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Экспериментальное исследование ЭМП электролизера Содерберга с помощью информационной системы мониторинга

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Аннотация. *Цель данной работы заключается в исследовании электромагнитного поля процесса получения первичного алюминия и его влиянии на технологический процесс. В работе доказано, что оптимизация технологического процесса – актуальная задача мирового масштаба; проведен ряд экспериментальных исследований по формированию электромагнитного поля внутри электролизера в лабораторных условиях. Выполненные исследования по влиянию повышения силы тока на стабильность электромагнитных полей подтверждают возможность работы электролизера в рассматриваемом режиме.*

Ключевые слова: система мониторинга, электромагнитное поле, металлургическая печь, алюминиевый электролизер

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Research article

Experimental study of the EMF of the Soderbergh electrolyzer using an information monitoring system

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Abstract. *An information system for monitoring the electromagnetic field of the electrochemical electrolysis process has been developed, the main element of which is a spatially distributed sensor. This system makes it possible to identify the characteristics of the electromagnetic field at several points in space. Also, such a system can be used to support decision-making when developing a control action. An electrical circuit of a spatially distributed electromagnetic field sensor has been developed, theoretical and experimental studies have been carried out; the analysis of the results of the study was carried out.*

Keywords: monitoring system, electromagnetic field, metallurgical furnace, aluminum electrolyzer

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Introduction. At present, in various industries there is a great need to implement high-quality control of spatially distributed objects, i.e., objects whose physical dimensions cannot be neglected [1]. In other words, there is a need to control the field of values of the physical quantity by which regulation is carried out. The nature of this quantity can be absolutely different: thermal conductivity, diffusion, magnetism, solid state physics and much more. The problem is that the existing classical theory of automatic control, using a mathematical apparatus applicable to concentrated objects, does not allow solving this problem. Therefore, the study of systems with distributed parameters leads to the development or adaptation of a mathematical apparatus that can be used for the subsequent synthesis of a regulator for these systems.

For over a hundred years, the technology of aluminum production and design features of electrolyzers have been improving. It has been proven experimentally that there is a need to model the processes occurring inside the electrolyzer, since they have an aggressive natural character and do not allow for accurate measurement of the dynamic parameters in the bath during electrolysis [2]. The use of mathematical modeling, taking into account all possible factors of the technological process (TP), as well as industrial conditions for conducting electrolysis, allows us to study the magnetic hydrodynamics of the stability of the bath. An integrated approach to solving the problem allows us to consider this process taking into account all the interrelated parameters.

One of the striking examples of systems with distributed parameters are all kinds of heating installations. The paper considers installations for electrolysis of molten salts, oxides and alkalis with subsequent production of metal – aluminum.

Primary aluminium is produced by a complex process of electrochemical reduction of aluminium oxide in Hall-Héroult cells. In aluminium smelters, a workshop contains multiple electrolytic cells connected in series to form one or more series. Within each cell, electric current flows through the anodes, the bath, the molten metal and the cathode hydrocarbon block via a busbar from one cell to the next [3]. High-intensity electric currents generate strong magnetic fields that can cause movement within the molten aluminium layer. These flows are of magnetohydrodynamic (MHD) nature and pose a threat to the stability of the cell. The strong electromagnetic field (EMF) generated by high-power currents inside aluminium electrolytic cells disrupts the MHD stability, significantly affecting the technology of the electrolysis process, which in turn affects the efficiency of the bath and the quality of the smelted metal. All this can lead to significant energy losses and an increase in the level of environmental pollution.

In many countries, as the technology of metal smelting in electrolytic cells has improved, either simplified or more detailed models for MHD conditions have been developed, but the problem is still a concern, and this study is motivated by the need to investigate EMF in the modernization of electrolytic cells and in order to improve the efficiency of industrial aluminum production, i.e., to reduce energy costs and increase the metal yield by current [3].

The object of the study is aluminum electrolyzers of the upper current lead, operating according to the "Soderberg" technology. The subject of the study is electromagnetic processes in aluminum electrolyzers.

