Optimization of the arsenic removal process from enargite based complex copper concentrate

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Abstract
Selective arsenic extraction from enargite based complex concentrate from Copper Mine in Bor (Serbia), using sodium hypochlorite as a leaching agent, was investigated in this paper. The aim was to assess the optimal conditions for the most efficient arsenic removal from the investigated concentrate, based on factorial design applied to experimentally obtained data. Five important factors with three factor levels were used as the input variables and experimentally obtained arsenic extraction yield was taken as the output variable. The first and the second final order model equations were obtained. It was found that the leaching temperature had the strongest effect on the arsenic extraction. The strongest positive interaction was between the sodium hypochlorite molar concentration and the stirring speed during extraction.

Keywords: enargite, extraction, experiment, modeling, variable.

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Most of the world's refined copper production is based on pyrometallurgical processing of copper concentrates, which includes roasting, smelting and refining in order to obtain high-quality copper cathodes. In Europe, ore deposits that contain metals in viable concentrations have been progressively depleted and few indigenous sources remain. Most concentrates are therefore imported from a variety of sources worldwide.

Some metals are essential as trace elements but at higher concentrations are characterised by the toxicity of the metal, ion or compounds and many are included under various lists of toxic materials [1]. Enargite (Cu_3AsS_4) is one of the most common contaminants in copper concentrates, as it leads to formation of volatile arsenic compounds during roasting and smelting, and it is accompanied by various environmental problems [2]. In order to have sufficiently low levels of arsenic prior to entering the acid plant, gases have to be cooled then submitted to a process step eliminating the bulk of arsenic as As_2O_3. Subsequent to this step, the residual arsenic is eliminated from the gas by a wet process, usually in a electrostatic precipitator. Different dry and wet methods for removal of arsenic from SO_2-bearing gases were described by Dalewski [3]. As a result, most smelters do not practice smelting of copper concentrates containing arsenic in excess of 0.5 %, due to high

penalties and state legislative. Various techniques for arsenic removal from contaminated copper concentrate were proposed [4]. The World Health Organization (WHO) published 2nd Edition of Air Quality Guidelines for Europe in 2001, where it was explained that the value of arsenic in the air above $1.5{\times}10^{-3}$ µg m^{-3} presented a high risk for human lives [5,6].

Typical arsenic contents in the air surrounding industrial zones should be up to 50 ng m^{-3} [7], including the zone in the vicinity of the copper smelter plant in Bor (Serbia). On the other hand, practically it is difficult to obtain the proposed level of arsenic in the air, after smelting copper concentrates produced by a selective flotation procedure applied to the sulfide ore deposits [8]. Having in mind the tendency of copper prices that increased strongly from 2003, due to global copper demands and economic expansion of the BRIC* countries (world refined usage has more than tripled in the last 50 years thanks to expanding sectors such as electrical and electronic products, building construction, industrial machinery and equipment, transportation equipment, consumer and general products) [9], it is necessary to find the most optimal technological process for the removal of excess arsenic and other toxic elements before further pyrometallurgical processing of complex copper concentrate.

Arsenic in complex copper concentrates

Minerals which contain arsenic can be found in copper concentrates produced from Bor (Serbia) ore deposits – enargite (Cu_3AsS_4) and luzonite (Cu_3AsS_4),

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while realgar (*As₄S₄*) and arsenopyrite (*FeAsS*) are present in smaller quantities. The presence of enargite in copper based minerals leads to relatively high arsenic quantities in copper concentrates which considerably reduces their economic value due to hazardous emissions generated from the pyrometallurgical processing [10]. During the melting process, arsenic, present in the concentrate, forms dangerous oxide dusts and fumes difficult to stabilize for safe disposal [11]. Therefore, this problem becomes more challenging for all subjects that are directly or indirectly involved in the pyrometallurgical copper production from complex copper – sulphide concentrates.

The basic technological problem, which needs to be solved, is the question how to minimize the arsenic concentration emitted from the copper smelter plant, if the raw materials that are going to be used, besides high copper content, have high arsenic values. During pyrometallurgical processes of arsenic-containing copper ores or concentrates some of the arsenic inevitably reports to the final effluents, which have to be stabilized prior to disposal. The disposal of arsenic has been accomplished in practice by the formation of metal arsenates and metal arsenites, *e.g.*, Ca^{2+}, Cu^{2+} and Fe^{2+} due to their low solubility. Arsenic has been precipitated by adding lime to the solution, obtaining a calcium arsenate compound, $Ca_3(AsO_4)_2$ [12]. Twidwell *et al.* [13] investigated the stability and solubility of $Ca_3(AsO_4)_3$. They noted that the solubility decreased one to two orders of magnitude over the range of pH 9.0–12.6, in the presence of phosphate ions.

