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Study of Electroflotation Beneficiation of Low-Sulphide and Refractory Gold-Bearing Raw Materials

Ainur Berkinbayeva[1], Olga Atanova[1*], Bagdaulet Kenzhaliyev[1], Yuliya Efremova[1]

[1] JSC Institute of Metallurgy and Ore Beneficiation, Satbayev University, 29/33 Shevchenko Str., Almaty 050010, Kazakhstan

* Corresponding author's e-mail: ovatanova@mail.ru

ABSTRACT

The paper presents the results of experiments with electroflotation beneficiation of gold-bearing raw materials. Three variants of ore samples with 0.56, 1.2 and 5.9 g/t gold grades, which also have different mineralogical and phase composition, were taken as objects of study. Based on the ionization effects, as well as changes in electrostatic and electrokinetic properties of the flotation pulp components, different electrode locations in the flotation chamber were considered. Experiments have shown that for electroflotation processing of raw materials with weakly acidic and neutral medium, positive electric potential of pulp, as well as raw materials with complex mineralogical composition, the negative electrode (cathode) should be placed at the surface of foaming and concentrate assembly, and the positive electrode (anode) in the pulp flow. For electroflotation of raw materials with neutral, alkaline pH and negative electric potential of the pulp, the anode is placed at the surface of the concentrate formation and the cathode is placed in the pulp flow. Thus, additional electrolytic treatment of mineral slurry in the flotation process can increase the gold recovery in the flotation concentrate by an average of 20–30%.

Keywords: electroflotation; gold-bearing raw materials; ionization; electric potential; micro-bubbles.

INTRODUCTION

Much of the world research [Kyzas G.Z et al., 2016, 2018; Ryu B.G. et al., 2018] in the field of electric flotation regimes is based on the principles of formation of hydrogen and oxygen micro-bubbles in the process of passing an electric current through the pulp flow [Kim J. et al., 2021]. Most often, electroflotation methods find application in the field of ecologisation of industrial waste, in particular, are considered as wastewater treatment methods [Xie A. et al., 2022; Smolyanichenko A. et al., 2021]. However, in recent years, electroflotation processes have been actively studied in the field of hydrometallurgy. Thus, the influence of electric flotation on hydrometallurgical processes such as separation of quartz and magnetite [Liu A. et al., 2022], antimony concentrate production [Sozhenkin P.M., 2011], removal of iron, copper, lead, nickel and zinc ions in the presence of high-molecular weight compounds [Brodskiy V. et al., 2021], aluminum hydroxide recovery [Htay T.Z. et al., 2021], etc. has been studied in a number of works.

The selection of electroflotation parameters such as current density and voltage, electrode material, pH values of the medium is largely determined by the field of application of this technology. For example, for removal of ammonia compounds by electroflotation purification, it is suggested to use titanium-based electrode at an optimum current density of 28 A/m^2 and an initial pH value of 6.0 [Shadi A.M.H. et al., 2021]. It was also found by experiments [Putra R.S. et al., 2021] that application of low voltage (11 V) to the electrodes promotes to a greater extent the formation of bubbles with the average size of 0.01–0.09 mm^2, and further increase of voltage to 21–31 V results in increase of bubble size to more than 0.1 mm^2.

Studies of electro-flotation beneficiation of gold- bearing raw materials

In hydrometallurgical gold production, the use of electrolytic mechanisms is mainly envisaged in the production of cathode metal at the electrolysis stage. The use of electrochemical processes in flotation enrichment of gold-bearing raw materials is currently understudied. At the same time there are some scientific works revealing this direction [Kenzhaliyev B.K., 2019]. For example, the proposed technological scheme of noble metals recovery [Kenzhaliyev B. et al., 2020] provides the use of electroflotation treatment of solutions in the process of their carbon sorption. Researches of electroflotation enrichment processes [Reznik Yu.N. et al., 2011] also noted a role of active oxygen and hydrogen ions formed at electrode surfaces in a form of micro bubbles. The oxygen produced in this case contributes to active oxidation of sulfide minerals of gold-bearing raw materials [Trihadiningrum Yu. et al., 2019], as well as the active growth of bacterial cultures in a combined technique of biochemical leaching [Nurfitriani S. et al., 2020]. Practice of application of technologies of biochemical leaching, by bacterial cultures which similarly can be applied at a complex approach, including with methods of electroflotation, is opened in detail in works [Koizhanova A.K. et al., 2016, 2020, 2021].

