HSC Sim® simulation model of the Assarel copper flotation circuit based on process mineralogy and metallurgical testing

Ivan Korolev
Aalto University

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HSC SIM® SIMULATION MODEL OF THE ASSAREL COPPER FLOTATION CIRCUIT BASED ON PROCESS MINERALOGY AND METALLURGICAL TESTING

Ivan Korolev[1,2,*], Antti Remes[3], Ventsislav Stoilov[4], Angel Angelov[4], Todor Pukov[4], Stoyan Gaydardzhiev[1]

[1] *GeMMe – Laboratory of Mineral Processing & Recycling, University of Liège, Quartier Polytech 1, Allée de la Découverte 13, 4000 Liège, Belgium*

[2] *Outotec Research Center, PO Box 69, Kuparitie 10, 28101 Pori, Finland, ivan.korolev@outotec.com*

[3] *Outotec (Finland) Oy, PO Box 1000, Rauhalanpuisto 9, 02231 Espoo, Finland*

[4] *Assarel Medet JSC, 4500 Panagyurishte, Bulgaria*

ABSTRACT

The process modeling and simulation studies aim for better process operation and favorable environmental impact. The objective of this work is to set up a simulation model of the Assarel copper flotation circuit for planning and optimization of the process with the aim of increased metal recovery. The model is parameterized based on laboratory flotation tests of ore samples from the Assarel mine together with mineralogical studies by X-ray diffraction (XRD) and Mineral Liberation Analysis (MLA). A combination of several techniques allows reliable identification of mineralogical composition of the selected samples. The changes in the proportion between sulfide minerals in various products along the circuit have been also documented. Further, this information is used in the simulation model and in data reconciliation procedures for establishing mass balance. The simulation accuracy is studied by comparing the simulations with the plant survey based mass balance. Constructed simulation model can be used to run alternative process scenarios. As an example, the flotation circuit performance with different reagent regimes is simulated based on data from batch flotation tests. Two reagents were considered for this purpose, dithiocarbamate-based one and xanthogen formate/mercaptan blend. It has been revealed that these reagents do not have the same influence on the selective flotation. The one improves flotation of gold and overall recovery but without notable selective action. In contrast, the other showed better selectivity towards copper, rejecting more gangue and lowering gold recovery. The model is also applicable for process optimization studies with different feed compositions, flowrates and circuit configurations.

KEYWORDS

Process simulation, HSC Sim, flotation, copper ore, process mineralogy, MLA, XRD.

INTRODUCTION

In the pursuit for elevated technological indicators, finding an optimal set of process parameters fully utilizing the potential of the equipment is a key factor to success. Over the past decades, there has been a substantial development in flotation circuit optimization through performance benchmarking using metallurgical modelling and steady-state computer simulation. Practical simulation engineering tools are based on experimental data obtained from laboratory tests and from plant surveys and operation data. With the help of flotation models, it is possible to study grade-recovery response with different feed compositions and throughputs, and with various cell-operating parameters, as well as to evaluate and design different flowsheet configurations. Outotec's HSC Chemistry® software, which incorporates simulation and mass balancing modules alongside with several other tools, can assist with this optimization (Mattsson et al., 2015).

The main objective of the present work is to investigate the industrial copper flotation process practiced at the Assarel processing plant in order to replicate it in a simulation model. Also, it is demonstrated how this model can be utilized to explore opportunities for improved recovery of the major economic metals present in the ore and to propose measures for reducing metallurgical losses. This is done through application of mineral processing methods in line with the latest standards in the field.

ASSAREL MINE AND PROCESSING PLANT

The Assarel porphyry copper deposit is located in the central part of Panagyurishte metallogenic zone, which belongs to Late Cretaceous Apuseni-Banat-Timok-Srednegorie magmatic belt. The Assarel-Medet ore field encompasses the major part of the porphyry Cu-Mo ore resources in Bulgaria. The mineralogy of the ore in Assarel deposit is complex, with high contents of pyrite and friable clay minerals due to strong hydrothermal alteration of host rocks (Ranchev et al., 2015). Based on copper mode of occurrence, the mineralization of the Assarel deposit is differentiated between primary, secondary and oxide ores. Chalcopyrite is the major ore mineral comprising about 80% of the copper in ore, with bornite and chalcocite as minor minerals. Secondary ores are located in the upper part of the deposit, with main minerals being chalcocite, covellite, bornite and Cu-sulfosalts. Gold content vary as function of the host rocks and alteration type, and spatially coincides with the maximum contents of copper, quartz and andalusite within the orebody, and with sulfur, alunite and diaspore outside the boundaries of orebody (Strashimirov et al., 2002).

