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Increasing the Efficiency of Underground Block Leaching of Metal

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Abstract

The purpose of this study is to increase the efficiency of underground block metal leaching by increasing the metal content in the pregnant solution using the cavitation effect. To achieve this goal, it is proposed to process (cavitate) the leaching solution on the injector. The following research methods were used in this study: analysis of the current state of scientific and technical problems and research, laboratory work to establish the effect of the treated (cavitated) solution on the metal content in the pregnant solution, collection and processing of statistical data from laboratory work, analysis of research results, and preparation of conclusions. According to the results of laboratory research, leaching with a treated solution on an injector leads to an increase in the content of a useful component in the pregnant solution. The maximum increase in the metal content in the pregnant solution was achieved by processing the leaching solution for 5 min. The effectiveness of the solution over time after treatment was maintained for a long time (up to one month). Changes in the solution pressure did not affect the effectiveness of the treated leaching solution. The scientific novelty of this work consists of determining the dependence of the content of the useful component in the pregnant solution on the time of processing the leaching solution on the injector and the leaching time, which determines the optimal time for processing the solution on the injector to obtain the maximum metal content in the pregnant solution. The dependence of the content of the useful component in the solution on the pressure during leaching with untreated and treated solutions on the injector was obtained.

Keywords: Block Leaching; Leaching Solution; Pregnant Solution; Processing of The Solution; Injector; Metal Content; Sulfuric Acid; Reagent; Pressure of the Solution.

1. Introduction

The industrial development of new sources of raw materials, including low-grade ores of various genetic and industrial types, is becoming increasingly important owing to the trend of decreasing metal content in ores observed in recent years. One of the most promising methods for the extraction of such raw materials is geotechnological (heap, underground leaching of metals from ores), owing to its simplicity, low capital and operating costs, and less complex system of environmental measures [1, 2]. There is experience in using technologies for underground block leaching of metals from rock ores, the main disadvantages of which are a low extraction coefficient and a long leaching duration. A promising direction for metal extraction, which was developed in the last century, is the physicochemical method of ore extraction using reagents, in which metals are extracted from ores by changing the phase state of the mineral [3-5].

Underground and heap leaching of copper and uranium from ores and dumps has been widely applied in real-world practice [6, 7]. The USA, the countries of the African continent, and Australia are the main regions in which underground

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and heap leaching of ores are widely used. This is explained by the favorable natural conditions and type of copper ores that are most suitable for leaching. Both underground and heap leaching are used in the USA, which is explained by the possibility of cost-effective processing of low-grade raw materials owing to a decrease in the average copper content of ores. Studies have been conducted on underground and heap leaching of As, Co, Bi, Ti, and Au [8]. A review of the literature on underground and heap leaching shows that these processes are widely used for the processing of Cu-, U-, and Au-containing ores. Methods for the underground and heap leaching of rare and dispersed metals are under development or pilot testing [9, 10].

Leaching of lead and zinc sulfides is more complicated; galenite and sphalerite are usually associated with pyrite. It is difficult to select effective solvents for converting lead and zinc into soluble compounds. It is necessary to proceed with the following requirements for them to do so: the maximum possible selective leaching of minerals from ores and the absence of secondary reactions between the host rocks and solutions with the formation of insoluble sediments or excess gases that could colmatage the pores in the ore body [11]. The following solvents can be used for the leaching of sulfides: sulfuric, nitric, and hydrochloric acids; solutions of iron (III) sulfate; metal chlorides (containing metals with the highest degree of oxidation, copper and iron chlorides); iron nitrates; and ammonia with simultaneous oxidation of sulfides with oxygen [12, 13]. The global experience in the application of physical-chemical technology for extracting uranium from rock ores using underground methods is still insufficient because of the low extraction ratio [14, 15]. The most effective option for underground leaching using mining workings from the perspective of production economics at the present stage of mining development is a mining system with ore storage. However, the percentage of metal extraction depends significantly on the average linear size of a piece of blasted ore when leaching using underground workings [16-18].

The analysis of the aforementioned scientific papers shows that the use of underground block leaching is limited by a low metal recovery coefficient, which mainly depends on the granulometric composition of the cut ore shrinkage, the permeability of the ore shrinkage, and the type and concentration of the reagent. Therefore, the main part of the study is devoted to improving the quality of ore crushing during cutting and the effect of the granulometric composition of the ore on the recovery coefficient and reagent consumption. However, these studies were aimed at reducing the yield of oversized pieces of cut ore. They did not consider that improving the granulometric composition of ore by reducing the size of ore pieces leads to an increase in the proportion of ore fines (dispersed particles). The leaching solution interacted with the dispersed particles to form a dispersed system when filtered through ore shrinkage. This system changes the composition and structure of the ore as its particles move from an incoherent porous medium to a solution. As a result, the pore size decreases, and the incoherent porous medium becomes sealed; thus, the process of commutation occurs. In addition, an increase in the proportion of small fractions in the cut ore leads to an increase in the consumption of the leaching solution and the cost of leaching. The proposed technological solutions for increasing the efficiency of leaching, such as increasing the temperature and acidity of the solution, require significant costs and increase the cost of the final product.