The method of electrolytic processing of waste slurry from gold recovery plant is also known [Sekisov A.G. et al., 2017]. According to this method, before discharge into the tailings pond, the slurry is subjected to electro-flotation, with electrochemical release of small hydrogen bubbles on cathodes, which bind with small slime particles of sulphide minerals and small particles of “free” gold. When they come in contact with larger air bubbles and collector reagent residues, agglomerates are formed, which are brought to the surface and form a conditional flotation concentrate. Oxygen bubbles emitted at the anode, as noted earlier, are involved in the oxidation of sulphide mineral particles.

MATERIAL AND METHODS

The main purpose of the research was to test electroflotation technology directly in the main stage of raw material processing rather than as a pretreatment or supplementary treatment. In addition to the previously described effects of producing microbubbles produced by the electrolytic decomposition of water to form gaseous oxygen and hydrogen, as well as the oxidising effect of oxygen, the electrical potential of the gold-bearing mineral pulp was taken into account during the experiments. Experiments with two variants of cathode and anode arrangement in flotation chamber were worked out taking into account electric potential indicator. The variant of location of cathode (-) closer to the surface – layer of concentrate formation is the most actual in case of gold predominance in the ore raw material in a free form, and also in the form of thin inclusions in minerals with positive electro-potential. In cases where the gold in the ore being treated is mainly associated with crystalline lattices of minerals with a negative electric potential, the location of the anode (+) in the upper layer of the concentrate formation will be appropriate. In some cases, it may also be possible to position the cathode and anode at the same level to provide an electrolytic effect on the mineral particles in the slurry and to produce micro-bubbles at the electrode surfaces. Options for electrode arrangement in the flotation cell are shown in the diagram in Figure 1.

Electrolytic influence, besides promoting formation of additional micro-bubbles, will also influence ion-exchange processes in a mineral slurry. Thus, in the process of flotation beneficiation there is an active interaction of colloidal particles on the ionic and molecular level, with reagents-gatherers and surfaces of bubble films, predominantly of the cationic type. Therefore, applying electric current to the mineral slurry solution, based on the Debye-Hückel theory, will affect the ionic strength of the interacting particles in the flotation process. In addition to the described effects, electrolytic exposure contributes to increase of ionization, as well as electrostatic and electrokinetic properties of solid mineral particles and gas bubbles in the pulp solution during flotation (Figure 2). Electrical changes in physical and chemical properties of slurry particles, in particular affect the wetting properties of waste rock particles and the hydrophobicity of gold-bearing fragments.

RESULTS AND DISCUSSION

Experiments on electric flotation beneficiation included intensification of gold recovery into froth concentrate by feeding electric current into the

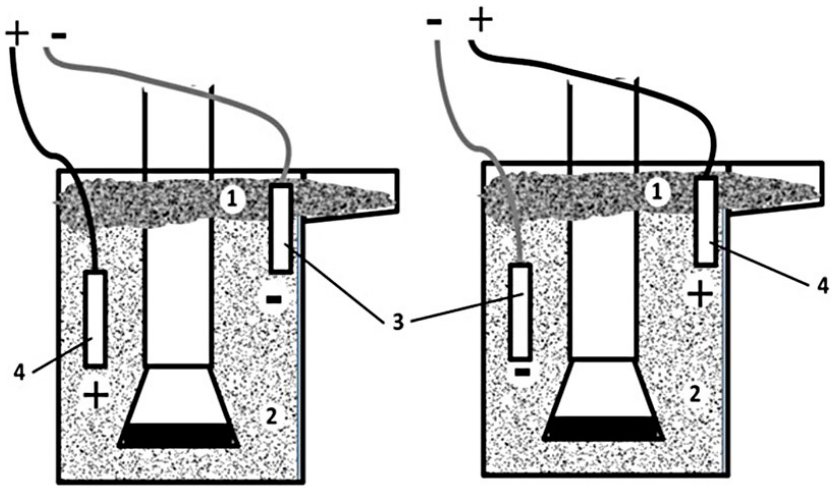

Figure 1. The main three electrode arrangements in the flotation cell are shown in the diagram; 1 – foam concentrate formation layer, 2 – slurry flow, 3 – cathode, 4 – anode