Current mining operations at the Assarel mine are carried out using conventional open-pit mining methods, comminution and flotation of the copper ore and biochemical heap leaching of the low-grade overburden. The Assarel concentrator processes about 14 Mt of copper ore per year with an average grade of 0.32% Cu. The flotation process is performed in two stages – bulk sulfide flotation and selective copper flotation (Figure 1). The purpose of the bulk circuit is to assure high recovery of sulfide minerals. Rejection of gangue minerals is maintained at maximum possible level. All sulfide minerals are recovered to the collective concentrate, which is passing through regrinding ball mill and feeding the selective flotation circuit. In selective circuit, the material is separated into high-grade copper concentrate containing some gold and pyrite tailings that are recirculated inside the flowsheet.

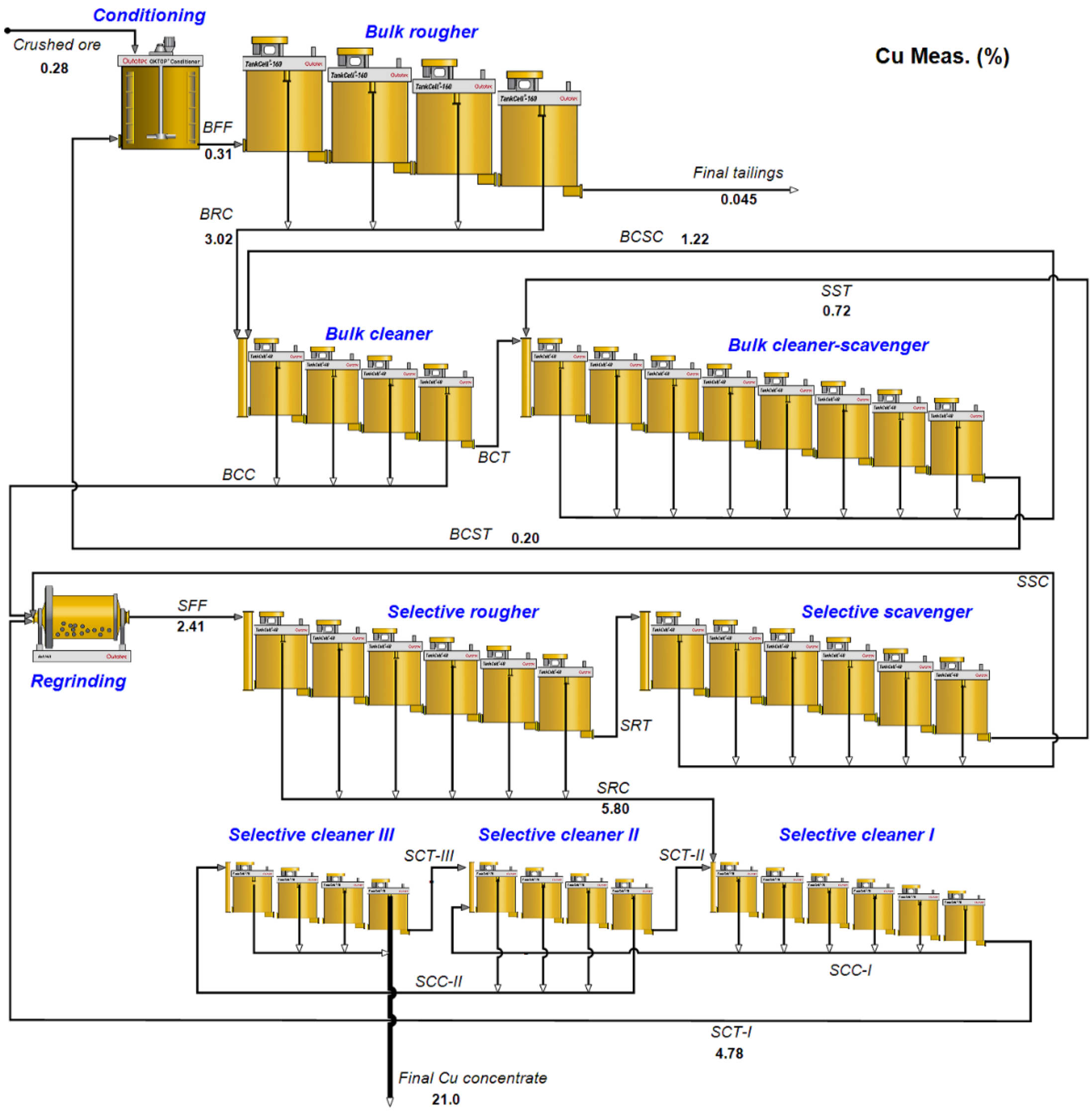

Figure 1 – Flowsheet of the Assarel flotation circuit.