To find the possible solution to the problem of arsenic in complex copper concentrates, authors have explored the possibilities of using hydrometallurgical treatment applied to the complex copper concentrate in order to dissolve arsenic, before further pyrometallurgical processing.

The available literature in this area is mainly based on the study of the chalcopyrite behavior [14–16], while the enargite characteristics have not been widely investigated. Recently, research aims have been directed to determining the influence of different leaching media on the arsenic utilization from copper ores and concentrates [2,4,17–32].

Basically, all techniques for the arsenic removal from enargite, applied in practice or still in the experimental phase, described in the literature, can be divided in two groups:

1. enargite leaching in acidic solutions and
2. enargite leaching in alkaline solutions.

The application of alkaline solutions of sodium sulfide gives priority to arsenic leaching, while copper, which remains as part of the solid residue, is suitable for further pyrometallurgical treatment.

Authors decided to evaluate the possibility of enargite leaching with sodium hypochlorite, because the process is technically attractive in terms of its potential use in a commercial scale based on the previous investigations of this matter. Selective oxidative alkaline leaching solution of enargite with hypochlorite may be used to remove arsenic from copper concentrates. Experimental investigations, presented in this paper, have shown that more than 90% of arsenic can be separated by extraction from alkaline enargite leaching at temperatures above 60 ºC in atmospheric conditions.

Enargite leaching with hypochlorite can be described by the following chemical reaction:

$$Cu_3AsS_4 + 11NaOH + \frac{35}{2}NaClO = 3CuO +$$

$$+ Na_3AsO_4 + 4Na_2SO_4 + \frac{11}{2}H_2O + \frac{35}{2}NaCl$$
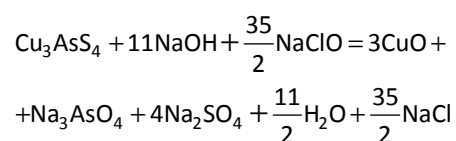
These results are in agreement with literature data [8,10,11,17] in terms of the tenorite formation (CuO) as a product of enargite oxidation in the described conditions.

After successful transport of arsenic into solution, arsenic can be stabilized by means of sedimentation with $Ca(OH)_2$ [33]. The mechanism of leaching with sodium hypochlorite was described in details in references [10,33,34].

The technique, used to obtain the optimal conditions for the future technical approach to research the problem, was a mathematical modeling, based on the factorial experimental design.

Environmental issue

Some ore bodies in the Bor copper mine, besides the copper bearing minerals, contain the minerals: Se, Bi, Cr, Sb, Cd, As, Zn, Pb, S, Ni, Fe and Hg, which partially remain in the final copper concentrate, even after the flotation separation process. The largest problem is with the sulfide copper minerals containing arsenic, which are converted into the copper concentrates entirely, being unable to separate them from the other sulfidic copper bearing minerals. At the increased temperatures of copper extraction in the pyrometallurgical processes, heavy metal sulfidic minerals are oxidized or sublimated, leaving the smelting unit in the form of fumes or in the PM form [35]. Modern copper smelters are equipped with contemporary facilities for PM removal from the off gases, as well as for high SO_2 utilization. However, even such facilities present the largest environmental polluters in the regions where they operate [36]. Copper smelters, using the outdated technologies, or smelting the low quality concentrates, are emitting the PM_{10} and the SO_2 high above the prescribed limits, which presents a serious hazard for peoples' health [5,37].

This is why the investigation, presented in this paper, was based on the complex copper based concentrate obtained from the Bor copper mine (ore body H), containing 9.52% Cu and 11.0% S, accompanied by the 3.44% As. With such a high arsenic content, this material shouldn't be treated for copper extraction pyrometallurgicaly in its initial form, under any circumstances.

Theoretical fundamentals

Mathematical modeling aims to describe the different aspects of the real world, their interaction and their dynamics through mathematics. Nowadays modeling has a key role in fields such as the environment and industry [38]. The aim of the modeling in this study was to obtain the mathematical model equation through which it will be possible to carry out the optimization of arsenic removal from enargite based complex copper concentrates.