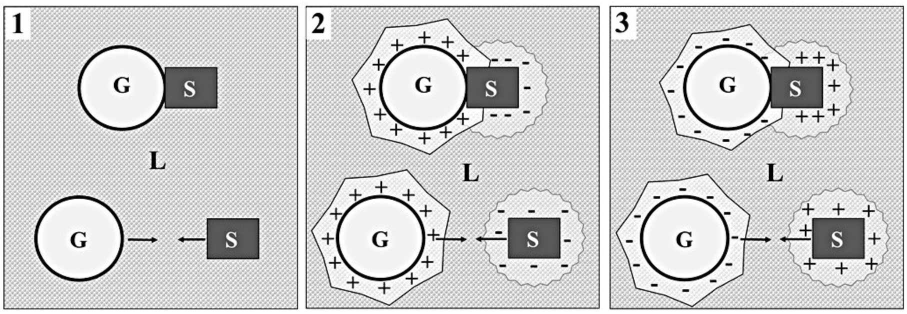

Figure 2. Effect of electrolytic treatment in the flotation process of a mineral slurry of the gas-liquid-solid system (G-L-S); 1 – standard flotation: fixation of sulfide gold-bearing particles on the surface of the bubble; 2 – electroflotation: fixation of non-sulfide gold-bearing particles with negative ionization, on the surface of the bubble with positive ionization; 3 – electroflotation: fixation of non-sulfide gold-bearing particles with positive ionization, on the surface of the bubble with negative ionization

flotation chamber in the voltage range of 2.5–10 V. Depending on the electrical potential, initial pH of the medium, mineralogical and chemical compositions of the gold-bearing slurry fed for flotation beneficiation, different arrangement of electrodes in the flotation chamber was used. Experimental methodology assumed the following main variants of electrode arrangement in flotation chamber: 1) cathode (–) at the surface of foam concentrate formation; anode (+) in the centre or at the bottom of the chamber, in areas of tailings accumulation; 2) anode (+) at the surface of foam concentrate formation; cathode (–) in the centre or at the bottom of the chamber, in areas of tailings accumulation.

To determine the variants of cathode and anode placement the electric potential of pulp, pH environment, gold forms and phase composition were measured beforehand. After that flotation beneficiation options with different electrode locations were tested. Electrolytic flotation reagent consumption did not exceed standard flotation beneficiation (xanthogenate not more than 200 g/t, blowing agent not more than 130 g/t). In some types of ore, the application of low-voltage electric current to the slurry can also significantly reduce the use of blowing agents and depressors. This effect is achieved due to the influence of electric current on the foaming process, which leads to a more intensive production of foam concentrate.

Studies were conducted on samples of gold-bearing mineral raw materials, represented by different phase composition and gold content. The results of electro-flotation enrichment of the following mineral samples are presented as illustrative examples:

1) mixed type ore, with gold content of 1.2 g/t;
2) low-sulphide heap leach poor ore, with a gold content of 0.56 g/t;

3) lay-up sorption tailings, of complex composition, with gold content of 5.9 g/t.

In parallel with the electroflotation experiments, tests were carried out using the standard flotation beneficiation technique as a control. Reagent regimes in standard and electrolytic flotation experiments were kept at the same level: xanthogenate from 100 to 200 g/t, blowing agent from 65 to 130 g/t (depending on initial gold content and raw material type). The solids content of the slurry was 25%. The test samples were crushed to a particle size class of 80% – 0.071 mm. For ore samples, experiments included one stage of flotation enrichment, for samples of difficult to concentrate and refractory sorption tailings experiments included two stages of flotation. Measurements of electro-potentials and pH values of the slurry were carried out on a Consort 931C pH-meter, with an electrode for pH and mV values.One of the objects of the experiments was an ore mainly composed of silicate and carbonate minerals, with minor fragments of pyrite. The results of the experiments with low-sulphide ore of mixed type with gold content of 1.2 g/t, sulphur 0.5% are presented in Table 1. Preliminary measurement of slurry electropotential at 25% solids showed a value of minus 109 mV, pH 8.2.

The Table shows that the effect of low-voltage (5 V) electric current significantly improves gold recovery in the concentrate. For this type of minerals, there was no increase in the mass yield of the concentrate, higher gold content in the end allowed to increase the degree of recovery by 41 % in comparison with the standard flotation beneficiation. Conventional flotation has a mass yield of concentrate of 23.17% with a gold content of 3.1 g/t, resulting in a 57.6% recovery, with 0.65 g/t remaining in the tailings. Use of electro-flotation beneficiation, by placing the anode in the foam concentrate formation area and the cathode in the pulp stream, resulted in a richer concentrate with 7.32 g/t, while decreasing the mass yield to 16.37%. Electroflotation tailings analyses have shown extremely low gold grades of less than 0.02 g/t. Thus, 98.62% gold was recovered during the first flotation stage.

The ore from the heap leaching area was used for the next experimental variant. Analysis of gold content showed a value of 0.56 g/t and sulphur content of 0.2%. Although this ore was also low-sulphide, almost half of the residual gold was associated with sulphide minerals, the rest was in the form of thin phenocrysts in quartz. Measurement of the electrical potential of the poor low-sulphide ore taken from the heap leach pad showed a value of plus 70 mV, pH 7.4. The results of the flotation beneficiation tests are shown in Table 2.

