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A methodology for the conceptual design of concentration circuits: Group contribution method

Felipe D. Sepúlveda[a], Luis A. Cisternas[a,*], Maritza A. Elorza[a], Edelmira D. Gálvez[b]

[a] Universidad de Antofagasta, Chile
[b] Universidad Católica del Norte, Chile

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ABSTRACT

This paper presents a new methodology for the conceptual design of concentration circuits based on the group contribution method. The methodology includes three decision levels: (1) definition and analysis of the problem, (2) synthesis and screening of alternatives, and (3) final design. In this manuscript, the emphasis is on the description of the methodology, justification of the assumptions, and group contribution method. The group contribution models were developed to estimate the global recovery in concentration circuits. The procedure is general and can be applied to any circuit consisting of stages that generate two product streams: concentrate and tail. The developed models can be applied to estimate the recoveries in concentration circuits with a maximum of six stages. The models were fitted using mass balance data from 46 circuits, generating 35 process groups. Case studies were used to illustrate the methodology.

1. Introduction

Flotation circuits are a common procedure for the concentration of a broad range of minerals and are also a common technology used in wastewater treatment. Froth flotation is based on differences in the ability of air bubbles to adhere selectively to specific mineral surfaces in a solid/water slurry. Particles with (without) attached air bubbles are (are not) carried to the surface and removed (stay in the liquid phase). The current practice for the design of these circuits is based on seven steps (Harris et al., 2002): (1) mineralogical examination in conjunction with a range of grinding tests, (2) a range of laboratory scale batch tests and locked cycle tests, (3) a circuit design based on scale-up of laboratory kinetics, (4) preliminary economic evaluation of the ore body, (5) pilot-plant test of the circuit design, (6) economic evaluation, (7) full-scale plant design. This procedure presents several problems, including (1) the design of the circuit in step three is based on a rule-of-thumb scale-up from laboratory data that depends heavily on the designer's experience, (2) the laboratory and pilot plant are costly and take significant time, and the designed circuit analysis is therefore not performed in depth, (3) other aspects, such as system dynamics, are not considered in the design process.

Froth flotation design and operation is a complex task because several important parameters are interconnected (Barbery, 1983; Gupta and Yan, 2006). The parameters can be classified into four types of components, as shown in Fig. 1. If any of these factors is changed, it causes or demands changes in other parts. It is impossible to study all of the parameters at the same time; for example, if six parameters are selected for study in four stage circuits, over 8 million tests are needed for a two-level fractional experimental design. In addition, for a given number of stages, there are several circuit configurations. If five flotation stages are considered, there are over one million potential circuits. For reasons of cost and time, only a fraction of the alternatives are analyzed, and only a small number of experiments are performed. In other words, the design analysis is not performed in depth.

In the literature, various methodologies for the design of flotation circuits have been proposed, with most using optimization techniques. In these methodologies, the alternatives are presented through a superstructure, a mathematical model is developed, and an algorithm is used to find the best option based on an objective function. There are at least three reviews of studies concerning the optimal design of a flotation circuit including that of Mehrotra (1988), Yingling (1993a) and Méndez, Gálvez, and Cisternas (2009). Some examples that use this strategy are Yingling (1993b), Hulbert (1995, 2001), Schena, Villeneuve, and Noël (1996), Schena, Zanin, and Chiarandini (1997), Cisternas, Gálvez, Zavala, and Magna (2004); Cisternas, Mendez, Gálvez, and Jorquera (2006), Guria, Verma, Mehrotra, and Gupta (2005a,b) and Ghobadi, Yahyaei, and Banisi (2011). The differences between these studies depend on the superstructure used, the mathematical representation of the problem, and the optimization algorithm used. However, one problem

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* Corresponding author. Tel.: +56 552637323.
E-mail address: lcisternas@uantof.cl (L.A. Cisternas).

