ОБОГАЩЕНИЕ ПОЛЕЗНЫХ ИСКОПАЕМЫХ

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Studying electrical parameters of contact and contactless polarization of particles under the electrochemical treatment of mineral suspensions

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Abstract

Introduction. *Electrochemical treatment of mineral suspensions is used in electrochemical conditioning of flotation pulp and electrochemical dissolution of minerals and metals in the processes of gold-bearing products electrochemical chlorination.*

Research objective *is to develop and implement the procedures for determining the values of the liquid phase resistance, contact resistance under contact polarization, and ion discharge energy loss resistance under contactless polarization of the electrically conductive part.*

Methods of research. *Equivalent circuits of electrochemical processes have been built for various electrochemical cells. Circuits for various polarizations of electrically conductive particles are established. A formula is proposed for calculating the electrically conductive particle resistance through the electrical resistivity of a unit of volume. A procedure has been developed for calculating the liquid phase resistance through the resistance increment under changing distance between the electrodes. The contact area and pressure influence on the value of the contact resistance is studied through the contact of pyrite and chalcopyrite with an iron electrode.*

Results. *When studying the electrical resistivity of the liquid phase, it was found that increased distance between the current-carrying electrodes leads to an equivalent increase in the liquid phase resistance. It has been established that increased pressure and contact area between the contacting particles and the current-carrying electrode results in decreased contact resistance. The contact resistance between the particle and the electrode in the electrolyte solution is much less than the contact resistance under dry surfaces contact. This phenomenon is explained by electrons tunneling through the electrolyte film. The obtained experimental data on the determination of the liquid phase resistance, contact resistance and ion discharge energy loss resistance make it possible to mathematically describe the processes of electrochemical chlorination under a large number of particles in the pulp.*

Conclusions and scope of results. *Procedures have been developed and specific data have been obtained on the liquid phase resistance, contact resistance, and ion discharge resistance. They can be used for practical application when implementing electrochemical technologies for mineral suspensions treatment.*

Keywords: *electrochemical treatment; mineral suspensions; contact polarization; contactless polarization; electrically conductive particle; bipolar electrode; electrical resistivity of the liquid phase; ion discharge energy loss resistance.*

Introduction. Electrochemical treatment of mineral suspensions is becoming more common in mineral processing and hydrometallurgy. Methods for the electrochemical conditioning of flotation pulps, reagents, and industrial and reclaimed water [1] are developed as well as methods for the electrochemical dissolution of minerals and metals [2–6].

Direct current acting upon on the mineral suspension, depending on the parameters, is accompanied by the electrolysis processes with the release of gaseous oxygen, chlorine, and hydrogen, the process of acid and alkali formation and electrically conductive particles polarization, and the process of excitation of oxidizing anodic and reduction cathodic electrochemical reactions on their surface [6, 7].

Electrochemical processes are characterized by the fact that the electric current flows through the solid phase (current-carrying electrodes, conductive particles) in the form of electrons, while through the liquid phase it flows in the form of ions. There are resistances to the ion discharge on the surface of electrically conductive particles [4, 8].

In a constant electric field, cations and anions move towards each other. The speed of anions and cations in an electric field depends on the medium viscosity and ions concentration and mobility [5, 9].

Since the electric current flow in the liquid phase obeys Ohm's law, an important characteristic is the liquid phase electrical conductivity or its reciprocal, the resistance. The liquid phase resistance is commonly determined at increased values of the current frequency, in order to eliminate the effect, the electrochemical processes on the current-carrying electrodes have on the electrical conductivity [3, 10]. It is obvious that the electrical conductivity measured in this way will not correspond to the liquid phase electrical conductivity when a direct current passes through it when the electric current carriers (ions) come into motion due to the electric field strength gradient.

It is impossible to accurately determine the liquid phase resistance under the specific conditions of the electrochemical process using the existing methods.

When determining the parameters of a direct current flow through a mineral suspension, it is necessary to set the values of ion discharge energy loss resistance on the anode- and cathode-polarized surfaces of electrically conductive particles. The physical interpretation of the ion discharge resistance is that the ions overcome the electric field of the electrical double layer (EDL) [11].

When a direct current flows through a suspension, contact and contactless polarization of electrically conductive particles of the solid phase are possible [12–14].

In contact polarization of electrically conductive particles, the contact resistance between the particle and the current-carrying electrode is of decisive importance for the excitation of electrochemical reactions on the particle surface [12, 13].

In contactless polarization, electrically conductive particles act as a bipolar electrode. The surface of the particle directed towards the anode is cathodically polarized, and the surface of the particle directed towards the cathode is anodically polarized. Cathodic and anodic processes can be simultaneously excited on a particle [15]. To excite electrochemical reactions on a bipolar particle, it is necessary to create a potential gradient on the particle sufficient to overcome the ion discharge resistance on the cathode and anode sides of the particle [16, 17].

To provide the required preset conditions for the mineral suspensions electrochemical treatment, it is necessary to determine the values of the direct current flow electrical parameters [18–21].

This research studies the parameters of contact and contactless polarization of particles, the procedures for determining are proposed, and suspension liquid phase resistances, the contact resistances of the zone of contact between particles and current-carrying electrodes, and ion discharge energy loss resistance on the anode and cathode sides of a bipolar particle are determined for specific conditions.

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Methods of research. To study the electrical parameters of electrochemical processes in various modes, electrochemical cell variants are considered, the schematic diagrams of which are shown in Figure 1.