To obtain a reliable statistical model, previous knowledge of the investigated procedure is surely required. The three steps used in the experimental design include the statistical design of experiments, the estimation of coefficients through a mathematical model with response prediction, and the statistical analysis [39].

The experimental design methodology, widely used to estimate main effects and interaction effects, is also the 2^n factorial design, where each variable (X_i; $i = 1–n$) is investigated at two levels minimum [40,41]. In a factorial design, all levels of each independent variable are combined with all levels of the other independent variables to produce all possible conditions.

When the factor number (n) increases, the number of runs for a design complete replicate also increases rapidly. The first order model can be used to perform the process modeling, defined by the following equation:

$$y = b_o + \sum_{i=1}^{n} b_i x_i + \sum_{i=1}^{n}\sum_{j>1}^{n} b_{ij} x_i x_j \qquad (1)$$

Or the second order model, which is:

$$y = b_o + \sum_{i=1}^{n} b_i x_i + \sum_{i=1}^{n} b_{ii}(x_{i2} - \overline{x_{i2}}) + \sum_{i=1}^{n}\sum_{j>1}^{n} b_{ij} x_i x_j \qquad (2)$$

Where:

$$\overline{x_{i2}} = \frac{1}{N}\sum_{i=1}^{N} x_{i2} \qquad (3)$$

Where N is the total number of experiments, including the holdout cases.

This way, with the following approximation:

$$b_o' = b_o - \sum_{i=1}^{n} b_{ii}\overline{x_i^2} \qquad (4)$$

the second order model can be presented as:

$$y = b_o' + \sum_{i=1}^{n} b_i x_i + \sum_{i=1}^{n} b_{ii} x_{i2} + \sum_{i=1}^{n}\sum_{j>1}^{n} b_{ij} x_i x_j \qquad (5)$$

The estimation of the developed model accuracy (for both the first or the second order) can be done using the root means squared error (*RMSE*) calculation between the model predicted and experimentally obtained value of the output variable, applied to the holdout cases, which are added to the experimental plan to estimate pure experimental errors:

$$RMSE = \sqrt{\frac{1}{m_o}\sum_{i=1}^{m_o}\left(y_i - y_i'\right)^2} \qquad (6)$$

Where y_i is the model predicted and y_i' is the actual value of the output variable, m_0 is the number of holdout cases.

EXPERIMENTAL

One of the possible solutions for the environmental problems caused by pyrometallurgical treatment of complex copper concentrates may be leaching of natural enargite with sodium hypochlorite under alkaline oxidizing conditions with enargite converted into crystalline CuO and the arsenic solubility forming AsO_4^{3-}.

The XRD analysis results of the initial concentrate sample, are given in Figure 1.

Based on the results shown in Figure 1, it can be seen that the crystalline form of the given sample consists of enargite, chalcopyrite, tennantite, olivine and quartz.

Chemical composition of the enargite based complex copper concentrate is shown in Table 1.

The experimental procedure included the concentrate sample preparation – grinding to coarseness of 80% – 0.074 mm, as it the most dominant fraction in conventional copper concentrates), followed by the hydrometallurgical treatment. Leaching of samples was done in a 1 dm^3 three-neck tank with a condenser, a mechanical stirrer and an ultra-thermometer (Fig. 2). The leaching process kinetic experiments were performed at different hypochlorite concentrations (X_1), with different solid to liquid ratios (X_2). The leaching solution was mechanically stirred at different rates (X_3). Leaching temperatures were in the range: 25–60 °C (X_4), and time intervals up to 120 min (X_5).

The reaction progress was determined by analyzing arsenic from the obtained leaching solution using the

ICP-AES method (Inductively Coupled Plasma Atomic Emission Spectroscopy). Based on the arsenic content in the initial sample, the amount of extracted arsenic (Y) was determined.
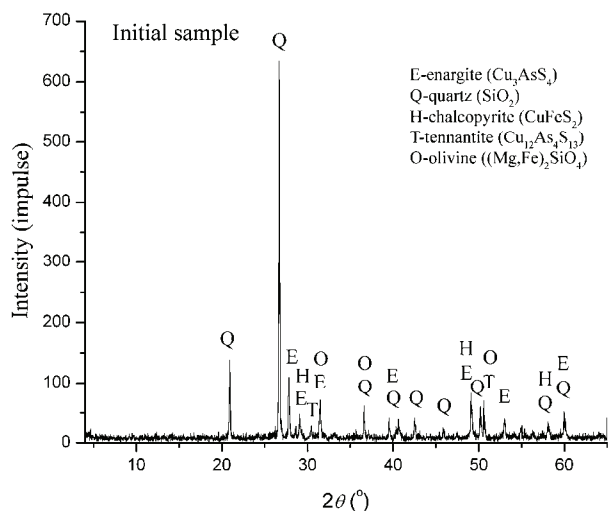