This problem can be solved by processing the leaching solution using a special injector, which creates a cavitation effect in solution flow [19-21]. As it is known, cavitation in a liquid is accompanied by various chemical reactions, while accelerating some chemical reactions and initiating others. These reactions occur within a short period of time [22, 23].

The essence of this technology lies in the fact that the leaching solution passes through a flow injector before it is fed into the ore mass. An injector is a tube with several partitions inside or with a narrow section [24, 25]. The partitions have one or more holes (channels) that are evenly distributed on the working surface of the disk and can have different shapes and sizes. Cavitation occurs in the liquid flow when the liquid passes through holes in the disk or through the narrowed part of the tube. As a result of mechanical action on continuous media, their structure and temperature change, which is accompanied by the breaking of bonds between atoms and the destruction of the crystal lattice.

2. Material and Methods

Laboratory studies were conducted to investigate the effect of the leaching solution processed by the injector on the efficiency of underground block leaching. Leaching was performed using copper sulfate in a sulfuric acid solution at a concentration of 10 g/l. A flowchart of the research methodology is shown in Figure 1.

Laboratory work was conducted in two stages. The required volume of sulfuric acid solution was passed through a special injector to induce a cavitation effect during the first stage. The laboratory installation (Figure 2) consisted of a closed circuit, which included an electric centrifugal pump (1), flow injector (2), pipeline (3), container for the solution (4), and drain tap (5).

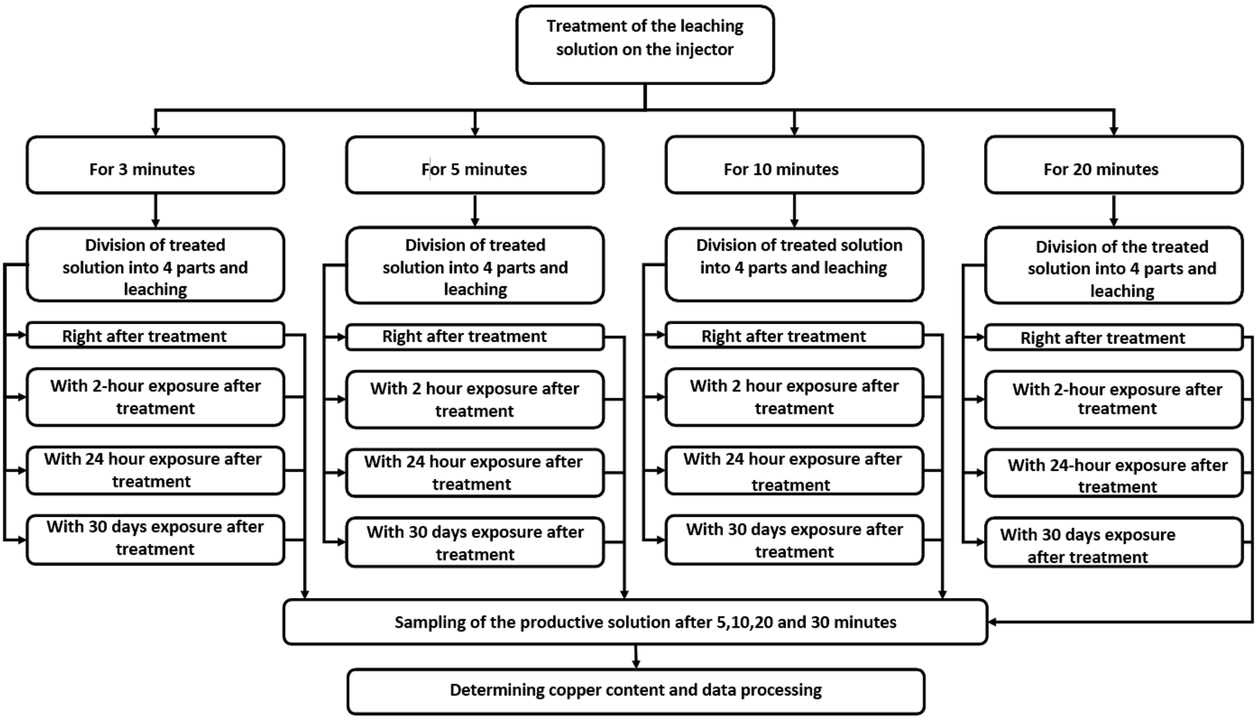

Figure 1. Flowchart of the research methodology

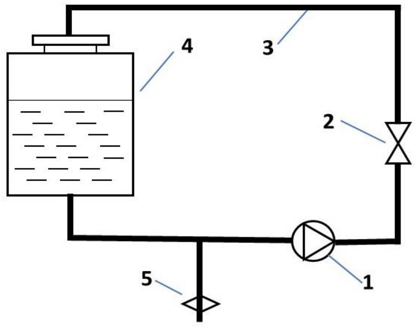

Figure 2. Laboratory installation (1- pump; 2-flow injector; 3- pipeline; 4- container with a solution for processing; 5- drain valve)

The sulfuric acid solution was poured into container 4 and passed through an injector with the help of a pump - 1 this solution was passed through an injector. The leaching of copper was carried out using a laboratory stirrer with the treated solution during the second stage. A mechanical mixer BP 8000 EKROS with a thermostatic glass cup was used for the leaching (Figure 3-a). The content of the mineral in the solution was determined using a photoelectric photometer KFK-3-"ZOMS" (Figure 3-b).