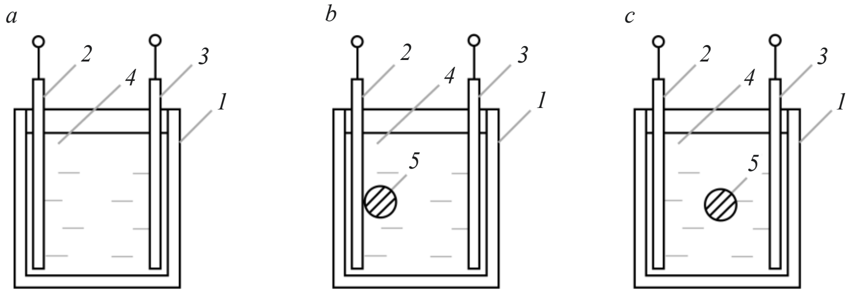

Figure 1. Basic diagrams of electrochemical cells without an electrically conductive particle – *a*, with a contact of an electrically conductive particle and a conductive anode – *b*, with an electrically conductive particle in the liquid phase – *c*: *1* – electrochemical cell body; *2* – conductive anode; *3* – conductive cathode; *4* – liquid phase; *5* – electrically conductive particle

Рисунок 1. Принципиальные схемы электрохимических ячеек без электропроводной частицы – *a*, с контактом электропроводной частицы и токопроводящего анода – *b*, с электропроводной частицей в жидкой фазе – *c*: *1* – корпус электрохимической ячейки; *2* – токоподводящий анод; *3* – токоподводящий катод; *4* – жидкая фаза; *5* – электропроводная частица

To calculate the electrical parameters of processes in electrochemical cells, similarly to [15], equivalent circuits are compiled and shown in Figure 2, where R_a, R_c are the resistances of the current-carrying anode and cathode; R_ela, R_elc are the ion discharge energy loss resistances on the current-carrying anode and cathode; R_l is the liquid phase resistance; R_lpa, R_lpc are the liquid phase resistances involved in the supply of electricity to the particle from the anode and cathode sides; R_p is the particle resistance; R_con is the contact resistance between the particle and the current-carrying electrode; R_elap, R_elcp are the ion discharge energy loss resistances on the anode and cathode sides of the particle.

The total resistance of the circuit R, equivalent to two electrodes in the liquid phase (Figure 2, *a*), is determined by the sum of the resistances that make up the circuit:

$$R = R_\mathrm{a} + R_\mathrm{ela} + R_l + R_\mathrm{elc} + R_\mathrm{c}.$$

When an electrically conductive particle contacts a current-carrying anode (Figure 2, *b*), the contact area is many times smaller than the anode area. Approximately, it can be assumed that in parallel with the resistance R_ela, a circuit is switched on which makes up the contact resistance R_con, the particle resistance R_p, and ion discharge energy loss resistance on the particle R_elap. Then the total resistance R is determined by the formula:

$$R = R_\mathrm{a} + \frac{R_\mathrm{ela}\left(R_\mathrm{con} + R_\mathrm{p} + R_\mathrm{elap}\right)}{R_\mathrm{ela} + R_\mathrm{con} + R_\mathrm{p} + R_\mathrm{elap}}.$$

When an electrically conductive particle is placed in the liquid phase without contact with the electrodes (Figure 1, *c*), the particle is polarized as a bipolar electrode. The surface of the particle directed to the current-carrying anode is cathodically polarized, while the surface of the particle directed to the current-carrying cathode is anodically polarized.

The total resistance R of the circuit with an electrically conductive particle in the liquid phase (Figure 2, *c*) is determined by the formula:

$$R = R_\mathrm{a} + R_\mathrm{ela} + \frac{\left(R_\mathrm{la} + R_\mathrm{elcp} + R_\mathrm{p} + R_\mathrm{elap} + R_\mathrm{lc}\right) R_\mathrm{l.one}}{R_\mathrm{la} + R_\mathrm{elcp} + R_\mathrm{p} + R_\mathrm{elap} + R_\mathrm{lc} + R_\mathrm{l.one}} + R_\mathrm{elc} + R_\mathrm{c},$$

$R_\mathrm{l.one}$ is the resistance of the liquid phase, which is not involved in the supply of electricity to the particle; R_la and R_lc are the resistance of the liquid phase involved in the supply of electricity to the particle from the side of the current-carrying anode and cathode.

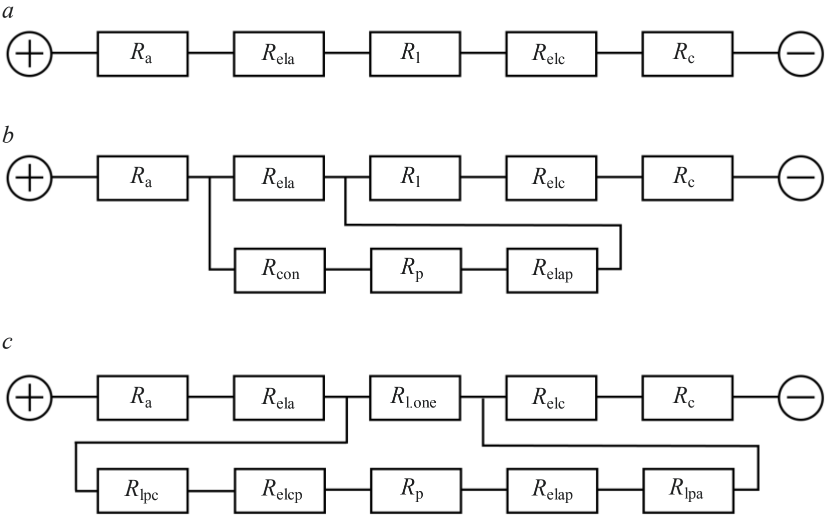

Figure 2. Electrical circuits equivalent to electrochemical cells with conductive electrodes in the liquid phase – *a*, upon contact of an electrically conductive particle with an anode – *b*, with an electrically conductive particle in the liquid phase – *c*

Рисунок 2. Электрические схемы, эквивалентные электрохимическим ячейкам с токоподводящими электродами в жидкой фазе – *a*, при контакте электропроводной частицы с анодом – *b*, с электропроводной частицей в жидкой фазе – *c*; R_a, R_c – сопротивления токоподводящих анода и катода; R_ela, R_elc – сопротивления торможения разряда ионов на токоподводящих аноде и катоде; R_l – сопротивление жидкой фазы; R_lpa, R_lpc – сопротивления жидкой фазы, участвующей в подводе электричества к частице с анодной и катодной сторон; R_p – сопротивление частицы; R_con – сопротивление контакта между частицей и токоподводящим электродом; R_elap, R_elcp – сопротивления торможения разряда ионов на анодной и катодной сторонах частицы; $R_\mathrm{l.one}$ – сопротивление жидкой фазы, не участвующей в подводе электричества к частице

To calculate the equivalent circuits shown in Figure 2, all the resistances in the circuits should be determined.

