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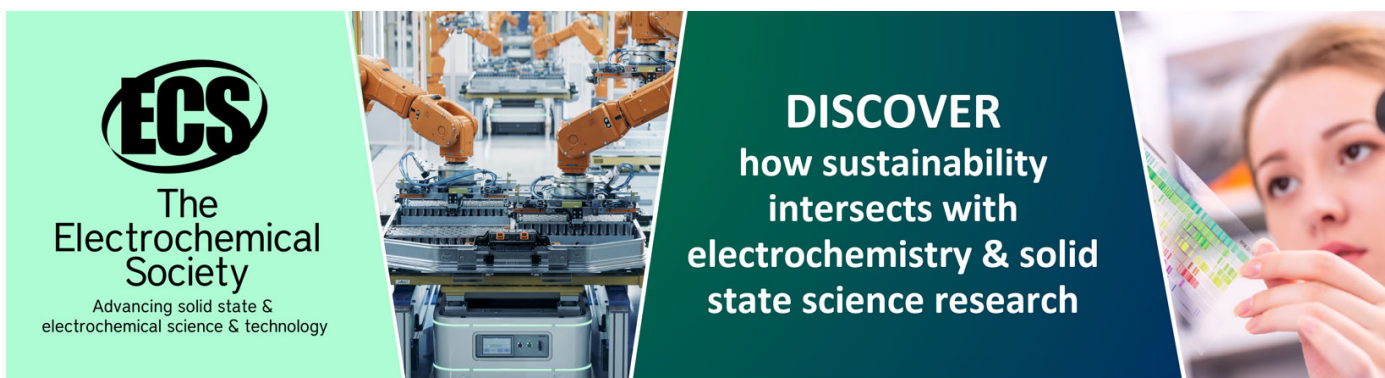
## Studies on Polish copper ore beneficiation in Jameson cell

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## Studies on Polish copper ore beneficiation in Jameson cell

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**Abstract.** The paper presents the preliminary studies concern the results of Polish copper ore beneficiation in Jameson cell. To investigate the simultaneous influence of flotation machines type, grain size (0-25, 25-45, 45-75 µm), type (isobutyl and ethyl xanthate aqueous solution) and dosage (100, 150 g/Mg) of collector, flotation time on the efficiency of the process, the multi-level experiment has to be performed for carbonate lithological type of copper. Comparing results of flotation test it can be concluded that the best results were obtained for 0-25 µm with the use of isobutyl xanthate aqueous solution in a dosage equal to 100 g/Mg. Tests of significance (MANOVA, ANOVA) showed a high influence of factors on the difference between an efficiency of separation in the most cases. This paper shows an attempt to create a model for the copper ore enrichment process at Jameson cell. The equations were described using a logarithmic substitution. The model evaluation was made based on mean squared error MSE and coefficient of determination R<sup>2</sup>.

### 1. Introduction

Copper prices on world markets and the necessity of obtaining copper ore from more and more hard to process and poorer parts of deposits mean that the efficiency of the processing is constantly being improved. In the case of exploitation of such minerals, flotation remains the main process with goal of separating metal minerals from gangue. At the same time, it is not easy to carry out because many factors affect the result. Among them, it can be listed the entire range of properties of the feed, parameters and conditions of separation as well as the characteristics of the devices [1, 2, 3, 4].

Polish copper ore deposits are of sedimentary type, which are characterized by different mineralogical-petrographic and physicochemical features. Additionally, these deposits have complex chemical composition and a fine-grain mineralization. The crucial property is an occurrence of three lithological types (carbonate, shale and sandstone) conditioning a high variability in susceptibility to enrichment processes [3, 4, 5]. In the work [6] a big variation in copper content in the deposit was described. However, the correlation between the content of copper in the deposit and beneficiation effect is not significant.

To obtain a high-quality copper concentrate a multi-level flotation is applied in Polish enrichment plants. The most important condition for its application is a high level of minerals liberation of different sizes [7]. Numerous works indicate that the best flotation results are achieved for a feed with



particle size below 0.02 mm or even less. The problem of deep grinding appears and it is unavoidable for Polish copper deposit [8]. It is important to consider the feed properties in an individual way, which was justified by presence of diversified lithological types. Considering a sulphide mineral size distribution, it was stated that copper minerals for sandstone type are 0.1-0.5 mm, carbonate around 0.14-5 mm and for shale type copper minerals are equal to 0.007-0.01 mm. In particular mines, these values differ among themselves. In the work enrichment results of copper ore from Polkowice-Sieroszowice mine were presented. It is characterized by the biggest share of dolomite lithological type (about 62%) characterizing by mineral size below 100  $\mu\text{m}$ .

Considering the size of Polish copper mineral particles, which determine high efficiency of flotation, it is necessary to ensure the appropriate size of air bubble particles. This guarantees a high probability of creating solid-air bubble aggregates. Flotation efficiency of the mechanical cells for fine particles ( $<20 \mu\text{m}$ ) is believed to be low due to relatively low collision probability of fine particles and the high levels of turbulence, respectively. The Jameson cell have a greater potential for recovery in this regard compared to mechanical cells. The reason is a possibilities of produce finer bubbles (e.g., 200-700  $\mu\text{m}$ ) in the Jameson cell [9, 10]. It can be stated that there are certain indications that the second type of device should be used.