The purpose of the work is to study the aluminum electrolyzer system, in particular the process of electromagnetic field formation. In accordance with the purpose, object and subject of the study, the following tasks are solved in the work:

1. Development of research methodology.
2. Description of a mathematical model of a physical process.
3. Conducting experimental studies on the formation of an electromagnetic field inside an electrolyzer under laboratory conditions.

Materials and research methods. The process of obtaining aluminum during the electrolysis reaction consists of hydrodynamic, electromagnetic, chemical and thermal subprocesses. The relationship between them is predominantly nonlinear, which is explained by the complexity of modeling the processes both separately and in their interrelationship.

The electrolyte melt consists of many components, the configuration of which is described using hydrodynamics. Hydrodynamics is also responsible for changing the velocities of the phases in which the mixture is located. But the movement inside the melt itself occurs as a result of the effect of the Lorentz force on it, caused by the interaction of the magnetic field from the current-carrying elements with the currents in the metal melt. At values of oscillatory movements close to critical, MHD instability occurs, which leads to large losses of metal. Thus, electromagnetic processes describe the current density, the intensity of magnetic and electric fields [4].

The production of aluminum by electrolytic method is described by its reduction from the chemical point of view and combustion of the anode with the accompanying release of gases. The chemical reaction occurs not in the thickness of the melt, but near its surface.

Compared to chemical processes, electromagnetic processes have a significantly higher flow rate. The area of action of the accumulated charge near the melt surface is extremely small compared to the geometric dimensions of the electrolyzer bath, which is why the combined mixture can be assessed as having no charge. Thus, it is possible to exclude the contribution of the chemical reaction to the formation of electromagnetic fields.

Maintaining the temperature at a certain level is the key to the successful process, since changing it above or below critical values has a detrimental effect on both the quality of the smelted metal and the electrolyzer itself as a whole. For example, when the temperature increases, not only does the mixture mix due to a change in the densities of the electrolyte and aluminum, but the side walls of the electrolyzer bath also melt. A decrease in temperature below the norm also provokes consequences: the melt begins to crystallize and settle on the walls and bottom of the bath. In case of failures in thermal processes, in all cases the geometry of the working space of the bath changes, which also affects the MHD stability of the process of electrolytic production of aluminum [5].

The efficiency of electrolysis series management using the EcoSoderberg technology is improved by studying electromagnetic fields during the intensification of aluminum production. The potential increase in current strength is included in the design characteristics of the S-8BME type electrolyzer. For example, an increase in such an indicator as current strength by 1 kA leads to an increase in production output by several tons per year.

The anode device is designed to supply current to the electrolyzer bath, where the electrolysis process takes place. Specific capital investments and power consumption are proportional to the anode current density, in this regard, the technological and electrical modes are taken into account. For example, the productivity per unit area of the electrolyzer increases with an increase in current strength, which leads to increased power consumption and requires economically advantageous indicators. But with a given productivity, a lower current density is possible, provided that the design dimensions of the electrolyzer are changed and its thermal insulation is strengthened, only then will it be possible to maintain the specified thermal mode and reduce power consumption [6].

The conversion of aluminum plants to electrolyzers operating using prebaked anode technology is not economically viable, as it requires large financial outlays. In this regard, the task of upgrading the Soderberg technology at existing aluminum plants arises in order to make them more competitive and environmentally friendly [4]. This solution to increase the productivity of electrolyzers helps to reduce the maintenance costs of electrolyzers due to the mechanization and automation of the process. Energy and technological indicators must be calculated in accordance with the projected current strength. To evenly distribute the magnetic field in the melt, it is necessary to use a high-quality busbar system that is capable of supplying and removing high-current from the electrolyzer [5, 6].

Using the example of calculating the mathematical model of the Soderberg electrolyzer (S-8BME), studies are conducted on the effect of increasing the current strength on the process of forming electromagnetic fields in the bath. The increase in productivity occurs by adjusting process parameters such as current strength, voltage, MPR and consumed alumina.