(a) (b)

Figure 3. A mechanical mixer BP 8000 EKROS with a thermostatic glass cup (a) and a photoelectric photometer KFK-3-"ZOMS" (b)

Initially, the operating frequency of the light in the device was determined using a CuSO4 solution according to the manufacturer's instructions for using the photometer. The device was calibrated using copper sulfate solutions with different concentrations of copper. The calibration graph exhibits a linear relationship with copper. This made it possible to use the coefficient of the ratio of copper content to the readings of the device.

Preliminary experiments were conducted before the start of a series of leaching experiments. Based on the results, the volume of the leaching solution was 150 ml, the rotation speed of the mixer was 45 rpm, and the leaching time was selected. The weight of the conditional metal was 1.2 g at a concentration of 10 g/l of sulfuric acid in a solution. Simultaneously, complete completion of the reaction was achieved.

$$CuO + H_2SO_4 = CuSO_4 + H_2O \tag{1}$$

Stops for sampling the solution were performed after 5, 10, 20, and 30 min of the experiments.

Leaching experiments were performed as follows. The required amount of sulfuric acid solution was then poured into a thermostated glass. Afterwards, a copper sample was placed in the solution, and after a certain time, a sample of the solution was taken for analysis. The sample was filtered and placed in a photometer cuvette to free the sample solution from particles of the conditional metal contained in it. The main indicator during laboratory studies is the change in the mineral content of the solution using various processing methods. However, considering the large volume of the leached solution supplied in industrial conditions, which incurs significant energy costs for its processing, we conducted studies on the possibility of processing only concentrated sulfuric acid used to strengthen the mother liquor. Acid (1.5 liters of) was poured into the unit and processed for 5 min. Then, a solution containing 10 g/l was prepared from this acid was prepared and tested during leaching. The results were compared with those from the same experiment but without acid preprocessing.

The copper content in the solution after leaching increased by 14%. Consequently, there is no need to process the entire leaching solution under industrial conditions; it should be limited to the processing of the restorative concentrated sulfuric acid. This reduces energy costs.

Copper leaching was carried out with solutions processed for 3, 5, 10, and 20 min during the study, with sampling times of 5, 10, 20, and 30 min. Transportation of the leaching solution from the processing site to the stored ore in the block takes a certain amount of time, as does the passage of the solution through the bulk of the broken ore also takes time. Therefore, studies were also carried out with the solution immediately after processing, after aging the solution for 2 and 24 h, and after 30 days to establish the preservation of the effectiveness of the leaching solution over time. To compare the results, copper was leached first with an unprocessed solution and then with the processed solutions.

3. Results and Discussion

The results of the studies on changes in the copper content in the pregnant solution during leaching with un-processed (0 min) and processed solutions for 3, 5, 10, and 20 min are shown in Table 1.

Table 1. Changes in the copper content in the pregnant solution (mg/l) with unprocessed and processed solutions

	Ageing time of solution after processing (T)				Leaching time (tb. min)	Processing time
	Immediately after processing	After 2 hours	After 24 hours	After 30 days		
Copper Content in the Solution (Cm.mg/l)	4.08	4.08	4.08	4.08		0
	4.78	4.48	4.34	4.26		3
	5.14	4.80	4.78	4.41	5	5
	4.96	4.80	4.62	4.73		10
	4.27	4.30	4.37	4.41		20
	4.33	4.33	4.33	4.33		0
	4.80	4.55	4.51	4.44		3
	5.15	5.06	4.91	4.46	10	5
	5.17	5.09	4.78	5.15		10
	4.33	4.67	4.55	4.67		20
	4.61	4.61	4.61	4.61		0
	5.18	5.08	4.74	4.66		3
	5.29	5.24	5.10	4.77	20	5
	4.90	5.23	5.09	5.35		10
	4.60	4.80	4.82	4.86		20
	4.70	4.70	4.70	4.70		0
	5.23	5.20	4.90	4.73		3
	5.36	5.16	4.95	4.82	30	5
	5.09	5.40	5.23	5.42		10
	4.73	4.91	4.90	4.96		20

Changes in the copper content of the pregnant solution (α_{cu}) during leaching with the unprocessed (0 min) and processed solutions were obtained from the time of leaching and processing (t_{pr}) of the solution immediately after processing, as shown in Figure 4.