EXPERIMENTAL WORK

Sampling Campaign

Within the scope of this work, plant survey was performed at the Assarel flotation plant. Sampled streams are highlighted on the flowsheet (Figure 1) with numbers showing the measured Cu grade of the taken sample. The objective of the plant survey is to collect data from the process, establish mass balance and analyze the performance of the process. Results from the sampling campaign coupled with laboratory scale tests and process modeling were used to evaluate the possible benefits of plant modernizations. The process audit, however, gives a detailed analysis of the process performance only at the moment of sampling; for conclusions about plant efficiency in general, the audit has to be carried out several times with diverse conditions, e.g. ore types, feed composition etc. The "rule of thumb" is that all streams required for establishing the mass balance must be sampled and the elemental analyses should cover the main elements present in the ore, enabling satisfactory element-to-mineral conversions. Cu, Fe and S were assayed by means of ICP-OES and Au was analyzed by fire assay. In addition to the elemental assays, pulp density was also measured for each sample. For better understanding of characteristics and process behavior of the ore and flotation products, mineralogical studies were performed with the use of different analytical techniques.

X-Ray Diffraction (XRD)

For the XRD analysis, a few milligrams of material have been crushed in an agate mortar and then deposited on a zero-background silicon sample holder. The holder has been inserted in the Bruker D8 ECO diffractometer and exposed to the Cu-Kα radiation (λ=0.1542 nm). The radiation was filtered with a Ni filter, in order to completely remove the Kβ contribution. An angle 2θ between 2 and 70° was scanned, with a step of 0.02° and counting time of 1 s per step. The X-ray powder diffraction patterns were interpreted using the EVA 3.2 software to identify the mineral phases by comparison with the ICDD database. The XRD analysis is very useful in qualitative determination of major mineral species, such as silicates, present in ore samples. Although quantitative estimation of sample modal mineralogy is possible with Rietveld refinement, it was not used in this study, as the detection limit of the method is rather high compared to other automated mineralogy techniques (Lotter, 2011).

The results of XRD analysis show that predominant rock-forming minerals are quartz, plagioclase, calcite and phyllosilicates – chlorite, muscovite, pyrophyllite and kaolinite. Ore minerals are represented by chalcopyrite, pyrite and pyrrhotite. Secondary copper sulfide minerals (bornite, covellite and chalcocite) were identified in all analyzed streams, but their reliable discrimination was complicated due to minor quantities in respect to chalcopyrite and use of Cu-Kα source of X-rays. Molybdenite, which is typical for porphyry copper ores (Strashimirov et al., 2002), was detected in concentrate streams in very low concentrations making it not feasible to recover as a separate product.

Mineral Liberation Analysis (MLA)

The MLA is performed with FEI Quanta 650 scanning electron microscope equipped with two parallel Bruker X-Flash EDS detectors. The applied acceleration voltage and the electron beam intensity were 25 kV and 10 nA respectively and the collecting time was 10 ms per spectra. Collected data was processed with the use of FEI MLA 3.1 software. The major benefit of the automated SEM-MLA method is that along with sample composition it provides as well information about mineral associations (Lamberg and Rosenkranz, 2014).

Figure 2 shows associations between main sulfide minerals and non-sulfide gangue in feed streams of bulk and selective rougher units. In the plant feed almost 80% of copper minerals are liberated, with the rest being locked with pyrite, quartz and silicate gangue. With decrease of particle size, the percentage of sulfide minerals (e.g., chalcopyrite, covellite, and pyrite) in bulk flotation feed is growing. However, in fine size class 0-45 µm the proportion of sulfides has diminished due to the higher amount of clays and micas, which are very friable and tend to concentrate in slime fraction. Furthermore, gangue minerals showing very high degree of liberation, which is decreased in selective flotation feed. This suggests that the proportion of gangue minerals in selective flotation feed is lower and they are more intimately intergrown with sulfide minerals. However, after regrinding 95% of pyrite is liberated, whereas only 68% of copper minerals in selective flotation feed shows full liberation. Due to low Au grade and limited number of samples, it was not possible to draw any conclusions from MLA regarding the mode of occurrence of gold.

