Mathematical modeling in the organization of the production process of leaching metals

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Abstract. The following will describe the process of how you can use mathematical modeling to organize the production of metal leaching. Mathematical models and results of computational experiments are presented. The results of studying the thickness of films of sulfuric acid-chloride solutions containing the addition of surfactants surface-active substance (SAS), which are formed when they pour out onto a frosted glass surface as a model of the surface of a piece of ore, are presented. A mathematical model how the film thickness changes depending on the feed rate of the solution and its composition, as well as on the angle of inclination of the glass surface has been determined. Underground leaching of metals from ores stimulates the search for ways and means of intensifying the process. Due to the addition of a surfactant, the leaching process is accelerated, since the thickness of the films of leaching solutions flowing over the surface of ore minerals decreases. This direction is relevant in modern science, and research in this direction the growth of indicators allows the national economy to improve and helps to improve and increase knowledge for further development of the metallurgical industry in Russia. The article also discusses the results of studies on the electrochemical leaching of metals from polymetallic ore by sulfuric acid-chloride solutions with the addition of a surfactant with asymmetric current pulses. Mathematical models of the dependence of leaching indicators on the density and duration of the flow of direct and reverse polarity are presented. For ease of perception and better visualization, a table was compiled, which reflects the results of comparative analysis to assess the further possibility of processing secondary raw materials.

1. Introduction

One of the factors that have a significant impact on the course of the process of underground electrochemical leaching of metals from ores is the capacity of the double electric layer, which forms on the surface of ore minerals when flowing around them with leaching solutions [1, 4, 17]. The literature known to the authors of this work provides information on the magnitude of the Electrical Double Layer (EDL) capacity on the surface of sulfide minerals in sulfuric-chloride solutions [2].

Experimental studies to determine the capacity of EDL on the surface of some sulfide minerals in sulfuric-chloride solutions with the addition of surfactants SAS [3, 5] were carried out in the Geotechnology laboratory of the NCIMM (STU).
The measurements were carried out using a universal meter L, C, R E7-11 at a frequency of 100 Hz in a plexiglass cell, into which the studied mineral electrodes were alternately placed, made of the main ore-forming minerals of the Sadon group of polymetal deposits: galena, sphalerite, pyrite, and chalcopyrite. The dimensions of the studied electrodes were 10x10x20 mm. The working surface was a polished end face of each electrode with dimensions of 10x10 mm. To improve the electrical contact between the mineral electrode and the current-supplying conductor, a contactol layer was applied to a section of this face. After its hardening, this part of the electrode face was electrically and waterproofed, as well as the rest of the electrode faces, so the actual size of the working surface of the mineral electrodes was 10x1 mm. To determine the EDL capacitance on the surface of the studied electrodes, an auxiliary copper electrode 80x80 mm in size was also placed in the measuring cell. The surface area of the auxiliary electrode exceeded the area of the working surface of the studied electrodes by a factor of 640 times [18-20].

In the course of the research, the dependence of the EDL capacity on the composition of the sulfuric acid-chloride solution with the addition of surfactants was studied for each of these minerals. The experiment planning method was used (Box-Behnken three-level non-compositional plan). The conditions and results of the experiments are presented in Table 1.

| №№ | Content in solution, kg/m³ | The value of the capacity of EDL on the surface of the mineral, C, mF |
|----|------------------|---------------------------------------------------------------|
|   | Sulfuric acid, C₁ | Sodium chloride, C₂ | Galena | Sphalerite | Pyrite | Chalcopyrite |
| 1  | 1.94             | 19.4              | 52.186 | 5.238     | 17.945 | 49.47 |
| 2  | 9.7              | 19.4              | 58.782 | 10.185    | 27.839 | 60.431 |
| 3  | 1.94             | 155.2             | 59.849 | 30.07     | 46.366 | 77.018 |
| 4  | 9.7              | 155.2             | 72.459 | 35.405    | 48.209 | 87.106 |
| 5  | 1.94             | 87.3              | 56.842 | 20.176    | 40.158 | 67.124 |
| 6  | 9.7              | 87.3              | 64.99  | 29.682    | 40.255 | 76.533 |
| 7  | 5.82             | 19.4              | 54.417 | 9.7       | 26.772 | 58.2 |
| 8  | 5.82             | 155.2             | 63.632 | 30.555    | 46.851 | 83.032 |