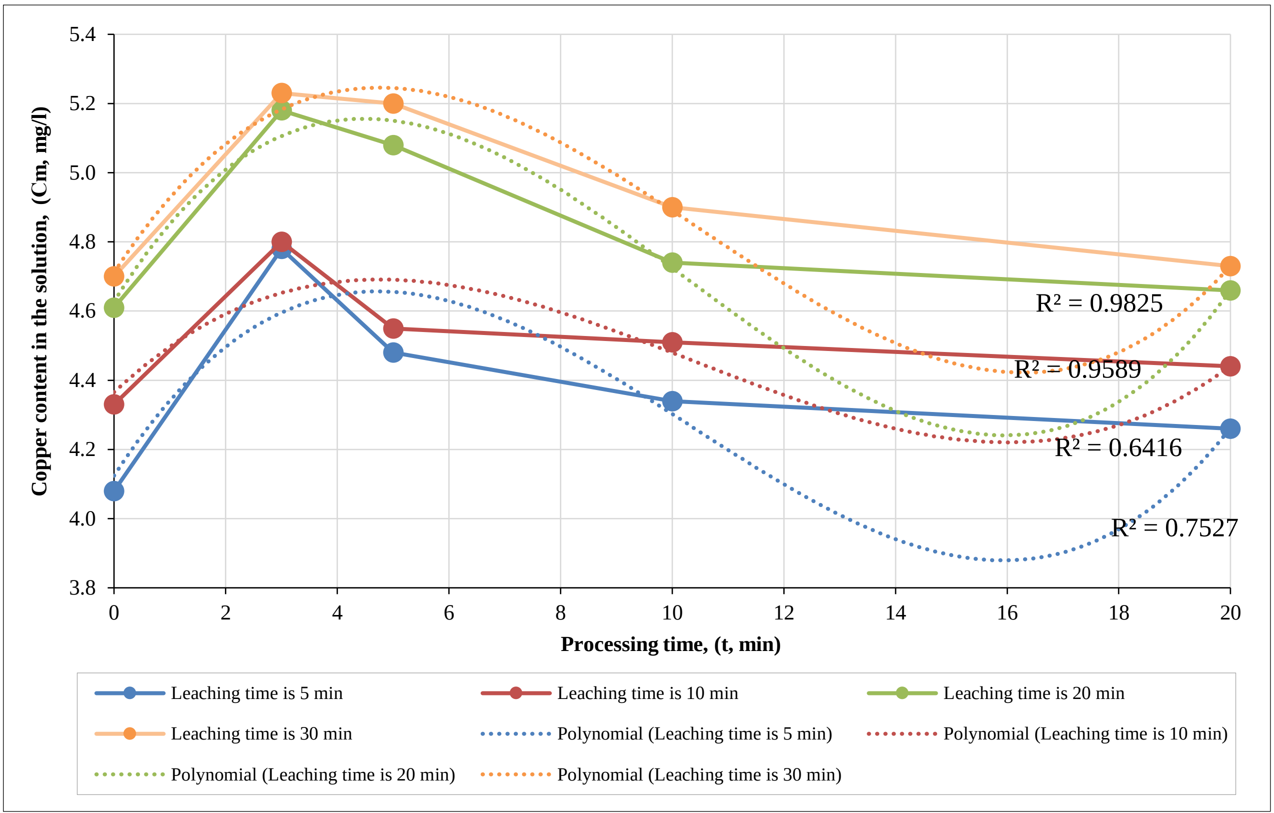

Figure 4. Changes in the copper content in the pregnant solution (α_{cu}) when leaching with unprocessed and processed solutions from the time of leaching and processing (t_{pr}) of the solution immediately after processing (Polynomial)

The convergence of the experimental data on the copper content from the leaching time in the polynomial form, with the number of terms equal to 3 in indicator R^2, increases with increasing leaching time, as shown in Figure 4.

As shown in Table 1, the copper content in the production solution is expected to increase during leaching with unprocessed and processed solutions, with an increase in the leaching time from 5 min to 30 min. The increase in the copper content in the pregnant solution changes from 4.06 mg/l to 4.88 mg/l when leaching with an unprocessed solution, and when leaching with a processed solution for 5 minutes and immediately after processing, it changes from 5.14 mg/l to 5.36 mg/l, that is, an increase of 10-26%.

An increase in the copper content in the production solution was observed with an increase in the processing time of the leaching solution from 3 to 5 min. For example, processing the leaching solution for 3 minutes and leaching immediately after processing for 10 minutes resulted in an increase in the copper content in the pregnant solution compared to leaching with an unprocessed solution from 4.33 mg/l to 4.80 mg/l; when processing the solution for 5 minutes, it changes from 4.23 mg/l to 5.15 mg/l. During leaching with the solution processed for 3 min, the copper content increased by 11%, and after 5 min of processing, it increased by 22%.

A further increase in the processing time of the leaching solution to 10 and 20 min and leaching immediately after processing led to a gradual decrease in the copper content of the pregnant solution. For example, the copper content in the pregnant solution decreased to 4.9 mg/l versus 5.3 mg/l when processing a solution for 5 minutes when a leaching solution was processed for 10 minutes and a leaching time was 20 minutes. A further increase in the processing time to 20 min led to a decrease in the copper content of the solution to 4.6 mg/l. This is explained by the fact that there was noticeable evaporation of sulfuric acid owing to an increase in the temperature of the solution, which led to a decrease in its concentration in the solution with an increase in the processing time of the solution on the injector for 10 min, especially for 20 min.