## **2. Jameson cell**

At the beginning, the Jameson flotation cell was used for coal slimes in Australia [11] but since then, it has been successfully applied for coal and copper beneficiation, as well processing of molybdenite and lead ores. The Jameson cell is suitable for processing of fine particles (below 100  $\mu\text{m}$ ) due to fine bubbles (200–1000  $\mu\text{m}$ ) generated in the cell [9]. The flotation of coarse particles is unsatisfactory, which can be explained by low energy of an air bubble, which is not able to keep mineral particle on its surface or turbulences during a floating [9, 12]. Common features of Jameson cell include small tank residence times, high concentrate production rates and a high shear rate to produce very fine bubbles. However, this machines operates with not compressed air input and the vacuum developed within the downcomer produces interactions unlike conventional pneumatic devices [13, 14].

The Jameson cell has two main parts, the downcomer (providing a primary contact of particles and bubbles) and the separation tank (elementary phenomena of creating the bubble-particle aggregate and a floating it to the foam). Pulp is pumped into the downcomer through a nozzle, creating a high-pressure jet and air entrainment till the bubble formation with a plunging jet is achieved. The pulp zone is where secondary contact of bubbles and particles occurs, and air bubbles disengage from the pulp. The froth zone is where entrained materials are removed from the froth by froth drainage and/or froth washing [9, 15].

## **3. Aims and experimental description**

The main purpose of the work was to examine the effectiveness of the flotation process of hardly enriched copper ores in Jameson cell. A multi-parameter analysis was carried out basing on the results of the flotation tests and the process models were generated. The sample of copper ore was collected in Polkowice Enrichment Plant in Poland. The carbonate lithological type was separated from the samples, subjected to further preparatory work and finally it was tested in Jameson cell to investigate the simultaneous influence of particle size, type and dosage of collector, flotation time on the efficiency of the flotation. The multi-level experiment was performed in Dumlupınar University in Kütahya, Turkey. For carbonate lithological type of copper ore three size fractions (45-75, 25-45, 0-25  $\mu\text{m}$ ) were separated. During the flotation tests two types of collectors (isobutyl and ethyl xanthate aqueous solution) in two dosages (100, 150 g/Mg) were used. The single experiment assumed testing of feed in a cycle with a cleaning flotation. Samples of the froth concentrates were collected after the following time: 1, 2, 4, 6, 9, 12, 17, 22, 30 [min]. The solid ratio was equal to 1.96%. Nasfroth in dosage 50 g/Mg was used as a frother during tests. Samples were examined by means of X-ray fluorescence to determine a copper content in flotation product. The evaluation of the process was carried out in accordance with a copper content and copper recovery in concentrate and tailings.

#### 4. Calculation methods

To assess flotation efficiency evaluation indicators were calculated (1-4). They are described in table 1 [1, 3, 12]. The results were compiled with factor parameters, which was a basis to carry out a statistic analysis and a modelling.

**Table 1.** Evaluation process indicators.

| Copper recovery in concentrate $\varepsilon_i$                           | Copper recovery in tailings $\eta_i$                                  | Copper content in concentrate $\beta_i$                                             | Copper content in tailings $\nu_i$                                                      |
|--------------------------------------------------------------------------|-----------------------------------------------------------------------|-------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------|
| $\varepsilon_i = \frac{\beta_i}{\alpha} \sum_{j=1}^i \gamma_j \quad (1)$ | $\eta_i = \frac{\vartheta_i}{\alpha} \sum_{j=i}^n \gamma_j \quad (2)$ | $\beta_i = \frac{\sum_{j=1}^i \gamma_j \lambda_j}{\sum_{j=1}^i \gamma_j} \quad (3)$ | $\vartheta_i = \frac{\sum_{j=i}^n \gamma_j \lambda_j}{\sum_{j=i}^n \gamma_j} \quad (4)$ |
| $\alpha$ – a copper content in the feed,                                 |                                                                       | $\lambda_i$ – content of copper in a product,                                       |                                                                                         |
| $\gamma_i = \frac{m_i}{\sum_{i=1}^n m_i}$ – a yield of a product,        |                                                                       | $m_i$ – an amount of a product,                                                     |                                                                                         |
| $\sum_{j=1}^i \gamma_j = 100 - \sum_{j=1}^{i-1} \gamma_j$                |                                                                       |                                                                                     |                                                                                         |

The family of variance analysis methods is widely use and universal tools to examine complex phenomenon, which depend on many different factors. Those methods enable to check an existence and a strength of the influence of parameters, like particle size, types and dosages of collector over the final results of flotation process. Based on mean sums of square effects and errors it is possible to verify the accuracy of experiments performance for appropriate number of repetition count. Before the use of ANOVA/MANOVA some basic assumptions have to be made (representativeness of the dataset and sampling, the normality of distributions of the dependent variables, the homogeneity of the intergroup variance). The verification of normality assumption can be based on the Kolmogorov-Smirnov, Shapiro-Wilk, Lilliefors, D'Agostino-Pearson or Q-Q plot test. In case of homogeneity of variance, it is possible to use following tests: Neyman and Pearson, Bartlett, Cochran, Scheffy, Levene, Brown and Forsythe ones. The choice depends on type of data [10, 16, 17].

ANOVA allows to examine an influence of one parameter (e.g. collector type) on one dependable variable (e.g. copper recovery in tailings). It can be use in multifactorial scheme, so this approach enables studying the influence of different parameters on flotation results describing only by one evaluation index. Despite the fact those methods are still one-dimensional contrary to MANOVA, which is multidimensional variance analysis. It makes possible to examine an influence of one or more parameters on efficiency of flotation in terms of all chosen indicators ( $\beta$ ,  $\nu$ ,  $\varepsilon$ ,  $\eta$ ). Based on that information it can be concluded that comparison of parameters and indicators values must be done in different manner which depends on sort of methods. In ANOVA case operations are proceeded on population mean values but MANOVA is more extensive and it uses the multivariate vector of dependent variables. A detailed description of calculation methodology is presented in works [10, 18, 19, 20] for both approaches.