The resistances of the current-carrying anode and cathode R_a, R_c can be determined through the electrical resistivity of the material and the geometry of the electrodes:

$$R_a = \rho_a \frac{H_a}{L_a B_a}; \qquad R_c = \rho_c \frac{H_c}{L_c B_c},$$

where ρ_a and ρ_c are anode and cathode electrical resistivities, Ohm · m; H_a and H_c are anode and cathode lengths, m; L_a, L_c are anode and cathode widths, m; B_a and B_c are anode and cathode thicknesses, m.

In a similar way, the particle resistance can be determined in terms of particle unit volume electrical resistivity and particle volume:

$$R_p = \rho_p V,$$

where ρ_p is the electrical resistivity of a particle, Ohm/m^3; V is the particle volume, m^3.

To determine the liquid phase resistance for specific electrochemical process conditions, a procedure is proposed based on the determination of electrical parameters under variable values of the distance between the current-carrying electrodes.

The total resistance R of an electric cell with current-carrying electrodes is determined by Ohm's law.

A greater distance between the current-carrying electrodes under a constant cross section of the liquid phase results in resistance increment by the value of resistance ΔR_l of the additional liquid phase volume.

There is an assumption that under a constant concentration of ions in the liquid phase and a constant value of the electric current flowing through the electrochemical cell, the ion discharge energy loss resistances R_{ela}, R_{elc} will not change their values significantly. Based on the assumption, the resistance increment ΔR_l can be determined as the difference in resistances at higher and lower distances between current-carrying electrodes:

$$\Delta R_l = R_{two} - R_{one},$$

where R_{one} and R_{two} are the total resistance of the electrical circuit under a smaller and greater distance between the current-carrying electrodes.

Studies on the contact resistance value determination were carried out on the example of sulfide minerals (pyrite and chalcopyrite) contact with an iron rod. An installation was used to measure the contact resistance. The schematic diagram of the installation is shown in Figure 3.

The installation consists of a mineral plate *1* placed on an insulating plate *2*, an iron rod *3* covered with an insulating coating *4* on the outside. The rod *3* is inserted into the guide tube *5* of the tripod *7*. A load *6* of variable mass is placed on top of the rod *3*.

Since the resistances of the electrical wires, iron rod, and mineral plate are fractions of an Ohm, the contact resistance between the iron rod and the mineral sample was measured with a small error using an ohmmeter *8*. The influence of the contact area and pressure on the mineral particle per the resistance value has been studied. The pressure on the contact area of the mineral was changed using weight *6* mounted on an iron rod, taking into account the weight of the iron rod.

The studies were carried out under the contact of mineral surfaces *1* and rod *3* and under the contact with the surface of a mineral moistened with a 5% NaCl solution.

Studies on the ion discharge energy loss resistance determination were carried out using the electrochemical cell shown in Figure 1, *a*. The electrical parameters were measured with and without the vertical electrically conductive plate that blocks the liquid phase into two compartments. Changes in resistance ΔR with the blocking mineral particle, under otherwise equal conditions, are the sum of the ion discharge energy loss resistances on the cathode and anode sides of the bipolar plate.

Experimental results. ***Experimentally, the procedure for determining the liquid phase electrical resistivity*** R_1 was implemented in an electrochemical cell 0.036 m wide, 0.06 m high, and 0.65 m long. Current-carrying electrodes made of graphite with a width equal to the width of the electrochemical cell were installed in the cell at a distance from each other with a gap of 0.2; 0.4; 0.6 m. NaCl solution with a concentration of 50 g/l was poured into the electrochemical cell to a level of 0.024 m.

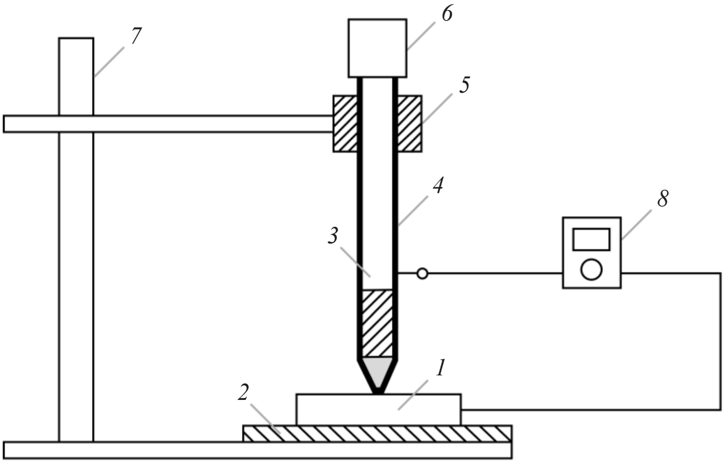

Figure 3. Schematic diagram of an installation for measuring the contact resistance between sulfide minerals and an iron rod: *1* – model mineral plate; *2* – insulating plate; *3* – iron rod; *4* – insulating coating; *5* – guide tube; *6* – load; *7* – tripod; *8* – ohmmeter

Рисунок 3. Принципиальная схема установки для измерения контактного сопротивления между сульфидными минералами и железным стержнем: *1* – модельная пластина минерала; *2* – изоляционная пластина; *3* – железный стержень; *4* – изоляционное покрытие; *5* – направляющая труба; *6* – груз; *7* – штатив; *8* – омметр

In each mode, the current was set to 0.1 A, and the voltage on the electrodes was recorded. The electrical parameters observation data are given in Table 1.

It has been found that, under specific experimental conditions, when the distance between the current-carrying electrodes is increased by 200 mm (from 200 to 400 and from 400 to 600 mm), the voltage on the electrodes increases by 3.1 V, and the resistance increases by 31 Ohm (ΔR = 31 Ohm).