This research has also proven the preservation of the effect of leaching solution processing for a long time. Figures 5 and 6 show the changes in metal content over time after processing the solution and leaching time.

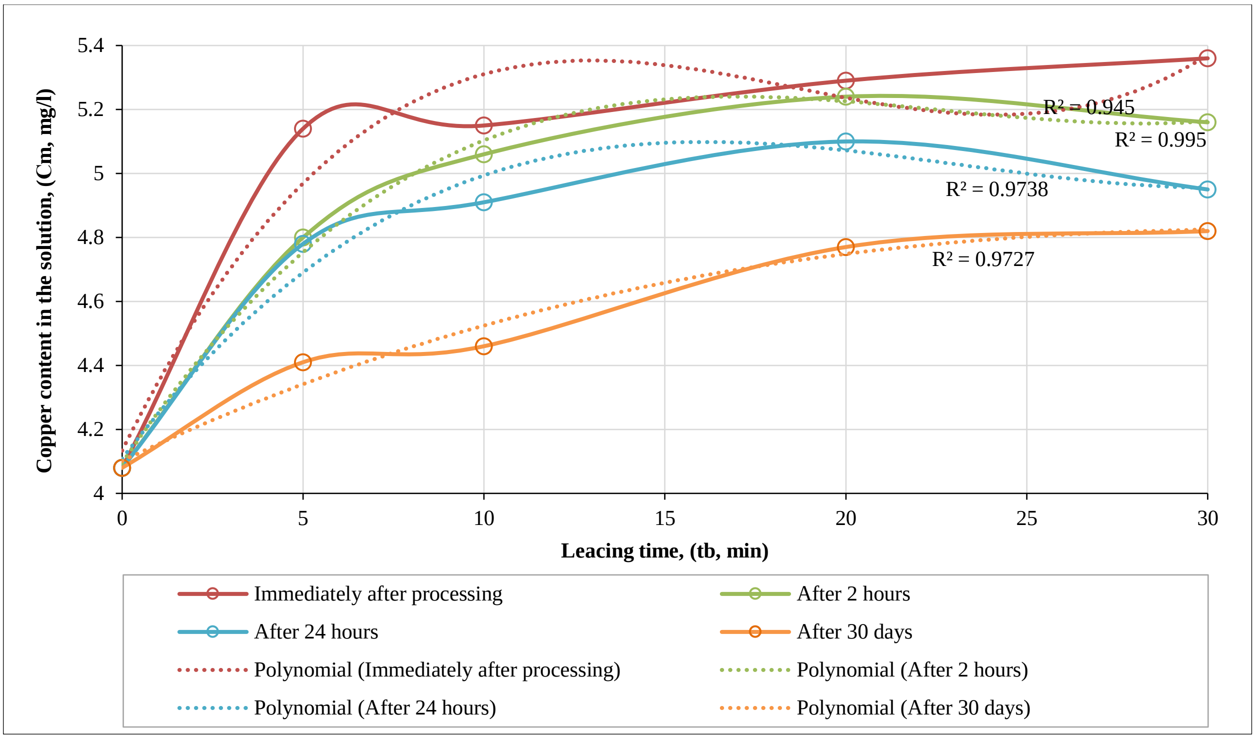

Figure 5. Change in metal content over time after processing of the solution and leaching time (processing time of the solution t_{pr} = 5 min; Polynomial)