Mathematical models of the dependence of the capacity of EDL, formed on the surface of ore minerals, on the composition of the solution with the addition of surfactants SAS, obtained as a result of processing the experimental data, are presented in Table 2. The adequacy of the obtained models to the experimental data is not less than 95%.

| Mineral          | Regression equation                              |
|------------------|--------------------------------------------------|
| Galena           | $C = 60.95 + 4.70C₁ + 5.25C₂ + 1.85C₁^2 - 0.100C₂^2 + 1.55C₁C₂$ |
| Pyrite           | $C = 43.225+2.033C₁+11.833C₂ - 1.775C₁^2 - 5.275C₂^2 - 2.075C₁C₂$ |
| Sphalerite       | $C = 25.6+3.4C₁+12.183C₂ + 0.1C₁^2 - 4.85C₂^2 + 0.1C₁C₂$ |
| Chalcopyrite     | $C = 76.225+5.233C₁+13.583C₂ - 2.175C₁^2 - 3.425C₂^2 - 0.225C₁C₂$ |

An analysis of the experimental data and the obtained regression equations showed that an increase in the concentration of sulfuric acid and sodium chloride within the experimental ranges leads to an increase in the value of the EDL capacity on the surface of all studied minerals. This nature of the change in the magnitude of the EDL capacitance can be explained by an increase in the concentration of electric charge carriers in the solution. Using the method of parametric sensitivity of the function $Y = f (X₁, X₂)$, it was found that the concentration of sodium chloride and then sulfuric acid has the
The strongest effect on the magnitude of the EDL capacity on the surface of all studied minerals. Comparison of the results obtained in these studies and presented in [2] indicates that the addition of surfactants according to SAS [3–6] in sulfuric acid-chloride solutions leads to a decrease in the capacity of DES by 2.5–3%. 

2. Materials and methods

The thickness of the leaching solution films flowing over the surface of the ore lumps during the infiltration or film-droplet mode of underground and heap leaching is one of the most important factors that determine the distribution of the current between the ore and the solution and, consequently, the efficiency of using electrical process intensifiers. The study of the regularities of the formation of films of solutions directly on lumps of ore and their parameters is complicated by the different wetting of ore and nonmetallic minerals, the changing curvature of the surface of unpolished and unequal surface roughness in different areas of the polished pieces of ore. The difficulty of maintaining the same flow of solutions over the entire surface and other factors. Therefore, the study of the regularities of changes in the thickness of the resulting films of solutions is carried out by modeling methods using as a model of the surface of ore pieces of a frosted glass surface, as the most wettable material. In the literature known to the authors, there is information about the thickness of the films of binary solutions of underground leaching containing sulfuric acid and sodium chloride [1].

In this work, we present materials for studying the thickness of films formed during the flow of sulfuric acid-chloride solutions containing the addition SAS of surfactants over the matted surface of a glass plate 200 mm long and 30 mm wide. The plate was fixed on one of the short sides on a vertical stand with the possibility of rotation around the axis of attachment. which made it possible to install it with a deviation from the vertical at an angle from 0 to 90° using a micrometric screw with attachments fixed on the same stand. The long sides of the plate were coated with a thin layer of stearin 0.5 mm wide for edge effects, so the width of the solution flow in the experiments was 29 mm. The measurements were carried out by the electro contact method [7]; in order to increase the measurement accuracy, the solution “adhering” to the measuring needle was removed with filter paper after each measurement. The measurement of the film thickness was carried out on the axis of the solution flow. Due to the action of surface tension forces, it is here that it has its maximum value. When calculating the average value of the film thickness was assumed that the cross-section of the film has the shape of a segment of a circle.