Electrical resistivity of the liquid phase:

$$\rho_1 = \frac{\Delta R(BH)}{\Delta L} = \frac{31 \cdot 0{,}036 \cdot 0{,}024}{0{,}2} = 5{,}35 \cdot 10^{-4}\ \text{Ohm} \cdot \text{m}.$$

The values of contact resistances between a metal rod and the minerals of pyrite and chalcopyrite are studied under a contact area of 0.1 mm^2 and 0.5 mm^2 under the pressure of 50 to 200 Pa. The observation data for the contact resistance under the dry surfaces contact are given in Table 2.

It has been found that an increase in pressure in the range from 50 to 200 Pa and an increase in the contact area result in decreased contact resistance.

The observation data for the contact resistance between a metal rod and a mineral moistened with a 5% NaCl solution are shown in Table 3.

Table 1. Observation data of electrolysis electrical parameters of sodium chloride solution with a concentration of 50 g/l

Таблица 1. Результаты замеров электрических параметров электролиза раствора хлорида натрия концентрацией 50 г/л

Distance between the current-carrying electrodes, mm	Current through the system, A	Voltage, V	Total resistance, R_1, Ohm	ΔR, Ohm
200	0.1	3.7	37	–
400	0.1	6.8	68	31
600	0.1	9.9	99	31

It has been established that in the NaCl solution, the contact resistance decreases as compared to the contact resistance under the surfaces contact. This phenomenon can be explained by electrons tunneling through the electrolyte film [12, 13]. Calculations of the contact resistance conditioned by electrons tunneling were performed using formula (7) from work [12].

Table 2. Observation data of contact resistance in contact with dry surfaces

Таблица 2. Результаты измерения контактного сопротивления при контакте сухих поверхностей

Pressure, Pa	Contact area, m^2	Contact resistance, Ohm	
		Pyrite	Chalcopyrite
50	0.1	425	180
	0.5	340	98
100	0.1	375	160
	0.5	280	90
200	0.1	325	130
	0.5	220	60

The values of the electrical resistivity of ion discharge energy loss per unit area of bipolar particle contacts in a NaCl solution are further calculated.

Studies to determine the values of the ion discharge energy loss resistance on the anode and cathode sides of a bipolar electrically conductive particle were carried out with copper or pyrite plates installed in the electrochemical cell. An electrochemical cell 600 mm long, 26 mm wide, and 56 mm high was used. A bipolar plate 2 mm thick, 26 mm wide, and 56 mm high was placed in the center of the electrochemical cell. A NaCl solution with a concentration of 50 g/l in a volume of 650 ml was poured into the cell. A current equal to 0.5 A was applied to the current-carrying electrodes, the voltage on the electrodes was recorded, and the total resistance of the circuit was calculated using Ohm's law, with and without a bipolar plate. The difference in resistance values was taken as the ion discharge energy loss resistance. The experimental results are given in Table 4.

It follows from Table 4 that the ion discharge energy loss resistance on a copper plate will be 16 Ohm, and 18 Ohm on a pyrite plate. The electrical resistivity of ion discharge energy loss on the anode and cathode sides was 14,679 Ohm/m^2 on the copper plate and 16,514 Ohm/m^2 on the pyrite plate.

Table 3. Observation data of the contact resistance between a metal rod and a mineral surface moistened with a NaCl solution

Таблица 3. Результаты измерения контактного сопротивления между металлическим стержнем и смоченной раствором NaCl поверхностью минерала

Pressure, Pa	Contact area, m^2	Contact resistance, Ohm	
		Pyrite	Chalcopyrite
50	0.1	400	170
	0.5	320	89
100	0.1	350	148
	0.5	258	77
200	0.1	305	125
	0.5	198	50

Discussion. The paper considers variants of contact and contactless polarization of particles under the electrochemical treatment of mineral suspensions. It is proposed to determine the electrical parameters of the mineral suspensions electrochemical treatment process through the equivalent circuits calculation. Procedures are proposed for determining the liquid phase resistances, the contact resistances of the contact area between the particle and the electrode, the ion discharge resistances on the anode and cathode sides of the electrically conductive particle for specified conditions of the process implementation. The procedure developed by the authors proposes to determine the liquid phase resistance through the resistance increment under the changing distance between the electrodes and makes it possible to accurately determine the liquid phase resistance under specific conditions of electrochemical treatment. The contact resistance

Table 4. Observation data of electrical parameters of an electrical circuit with and without a bipolar plate

Таблица 4. Результаты измерения электрических параметров электрической цепи при отсутствии и наличии биполярной пластины

Parameter	Copper plate	Pyrite plate
Current, A	0.1	0.1
Voltage without a plate, V	10.0	10.0
Voltage with a plate, V	11.6	11.8
Resistance without a plate R_{one}, Ohm	100.0	100.0
Resistance with a plate R_{two}, Ohm	116	118
$\Delta R = R_{\text{two}} - R_{\text{one}}$	16	18
Width R of the area of immersion, m	0.026	0.026
Depth H of the area of immersion, m	0.042	0.042
Contact area $F = 2RN$, m^2	0.00109	0.00109
Electrical resistivity of the ion discharge energy loss on the anode and catode sides of a bipolar plate $\Delta R/F$, Ohm/m^2	14 679	16 514

of the electrode contact area and the electrically conductive particle with a liquid phase film between the contacting elements reduces the contact resistance due to electrons tunneling through the liquid phase. The presence of ion discharge resistance on the anode and cathode parts of the electrically conductive particle necessitates higher voltage on the working electrodes to overcome the resistance and excite electrochemical reactions.

Experimental data on the determination of liquid phase resistances, contact resistances, and ion discharge energy loss resistances on the surface of an electrically conductive particle offer opportunities for modeling processes with a large number of particles in the pulp.

Conclusions. The paper substantiates and experimentally implements the procedures for determining the values of liquid phase resistance, contact resistance in contact polarization, and ion discharge energy loss resistance in contactless polarization of electrically conductive particles. The possibilities of calculating the electrical parameters of electrochemical processes are determined by calculating the equivalent circuits of the process.