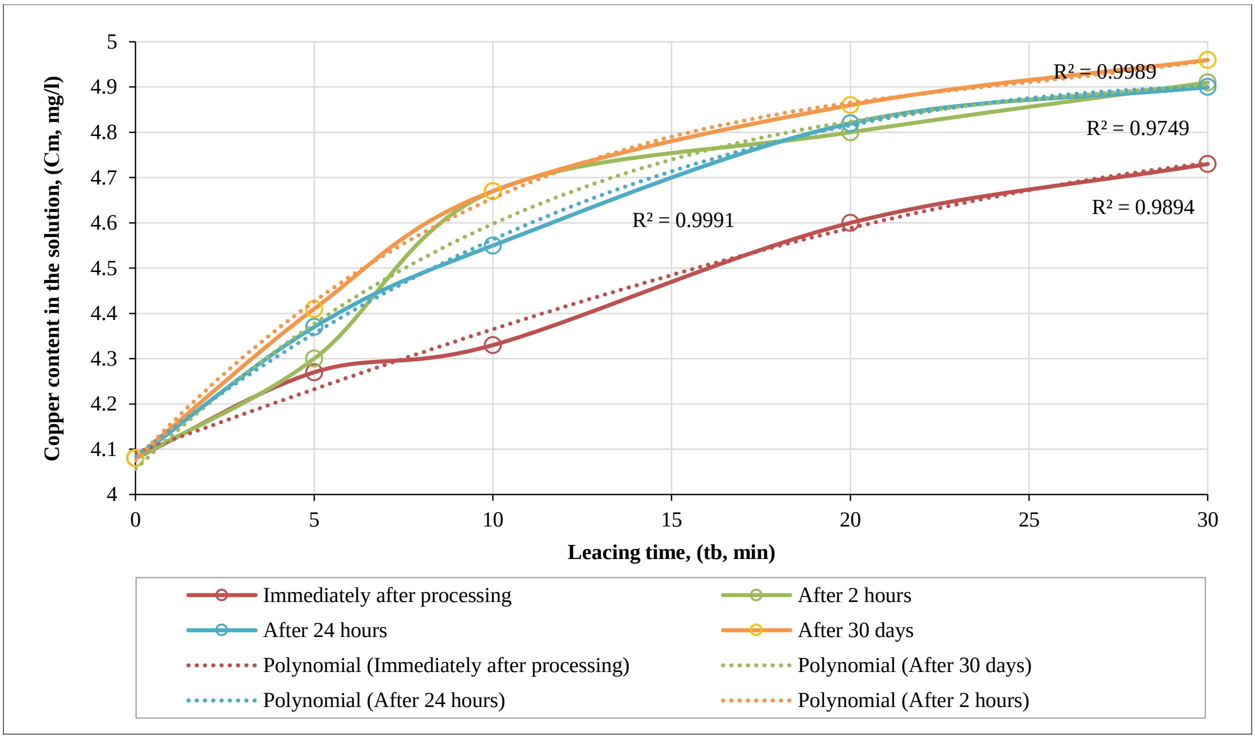

Figure 6. Change in metal content over time after processing of the solution and leaching time (processing time of the solution t_{pr} = 20 min; Polynomial)

The convergence of experimental data on the change in copper content from leaching time occurs in a polynomial form with a number of terms equal to 3, as can be seen from Figures 5 and 6, which leads to the conclusion that the level of convergence is high.

As can be seen from Figure 5, when processing a solution for 5 minutes and carrying out leaching for 10 minutes immediately after processing leads to an increase in the copper content in the pregnant solution from 4.23 mg/l to 5.15 mg/l, that is, by 21.7%. Leaching with the processed solution over a period of 2 hours, 24 hours led to a gradual decrease in the copper content in the pregnant solution from 5.15 mg/l to 5.06 mg/l and 4.91 mg/l, that is, by 1.7% and 4.7%, respectively, compared with leaching immediately after processing. There was a significant increase in the copper content in the pregnant solution during leaching for up to 20 min, and there was no significant increase; in some cases, a decrease in the copper content in the solution occurred during leaching for 30 min. The effect of leaching solution processing was maintained for a long time, with a slight decrease when the leaching solution was processed for 3 and 5 min. An increase in the copper content in the ore was also observed when processing the leaching solution for 20 min (Figure 6), but it was lower than when processing the leaching solution for 5 min. For example, the copper content in the pregnant solution was 5.05 mg/l when processing a leaching solution for 5 min and a leaching time of 10 minutes after two hours of exposure; and it is 4.65 mg/l when leaching with a solution treated for 20 min. The decrease in the efficiency of the leaching solution during treatment for 20 min is explained by the evaporation of sulfuric acid owing to an increase in the temperature of the solution during processing, which led to a decrease in its concentration in the solution.

Studies on leaching with processed solutions in injectors have shown that its effectiveness after processing is maintained for a long time; therefore, its properties will be the same during transportation from the surface to the pile of ore in the underground block and during metal leaching for a certain time [26, 27]. However, the leaching solution was piped into the ore pile in the block during the metal block leaching. As a standard, the leaching solution from the surface to the required horizon was piped along the shaft, followed by horizontal working to the mining block. The pressure of the supplied solution may change depending on the depth of the deposit block being mined, particularly on the vertical section of the pipeline. Therefore, the question is how an increase in pressure can affect the effectiveness of the solution after processing.

A high-pressure stainless-steel reactor was used to address this problem. The installation (Figure 7) consisted of a container (1), a pressure gauge (2), a filler plug (3), and a nitrogen cylinder (4). The experiments were conducted as follows: a solution of 150 ml of sulfuric acid with a concentration of 10 g/l was poured into the container, 1.2 g of copper sulfate was filled, and the filler plug was twisted. Subsequently, the required pressure was created from the nitrogen cylinder through a high-pressure hose and an additional fitting in the reactor, which was maintained for 20 min.