Figure 1. The XRD analysis results of the initial ore feed.

Table 1. Chemical composition of the initial sample

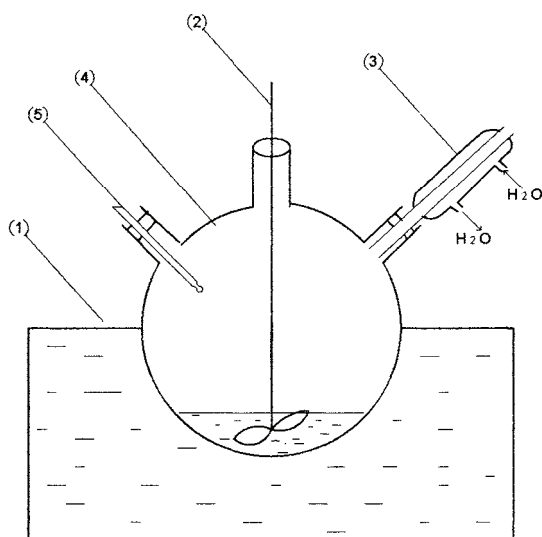| Element	Cu	Zn	Fe	Pb	Ni	Cd	Sb	S	As
mass %	9.52	0.18	10.07	0.006	0.0005	0.0009	0.15	11,0	3.44

Figure 2. Schematic view of the apparatus used for the experiments; (1) – ultrathermostat; (2) – mechanical stirrer, (3) – condenser,(4) – three-neck tank; (5) – ultrathermometer.

RESULTS AND DISCUSSION

As indicated in previous sections, there are five factors important for the investigated process, namely, the sodium hypochlorite solution concentration (variable X_1); the solid sample mass (variable X_2); stirring rates (variable X_3); leaching temperatures (variable X_4) and leaching time intervals (variable X_5). The low, medium and high levels of all factors, are shown in Table 2.

Both, the first (Eq. (1)) and the second (Eq. (5)) order models were used to fit the obtained experimental data. When five factors (X_1 to X_5), and three factor levels are taken into consideration, the SPSS software [42] resulted in the factorial experimental design that required 16 runs. Six holdout cases were added to the experimental plan to estimate only experimental errors (Table 3). The experiments were run at random order to avoid systematic errors.

After conducting all 22 experiments, the results of arsenic extraction were included in the database as the output variable – Y (Table 2). Experiments 20, 21 and 22, were repeated to asses the replicability of the obtained experimental results. Results of repeated experiments were in accordance with results presented in Table 2, with an error of ±0,5%.

Using the multiple linear regression analysis (MLRA) on the results of the first 16 experiments, presented in Table 3, a first order model (Eq. (1)) was obtained.

Based on these results, the final first order model equation resulted from the regression analysis (Eq. (7)):

$$Y = 2.749 + 106.465X_1 - 210.109X_2 - 0.045X_3 + 2.352X_4 + 0.828X_5 + 279.439X_1X_2 + 0.172X_1X_3 - 6.615X_1X_4 + 0.075X_1X_5 + 0.135X_2X_3 + 3.187X_2X_4 - 0.277X_2X_5 - 0001X_3X_5 - 0.010X_4X_5 \qquad (7)$$

Table 2. Factor levels

Factor	Low level (−)	Medium level (0)	High level (+)
Sodium hypochlorite molar concentration (X_1)	0.18	0.30	0.42
Mass of the solid sample, g (X_2)	0.30	0.50	0.70
Stirring speed, rpm (X_3)	100	300	600
Leaching temperature, °C (X_4)	25	40	60
Leaching time, min (X_5)	20	60	120

The internal validity of the obtained model was than tested using control tests made on six holdout cases presented in Table 3. After calculating the Root Means Squared Error (Eq. (6)) between the model predicted and experimentally obtained copper extraction, for holdout cases, it was concluded that the data obtained experimentally and the model estimations are in good agreement.