New experimental data can be turned to practical use when implementing the electrochemical technologies of mineral suspensions treatment.

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Исследование электрических параметров контактной и бесконтактной поляризации частиц при электрохимической обработке минеральных суспензий

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Реферат

Введение. *Электрохимическая обработка минеральных суспензий находит применение при электрохимическом кондиционировании флотационных пульп, электрохимическом растворении минералов и металлов в процессах электрохимической хлоринации золотосодержащих продуктов.*

Целью работы *являются разработка и реализация методик определения значений сопротивления жидкой фазы, контактного сопротивления при контактной поляризации и сопротивления торможения разряда ионов при бесконтактной поляризации электропроводных части.*

Методология. *Для различных вариантов электрохимических ячеек составлены эквивалентные электрические схемы электрохимических процессов. Определены схемы для различной поляризации электропроводных частиц, предложена формула для расчета сопротивления электропроводной частицы через удельное сопротивление единицы объема. Разработана методика расчета сопротивления жидкой фазы через прирост сопротивления при изменении расстояния между электродами. На примере контакта пирита и халькопирита с железным электродом исследовано влияние площади контакта и давления на величину контактного сопротивления.*

Результаты. *При исследовании удельного сопротивления жидкой фазы установлено, что увеличение расстояния между токоподводящими электродами приводит к эквивалентному увеличению сопротивления жидкой фазы. Установлено, что увеличение давления и площади контакта между контактируемыми частицами и токоподводящим электродом* *приводит к снижению контактного сопротивления. Контактное сопротивление между частицей и электродом в растворе электролита значительно меньше по сравнению с контактным сопротивлением при контакте сухих поверхностей. Это явление объясняется образованием туннельного перехода электронов через пленку электролита. Полученные экспериментальные данные по определению сопротивления жидкой фазы, контактных сопротивлений и сопротивления торможения разряда ионов позволяют выполнить математическое описание процессов электрохимической хлоринации при большом количестве частиц в пульпе.*

Выводы и область применения результатов. *Разработаны методики и получены конкретные данные по сопротивлениям жидкой фазы, контактным сопротивлениям и сопротивлению разряда ионов, которые могут быть использованы для практического применения при реализации электрохимических технологий обработки минеральных суспензий.*

Ключевые слова: *электрохимическая обработка; минеральные суспензии; контактная поляризация; бесконтактная поляризация; электропроводная частица; биполярный электрод; удельное сопротивление жидкой фазы; сопротивление торможения разряда ионов.*

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Methods of research. To study the electrical parameters of electrochemical processes in various modes, electrochemical cell variants are considered, the schematic diagrams of which are shown in Figure 1.

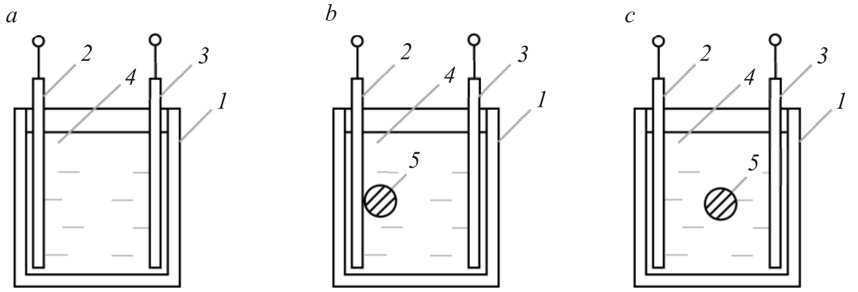

Figure 1. Basic diagrams of electrochemical cells without an electrically conductive particle – *a*, with a contact of an electrically conductive particle and a conductive anode – *b*, with an electrically conductive particle in the liquid phase – *c*: *1* – electrochemical cell body; *2* – conductive anode; *3* – conductive cathode; *4* – liquid phase; *5* – electrically conductive particle

Рисунок 1. Принципиальные схемы электрохимических ячеек без электропроводной частицы – *a*, с контактом электропроводной частицы и токопроводящего анода – *b*, с электропроводной частицей в жидкой фазе – *c*: *1* – корпус электрохимической ячейки; *2* – токоподводящий анод; *3* – токоподводящий катод; *4* – жидкая фаза; *5* – электропроводная частица

To calculate the electrical parameters of processes in electrochemical cells, similarly to [15], equivalent circuits are compiled and shown in Figure 2, where R_a, R_c are the resistances of the current-carrying anode and cathode; R_{ela}, R_{elc} are the ion discharge energy loss resistances on the current-carrying anode and cathode; R_l is the liquid phase resistance; R_{lpa}, R_{lpc} are the liquid phase resistances involved in the supply of electricity to the particle from the anode and cathode sides; R_p is the particle resistance; R_{con} is the contact resistance between the particle and the current-carrying electrode; R_{elap}, R_{elcp} are the ion discharge energy loss resistances on the anode and cathode sides of the particle.

The total resistance of the circuit *R*, equivalent to two electrodes in the liquid phase (Figure 2, *a*), is determined by the sum of the resistances that make up the circuit:

$$R = R_{\mathrm{a}} + R_{\mathrm{ela}} + R_l + R_{\mathrm{elc}} + R_{\mathrm{c}}.$$

When an electrically conductive particle contacts a current-carrying anode (Figure 2, *b*), the contact area is many times smaller than the anode area. Approximately, it can be assumed that in parallel with the resistance R_{ela}, a circuit is switched on which makes up the contact resistance R_{con}, the particle resistance R_p, and ion discharge energy loss resistance on the particle R_{elap}. Then the total resistance *R* is determined by the formula:

$$R = R_{\mathrm{a}} + \frac{R_{\mathrm{ela}}\left(R_{\mathrm{con}} + R_{\mathrm{p}} + R_{\mathrm{elap}}\right)}{R_{\mathrm{ela}} + R_{\mathrm{con}} + R_{\mathrm{p}} + R_{\mathrm{elap}}}.$$

When an electrically conductive particle is placed in the liquid phase without contact with the electrodes (Figure 1, *c*), the particle is polarized as a bipolar electrode. The surface of the particle directed to the current-carrying anode is cathodically polarized, while the surface of the particle directed to the current-carrying cathode is anodically polarized.