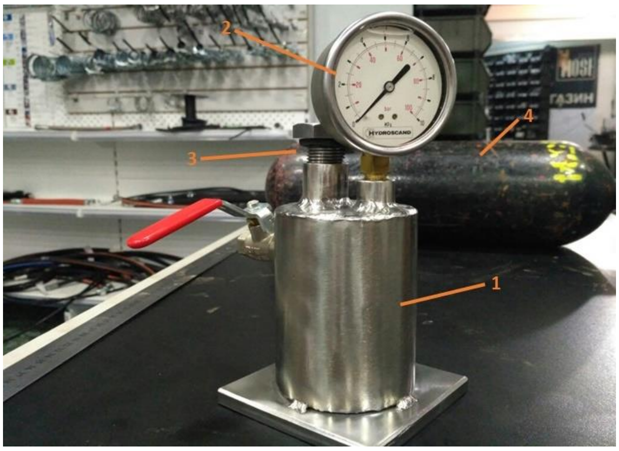

Figure 7. Installation for studying the effect of pressure on the change in the copper content in the solution

The pressure in the reactor was relieved after aging, the filler plug was opened, the solution was drained and filtered, and the amount of metal in the solution was determined. Thus, the experiments were carried out with a solution pre-processed for 8 min with an unprocessed solution.

Experiments were carried out in this reactor in the absence of pressure and pressures ranging from 0 to 50 atm. Changes in the copper content of the solution are listed in Table 2.

Table 2. Change in the copper amount (mg/l) after leaching at different pressures

Pressure. P. MPa (atm)	Metal content during leaching with unprocessed solution. mg/l	Metal content during leaching with processed solution. mg/l	Increase in metal content. %
0	0.78	0.96	23.1
1 (10)	0.80	1.0	25.0
2 (20)	0.83	1.03	24.1
4 (40)	0.84	1.02	21.4
5 (50)	0.82	1.01	23.2

The dependence of the change in copper content on the pressure in the chamber was obtained by processing the data in Figure 8.

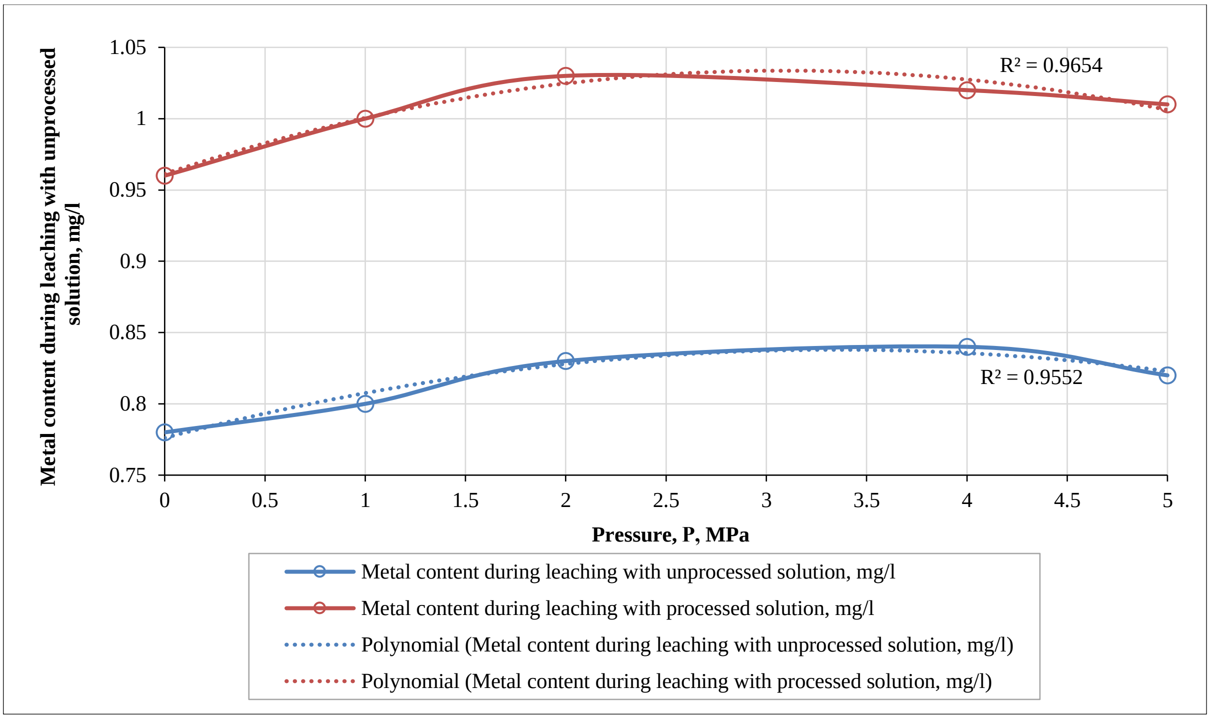

Figure 8. Change in the copper content from the pressure in the chamber

The convergence of experimental data on the change in copper content from pressure occurs in a polynomial form with a number of terms equal to 2, as can be seen from Figure 7, which leads to the conclusion that the level of convergence is quite high.

Unlike the leaching experiments conducted using a stirrer, there was no mixing of the solution in this series of experiments. Therefore, the intensity of the reaction was significantly lower in the solution after 20 min of leaching, and the Cu content ranged from 0.7 mg/l to 1.2 mg/l. The residual acid concentration in the solutions was up to 8 mg/l with this copper content. Meanwhile, the efficiency of the solution after processing was maintained, and the increase in the metal content in the processed solution after leaching at 50 atm exceeded that in the solution without processing by 23.2%. As can be seen from the table, a change in the pressure in the chamber from 0 MPa to 50 MPa did not lead to a noticeable change in the mineral content in the pregnant solution; the change in the mineral ranges from 21.4-25%. Experiments confirmed the absence of the influence of pressure on the effectiveness of both the untreated and treated solutions.

