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Approximate recovery values for each stage are sufficient to select the concentration circuit structures

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ABSTRACT

The optimal design of flotation circuits is a complex task because the mathematical model is non convex and it includes binary variables, making it difficult to obtain the global optimum solution. Furthermore, the modeling of the recovery of each concentration stage is complex, requires experimentation, and depends on many variables, including the selected circuit and mineral feed (which is heterogeneous and changes over time). These difficulties indicate that there are uncertainties in the actual values of the recovery of each stage and the information required to create the circuit design. This paper demonstrates that, for a specific mineral, few structures exist that are optimal for a wide range of values of concentration stage recoveries. This knowledge can be useful in circuit design, e.g., after selecting the circuit (or the most promising circuits), the equipment design parameters and operating conditions can be defined based on simulation and laboratory tests.

1. Introduction

Concentration circuits are a common technology for the concentration of a broad range of minerals and for wastewater treatment. The concentration technology used most frequently is flotation, although other technologies, such as gravity and magnetic concentration, are also used. Froth flotation is based on the differences in the ability of air bubbles to adhere to specific mineral surfaces in a solid/liquid slurry. Particles with attached air bubbles are carried to the surface and removed, while particles that are not attached to air bubbles remain in the liquid phase. The concept is simple, but the phenomena involved are complex because the results depend on what occurs in the two phases (froth and pulp phases) and involve other phenomena, such as particle entrainment. In flotation, several parameters are interconnected that can be classified into chemical (e.g., collectors, frothers, pH, activators, and depressants), operation (e.g., particle size, pulp density, temperature, feed rate and composition, and pulp potential), equipment (e.g., cell design, agitation, and air flow), and circuit (e.g., number of stages and configuration). If any one of these parameters is changed, then other parameters change; and studying all of the parameters simultaneously is impossible.

The flotation circuit design is a complex task because it is necessary to predict the behavior of each stage (recovery of each species), but the recovery of each stage depends on the circuit structure (among other variables). One approach to this design is to use a model that is able to predict the behavior according to the operating conditions and the circuit structure that is used. However, such models are empirical (Savassi et al., 1998); therefore, these models require testing under the conditions to which the model is used or are too complex for use in a design system based on optimization (Hu et al., 2013).

This paper argues that a complex model that would predict the behavior of the stages is not necessary when selecting the most appropriate circuits. The use of the approximate recovery values of each species in each stage is sufficient to identify the circuits that are best suited to treat a specific mineral. Once these circuits are identified, experimental techniques and/or simulation can be used to select the most suitable circuit design and recovery values.

First, the literature is reviewed to identify the background information relevant to the proposed approach. Next, the hypothesis proposed is demonstrated using an *a priori* approach based on exhaustive and probabilistic methods of proof.

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The process designs using superstructure optimization indicated that there are cases in which the best structure is not highly sensitive to the operational values. For example, Cisternas and colleagues studied the optimal structures for separation based on fractional crystallization (Cisternas, 1999) and found that in many cases, the best structure was independent of the changes in the operating conditions. Furthermore, Cisternas and coworkers (Cisternas and Rudd, 1993; Cisternas et al., 2006) determined that there are areas within a design region where one design is always superior to another, regardless of the operating conditions. Although this condition is not transferable to the flotation circuit design, the results set a precedent for efforts to study whether this assumption is valid in the design of flotation circuits.