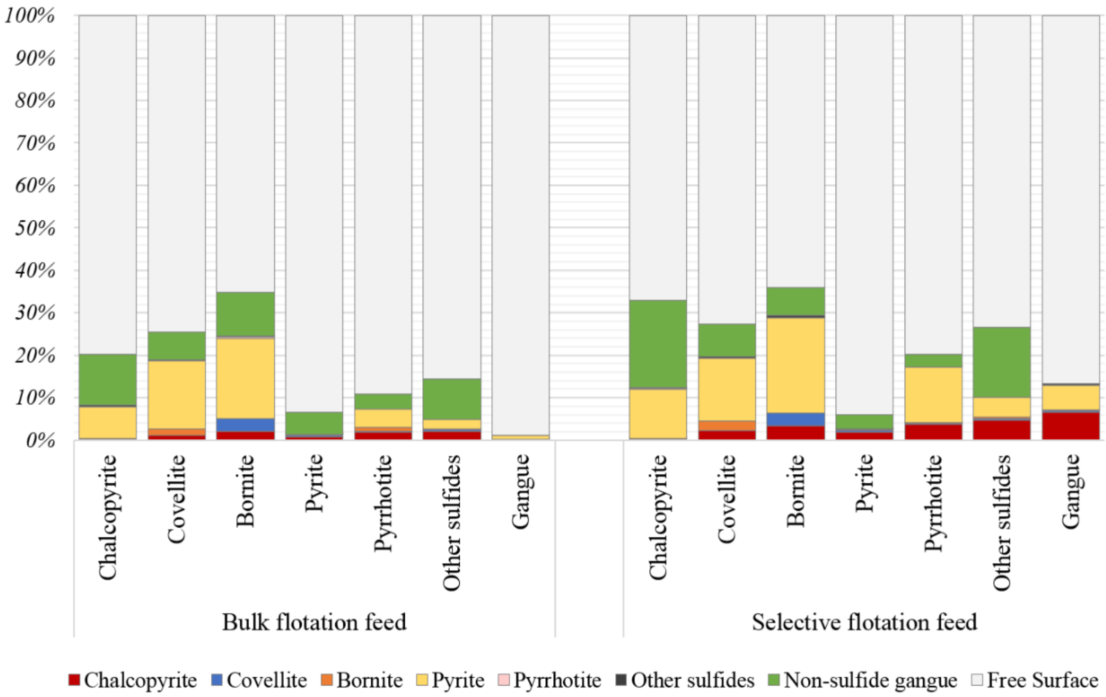

Figure 2 – Mineral associations and liberation degree in flotation feed streams.

Batch Flotation Tests

Flotation tests were performed in the Laboratory of Mineral Processing, University of Liège, on samples of crushed ore taken at the mine site during the sampling campaign. The objective was to model as close as possible the actual flotation circuit of the Assarel processing plant. The advantage of the laboratory testing is that experiments can be run in controlled, reproducible conditions with small amount of material (Lotter et al., 2014). The ore sample was ground inside Magotteaux ball mill until d_{72} = 100 µm and then slurry was transferred into bottom-driven Magotteaux flotation cell. Bulk flotation was carried out with the dosage of collector (NaIBX) equivalent to one used in plant for 8 min (Figure 3a). The bulk concentrate was reground with addition of lime until desired size distribution, pH and redox potential. In the selective flotation tests (Figure 3b), no reagent was added.

For the purpose of modeling the flotation kinetics of minerals, the copper sulfide species (chalcopyrite, bornite, covellite and chalcocite) were grouped together based on the MLA results and similar flotation behavior. Likewise, pyrite and pyrrhotite were also counted as one group of iron sulfides, whereas non-sulfide minerals were designated altogether as gangue. The experimental data was further fitted to first-order batch flotation kinetics model with rectangular distribution of floatabilities (Klimpel, 1980), and obtained parameters R_∞ and k_{max} were utilized in the simulation model:

$$R = R_\infty \left\{1 - \frac{1}{k_{max} \cdot t}\left(1 - e^{-k_{max} \cdot t}\right)\right\} \tag{1}$$

As seen from Figure 3a, in bulk flotation almost no gangue was reported to the concentrate, whereas sulfide minerals and gold had rather high recovery to the froth. After regrinding of the bulk concentrate (Figure 3b), iron sulfides and non-sulfide gangue minerals demonstrated similar low floatability, but copper sulfides and gold were recovered to the concentrate. Notably, gold flotation rate was very close and even slightly higher than that of copper, thus indicating predominant association of gold with copper sulfide minerals. Therefore, improving the recovery of copper would result in increased gold recovery to the final concentrate.