Information obtained from the application of ANOVA/MANOVA is useful to determine flotation mathematical models. It provides an opportunity to eliminate some insignificant factors for final results of flotation test. A multiple regression allows to determine quantitative relationship between parameters ( $x_1, x_2, x_3, x_4$ ) and response variable ( $y_i$ ). Formula (5) describes the general regression equations, which form is the basis for modelling.

$$Y_i = b_0 + b_1 \cdot x_1 + b_2 \cdot x_2 + b_3 \cdot x_3 + b_4 \cdot x_4 + e_i \quad (5)$$

where:  $y_i$  – process evaluation indicators,  
 $x_i$  – collector type,

$x_2$  – collector dosage,

$x_3$  – size fraction,

$x_4$  – flotation time,

$b_i$  – model parameter,

$e_i$  – standard estimation error.

In order to assess the accuracy of matching the regression functions to the experimental data, a mean squared error and a coefficient of determination were used. They are described by formula (6) and (7) [10, 18, 20, 21]:

$$MSE = \sqrt{\frac{1}{n-k} \sum (y_{ei} - y_{ti})^2} \quad (6)$$

$$R^2 = \frac{\sum_{i=1}^n (y_{ei} - \bar{y})(y_{ti} - \bar{y})}{\sum_{i=1}^n (y_{ti} - \bar{y})^2} \quad (7)$$

where:  $y_{ei}$  – an empirical value of parameter,

$y_{ti}$  – a theoretical value of parameter,

$\bar{y}$  – an arithmetic mean of empirical values of  $Y$ -random variable,

$n$  – number of cases,

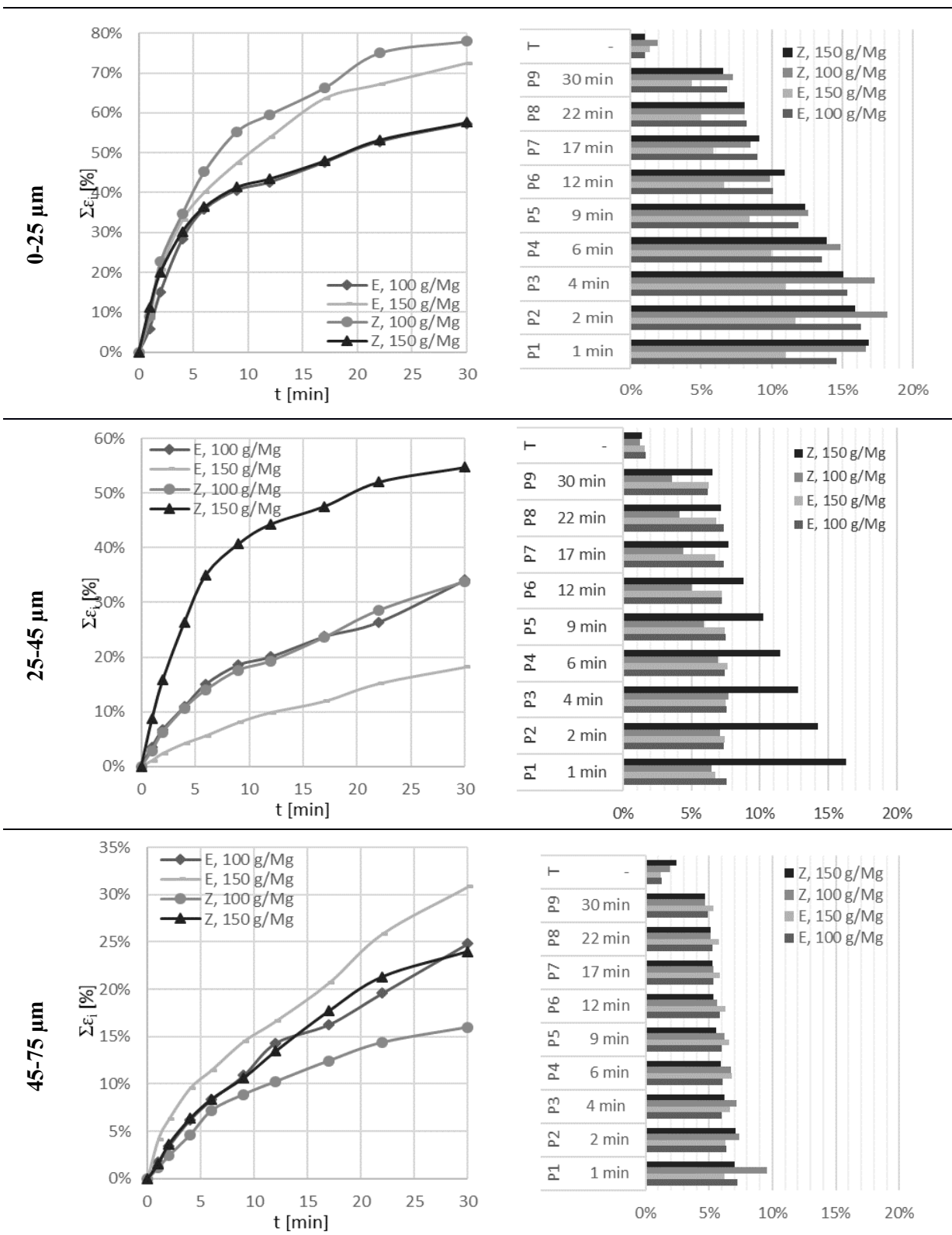
$k$  – number of variables in the model.