Table 3. Experimental design and arsenic leaching yield; [a] – holdout cases

Exp. No.	X_1, M_{NaClO} / mol dm^{-3}	X_2 Solid phase, g	X_3 Stirring speed, min^{-1}	X_4 Temperature, °C	X_5 Time, min	Y Arsenic yield, %
1	–	–	–	–	–	30.05
2	+	–	+	–	0	63.95
3	–	–	–	0	+	87.21
4	0	–	0	+	–	87.21
5	0	–	+	0	–	93.02
6	–	–	–	–	–	29.07
7	+	0	–	+	–	81.39
8	–	0	0	0	0	87.21
9	+	+	–	0	–	69.77
10	+	–	0	–	+	69.77
11	–	0	+	–	–	34.88
12	–	+	0	–	–	23.67
13	–	+	+	+	+	93.02
14	0	0	–	–	+	57.56
15	0	–	–	0	+	98.84
16	–	–	–	+	0	93,02
17[a]	0	0	–	0	0	75.58
18[a]	0	+	–	–	0	35.71
19[a]	+	0	–	0	0	75.58
20[a]	–	–	–	0	–	81.39
21[a]	+	+	+	–	+	75.58
22[a]	+	+	+	+	+	95.51

The coefficient of determination of the final first order model is $R^2 = 0.85$ as indicated in Figure 3. This coefficient is the squared value of the multiple correlation coefficients, which presents the linear correlation between the observed and model predicted values of the dependent variable. Its large value indicates a strong relationship.

Since the coefficient of determination of the first order model was not satisfactorily high, it was decided to apply the second order model (Eq. (5)) in the sub-
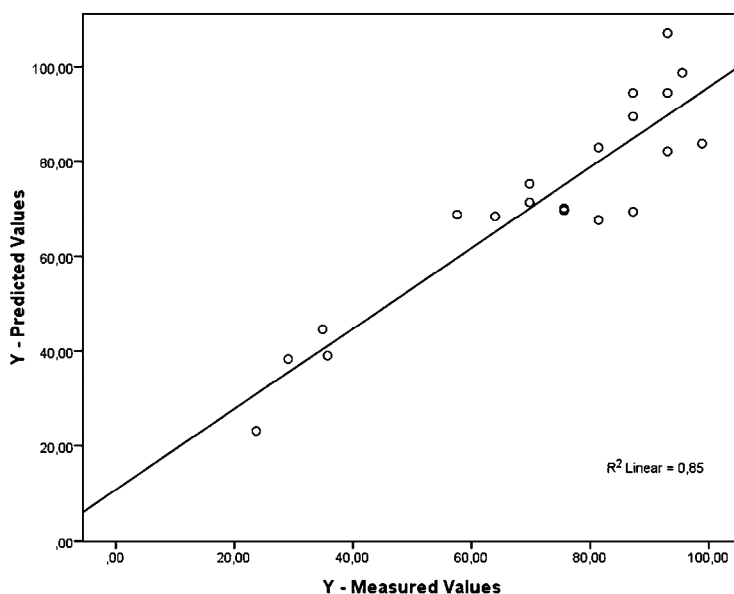

Figure 3. Correlation between experimentally determined and first order model predicted values of the arsenic extraction from the enargite sample; (— = regression lines; o = values calculated using the first order MLRA model).

sequent analysis.

The values of obtained model coefficients, which have statistical significance ($p < 0.01$), are indicated in Table 4.

Based on these results (Table 4), the final second order model equation obtained by using the stepwise method in six iterations, is presented in Eq. (8):

$$Y = -130.414 + 8.105X_4 + 0.444X_5 - 0.073X_4^2 + 0.093X_1X_3 - 0.599X_2X_4 - 0.006X_4X_5 \qquad (8)$$

Only the variables with the significant level ($p < 0.05$) remained in the final model equation.

According to the coefficients in the Eq. (8), it is possible to analyze the regression equation and to determine the effect of each factor. Accordingly, the regression equation shows the principal effects of the five selected factors on the arsenic yield. If observing only the unstandardized coefficients (b unstandardized in Table 4), the leaching temperature (X_4) has the strongest effect on the response since the corresponding coefficient ($b = 8.105$) is larger than the coefficients of other investigated factors. The positive sign of this coefficient indicates that an increase in the leaching temperature improves the arsenic removal from the enargite sample.

