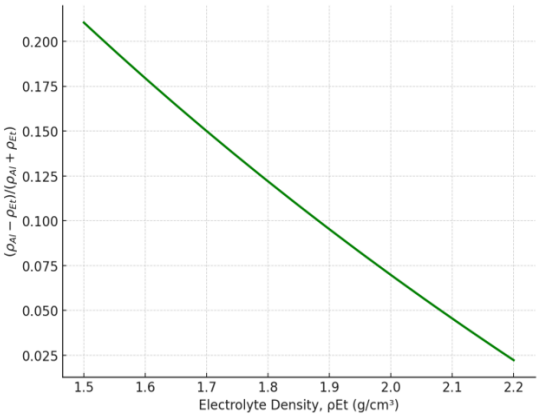

Figure 1: Dependence of the parameter (ρAl − ρEt)/(ρAl + ρEt) on electrolyte density (ρAl = 2.3 g/cm³).

Figure 1 shows that with an increase in the density of the electrolyte, the value of the parameter $(\rho_{Al} - \rho_{Et})/(\rho_{Al} + \rho_{Et})$ (6) decreases; consequently, the resistance of the interphase boundary to wave formation increases.

Equation (6) defines the total energy of the wave, i.e. the energy of vertical displacement plus the energy of horizontal displacement. In wave physics, it has been proven that the horizontal velocity of a wave on the surface of a liquid with a melt depth H and wavelength λ [1]is equal to [21]-[31]:

$$c = \sqrt{\frac{g\lambda}{2\pi}\tanh\left(\frac{2\pi H}{\lambda}\right)}, \quad (7)$$

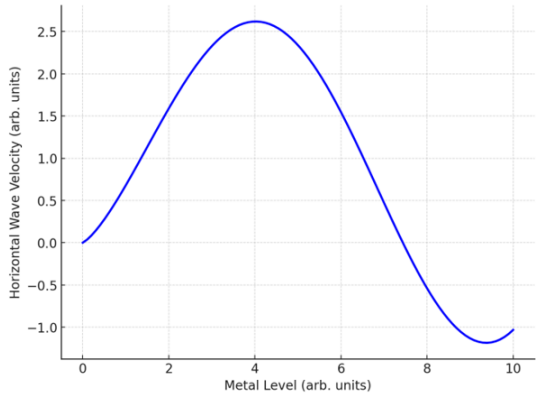

Figure 2: Dependence of horizontal wave velocity on metal level.

In accordance with the law of conservation of energy, the consequence of (6) and (7) is that a decrease in the metal level will lead to a decrease in the metal circulation rate, but to an increase in the amplitude of the waves, which will lead to an increase in the metal-electrolyte interface surface and thereby accelerate the reverse reaction (3).

Due to the fact that in the case of an electrolyzer the surface of the melt is not open (the waves are internal, with limitations: neither the depth of the metal nor the MPR can be considered infinitely large), the dependence of the metal circulation rate on the interpolar distance will have exactly the same appearance as in Figure 2 [11].

This allows us to explain the empirical fact of an increase in current efficiency with an increase in the MPR and with an increase in the metal level, with the fact, however, that after a certain limit this dependence is practically absent.

4 DISCUSSION

The specific energy consumption in the electrolytic production of aluminum increases with an increase in the rate of the reverse reaction (3), the rate of which increases due to:

- reduction of the metal level; this follows from (7) – when the metal level decreases, especially below a certain critical level, this happens quickly, the height of the waves on the metal surface increases. This leads to an increase in the metal-electrolyte interface, accompanied by an increase in low-frequency noise;
- reduction of the interpolar distance; this also follows from (7), and is also accompanied by an increase in low-frequency noise. However, this does not have such a strong effect on the specific energy consumption, due to the parallel reduction in voltage (1).

The consequence of the reasoning presented in this article is:

- explanation of the nature of magneto hydrodynamic (hereinafter MHD) instability as a situation in which the wavelength of the melt becomes a multiple of the geometric size of the cathode, which leads to the appearance of resonance;
- explanation of the nature of the persistent anode effect as a situation in which the electrolyte flow regime changes from laminar to turbulent. It should be emphasized that the persistent anode effect and MHD instability have different natures.

The following factors contribute to the emergence of a non-quenchable anode effect (5):

- decrease in electrolyte viscosity;
- increase in electrolyte density.

Theoretical inefficiency of the "slotted anode" in terms of reducing specific energy consumption. In order to reduce the wave height, the anode gap must be comparable to the melt depth, which is impossible; on the other hand, this can explain the well-known fact - the difference in current output between electrolyzers with pre-baked anodes and self-baking anodes.

5 CONCLUSIONS

The main conclusions of the study can be summarized as follows:

1) The specific energy consumption in electrolytic aluminium production increases as the metal level decreases due to the increase in waves on the metal surface.
2) The increase in the height of the metal wave can be identified by the growth of low-frequency noise (magnetohydrodynamic instability) in the aluminium production electrolyser.
3) The specific energy consumption in electrolytic aluminium production increases as the interpole distance in the aluminium electrolysis cell decreases due to a direct reduction in productivity. This is also accompanied by an increase in low-frequency noise (magnetohydrodynamic instability). The reduction in electricity consumption is partially offset by a direct reduction in voltage across the electrolyser as the interpole distance is decreased. Data on the dynamics of low-frequency noise levels (magnetohydrodynamic instability) can be used to assess the performance of an aluminium electrolyser.
4) When a situation arises where the wavelength of the melt becomes a multiple of the cathode's geometric size, resonance is possible, which in general leads to a severe technological disruption and a significant reduction in the electrolyzer's productivity, a phenomenon known in industrial practice as the "persistent anode effect."
5) In general, the non-extinguishing anode effect is a situation where the flow of electrolyte in an aluminium electrolyser changes from laminar to turbulent.
6) The non-fading anode effect, resulting from a change in the electrolyte flow regime from laminar to turbulent in an aluminium electrolyser, is intensified by a decrease in electrolyte viscosity and an increase in its density.
7) The use of "slotted" anodes as an energy-saving practice is justified when the depth of the slots is comparable to the depth of the melt in the electrolyser tank.

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