## 5. Results and discussion

In order to carry out an experimental plan it was necessary to collect copper ore in Poland and prepare samples to flotation test in Dumlupinar University, where Jameson cell was available to use. Cooperation of DPU and AGH University results in performance of studies. The final results were presented in the figure 1.

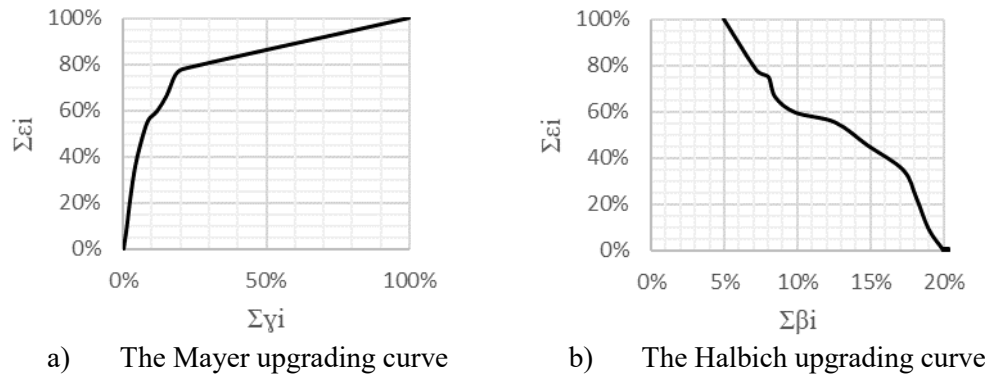
It can be concluded that the beneficiation of copper ore for size fractions below 75  $\mu\text{m}$  is hard to perform in both Jameson cell and conventional Denver flotation machine. Table 1 presents the results of flotation tests for narrow size fractions (0-25  $\mu\text{m}$ , 25-45  $\mu\text{m}$ , 45-75  $\mu\text{m}$ ). Considering the copper recovery and copper content in concentrates it can be stated that in order to obtain the best results during the separation process in Jameson cell the process should be conducted for 0-25  $\mu\text{m}$  particle size. In case of 25-45  $\mu\text{m}$  size fraction evaluation indicators values decline. The copper recovery decreases on average about 20% according to collector type and dosage. For particle size 45-75  $\mu\text{m}$  the process is unprofitable. Differences between each size fractions are not too big, but it is a factor, which affect significantly the final results.

During the flotation an isobutyl xanthate aqueous solution (Z) and an ethyl xanthate aqueous solution (E) were used as collectors. Reagents were added in two dosages which were equal to 100 g and 150 g per 1 Mg of feed, respectively. For finest size fraction, 0-25  $\mu\text{m}$  the best results were obtained for the isobutyl xanthate aqueous solution in dosage 100 g per 1 Mg of feed. The copper recovery was similar for an ethyl xanthate aqueous solution in dosage 150 g per 1 Mg of feed, but the quality of flotation concentrate decreased significantly. It can be stated very clearly that an isobutyl xanthate aqueous solution caused an increase in copper recovery in concentrates during processing of 25-45  $\mu\text{m}$  particle size fraction. This reagent seems to be better for finest size fractions. In the last case (45-75  $\mu\text{m}$ ) a little bit better results were obtained when an ethyl xanthate aqueous solution was used for the separation, but the particle size distribution is inadequate for the Jameson cell work conditions.