Using the laboratory setup for magnetic field identification, experimental studies are conducted to identify the non-uniformity of the electromagnetic field in the electrolyzer bath. Non-uniformity of the electromagnetic field is possible due to the formation of leakage currents, equipment failure, or incorrect operation of the electrolyzer system. The laboratory setup records the characteristics of the electromagnetic field, on the basis of which three-dimensional graphs are subsequently constructed corresponding to the layers of the spatially distributed electromagnetic field sensor. For a more visual representation of the homogeneity of the electromagnetic field, interpolation models of electromagnetic fields are constructed using MATLAB based on the data obtained.

Description of the mathematical model of the physical process. To regulate a large number of technical, economic and technological indicators, two control actions are used: changing the consumed alumina, which enters the electrolysis bath, and regulating the distance between the anode and the electrolyte solution, i.e., changing the MPR [7]. In this regard, the development of the mathematical model is aimed at calculating the parameters and control actions of the process of electrolytic production of aluminum, as well as creating new control algorithms and studying existing scenarios.

The parameters of the electrolyzer operation are calculated using the material, energy and electrical balance. The material balance is responsible for the raw material consumption and the concentration of alumina in the electrolyte. The heat exchange between the electrolyzer and the environment is characterized by the energy balance, so it becomes possible to determine the amount of electricity consumed due to the change in the temperature of the electrolyte melt. The electrical balance allows you to calculate the voltage on the bath and the value of the MPR. Thus, the MPR, the electrolyte temperature and the concentration of alumina are fundamental parameters for process control [7].

The amount of alumina consumed is determined by its strictly regulated concentration in the electrolyte and is expressed from the material balance:

$$m_{эл} \cdot \frac{dC_{Al_2O_3}}{dt} = G_{Al_2O_3\,расх} - k_{Al} \cdot G_{Alt},$$

where $C_{AL_2O_3}$ is the concentration of Al_2O_3 in the electrolyte, mass fraction; m_{el} is the mass of the melt, kg; $G_{AL_2O_3 consumption}$ is the consumption of alumina, kg/s; k_{Al} is the stoichiometric coefficient of decomposition of Al_2O_3.

Conducting an experiment using a hardware and software complex. The principle of operation of a spatially distributed sensor for identifying an electromagnetic field (Fig. 1) is as follows: using 125 analog Hall effect sensors "SS 49 E" board “Arduino UNO” based on the «ATmega328P» microcontroller collects EMF parameters, then the data is transferred to an application that visualizes the data, which, in turn, allows for a visual assessment of the homogeneity of the EMF.

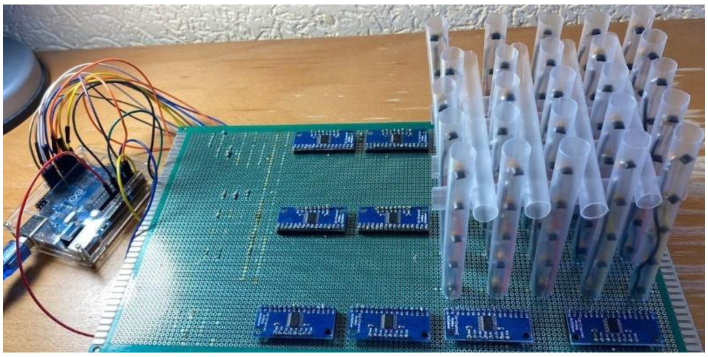


Figure 1 – Spatially distributed electromagnetic field sensor

The magnetic field is characterized by three values: magnetic induction, magnetization and magnetic field strength. The relative magnetic permeability for aluminum is equal to one and the medium under consideration is not a vacuum, in this regard, magnetic induction is equivalent to magnetic strength. With an increase in current strength, the electromagnetic forces acting on the melt increase squared, since they are equal to the product of the values of magnetic field strength and current strength.

This device is used to take readings from sensors, after which, based on this data, interpolation models are constructed in the MATLAB software environment.