The total resistance R of the circuit with an electrically conductive particle in the liquid phase (Figure 2, *c*) is determined by the formula:

$$R = R_{\mathrm{a}} + R_{\mathrm{ela}} + \frac{\left(R_{\mathrm{la}} + R_{\mathrm{elcp}} + R_{\mathrm{p}} + R_{\mathrm{elap}} + R_{\mathrm{lc}}\right) R_{\mathrm{l.one}}}{R_{\mathrm{la}} + R_{\mathrm{elcp}} + R_{\mathrm{p}} + R_{\mathrm{elap}} + R_{\mathrm{lc}} + R_{\mathrm{l.one}}} + R_{\mathrm{elc}} + R_{\mathrm{c}},$$

$R_{\mathrm{l.one}}$ is the resistance of the liquid phase, which is not involved in the supply of electricity to the particle; R_{la} and R_{lc} are the resistance of the liquid phase involved in the supply of electricity to the particle from the side of the current-carrying anode and cathode.

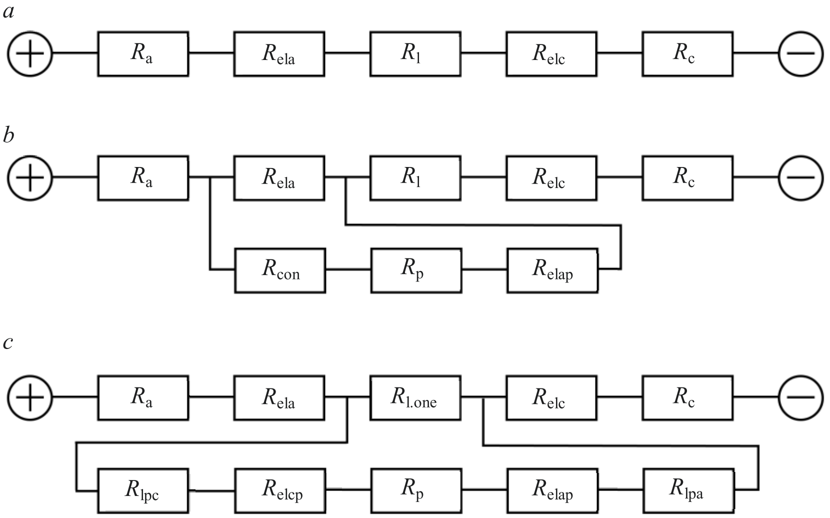

Figure 2. Electrical circuits equivalent to electrochemical cells with conductive electrodes in the liquid phase – *a*, upon contact of an electrically conductive particle with an anode – *b*, with an electrically conductive particle in the liquid phase – *c*

Рисунок 2. Электрические схемы, эквивалентные электрохимическим ячейкам с токоподводящими электродами в жидкой фазе – *a*, при контакте электропроводной частицы с анодом – *b*, с электропроводной частицей в жидкой фазе – *c*; R_{a}, R_{c} – сопротивления токоподводящих анода и катода; R_{ela}, R_{elc} – сопротивления торможения разряда ионов на токоподводящих аноде и катоде; R_{l} – сопротивление жидкой фазы; R_{lpa}, R_{lpc} – сопротивления жидкой фазы, участвующей в подводе электричества к частице с анодной и катодной сторон; R_{p} – сопротивление частицы; R_{con} – сопротивление контакта между частицей и токоподводящим электродом; R_{elap}, R_{elcp} – сопротивления торможения разряда ионов на анодной и катодной сторонах частицы; $R_{\mathrm{l.one}}$ – сопротивление жидкой фазы, не участвующей в подводе электричества к частице

To calculate the equivalent circuits shown in Figure 2, all the resistances in the circuits should be determined.

The resistances of the current-carrying anode and cathode R_{a}, R_{c} can be determined through the electrical resistivity of the material and the geometry of the electrodes:

$$R_\text{a} = \rho_\text{a} \frac{H_\text{a}}{L_\text{a} B_\text{a}}; \qquad R_\text{c} = \rho_\text{c} \frac{H_\text{c}}{L_\text{c} B_\text{c}},$$

where ρ_a and ρ_c are anode and cathode electrical resistivities, Ohm · m; H_a and H_c are anode and cathode lengths, m; L_a, L_c are anode and cathode widths, m; B_a and B_c are anode and cathode thicknesses, m.

In a similar way, the particle resistance can be determined in terms of particle unit volume electrical resistivity and particle volume:

$$R_\text{p} = \rho_\text{p} V,$$

where ρ_p is the electrical resistivity of a particle, Ohm/m^3; V is the particle volume, m^3.

To determine the liquid phase resistance for specific electrochemical process conditions, a procedure is proposed based on the determination of electrical parameters under variable values of the distance between the current-carrying electrodes.

The total resistance R of an electric cell with current-carrying electrodes is determined by Ohm's law.

A greater distance between the current-carrying electrodes under a constant cross section of the liquid phase results in resistance increment by the value of resistance ΔR_l of the additional liquid phase volume.

There is an assumption that under a constant concentration of ions in the liquid phase and a constant value of the electric current flowing through the electrochemical cell, the ion discharge energy loss resistances R_ela, R_elc will not change their values significantly. Based on the assumption, the resistance increment ΔR_l can be determined as the difference in resistances at higher and lower distances between current-carrying electrodes:

$$\Delta R_\text{l} = R_\text{two} - R_\text{one},$$

where R_one and R_two are the total resistance of the electrical circuit under a smaller and greater distance between the current-carrying electrodes.

Studies on the contact resistance value determination were carried out on the example of sulfide minerals (pyrite and chalcopyrite) contact with an iron rod. An installation was used to measure the contact resistance. The schematic diagram of the installation is shown in Figure 3.

The installation consists of a mineral plate *1* placed on an insulating plate *2*, an iron rod *3* covered with an insulating coating *4* on the outside. The rod *3* is inserted into the guide tube *5* of the tripod *7*. A load *6* of variable mass is placed on top of the rod *3*.