Another important factor is the leaching time (X_5 with $b = 0.444$). This coefficient also has a positive sign indicating that leaching time increase leads to more efficient arsenic removal. On the other hand, other input variables ($X_1 - X_3$), do not have any statistical significance in the independent form. The design of experiments for arsenic removal, after leaching from enargite sample, also exhibits interactions between the various factors studied.

The strongest positive interaction is among the sodium hypochlorite molar concentration (X_1) and the stirring speed during leaching (X_3), with the coefficient $b = 0.093$. However, if analyzing the coefficient obtained after standardization of the input variables (beta standardized in Table 4), which removes the effect of magnitude of the value of different variables, the situation is to some extend different. It can be concluded that the strongest positive interaction is between the mass of the solid sample (X_2) and the

leaching temperature (X_4), with the coefficient $b = 0.176$. Anyhow, as expected, the principal influence on arsenic removal comes from the leaching temperature (X_4) and the leaching time (X_5).

The internal validity of the obtained model was than tested using control tests made on six holdout cases, presented in Table 3. After calculating the root means squared error (Eq. (6)) between the model predicted and experimentally obtained arsenic removal values, for holdout cases, it was concluded that the data obtained experimentally and the model estimations are in a good agreement.

The reliability of the final model was further tested using the ANOVA test. The results of ANOVA tests of developed model are presented in Table 5.

Table 5. Results of ANOVA test of the finally obtained second order model; dependent variable: Y

Source	Sum of squares	df	Mean squares	F	Sig.
Regression	10356.189	6	1726.031	78.529	0.000
Residual	307.712	14	21.979	–	–
Uncorrected total	10663.901	20	–	–	–

Significant *F* statistics (Table 5) indicate that using the model is better than guessing the mean [43,44].

Also, the significance value of F statistics is less than 0.05 which means that the variations explained by the model are not caused by chance. The regression ratio to residual is 97 pct:13 pct, advocating that 97 pct of the dependent variable (*Y*) values are explained by the model. The determination coefficient of the final model is $R^2 = 0.971$, as indicated in Figure 4. Its large value indicates a strong relationship between observed and the model predicted values of the dependant variable. Also, standard error estimate (SEE) for the model was calculated and it equaled to 4.68823. Accordingly, it was decided that the obtained second order model could be used to predict the arsenic removal from the enargite sample accurately enough.

Using the final model equation (Eq. (5)), which predicts the amount of arsenic removal accurately enough ($R^2 = 0.971$), it is possible to determine optimal con-

Table 4. The second order model of the arsenic removal process from the initial sample

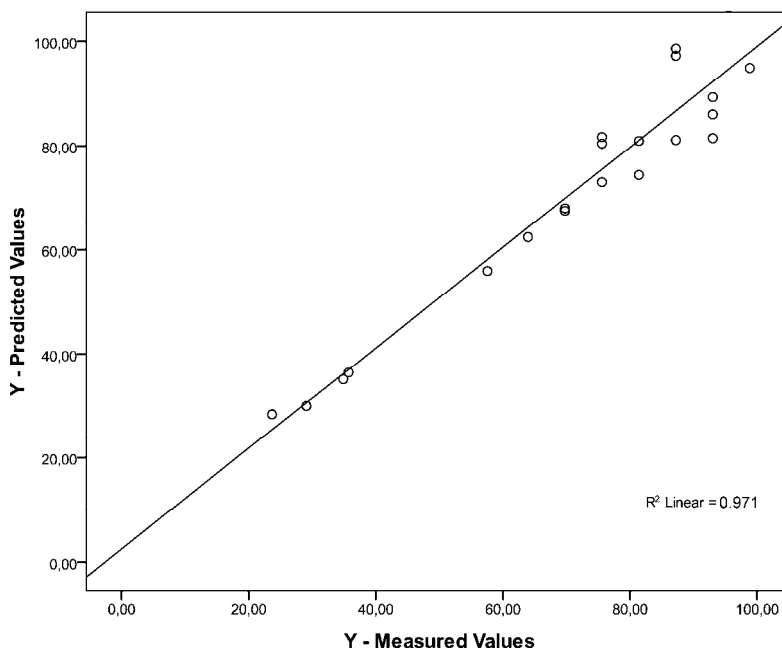| Model	b Unstandardized	Standard error	Beta standardized	t	Significance (p)
Constant	−130.414	14.248	/	−9.153	0.000
X_4	8.105	0.653	4.826	12.404	0.000
X_5	0.444	0.078	0.833	5.686	0.000
X_4X_4	−0.073	0.008	−3.688	−9.634	0.000
X_1X_3	0.093	0.014	0.330	6.530	0.000
X_2X_4	−0.599	0.176	−0.256	−3.400	0.004
X_4X_5	−0.006	0.002	−0.552	−3.209	0.006