When the laboratory setup is turned on, in the absence of an external EMF, it is possible to observe an electromagnetic field induced by currents from the wires included in its composition (Fig. 2).

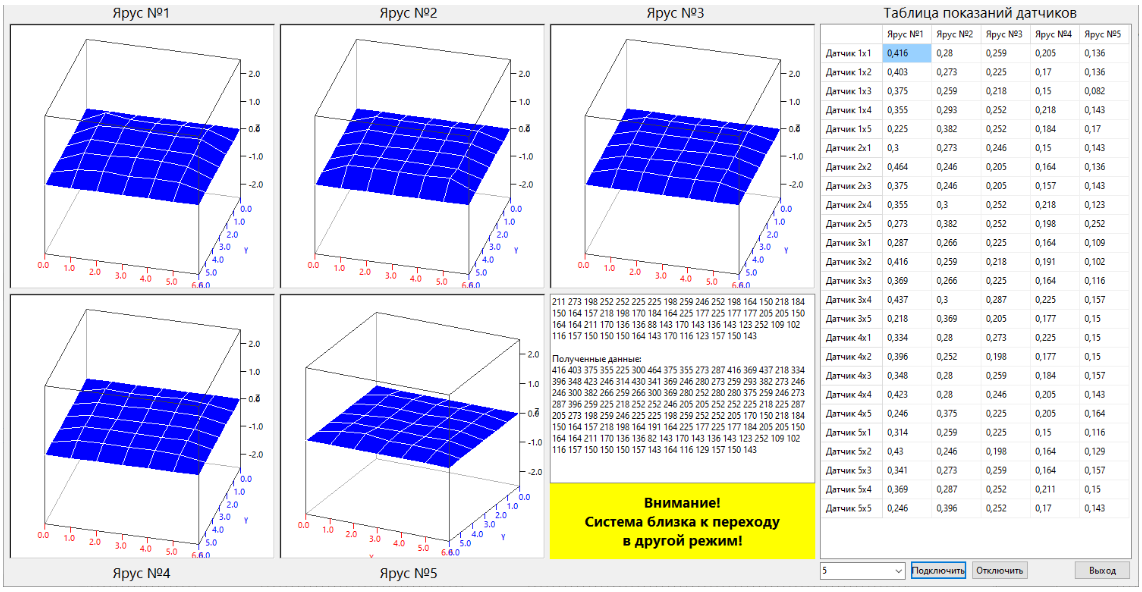


Figure 2 – Monitoring system in the absence of an external field source

The interpolation model of the MP from MATLAB in the middle layer (3rd layer) of the spatially distributed EMF sensor is shown in Fig. 3.

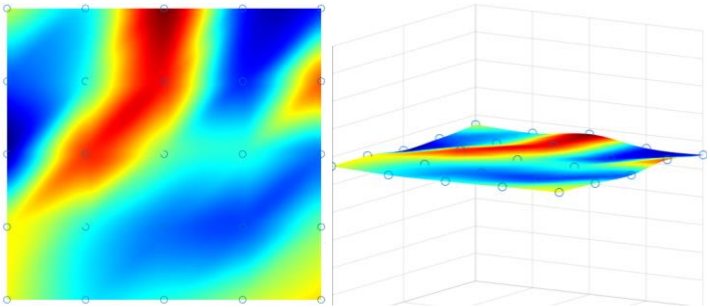


Figure 3 – Interpolation model in the absence of an external field source

With the help of a magnet used as a source of a permanent magnetic field (PMF) in the absence of electric power, conditions close to production are created (Fig. 4). The magnetic lines of force of this magnet are similar to the lines of the magnetic field created by the current passing through the anode in the electrolyzer. The vector distribution of the magnetic induction of a single permanent magnet is shown in Fig. 5.