Since the resistances of the electrical wires, iron rod, and mineral plate are fractions of an Ohm, the contact resistance between the iron rod and the mineral sample was measured with a small error using an ohmmeter *8*. The influence of the contact area and pressure on the mineral particle per the resistance value has been studied. The pressure on the contact area of the mineral was changed using weight *6* mounted on an iron rod, taking into account the weight of the iron rod.

The studies were carried out under the contact of mineral surfaces *1* and rod *3* and under the contact with the surface of a mineral moistened with a 5% NaCl solution.

Studies on the ion discharge energy loss resistance determination were carried out using the electrochemical cell shown in Figure 1, *a*. The electrical parameters were measured with and without the vertical electrically conductive plate that blocks the liquid phase into two compartments. Changes in resistance ΔR with the blocking mineral particle, under otherwise equal conditions, are the sum of the ion discharge energy loss resistances on the cathode and anode sides of the bipolar plate.

Experimental results. ***Experimentally, the procedure for determining the liquid phase electrical resistivity*** R_1 was implemented in an electrochemical cell 0.036 m wide, 0.06 m high, and 0.65 m long. Current-carrying electrodes made of graphite with a width equal to the width of the electrochemical cell were installed in the cell at a distance from each other with a gap of 0.2; 0.4; 0.6 m. NaCl solution with a concentration of 50 g/l was poured into the electrochemical cell to a level of 0.024 m.

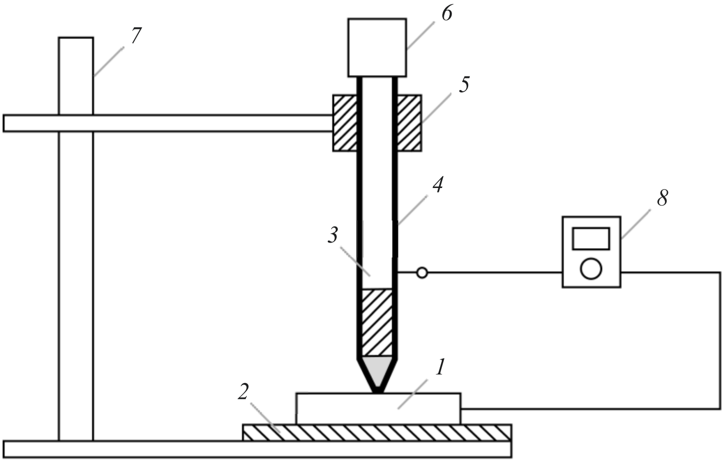

Figure 3. Schematic diagram of an installation for measuring the contact resistance between sulfide minerals and an iron rod: *1* – model mineral plate; *2* – insulating plate; *3* – iron rod; *4* – insulating coating; *5* – guide tube; *6* – load; *7* – tripod; *8* – ohmmeter

Рисунок 3. Принципиальная схема установки для измерения контактного сопротивления между сульфидными минералами и железным стержнем: *1* – модельная пластина минерала; *2* – изоляционная пластина; *3* – железный стержень; *4* – изоляционное покрытие; *5* – направляющая труба; *6* – груз; *7* – штатив; *8* – омметр

In each mode, the current was set to 0.1 A, and the voltage on the electrodes was recorded. The electrical parameters observation data are given in Table 1.

It has been found that, under specific experimental conditions, when the distance between the current-carrying electrodes is increased by 200 mm (from 200 to 400 and from 400 to 600 mm), the voltage on the electrodes increases by 3.1 V, and the resistance increases by 31 Ohm (ΔR = 31 Ohm).

Electrical resistivity of the liquid phase:

$$\rho_1 = \frac{\Delta R(BH)}{\Delta L} = \frac{31 \cdot 0{,}036 \cdot 0{,}024}{0{,}2} = 5{,}35 \cdot 10^{-4}\ \text{Ohm} \cdot \text{m}.$$

The values of contact resistances between a metal rod and the minerals of pyrite and chalcopyrite are studied under a contact area of 0.1 mm^2 and 0.5 mm^2 under the pressure of 50 to 200 Pa. The observation data for the contact resistance under the dry surfaces contact are given in Table 2.

It has been found that an increase in pressure in the range from 50 to 200 Pa and an increase in the contact area result in decreased contact resistance.

The observation data for the contact resistance between a metal rod and a mineral moistened with a 5% NaCl solution are shown in Table 3.

Table 1. Observation data of electrolysis electrical parameters of sodium chloride solution with a concentration of 50 g/l

Таблица 1. Результаты замеров электрических параметров электролиза раствора хлорида натрия концентрацией 50 г/л

Distance between the current-carrying electrodes, mm	Current through the system, A	Voltage, V	Total resistance, R_1, Ohm	ΔR, Ohm
200	0.1	3.7	37	–
400	0.1	6.8	68	31
600	0.1	9.9	99	31

It has been established that in the NaCl solution, the contact resistance decreases as compared to the contact resistance under the surfaces contact. This phenomenon can be explained by electrons tunneling through the electrolyte film [12, 13]. Calculations of the contact resistance conditioned by electrons tunneling were performed using formula (7) from work [12].

Table 2. Observation data of contact resistance in contact with dry surfaces

Таблица 2. Результаты измерения контактного сопротивления при контакте сухих поверхностей

Pressure, Pa	Contact area, m^2	Contact resistance, Ohm	
		Pyrite	Chalcopyrite
50	0.1	425	180
	0.5	340	98
100	0.1	375	160
	0.5	280	90
200	0.1	325	130
	0.5	220	60

The values of the electrical resistivity of ion discharge energy loss per unit area of bipolar particle contacts in a NaCl solution are further calculated.