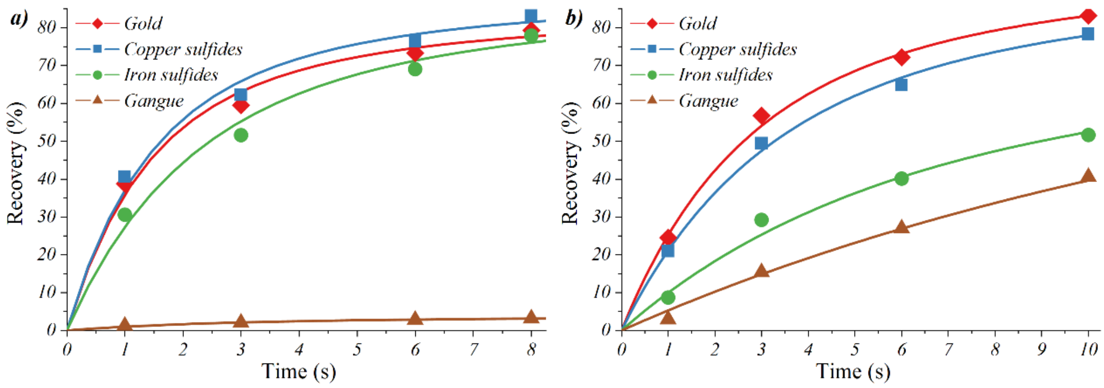

Figure 3 – Experimental data and fitted kinetic model of batch flotation: a) bulk; b) selective.

FLOTATION PROCESS SIMULATION

Data Reconciliation

Mass balancing is a common practice in pre-processing metallurgical data, for example, prior to calculating the recoveries of beneficiation processes. Mass balancing can be done for all process types, covering laboratory tests, pilot runs and full scale mineral beneficiation plants. For consistent plant material balances, recovery calculations and metal accounting, a reliable data reconciliation tool is essential. HSC Mass Balance module uses the so called element-wise weighted total least squares method (Markovsky et al., 2006; Tommiska et al., 2015). The method is robust, since it utilizes also the available assays and their accuracies for solving the bulk flowrates. This is especially important because all the measurements have certain error associated with sampling and precision of assaying method.

Model Calibration

HSC Chemistry Sim module utilizes a unique particle-based modeling approach (Lamberg, 2011, 2010). The material is set up similarly to real slurry streams and the chemical composition is calculated based on its particle composition. The flotation kinetics of minerals obtained in laboratory test was converted from batch to continuous form. In this particular case, discretized version of continuous Klimpel equation was used in HSC Sim:

$$R = R_{\infty}\left\{1 - \frac{1}{k_{max} \cdot \tau} \cdot \ln(1 + k_{max} \cdot \tau)\right\} \quad (2)$$

When the continuous plant simulation model is based on batch model fitted kinetic recovery equations, it often requires scaling-up. The scale up factor is a ratio between the required plant time compared and the laboratory time needed to achieve the same target recovery. By adjusting the scale up factor for each row of flotation cells, the model was calibrated to obtain the residence time equal to that observed at the plant. With this setup, the simulation gives rather accurate and robust results (Figure 4).

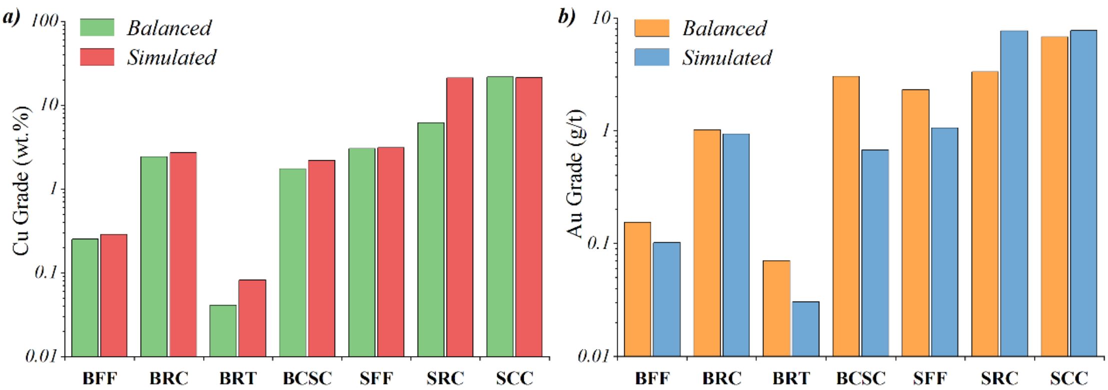

Figure 4 – Simulated vs. balanced grades of copper (a) and gold (b) in main process streams.