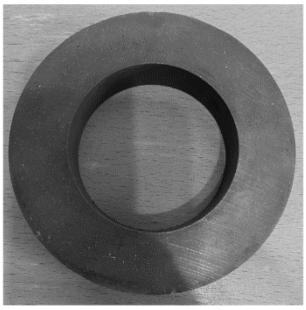


Figure 4 – Permanent ring magnet

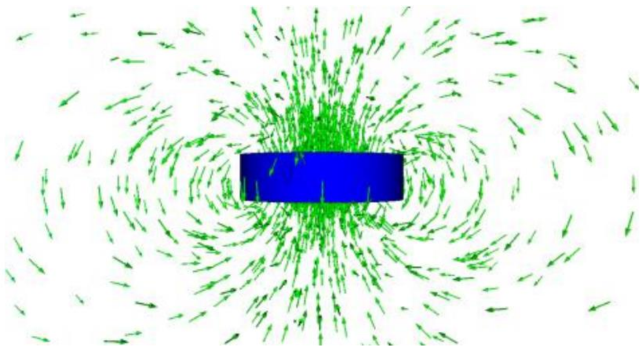


Figure 5 – Distribution of magnetic induction of an annular magnet

When placing a magnet in front of the EMF monitoring installation (Fig. 6), the following interpolation model of MF distribution is observed, presented in Fig. 7.

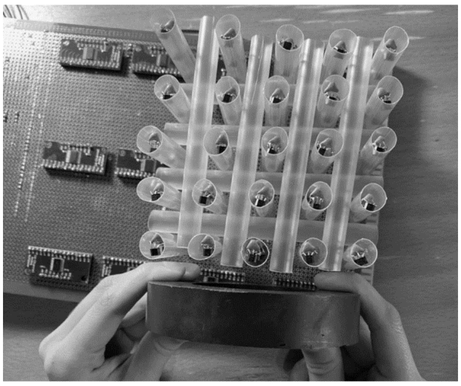


Figure 6 – Permanent magnet before installation

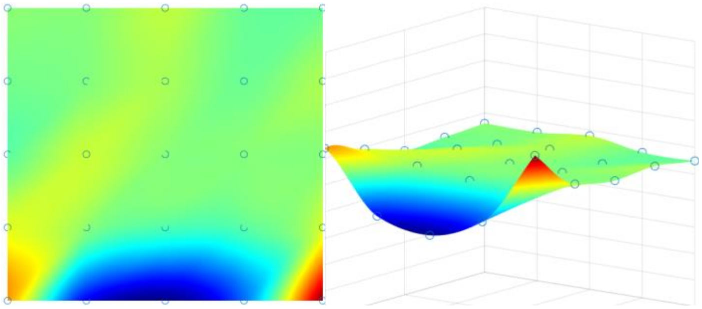
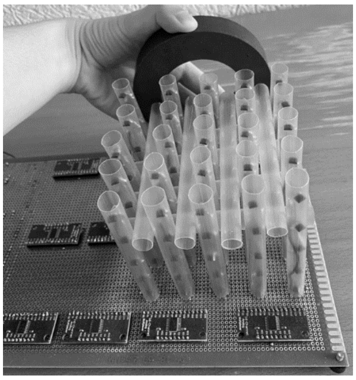


Figure 7 – The magnetic field in the middle third layer

When placing a magnet behind the EMF monitoring installation (Fig. 8), the following interpolation model of MF distribution is observed, presented in Fig. 9.



Figiure 8 – Permanent magnet behind the installation

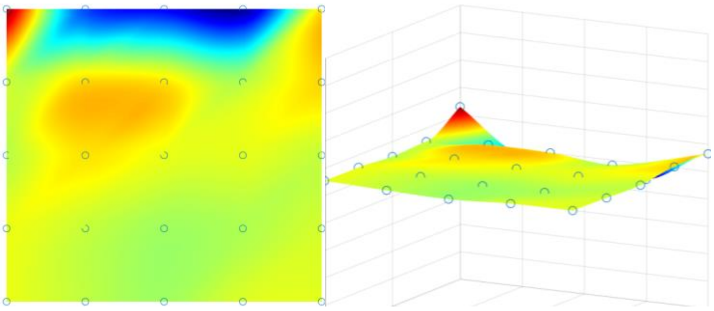


Figure 9 – The magnetic field in the middle third layer

When placing a magnet to the left of the EMF monitoring installation (Fig. 10), the following interpolation model of MF distribution is observed, shown in Fig. 11.