Figure 4. The correlation between experimentally determined and second order model predicted values of the arsenic removal from the enargite sample.

ditions for the operation management of the process, since the model fits the experimental results well enough. The optimization consists of finding such a set of operational variable values which would result in the optimal arsenic extraction yield. The localization of the optimum set of operational variable values can be obtained in various ways [39]. However, the layout of the surface contours plot is the easiest method to interpret, if having a model equation. Surface contour plots were analyzed, using Matlab 7.0 software [45] to determine the optimal solution. The surface response and contour plots, given in Figures 5 and 6, are drawn in the plane leaching temperature – leaching time when the remaining variables are kept at their optimal values responding to the experiment No. 15 (Table 3).

These curves allow us to determine the region of the work domain where the arsenic removal from the samples is optimal. Accordingly, if the sodium hypochlorite molar concentration (X_1) is 0.3 M; mass of the initial enargite sample (X_2) is 0.3 g; stirring speed (X_3) is 100 rpm then the arsenic removal (Y) can reach the value of 97.93% if leaching the enargite ore during 120 min at temperatures above 40 °C. This value closely agrees with the experimental arsenic removal of 98.84% in the experimental run 15.

CONCLUSIONS

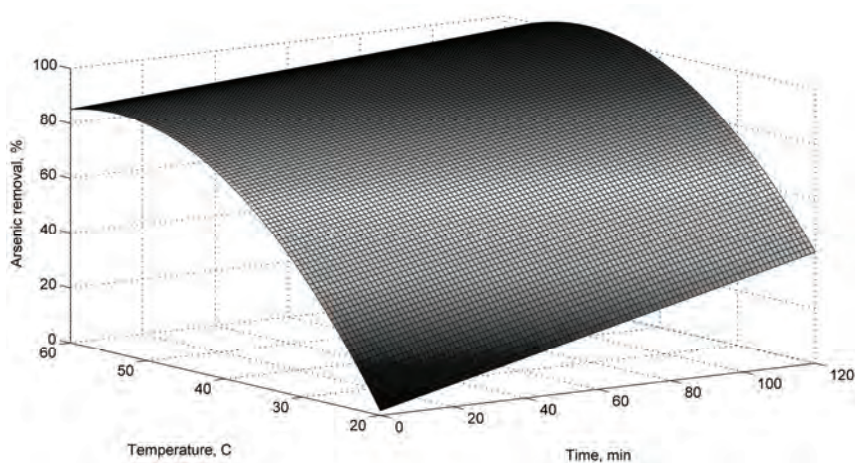The recovery of copper from complex concentrates with increased level of impurities has both economical

Figure 5. The surface response plot for the arsenic removal in the plane leaching temperature or leaching time at optimal values of the remaining variable (Exp. No. 15).
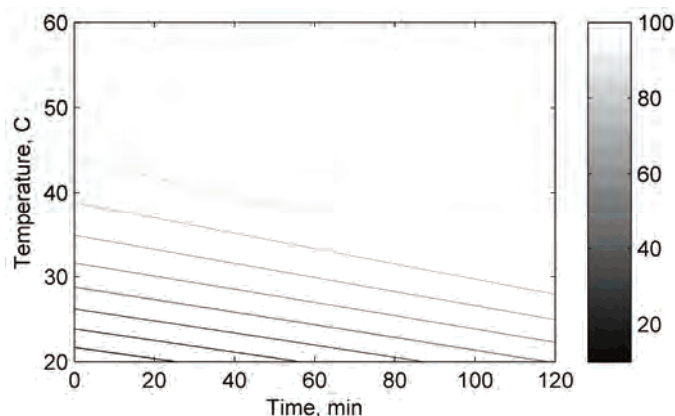
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Figure 6. The response contour plot for the arsenic removal in the plane leaching temperature or leaching time at optimal values of the remaining variable (Exp. No. 15).

and ecological aspects – high copper price on the world's market is making this project sustainable. Experimental work in this paper showed that arsenic from enargite can be dissolved by sodium hypochlorite in the form of AsO_4^{3-}, while copper remains in the solid phase in the form of CuO.