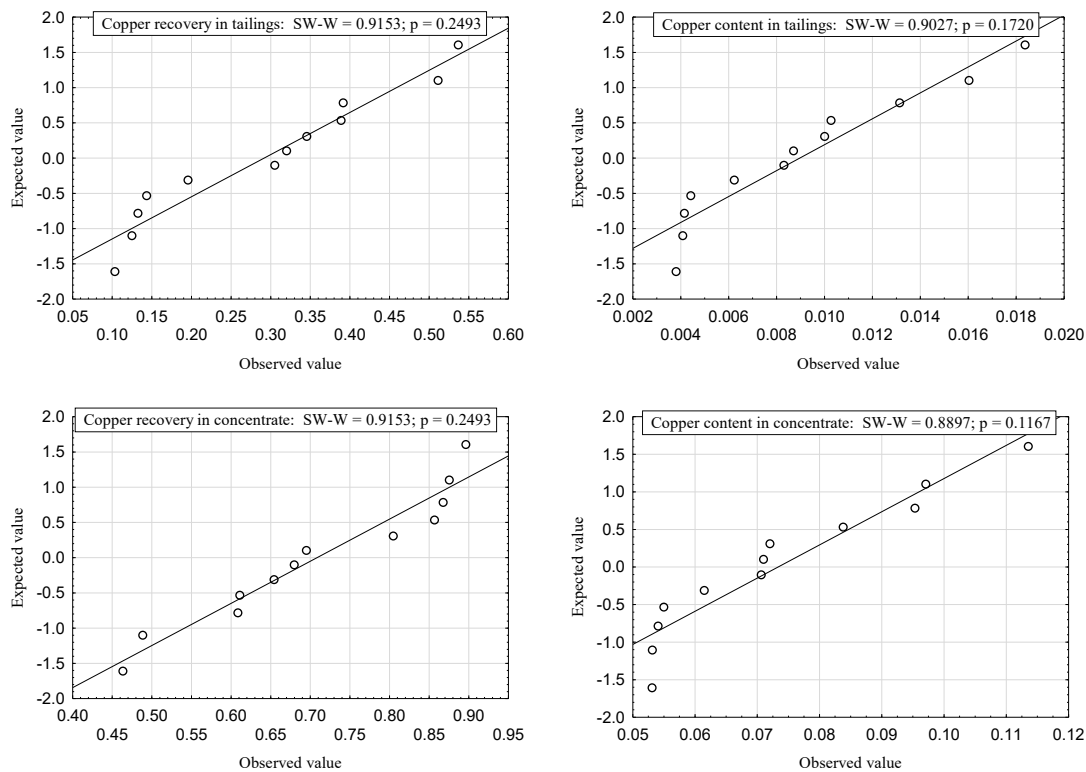


**Figure 1.** Final results of copper ore beneficiation in Jameson cell.





**Figure 2.** Beneficiations curves for a dolomite copper ore flotation test in Jameson cell (0-25  $\mu\text{m}$ , Z, 100 g/Mg).



**Figure 3.** Normal probability plots for examined variables with results for Shapiro-Wilk test (SW-W).

For the selected case of dolomite copper ore enrichment upgrading curves were drawn (figure 2). Their shapes confirm an occurrence of some problems with beneficiation. Especially Halbich upgrading curve indicates this conclusion.

Further analysis was based on a variance analysis. A large number of factors differentiating the effects of flotation enrichment affected the high degree of variability of the copper content and its recovery in the concentrate and tailings, and as a result, the normality assumptions were not met. Therefore, it was decided to eliminate the variable “time”, which obviously and significantly affects the final effects of the enrichment process. After this all the assumptions were met for the ANOVA and MANOVA application (figure 3).

The assumption of variance homogeneity was not met for all tested variables. However, after application of an elementary logarithmic substitution instead of original data the results of Levene’s test confirmed the possibility of the implementation of the planned analyses.

Result of MANOVA was shown in the table 2. It can be concluded that simultaneous effect of parameters (time, size fraction, collector type and dosage) is important for variability in test results of flotation process in Jameson cell. The conclusion was drawn on the basis of the multidimensional significance (Wilks' Lambda test).

In order to check a single effect of parameters on the efficiency of the process ANOVA tests were performed for each factor. Taking into account a copper content in concentrates and tailings it can be concluded that factor "dosage of collector" was not significant for their change. In case of copper recovery in both products the parameters "type of collector" occurred to be unambiguous. Additionally, it can be stated that the variables are not correlated. The values of Pearson correlation coefficient were equal to 0.

**Table 2.** MANOVA results.

| Independent variables | Wilks' Lambda $\lambda$ | F     | p    |
|-----------------------|-------------------------|-------|------|
| Particle size         | 0.182901                | 234.2 | 0.00 |
| Flotation time        | 0.033369                | 141.5 | 0.00 |
| Collector type        | 0.853637                | 30.0  | 0.00 |
| Collector dosage      | 0.879644                | 23.9  | 0.00 |

**Table 3.** ANOVA results.

| Independent variables | Copper content in concentrate |             | Copper content in tailings |             | Copper recovery in concentrate |             | Copper recovery in tailings |             |
|-----------------------|-------------------------------|-------------|----------------------------|-------------|--------------------------------|-------------|-----------------------------|-------------|
|                       | F                             | p           | F                          | p           | F                              | p           | F                           | p           |
| Particle size         | 602.44                        | 0.00        | 235.76                     | 0.00        | 774.82                         | 0.00        | 774.82                      | 0.00        |
| Flotation time        | 30.69                         | 0.00        | 134.47                     | 0.00        | 556.01                         | 0.00        | 556.01                      | 0.00        |
| Collector type        | 74.48                         | 0.00        | 7.73                       | 0.01        | <u>2.32</u>                    | <u>0.13</u> | <u>2.32</u>                 | <u>0.13</u> |
| Collector dosage      | <u>0.04</u>                   | <u>0.84</u> | <u>0.04</u>                | <u>0.84</u> | 8.36                           | 0.01        | 8.36                        | 0.01        |

Models for flotation process in Jameson cell were described by semi-logarithmic functions which are presented below as formulas (8), (9), (10) and (11). There some factors are omitted according to ANOVA results. The parameter "collector dosage" was not important from statistical point of view in cases of copper content in product. The similar situation concerned copper recovery in concentrate and tailings in connection with the influence of "collector type" on efficiency of flotation process.

$$\beta = 0.08706 - 0.00012 \cdot \ln x_1 - 0.0005 \cdot \ln x_3 - 0.01074 \cdot \ln x_4 \pm 0.01924 \quad (8)$$

$$\vartheta = 0.02297 - 0.00001 \cdot \ln x_1 - 0.00006 \cdot \ln x_3 - 0.00404 \cdot \ln x_4 \pm 0.00332 \quad (9)$$