As a result of electroflotation beneficiation of heap leaching area ore, the highest concentrate recovery of 89.7% is observed when the cathode is placed in the foaming layer and the anode in

Table 1. Results of experiments with mixed ore

Product	Standard flotation			Electroflotation – cathode (–) in concentrate, anode (+) in tailings.			Electroflotation - anode (+) in concentrate, cathode (–) in tailings.		
	Yield, %	Au, g/t	Au recovery, %	Yield, %	Au, g/t	Au recovery, %	Yield, %	Au, g/t	Au recovery, %
Concentrate	23.17	3.1	57.6	21.93	4.5	82.4	16.37	7.32	98.62
Tailings	76.83	0.65	42.4	78.07	0.27	17.6	83.63	<0.02	1.38
Total	100.00	1.2	100.00	100.00	1.2	100.00	100.0	1.2	100.00

Table 2. Results of experiments with poor ore from the heap leach area

Product	Standard flotation			Electroflotation – cathode (–) in concentrate, anode (+) in tailings.			Electroflotation - anode (+) in concentrate, cathode (–) in tailings.		
	Yield, %	Au, g/t	Au recovery, %	Yield, %	Au, g/t	Au recovery, %	Yield, %	Au, g/t	Au recovery, %
Concentrate	12.57	3.1	69.0	15.13	3.3	89.7	22.00	2.03	79.44
Tailings	87.43	0.2	31.0	84.87	0.07	10.3	78.00	0.15	20.56
Total	100.00	0.56	100.00	100.00	0.56	100.00	100.0	0.56	100.00

Table 3. Results of experiments with stored sorption tailings

Product	Standard flotation			Electroflotation – cathode (–) in concentrate, anode (+) in tailings.			Electroflotation - anode (+) in concentrate, cathode (–) in tailings.		
	yield, %	Au, g/t	Au recovery, %	yield, %	Au, g/t	Au recovery, %	yield, %	Au, g/t	Au recovery, %
Concentrate I	22.1	12.3	46.1	40.1	11.1	75.4	24.9	12.0	50.6
Concentrate II	14.7	6.6	16.4	9.48	7.85	12.6	16.0	7.11	19.3
General concentrate	36.8	10.0	62.5	49.58	10.5	88.0	40.9	10.1	69.9
Tailings	63.2	3.5	37.5	50.42	1.4	12.0	59.1	3.0	30.1
Total	100.0	5.9	100.0	100.0	5.9	100.0	100.0	5.9	100.0

the pulp flow. Also application of electric current with voltage of 4–5 V promoted increasing of mass yield of concentrates from the given type of mineral raw materials.

As a sample of refractory, difficult to concentrate raw material a sample of laying sorption tailings with initial gold content of 5.9 g/t was taken. This raw material is characterized by complex gold forms, high concentrations of arsenic-containing compounds, in particular arsenopyrite, and the gold content ranges from 3 to 15 g/t. Measurement of the electrical potential showed a positive value of plus 165 mV, pH 4.1. The flotation beneficiation tests comprised two stages. The results of the flotation beneficiation experiments of the stockpiled sorption tailings are shown in Table 3.

Electroflotation beneficiation of refractory sorption tailings, with cathode placement in the concentrate formation layer, resulted in a final gold recovery of 88.0% (75.4% in the first stage; 12.6% in the second stage). Conventional flotation beneficiation in two stages converted 62.5% of the gold to concentrate. Placing the anode in the concentrate eventually yielded 69.9% gold.

CONCLUSION

It was found in the course of the experiments that the electroflotation beneficiation method enables effective processing of low-sulfide, mixed ores, tailings and other mineralogical raw materials of complex composition. The tendency of deterioration of quality of processed mineral raw materials involved in metallurgical production requires innovative approaches, including flotation beneficiation methods. The complex mineralogical composition, presence of inhibitory impurities, difficult forms of inclusions of valuable components of processed ore raw materials lead to incomplete gold recovery and other associated metals in the concentrate. By applying electric current to the electrodes in the flotation cell, the gold content in the froth concentrate is increased. The mass yield of the froth concentrate in electric flotation, compared to standard flotation beneficiation, increases on average by 6–12%, depending on the physical and chemical properties of the slurry. Analysis of the gold content in electrolytic flotation tailings during processing poor, low-sulphide ores shows values less than 0.1 g/t, which in turn eliminates the need for control flotation and additional refining operations. The final gold recovery is increased by an average of 20 to 30% given the increase in mass yields and gold concentrations in the foam concentrate.

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