Mathematical modeling applied to experimental results, showed that the range of arsenic removal from natural enargite samples was a function of: the sodium hypochlorite molar concentration, the mass of the initial sample, the stirring speed, the leaching temperature and the leaching time. The principal influence on arsenic removal comes from the leaching temperature and leaching time. The positive sign of the coefficients in the final model equation indicate that increase of leaching temperature and leaching time leads to higher arsenic removal efficiency.

The obtained linear correlation dependence with $R^2 = 0.971$ was calculated using the experimental data acquisition, with experiments prepared according to the factorial experimental design methodology.

The region of the work domain where the arsenic removal from the samples is optimal was determined. The optimal arsenic removal of 97.93% can be achieved under following conditions: the sodium hypochlorite molar concentration (X_1) – 0.3 M; mass of the initial enargite sample (X_2) – 0.3 g; stirring speed (X_3) – 100 rpm; leaching time – 120 min and temperature above 40 °C.

The proposed model can be used to determine the experimental conditions that can generate the optimal arsenic removal after leaching the enargite sample. Using the model equation could support further analyze the effect of each process variable value change on the arsenic removal. Also, it can allow the calculation of kinetic parameters of the process. This would be the subject of authors' further investigations.

Acknowledgement

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IZVOD

OPTIMIZACIJA PROCESA UKLANJANJA ARSENA IZ KOMPLEKSNOG KONCENTRATA BAKRA NA BAZI ENARGITA

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U prikazanom radu ispitivana je selektivna ekstrakcija arsena iz kompleksnog koncentrata na bazi enargita iz rudnika bakra u Boru, korišćenjem Na-hipohlorita kao agensa za luženje. Osnovni cilj istraživanja sastojao se u utvrđivanju uticajnih parametara i njihovog međusobnog odnosa kako bi se ostvarilo maksimalno uklanjanje arsena iz ispitivanog koncentrata. Enargit (Cu_3AsS_4) spada u rasprostranjene kontaminante koncentrata bakra. Tokom procesa prženja i topljenja arsen obrazuje lako isparljiva jedinjenja koja vrlo negativno utiču na zagađenje ljudi, radne i životne sredine. Zakonska regulativa ne dozvoljava topionicama bakra da tope koncentrate sa više od 0,5% arsena. Za dobijanje optimalnih uslova procesa uklanjanja arsena iz kompleksnog koncentrata bakra na bazi enargita, korišćena je tehnika matematičkog modelovanja. Modelovanje je izvršeno primenom faktorskog dizajna na eksperimentalno dobijene podatke. Odabrano je pet karakterističnih parametara procesa – ulaznih varijabli, za koje se pretpostavlja da imaju uticaja na stepen ekstrakcije arsena: koncentracija rastvora hipohlorita, masa uzorka (koncentrata), brzina mešanja, temperatura luženja i vreme luženja. Faktorski (2^n) dizajn zahtevao je izvođenje 16 eksperimenata sa šest replikanata. Nakon izvođenja 22 eksperimenta, rezultati ekstrakcije arsena uzeti su kao izlazna varijabla. Proračunom su dobijene jednačine modela prvog i drugog reda. Koeficijenti u modelu drugog reda ukazuju da temperatura luženja ima najveći uticaj na ekstrakciju arsena. Drugi faktor po značaju je vreme luženja. Pozitivni predznaci ispred ova dva najuticajnija parametra ukazuju da povećanje temperature luženja, odnosno vremena luženja, utiču na povećanje stepena uklanjanja arsena iz ispitivanog koncentrata. Najveća pozitivna interakcija zapažena je između koncentracije hipohlorita i brzine mešanja tokom procesa ekstrakcije. Proračun RMSE (*root mean square error*) pokazao je dobro slaganje između vrednosti dobijenih eksperimentalnim istraživanjem i vrednosti dobijene modelovanjem. Pouzdanost finalnog modela testirana je primenom ANOVA testa.

Ključne reči: Enargit • Ekstrakcija • Eksperiment • Modelovanje • Varijabla