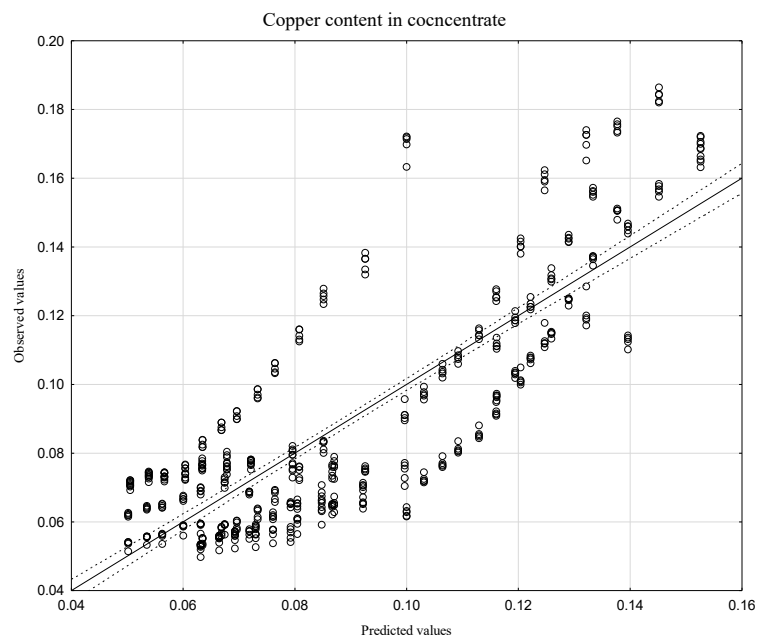
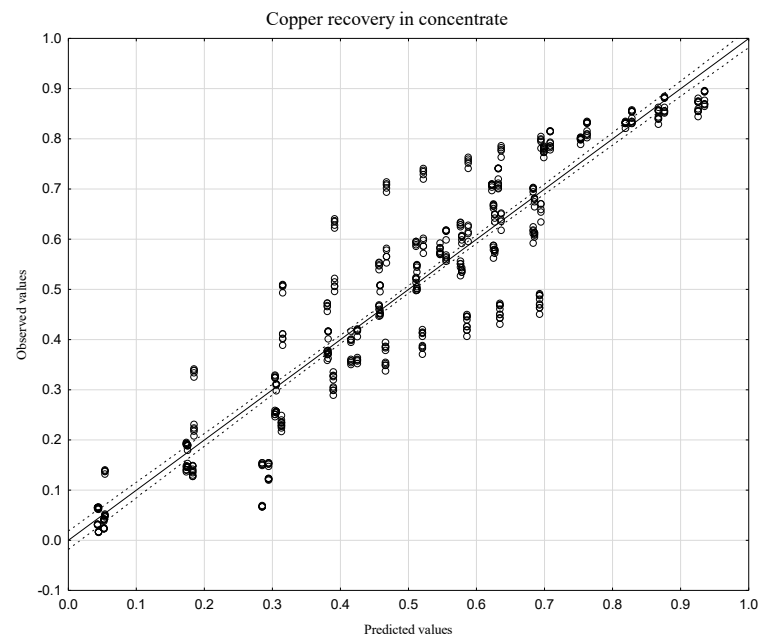
$$\varepsilon = -0.16139 + 0.04378 \cdot \ln x_2 - 0.00227 \cdot \ln x_3 + 0.18835 \cdot \ln x_4 \pm 0.09082 \quad (10)$$

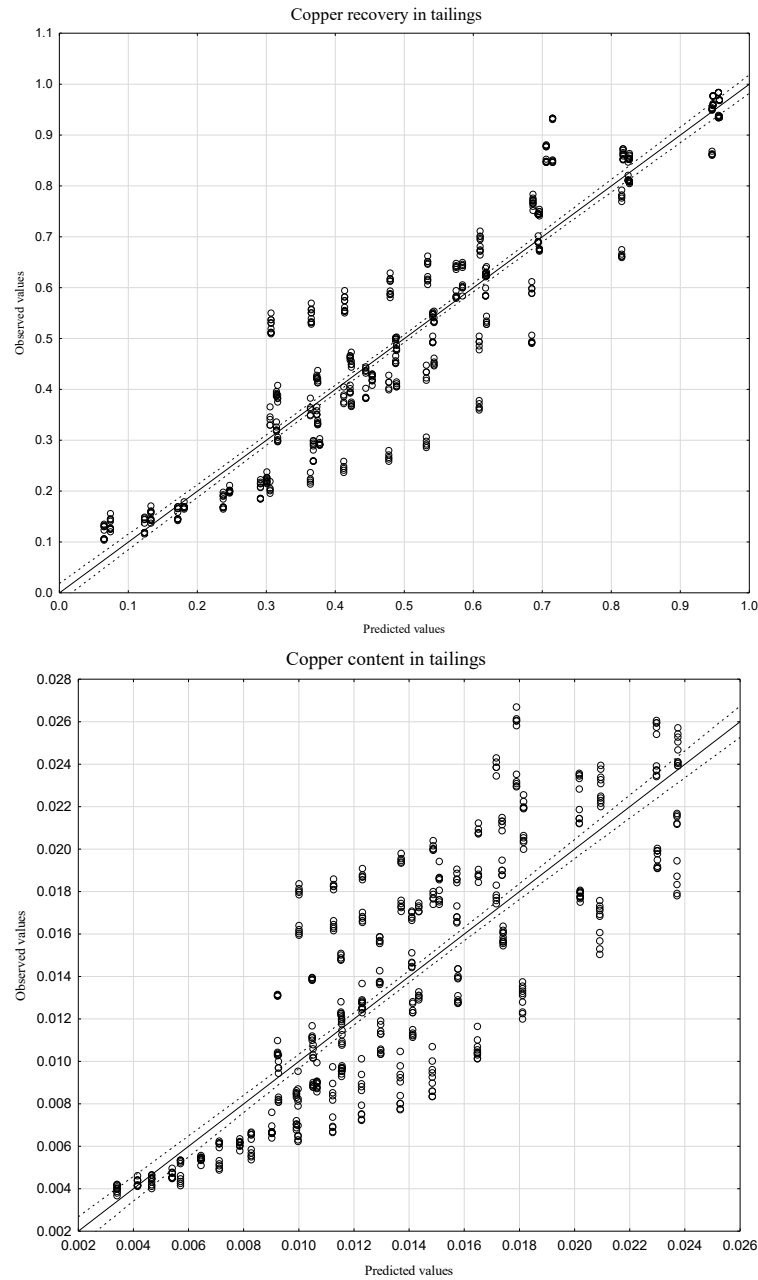
$$\eta = 1.16139 - 0.04378 \cdot \ln x_2 + 0.00227 \cdot \ln x_3 - 0.18835 \cdot \ln x_4 \pm 0.09082 \quad (11)$$