Analysis of the coefficient of convergence (R^2) and mean square error (RMSE) was performed using various regression methods to compare the proposed technology with previously conducted studies, such as leaching with nitric acid at high temperatures [28] and leaching with sodium cyanide with the addition of an oxidizer in the form of air [29] (Table 3).

Table 3. A comparative table of correlation and root-mean-square error indicators of proposed and previously conducted studies

Different technologies	Fit	Sum of Sine	Exponential		Fourier	Gaussian	Polynomial		
	Number of terms	1	1	2	1	1	1	2	3
Leaching with nitric acid at high temperatures	R-square	0,98	0.88	-0.38	0.95	0.97	0.91	0.98	0.99
	RMSE	2	5.04	24	2.27	2.4	4.15	1.86	1.48
Leaching with sodium cyanide with the addition of an oxidizer in the form of air	R-square	0.98	0.67	0.99	0.99	0.98	0.72	0.99	0.99
	RMSE	0.68	3.34	0.58	0.75	0.93	3.05	0.6	0.58
Proposed technology	R-square	0.94	0.59	0.99	095	0.93	0.61	0.95	0.99
	RMSE	0.16	0.34	0.026	0.21	0.17	0.33	0.15	0.06

The R^2 indicator does not differ significantly in terms of regression forms; however, in terms of the mean square error (RMSE), the indicators of the proposed technology are better, as can be seen from the comparative table with the proposed technology and previously conducted studies. The proposed technology for increasing the efficiency of metal leaching using a flow injector for metal processing makes it possible to increase the metal content in the pregnant solution to a maximum of 26%. Table 4 shows comparative data on various technologies for improving the efficiency of metal leaching.

Table 4. Comparative data of various technologies for improving the efficiency of metal leaching

The proposed technology and previously conducted research	Proposed technology	Leaching with nitric acid at high temperatures	Leaching with sodium cyanide with the addition of an oxidizer in the form of air
Increase of the metal content in the solution (%)	26	21	13

As shown in Table 4, the metal content increases to a maximum of 21% when leaching with a solution containing nitric acid at high temperatures. However, if we consider the high cost of nitric acid, as well as the significant costs of increasing the temperature of the immense volume of the supplied solution in production conditions, then this technology is not competitive compared to the proposed technology. The metal content in the solution increased to 13% when leaching with a solution of sodium cyanide, with the addition of an oxidizer in the form of air. However, the price of sodium cyanide is much higher than that of sulfuric acid, and the addition of an oxidizer in the form of air requires significant material and labor costs. The technology of treating a leaching solution with a flow injector can be used not only for block leaching, but also for underground in-situ leaching of uranium.

4. Conclusions

- Processing of the leaching solution using an injector leads to an increase in the mineral content of the pregnant solution, depending on the processing time of the leaching solution and the leaching time. For example, the increase in the copper content in the pregnant solution changes from 4.06 mg/l to 4.88 mg/l when leaching with an untreated solution and increasing the leaching time from 5 minutes to 30 minutes, and when leaching with a treated solution for 5 minutes and immediately after treatment, the increase in copper content changes from 5.14 mg/l to 5.36 mg/l, that is, an increase of 10-26%.
- It was proven that the effectiveness of the leaching solution decreased slightly over time after processing and was maintained for a long time (up to 30 days). For example, leaching with a treated solution over a period of 2 hours, 24 hours led to a gradual decrease in the copper content in the pregnant solution from 5.15 mg/l to 5.06 mg/l and 4.91 mg/l that is, by 1.7% and 4.7%, respectively, compared with leaching immediately after treatment. The reduction in copper content was 13% within 30 days of treatment.
- The dependence of the mineral content in the solution after leaching on the processing time of the leaching solution and the aging time of the solution after processing was determined.
- The change in the pressure of the solution does not affect the efficiency of the leaching solution processed on the injector.
- The maximum increase in the metal content in the pregnant solution was achieved by processing the leaching solution for 5 min. For example, the copper content increased by 11% when leaching with a solution treated for 3 min, and after 5 min of treatment, it increased by 22%. A further increase in the processing time of the leaching solution to 10 and 20 min and leaching immediately after treatment led to a gradual decrease in the copper content in the pregnant solution.

5. Declarations

5.1. Author Contributions

Conceptualization, K.Y.; methodology, K.Y. and E.A.; validation, D.A. and S.M.; resources, E.A. and K.Y.; writing—original draft preparation, K.Y. and E.A.; writing—review and editing, D.A., N.S., and S.M.; visualization, D.A. and N.S.; supervision, E.A.; project administration, E.A.; software, N.S.; funding acquisition, E.A. All authors have read and agreed to the published version of the manuscript.

5.2. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

5.3. Funding

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5.4. Conflicts of Interest

The authors declare no conflict of interest.

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