Studies to determine the values of the ion discharge energy loss resistance on the anode and cathode sides of a bipolar electrically conductive particle were carried out with copper or pyrite plates installed in the electrochemical cell. An electrochemical cell 600 mm long, 26 mm wide, and 56 mm high was used. A bipolar plate 2 mm thick, 26 mm wide, and 56 mm high was placed in the center of the electrochemical cell. A NaCl solution with a concentration of 50 g/l in a volume of 650 ml was poured into the cell. A current equal to 0.5 A was applied to the current-carrying electrodes, the voltage on the electrodes was recorded, and the total resistance of the circuit was calculated using Ohm's law, with and without a bipolar plate. The difference in resistance values was taken as the ion discharge energy loss resistance. The experimental results are given in Table 4.

It follows from Table 4 that the ion discharge energy loss resistance on a copper plate will be 16 Ohm, and 18 Ohm on a pyrite plate. The electrical resistivity of ion discharge energy loss on the anode and cathode sides was 14,679 Ohm/m^2 on the copper plate and 16,514 Ohm/m^2 on the pyrite plate.

Table 3. Observation data of the contact resistance between a metal rod and a mineral surface moistened with a NaCl solution

Таблица 3. Результаты измерения контактного сопротивления между металлическим стержнем и смоченной раствором NaCl поверхностью минерала

Pressure, Pa	Contact area, m^2	Contact resistance, Ohm	
		Pyrite	Chalcopyrite
50	0.1	400	170
	0.5	320	89
100	0.1	350	148
	0.5	258	77
200	0.1	305	125
	0.5	198	50

Discussion. The paper considers variants of contact and contactless polarization of particles under the electrochemical treatment of mineral suspensions. It is proposed to determine the electrical parameters of the mineral suspensions electrochemical treatment process through the equivalent circuits calculation. Procedures are proposed for determining the liquid phase resistances, the contact resistances of the contact area between the particle and the electrode, the ion discharge resistances on the anode and cathode sides of the electrically conductive particle for specified conditions of the process implementation. The procedure developed by the authors proposes to determine the liquid phase resistance through the resistance increment under the changing distance between the electrodes and makes it possible to accurately determine the liquid phase resistance under specific conditions of electrochemical treatment. The contact resistance

Table 4. Observation data of electrical parameters of an electrical circuit with and without a bipolar plate

Таблица 4. Результаты измерения электрических параметров электрической цепи при отсутствии и наличии биполярной пластины

Parameter	Copper plate	Pyrite plate
Current, A	0.1	0.1
Voltage without a plate, V	10.0	10.0
Voltage with a plate, V	11.6	11.8
Resistance without a plate R_{one}, Ohm	100.0	100.0
Resistance with a plate R_{two}, Ohm	116	118
$\Delta R = R_{\text{two}} - R_{\text{one}}$	16	18
Width R of the area of immersion, m	0.026	0.026
Depth H of the area of immersion, m	0.042	0.042
Contact area $F = 2RN$, m^2	0.00109	0.00109
Electrical resistivity of the ion discharge energy loss on the anode and catode sides of a bipolar plate $\Delta R/F$, Ohm/m^2	14 679	16 514

of the electrode contact area and the electrically conductive particle with a liquid phase film between the contacting elements reduces the contact resistance due to electrons tunneling through the liquid phase. The presence of ion discharge resistance on the anode and cathode parts of the electrically conductive particle necessitates higher voltage on the working electrodes to overcome the resistance and excite electrochemical reactions.

Experimental data on the determination of liquid phase resistances, contact resistances, and ion discharge energy loss resistances on the surface of an electrically conductive particle offer opportunities for modeling processes with a large number of particles in the pulp.

Conclusions. The paper substantiates and experimentally implements the procedures for determining the values of liquid phase resistance, contact resistance in contact polarization, and ion discharge energy loss resistance in contactless polarization of electrically conductive particles. The possibilities of calculating the electrical parameters of electrochemical processes are determined by calculating the equivalent circuits of the process.

New experimental data can be turned to practical use when implementing the electrochemical technologies of mineral suspensions treatment.

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Исследование электрических параметров контактной и бесконтактной поляризации частиц при электрохимической обработке минеральных суспензий

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Реферат

Введение. *Электрохимическая обработка минеральных суспензий находит применение при электрохимическом кондиционировании флотационных пульп, электрохимическом растворении минералов и металлов в процессах электрохимической хлоринации золотосодержащих продуктов.*

Целью работы *являются разработка и реализация методик определения значений сопротивления жидкой фазы, контактного сопротивления при контактной поляризации и сопротивления торможения разряда ионов при бесконтактной поляризации электропроводных части.*

Методология. *Для различных вариантов электрохимических ячеек составлены эквивалентные электрические схемы электрохимических процессов. Определены схемы для различной поляризации электропроводных частиц, предложена формула для расчета сопротивления электропроводной частицы через удельное сопротивление единицы объема. Разработана методика расчета сопротивления жидкой фазы через прирост сопротивления при изменении расстояния между электродами. На примере контакта пирита и халькопирита с железным электродом исследовано влияние площади контакта и давления на величину контактного сопротивления.*

Результаты. *При исследовании удельного сопротивления жидкой фазы установлено, что увеличение расстояния между токоподводящими электродами приводит к эквивалентному увеличению сопротивления жидкой фазы. Установлено, что увеличение давления и площади контакта между контактируемыми частицами и токоподводящим электродом* *приводит к снижению контактного сопротивления. Контактное сопротивление между частицей и электродом в растворе электролита значительно меньше по сравнению с контактным сопротивлением при контакте сухих поверхностей. Это явление объясняется образованием туннельного перехода электронов через пленку электролита. Полученные экспериментальные данные по определению сопротивления жидкой фазы, контактных сопротивлений и сопротивления торможения разряда ионов позволяют выполнить математическое описание процессов электрохимической хлоринации при большом количестве частиц в пульпе.*

Выводы и область применения результатов. *Разработаны методики и получены конкретные данные по сопротивлениям жидкой фазы, контактным сопротивлениям и сопротивлению разряда ионов, которые могут быть использованы для практического применения при реализации электрохимических технологий обработки минеральных суспензий.*

Ключевые слова: *электрохимическая обработка; минеральные суспензии; контактная поляризация; бесконтактная поляризация; электропроводная частица; биполярный электрод; удельное сопротивление жидкой фазы; сопротивление торможения разряда ионов.*

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