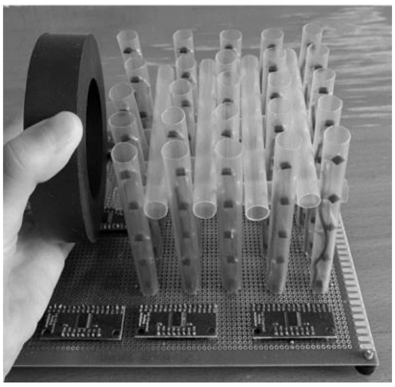


Figure 10 – Permanent magnet to the left of the installation

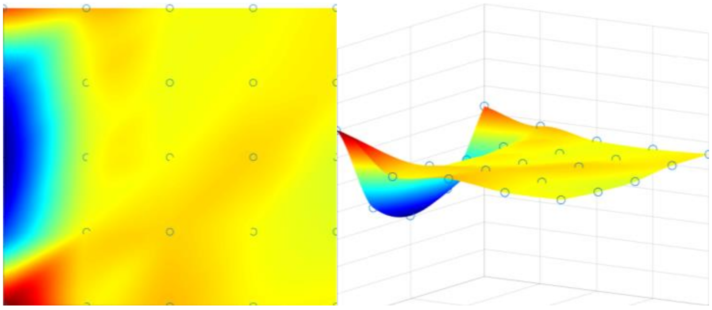


Figure 11 – The magnetic field in the middle third layer

When placing a magnet to the right of the EMF monitoring installation (Fig. 12), the following interpolation model of MF distribution is observed, shown in Fig. 13.

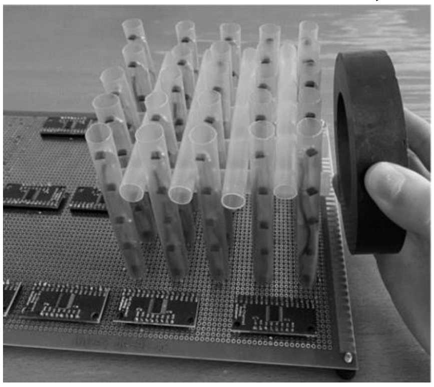


Figure 12 – Permanent magnet to the right of the installation

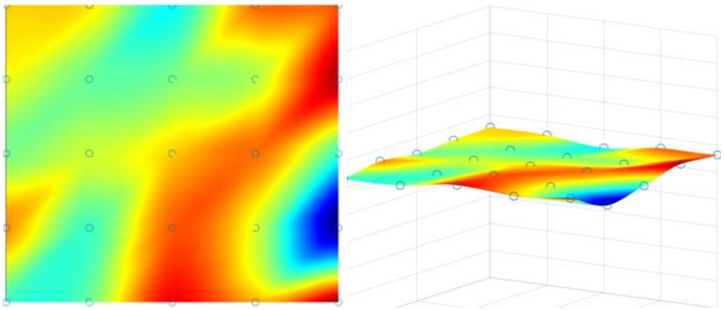


Figure 13 – The magnetic field in the middle third layer

When placing a magnet above the EMF monitoring installation (Fig. 14), the following interpolation model of MF distribution is observed, presented in Fig. 15-16.