Schena et al. (1997) presented a process synthesizer that was capable of determining the optimal network configuration of complex flotation plants, including regrinding units and upgrading one mineral value. The set of possible network configurations was derived from a general superstructure that features all of the potential connections between the flotation and regrinding units. The two variables with the most significant effect on the objective function were found to be the energy cost and the copper price. Thus, the synthesizer was also used to study the best modification of the plant design when the price of copper and the cost of energy change. The copper price was varied between 1500 $/ton and 2700 $/ton, and the energy cost was varied between 3 cents/kW h and 10 cents/kW h; the same flowsheet was obtained, but the stage recoveries were modified by changing the number of cells in the various banks of the flotation circuit. Additionally, Cisternas et al. (2004) developed a procedure for the design of flotation circuits based on mathematical programming using two-level hierarchical superstructures. The procedure allowed the flotation to be modeled using a first-order kinetic model. The method was applied to a copper flotation plant in several case studies, each with different numbers of cells per bank and therefore different values of recovery in each flotation stage. The optimal flotation circuit obtained was the same, but with different values for the mass flow rates, overall recovery, and concentrate grade. This result means that the same optimal structure comes from different operational conditions and cell designs in each bank. Later, Méndez et al. (2007, 2009) used different grinding circuits by implementing disjunctions to select between grinding, grinding-classification, classification-grinding, and classification-grinding-classification in the design of the flotation circuits. The application to a copper flotation plant indicates that the same flotation structure was obtained using different grinding circuits. These studies indicate that for these cases, the optimal flotation circuit depends strongly on the feed composition and the metal price but has a low dependence on the stage recovery. Jamett et al. (2012) presented a model for the design of flotation circuits with uncertainty using stochastic programming. The uncertainty was represented by several scenarios, including changes in the feed grade and the metal price. The model allows for changes in the residence time and the flow sheet structure for each scenario, while maintaining a fixed number of cells in each bank of flotation for all of the scenarios. The results indicated that the optimal flow sheet structure did not change for 8 of the 9 scenarios that were studied, but the recovery for each stage changed for each scenario. Recently, Hu et al. (2013) combined the powerful genetic algorithm optimization methodology with pulp and froth modeling in each flotation cell to determine the optimal layout for flotation circuits composed of up to eight cells. For circuits of four to eight cells, the optimal configuration was a rougher–cleaner circuit with a rougher stage of 3–7 cells and one cleaner cell. The concentrate from the rougher cells was directed to the cleaner cell, and the tailings from this cleaner cell were recycled to the head of the circuit. In this case, a complex model was used in each cell, and up to 8 cells were simulated; however, no change in the structure of the optimal configuration was observed.

In addition, Montenegro et al. (2009, 2010, 2013a) studied the effect of the uncertainty in the recovery of the rougher, cleaner, re-cleaner and scavenger stages on the global recovery and final concentrate grade, among other indicators, for 12 flotation circuits. The uncertainties in the recovery for each stage were represented by normal, triangular and uniform distribution functions with variations between 1% and 10%. In other words, the recovery at each stage was not modeled by any kinetic model, but was represented by distribution functions. The uncertainties were studied by considering the variation in each stage as well as in several stages simultaneously; 84 cases were considered. Monte Carlo simulation was used in the study, running over 6 million simulations. The results indicated that the best flotation circuits were not a strong function of the stage recoveries, i.e., for different values of stage recoveries, but there is a set of flotation circuits that performs the best. Later, Montenegro et al. (2013b) applied a shortcut computational method to analyze and compare alternative flotation circuits to treat high-arsenic copper ores. Twenty-seven circuits were evaluated based on the metric indices of efficiency, capacity, quality, economic, and environmental impact. The simulations were performed for an Australian sulfide ore containing chalcopyrite, tennantite, quartz, and pyrite. In the simulation, a constant stage recovery was assumed. To validate this assumption, the normalized indicators were calculated for several values of stage recovery for each mineral; three levels were selected at ±5, ±10, and ±20%, which can be considered a moderate, intermediate and high variation in the stage recovery, respectively. A random sampling of the case studies was selected to reduce the sampling error. The size of the sample was estimated using 28 combinations, which resulted in a 95% confidence level. Twenty-eight combinations were studied for twenty-seven circuits; therefore, 2,268 simulations were performed. The results of the simulations for moderate, intermediate and high variations were normalized for each combination of the stage recovery values. The averages and standard deviations of the 28 normalized values for a specific circuit and a specific indicator were calculated. The standard deviations were usually small, indicating that the indicators do not undergo large variations, despite changes in the stage recovery values. Usually, the circuit with the best results has a low standard deviation, i.e., these circuits give the best results, independent of the value of the stage recovery. Circuits with moderate results sometimes have significant variation, i.e., the position within the set of alternatives has greater variability. Despite the variation, the values never exceed the values of the best circuits; therefore, these circuits will never be selected based on this indicator.

All of these previous studies provide evidence that the selection of the best flotation circuit is not highly sensitive to the flotation stage recovery, and therefore, only approximate values can be used to select a set of optimal flotation circuit. This manuscript, as indicated previously, demonstrates that this conclusion is true.

2. Strategy used

The strategy involves a superstructure of stages that represents alternative flotation circuit configurations. The superstructure is based on a generic representation of a stage, which is used to represent all of the stages that are to be included in the design. In the superstructure, discrete variables are used to represent the different alternatives for the circuit configuration, and continuous