where:  $\beta$  – copper content in concentrate,  
 $\vartheta$  – copper content in tailings,  
 $\varepsilon$  – copper recovery in concentrate,  
 $\eta$  – copper recovery in tailings,  
 $x_1$  – collector type,  
 $x_2$  – collector dosage,  
 $x_3$  – size fraction,  
 $x_4$  – flotation time.

In all cases, the clouds of experimental points are wide (figure 4) which directly affects the great difficulties in the modelling process. It is not possible to obtain a model that will describe the phenomenon with 100% accuracy.







**Figure 4.** Comparison of experimental points and overall models for variables

The match of models and process evaluation indicators are presented in the table 4. In the overall approach, some difficulties can be noticed for accurately describing the phenomenon of flotation through created functions. Both values of the MSE and  $R^2$  confirm the occurring deviations. The selected factors have a significant impact on the final result of copper ore flotation in the Jameson cell and therefore it was a reason to generate additional models of copper recovery and content in products for size fractions. This is a very important parameter affecting the enrichment of raw materials at this machine. In a similar approach, as in the general models, equations (12-23) were created describing the effects of copper ore enrichment.

$$\beta_{<25} = 0.4527 - 0.00023 \cdot \ln x_1 - 0.0627 \cdot \ln x_2 - 0.01957 \cdot \ln x_4 \pm 0.0104 \quad (12)$$

$$\vartheta_{<25} = 0.03457 - 0.00001 \cdot \ln x_1 - 0.0031 \cdot \ln x_2 - 0.00546 \cdot \ln x_4 \pm 0.00193 \quad (13)$$

$$\varepsilon_{<25} = 0.35914 - 0.00016 \cdot \ln x_1 - 0.02853 \cdot \ln x_2 + 0.21797 \cdot \ln x_4 \pm 0.07118 \quad (14)$$

$$\eta_{<25} = 0.64086 + 0.00016 \cdot \ln x_1 + 0.02853 \cdot \ln x_2 - 0.21797 \cdot \ln x_4 \pm 0.07118 \quad (15)$$

$$\beta_{25-45} = -0.18266 - 0.00014 \cdot \ln x_1 + 0.05663 \cdot \ln x_2 - 0.00755 \cdot \ln x_4 \pm 0.01646 \quad (16)$$

$$\vartheta_{25-45} = 0.01382 + 0.00005 \cdot \ln x_1 + 0.00227 \cdot \ln x_2 - 0.00385 \cdot \ln x_4 \pm 0.00123 \quad (17)$$

$$\varepsilon_{25-45} = -0.38388 - 0.00116 \cdot \ln x_1 + 0.08875 \cdot \ln x_2 + 0.18589 \cdot \ln x_4 \pm 0.05889 \quad (18)$$

$$\eta_{25-45} = 1.38388 + 0.00116 \cdot \ln x_1 - 0.08875 \cdot \ln x_2 - 0.18589 \cdot \ln x_4 \pm 0.05889 \quad (19)$$

$$\beta_{45-75} = 0.05386 + 0.000004 \cdot \ln x_1 + 0.00389 \cdot \ln x_2 - 0.00509 \cdot \ln x_4 \pm 0.0584 \quad (20)$$

$$v_{45-75} = 0.0128 - 0.00006 \cdot \ln x_1 + 0.00124 \cdot \ln x_2 - 0.00281 \cdot \ln x_4 \pm 0.00102 \quad (21)$$

$$\varepsilon_{45-75} = -0.2345 + 0.00106 \cdot \ln x_1 + 0.07117 \cdot \ln x_2 + 0.16119 \cdot \ln x_4 \pm 0.04465 \quad (22)$$

$$\eta_{45-75} = 1.2345 - 0.00106 \cdot \ln x_1 - 0.07117 \cdot \ln x_2 - 0.16119 \cdot \ln x_4 \pm 0.04465 \quad (23)$$

For each of the equations a matching assessment was based on the coefficient of determination  $R^2$  and the mean squared error MSE (table 4). Considering the division into size fractions, the modelling results can be much better. The greatest difficulties appear in the description of copper content in concentrate for size fractions 25-45  $\mu\text{m}$  and 45-75  $\mu\text{m}$ . For the remaining flotation indicators, the accuracy of the description was above 90%. Only models of copper recovery and copper content in products deriving from flotation of the 0-25  $\mu\text{m}$  size fraction are entirely characterized by a better fitting. This may suggest the general models will more accurately reflect the final results of the enrichment of this size fraction.