The thickness of the films of sulfuric acid-chloride solutions with the addition of surfactants as a function of the angle of inclination of the surface. The composition and feed rate of the solution were determined in the course of the planned experiment using the Box-Behnken plan [8–11]. The ranges of variation of the independent variables are given in Table 2 and the experimental values of the thickness of the solution films are given in Table 3.

| Table 3. Levels (boundary conditions) of independent variables. |
|---------------------------------------------------------------|
| Independent variables | Solution feed rate, V_{liquid}, cm³/s | The angle of deviation of the plate surface from the horizontal, α, deg | Content in solution (g/l) |
|------------------------|----------------------------------------|---------------------------------------------------------------|------------------------|
| Main level. (X₀)       | 0.75                                   | 45                                                         | Sulfuric acid, C₁      |
| Variation interval. (ΔX₁)| 0.50                                  | 40                                                         | Sodium chloride, C₂    |
| Top level (+1)         | 1.25                                   | 85                                                         | 6                      |
| Lower level (-1)       | 0.25                                   | 5                                                          | 90                     |
|                        |                                        |                                                             | 4                      |
|                        |                                        |                                                             | 10                     |
|                        |                                        |                                                             | 2                      |
|                        |                                        |                                                             | 20                     |

As a result of mathematical processing of experimental data and elimination of statistically insignificant coefficients. the following regression equation was obtained:
\[ \delta_{e,av} = 0.3075 + 0.1149V_l - 0.1134\alpha - 0.0113C_1 + 0.0179C_2 + 0.00326V_l^2 + 0.12067\alpha^2 + 0.0166C_1^2 - 0.0089C_2^2 + 0.0124V_l C_1 + 0.0098V_l C_2 - 0.049\alpha C_1 - 0.0046\alpha C_2 - 0.0012C_1 C_2, \]  

where \( \delta_{e,av} \) – the experimentally determined average thickness of the solution film, mm;  
\( V_l \) – the solution feed rate, cm\(^3\)/s;  
\( \alpha \) – the angle of deviation of the plate surface from the horizontal, deg;  
\( C_1 \) – the content of sulfuric acid in solution, g/l;  
\( C_2 \) – the content of sodium chloride in solution, g/l.

The obtained regression equation is adequate to the experimental data with a significance level of 0.05. The reliability of the results obtained is in good agreement with the results of [1] confirmed by the compliance with the calculated values performed according to [9, 21], taking into account the data of the study of the physicochemical properties of solutions containing the surfactant additive SAS [2, 16] (the deviation does not exceed 3%), and given in Table 2:

\[ \delta = \sqrt{\frac{3\Gamma\mu}{\rho g \cos \beta}}, \]  

where \( \delta \) is the thickness of the liquid film flowing down an inclined or vertical wall, m;  
\( \Gamma \) – irrigation density per unit of wall width, kg/(m \cdot s); \( \Gamma = G_l/b \);  
\( G_l \) – mass flow rate of the flowing liquid, kg/s; \( G_l = V_l \rho \);  
\( V_l \) – volumetric flow rate of the flowing liquid, m\(^3\)/s;  
\( \mu \) – fluid viscosity, kg / (m \cdot s);  
\( \rho \) – density of the flowing liquid, kg / m\(^3\);  
\( g \) – acceleration of gravity, \( g = 9.81 \) m/s\(^2\);  
\( \beta \) – the angle between the wall and the vertical, for the experiments performed; \( \beta = 90^\circ - \alpha \).

The analysis of the regression equation showed that the greatest influence on the thickness of the films is exerted by the feed rate of solutions and the angle of inclination of the surface over which they flow. The influence of the composition of the solution is negligible.

3. Results and Discussion

As a result of processing the experimental data using a mathematical apparatus, the authors obtained a regression equation that determines the average film thickness of a solution containing a surfactant, and a mathematical model of the dependence of the EDL capacity [12–14; 15].

An analysis of the obtained equations allows us to conclude that the addition of a surfactant makes it possible to reduce the thickness of the films and leads to a decrease in DEL, which contributes to better leaching of metals.

4. Conclusion

On the basis of experimental data, regression equations have been established that describe the dependence of the electrode potential of galena, pyrite, sphalerite, and chalcopyrite on the concentration of sulfuric acid-chloride solutions used in underground leaching and containing a surfactant additive. The degree of influence of the reagents on the value of the potential of minerals has been determined on the basis of experimental data, regression equations are synthesized that relate the capacity of the electric double layer on the surface of some sulfide minerals in sulfuric acid-chloride solutions with the addition of surfactants.