The precision of the simulation model can be further increased through down-the-bank surveys. This would be used for froth surface area optimization based on the calculated froth carry rates or for air and level profiling down the bank of cells. Another layer of depth for the process model can be developed by carrying out a gas dispersion characterization simultaneously with sampling campaign.

Study of Process Scenarios with the Simulation Model

Calibrated simulation model can be used to run alternative process scenarios. In processing of sulfide ores with complex mineralogy and high clay content, the flotation performance might be improved by an appropriate selection of reagents (Kolev et al., 2013). As an example, the flotation circuit performance with different reagent regimes is simulated based on data from batch flotation tests. This approach allows studying the effect of addition of secondary collector in selective flotation without disturbing the operations at the processing plant. Moreover, using the computer model to investigate several alternative scenarios saves the time and resources, because the performance of whole plant is simulated based on flotation kinetics of minerals obtained in laboratory tests with small mass samples.

Two secondary collectors for selective flotation circuit were considered – dithiocarbamate-based reagent and xanthogen formate/mercaptan blend. The reagents were added to the pulp after regrinding of bulk concentrate and selective flotation tests were performed as described above. Parameters R_∞ and k_{max} of the Klimpel flotation kinetics model were determined for each experiment and then entered into the calibrated simulation model (Table 1).

Table 1 – Flotation kinetics parameters, rectangular distribution model.

Minerals	No reagent (base case)		Dithiocarbamate-based		Mercaptan/ xanthogen formate	
	R_∞	k_{max}	R_∞	k_{max}	R_∞	k_{max}
Gold	96.292	0.597	100	0.429	100	0.379
Copper sulfides	93.762	0.498	100	0.517	100	0.436
Iron sulfides	77.389	0.0203	100	0.0139	95.474	0.0151
Gangue	100	0.00103	100	0.00115	100	0.00096

The outcome of the simulation in terms of copper and gold grades grades and recoveries in the final concentrate are shown in Table 2. It was revealed that tested reagents would not have the same influence on the process of selective flotation. Dithiocarbamate-based reagent improves flotation recovery of both copper and gold, although without notable selective action. In contrast, the mercaptan/xanthogen formate blend showed better selectivity towards copper, rejecting more gangue but marginally lowering gold recovery. On that account, dithiocarbamate-based secondary collector was accepted for industrial-scale trials as a next step in improvement of overall plant performance.

Table 2 – Simulated grades and recoveries of copper and gold in final concentrate.

Reagent	Cu grade, wt.%	Cu recovery, %	Au grade, g/t	Au recovery, %
No reagent (base case)	21.15	70.91	7.74	70.52
Dithiocarbamate-based	23.15	76.19	8.00	71.46
Mercaptan/xanthogen formate	22.72	75.04	7.86	70.49

CONCLUSIONS

The simulation models of flotation plant flowsheet provide an efficient way to assess the existing circuit operation and to evaluate different circuit modernization scenarios without interruptions of continuous industrial operations. Simulation-based approach to process optimization enables the risk-free evaluation of plant scale response on the basis of mineral flotation kinetics established in laboratory batch experiments, thus substantially reducing the costs for full-scale testing. HSC Chemistry® includes high-end tools for fitting the recovery models for the data and simulating full-scale flotation plants. The mass balance calculation gives the basis to assess the performance of the surveyed circuit. By comparing these results to simulation output, it is possible to evaluate whether the process is operating at full performance.

Presented in this article case study of the Assarel processing plant demonstrates that even with limited amount of experimental and analytical testwork the robust and accurate enough simulation model could be built. Additionally, the practical application of this model to process improvement and decreasing metallurgical losses was illustrated on the example of reagent selection for selective flotation. The model can be further enhanced with detailed information about size-by-size mineralogy of process streams and operational conditions in the flotation cells; this will give a boost to its use in decision-making process related to day-to-day operations of the processing plant.

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