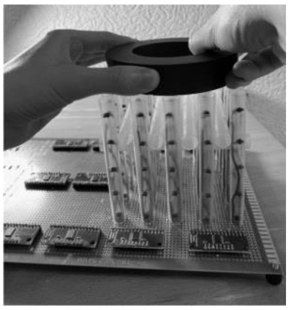


Figure 14 – Permanent magnet above the installation

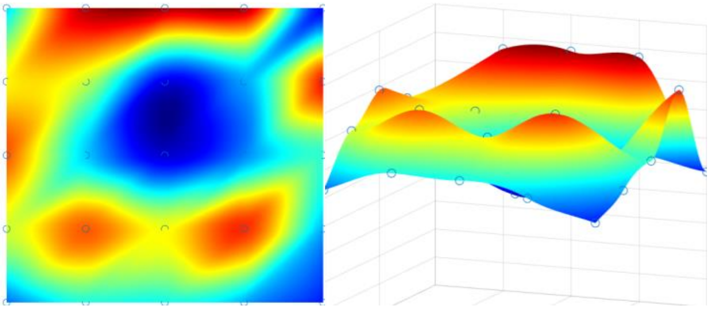


Figure 15 – Magnetic field in the upper part of the liquid metal (layer 5) for an electrolyzer with a capacity of 185 kA

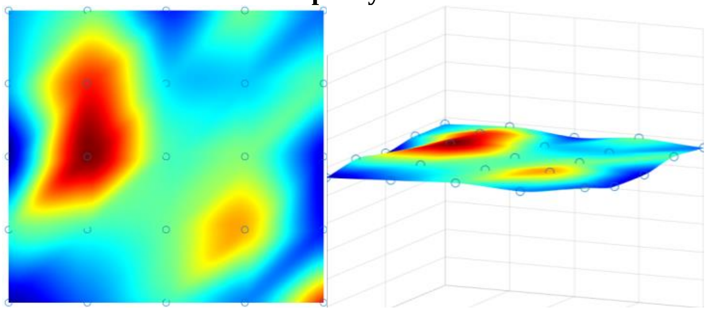


Figure 16 – Magnetic field in the lower part of the liquid metal (layer 5) for an electrolyzer with a capacity of 185 kA

It is worth paying attention to the fact of uneven formation of the electromagnetic field. This is due to the error of the sensors, which is eliminated by calibrating them, and to the poor quality of the welds, which do not ensure uniform passage of current to the anode. To improve the quality of the welds, statistical data is collected and diagnostics of the current-supplying buses are performed.

It can be seen that the simulated magnetic field has a constant vector length regardless of the field magnitude. The distribution of field values was also presented for different magnet orientations relative to the sensors. This fact also applies to industrial aluminum electrolysis plants. Ponderomotive forces in the electrolyte set the melt in motion - MHD instability. When an electric current is passed through the electrolyte solution, a circular motion of particles (ions) occurs. The magnetic field excited by the current sets the particles in motion, this is due to the effect of the Lorentz force on them.

Research results and their discussion. Aluminum is obtained through a chemical process called electrolysis, which is very energy-intensive. The strong magnetic field created by high-power currents inside aluminum electrolyzers disrupts magnetohydrodynamic stability, significantly affecting the technology of the electrolysis process, which in turn affects the efficiency of the bath and the quality of the smelted metal. All this can lead to significant energy losses and increased environmental pollution. Therefore, optimization of the aluminum production process is a pressing, large-scale task.

When increasing the current strength, it is necessary to observe the optimal economic (minimum cost price of aluminum) and technological values (current efficiency and specific power consumption). As experiments have shown, the design current strength of the S-8BM(E) electrolyzer can be increased to 185 kA. The used busbar design allows working at increased current strength, which is confirmed by minor changes in the movement of the melt and the distortion of the metal mirror.

The design dimensions of the designed electrolyzer remain equal to the initial data for the S-8BM(E) electrolyzer.

Conclusion. During the study, the set goals and objectives were achieved. The conducted experimental studies confirm the correctness of the theoretical conclusions. It is proven that optimization of the aluminum production process is a pressing global task.

The research methodology consists of calculating and evaluating its design and technological parameters under given conditions. After that, using a laboratory setup for identifying a magnetic field, experimental studies were conducted to identify the inhomogeneity of the EMF in the electrolyzer bath. In the MATLAB software environment, interpolation models of electromagnetic fields were constructed based on the data obtained.

The proposed design solution is aimed at intensifying production with optimal technological, economic and environmental indicators. The theoretical and experimental studies on the effect of increasing current strength on the stability of electromagnetic fields confirm the possibility of operating the electrolyzer in the selected mode.

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