**Table 4.** The assessment of model fit to experimental data.

| Model                         | MSE [%]         |       |       |       |
|-------------------------------|-----------------|-------|-------|-------|
|                               | All cases       | 0-25  | 25-45 | 45-75 |
| Copper recovery in products   | 9.05            | 7.04  | 5.92  | 4.42  |
| Copper content in concentrate | 1.92            | 1.03  | 1.63  | 0.64  |
| Copper content in tailings    | 0.79            | 0.19  | 2.16  | 0.1   |
| Model                         | $R^2$ value [%] |       |       |       |
|                               | All cases       | 0-25  | 25-45 | 45-75 |
| Copper recovery in products   | 86.71           | 91.63 | 92.52 | 94.41 |
| Copper content in concentrate | 68.33           | 87.66 | 48.49 | 47.45 |
| Copper content in tailings    | 70.66           | 90.53 | 90.53 | 95.14 |

## 6. Conclusions

The Jameson Cell is a co-current flotation device, in which a feed slurry is pumped through a fixed diameter orifice. Ultrafine bubbles are produced in the downcomer because of the high shearing provided by the jet action of the feed slurry. As a result of the high air-fraction generated within the downcomer, a superior bubble-particle collision environment is produced which provides greater flotation rate constant values for the hydrophobic species. However, the research on various raw materials proved (e.g. coal, copper or zinc ore) that the efficient flotation for fine feed particles is

possible when the probability of formatting permanent aggregates is high. In the case of Polish copper ore, the highest efficiency of the process can be indicated for 0-25  $\mu\text{m}$  of the size fraction with an application of the isobutyl xanthate aqueous solution in a dosage of 100 g/Mg of copper ore. In other cases, there is clear deterioration.

The separation of useful minerals from gangue in the Jameson cell depends on many different factors. Simultaneous analysis of all of them is not possible, but it is worth to use some multidimensional statistical methods for such complex operations. The analysis was performed for some parameters basing on ANOVA and MANOVA tests. It is necessary to pay attention to the fact that the use of variance analysis and the modelling require to introduce some data changes, such as eliminating of the time variable and inserting of a logarithmic transformation. The reason for that was the large variation of the results of flotation tests which was related to the factor effect as well as the measurement error which is not possible to eliminate.

The effect of four important operating parameters on separation performance main indicators, which are copper content and recovery in flotation products, was studied in detail with a goal to understand the process better. The results of the variation analysis showed that the factor "dosage of collector" was not significant for the copper content in products. At the same time a "type of collector" parameter was unambiguous for copper recovery. Furthermore, the models describing the copper content in products are linear functions of the collector type, particle size and separation time. On the other hand, the copper recovery functions depend on three variables: the collector dosage, the particle size of the feed and a separation time. In their entirety models are not fully describing the flotation indicators. When the problem is considered for each size fraction separately, fittings of models are better. In case of 0-25  $\mu\text{m}$  size fraction values of MSE and  $R^2$  confirm that the generated mathematical functions characterize a copper ore flotation in the best way. The matching is maintained at the level 90% with a mean square error equal to 7% for copper recovery equation, 1% for copper content in concentrate and 0.2% for copper content in tailings.

## References

- [1] Drzymała J 2007 *Mineral processing : foundations of theory and practice of minerallurgy* Oficyna Wydawnicza Politechniki Wrocławskiej [in Polish]
- [2] Foszcz D 2013 *Principles for determining optimal results of enrichment of multi-component copper ores* IGSMiE PAN [in Polish]
- [3] Potulska A 2008 *An influence of fine grinding operations on flotation effectiveness of domestic copper ore* PhD thesis PWr WGGG Wrocław [in Polish]
- [4] Zarudzka E 2010 *Influence of acid leaching of sulfid ores* PhD thesis PWr WGGG Wrocław [in Polish]
- [5] Piestrzyński A 1996 *Poland Monography KGHM Polska Miedź S.A. CBPM Cuprum* 200-323
- [6] Wieniawski A and Skorupska B 2016 *E3S Web of Conference MEC2016* 8 01064
- [7] Foszcz D, Trybalski K, Tumidajski T and Pawlos W 2009 *Cuprum: scientific and technical journal of ore mining* **2** pp 47-59
- [8] Łuszczkiewicz A and Wieniewski A 2006 *Mining and Geoengineering* **3(1)** pp 181-96
- [9] Sahbaz O, Uçar A and Öteyaka B 2013 *Minerals Engineering* **41** pp 79-85
- [10] Stanisław A 2007 *An affordable statistic course using STATISTICA PL on examples of medicine* Poland. StatSoft [in Polish]
- [11] Harbort G J, Manlapig E V and DeBono S K 2002 *Trans. IMM (Section C: Mineral Process. Extr. Metall). In: 111/Proceedings of the Australas. Inst. Min. Metall.* **307** C<sub>1</sub>-C<sub>2</sub>
- [12] Gonjito F C, Fornasiero D and Ralston J 2007 *Can. J. Chem. Eng.* **85** 739-47.
- [13] Harbort G J, De Bono S, Carr D and Lawson V 2003 *Minerals Engineering* **16** pp 1091-101
- [14] Lawson V 2016 *Enhancing the Performance of Cu-Mo Circuits Using the Jameson Cell* 12<sup>th</sup> IMPC
- [15] Tasdemir A, Tasdemir T and Öteyaka B 2007 *Minerals Engineering* **20** pp 1331-6

- [16] Napier Munn T J 2014 *Julius Kruttschnitt Mineral Research Centre* 0980362245
- [17] Pillai R N S and Bagavathi V 2010 *Practical Statistics* India Chand and company
- [18] Jajuga K 1993 *Statistical multidimensional analysis* Poland PWN [in Polish]
- [19] Niedoba T, Surowiak A and Pięta P 2016 *J. Pol. Miner. Eng. Soc.* **17(1)** pp 15-22
- [20] Maxwell S E and Delaney H D 2014 *Lawrence Erlbaum Associates*
- [21] Pease J D, Curry D and Young M F 2006 *Minerals Engineering* **19** pp 831-40