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References

[1] Brandl H Bosshard R and Wegmann M 2001 Computer-munching microbes: metal leaching from electronic scrap by bacteria and fungi *Hydrometallurgy* 59 (2–3) 319–326

[2] Karwowska E Andrzejewska-Morzuch D Łebkowska M Tabernacka A Wojtkowska M Telepko A and Konarzewska A 2014 Bioleaching of metals from printed circuit boards supported with surfactant-producing bacteria. *J. Hazard. Mater.* 264 203–210

[3] Mishra D and Rhee Y H 2014 Microbial leaching of metals from solid industrial wastes *J. Microbiol.* 52 1–7

[4] Natarajan G Ramanathan T Bharadwaj A and Ting Y P 2015 Bioleaching of metals from major hazardous solid wastes *Microbiol. Miner. Met. Mater. Environ.* ed B D Pandey and K A Natarajan (Boca Raton: CRC Press) A chapter 9 pp 229–262

[5] Brandl H 2008 Microbial leaching of metals *Biotechnology set.* 2nd (Weinheim: Wiley-VCH Verlag GmbH) chapter 8 pp 191–224

[6] Ilyas S and Lee J C 2014 Bioleaching of metals from electronic scrap in a stirred tank reactor *Hydrometallurgy* 149 50–62

[7] Ilyas S and Lee J C 2015 Bioprocessing of Electronic Scraps *Microbiol. Miner. Met. Mater. Environ.* ed B D Pandey and K A Natarajan (Boca Raton: CRC Press) A chapter 12 pp 307–328

[8] Petrov Yu S Khadzaragova E A Sokolov A A Sharipzyanova G Kh and Taskin A V 2020 Acquisition, transmission and storage of information on production-induced cycle in mining and metallurgy *Mining Informational and Analytical Bulletin* 11–1 178–188

[9] Sokolov A A Raus E V and Petrov Y S 2019 A mathematical model for assessing technological damage from the functioning of mining enterprises *Sustainable Development of Mountain Territories* 11(4) 554–559

[10] Ilyas S Anwar M A Niazi S B and Ghauri M A 2007 Bioleaching of metals from electronic scrap by moderately thermophilic acidophilic bacteria *Hydrometallurgy* 88 (1–4) 180–188

[11] Ilyas S Ruan C Bhatti H N Ghauri M A and Anwar M A 2010 Column bioleaching of metals from electronic scrap *Hydrometallurgy* 101 (3–4) 135–140

[12] Shchurov N I Myatezh S V Malozyomov B V Shtang A A Martyushev N V Klyuev R V and Dedov S I 2021 Determination of inactive powers in a single-phase ac network *Energies* 14 (16) 4814

[13] Shchurov N I Dedov S I Malozyomov B V Shtang A A Martyushev N V Klyuev R V and Andriashin S N 2021 Degradation of lithium-ion batteries in an electric transport complex *Energies* 14 (23) 8072 DOI: 10.3390/app11220848

[14] Boikov A, Payor V, Savelev R, Kolesnikov A 2021 Synthesis data generation for steel defect detection and classification using deep learning. *Symmetry* 7(13) 1176 DOI: 10.3390/sym13071176

[15] Balanovskiy A E, Astafyeva N A, Kondratyev V V, Karлина A I 2021 Study of mechanical properties of C-Mn-Si composition metal after wire-arc additive manufacturing (WAAM). *CIS Iron and Steel Review* 22 66–71

[16] Konyuhov V Yu, Gladkikh A M, Galyaudtinov I I, Severina Y D 2019 Economic aspects of green technologies. *IOP Conference Series: Earth and Environmental Science* 350 012036

[17] Yudaev I V, Daus Y V, Zharkov A V, Zharkov V Y 2020 Private solar power plants of Ukraine
of small capacity: features of exploitation and operating experience. *Applied Solar Energy* **56**(1) 54-62 DOI:10.3103/S0003701X20010119

[21] Sysoev I A, Kondrat’ev V V, Zimina T I, Karlina A I 2018 Simulation of the Energy States of Electrolyzers with Roasted Anodes at Elevated Currents. *Metallurgist* **61**(11-12) 943–949