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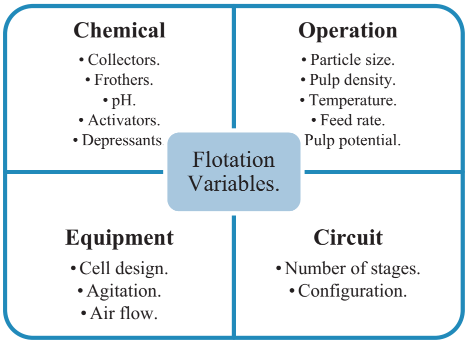

Fig. 1. Interconnected components and parameters in froth flotation circuits.

with these methods is that the recovery of each stage must be modeled, and because the recovery of each stage is a function of many variables, modeling is not the most appropriate method. Moreover, the number of alternatives is large; a survey of approximately 400 flotation circuits available in books, manuscripts and industrial process descriptions, gives the number of flotation stages as between 1 and 9, with the most common being 3–5 stages. Considering that each stage is typically composed of 4–8 cells, the number of alternatives is tremendous, and a simple stage model to achieve adequate convergence in mathematical programming problems is essential. If metaheuristic-based algorithms are used, it is possible to use more sophisticated stage models or cell models, but with problems of eight or more cells, it will be difficult to achieve convergence in a reasonable time. In summary, several methods for designing flotation plants have been proposed in the literature, but these are not applied in practice.

The flotation circuit synthesis problem determines the type of flotation stage and their sequence needed to achieve the concentration of the ore to some specified set of characteristics. The flotation design problem determines the optimal values for the conditions of operation and equipment related variables for the synthesized flotation circuit. The flow sheet modeling, synthesis and design problems are related since for generation and screening of alternatives, some forms of flow sheet models are needed. In addition, flow sheet models are needed for verification of the solutions of the synthesis/design problem. In contrast, a group-contribution based property estimation of a flow sheet requires knowledge of the process structure and the groups needed to uniquely represent it. An example of such a method is the d'Anterroches and Gani (2005) method for fractional distillation based process. The needed property is estimated from a set of a priori regressed contributions for the groups representing the process. Having the groups and their contributions together with a set of rules to combine the groups to represent any process therefore provides the possibility to "model" the process. This also means that the reverse problem of property estimation, that is, the synthesis/design of process having desired properties can be solved by generating feasible process structures and testing for their properties.

In this work, a new methodology is presented that integrates the first five design steps given by Harris et al. (2002) with the objectives of (1) better orienting the goals of the laboratory tests, (2) reducing laboratory and pilot plant testing, thereby achieving lower cost and execution times, (3) designing the flotation circuit based on a systematic procedure, and (4) speeding up the design procedure. The proposed methodology uses a completely different approach based on finding good designs (not necessarily optimal) between a more limited set of alternatives (eliminating unlikely alternatives) and evaluating the performance of each design using an approximate but simple model. The methodology, inspired by the work of d'Anterroches and Gani (2005) and Douglas (1985), considers three design decision levels (1) definition and analysis of the problem, (2) synthesis and screening of alternatives and (3) final design. This manuscript focuses on the description of the methodology, justification of the assumptions, and group contribution.

This work is divided into six sections, of which this introduction is the first. The second section describes the methodology, including the decision levels (see Table 1). In the third section, the justification of the assumptions is presented. The fourth section presents the group contribution method. Case studies, focusing on the first and second decision levels, are presented in the fifth section, and finally, the sixth section presents the conclusions and proposes future work.

2. Methodology

The methodology proposed is composed of three hierarchical levels: definition and analysis, synthesis and screening of alternatives, and final design (see Table 1). In the first level, the ore characteristics to be separated and the characteristics of the separation circuit are defined. Then, alternatives are generated and evaluated to select a few separation circuits for the final level. In the final level, the selected designs are improved by defining the characteristics of each separation stage, without modifying the circuit structure.

2.1. *Level I: definition and analysis of the problem*

In this level, the problem is defined, including the characterization of the feed, the design goals and design and operation restrictions.

The material to be fed to the process must be characterized. There are several ways to perform this characterization, including mineralogical examination, grinding tests, laboratory-scale batch test, and flotation kinetics tests. The decision of which test is most relevant to the project is made by the designer's experience. However, the components that will be fed to the circuit must be defined. These components may be different mineralogical compositions, different sizes or both. The feed mass flow rate and the stage recovery for each component must be known.

Only an approximate recovery value is needed for each component and each stage in the circuit, e.g., rougher, cleaner and

Table 1
Levels of the hierarchical decision.

	Level name	Design activities
Level I	Definition and analysis of the problem	Feed characterization Design goals Estimated stage recovery values Number of stages
Level II	Synthesis and screening of alternatives	Generation of feasible circuit alternatives Circuit modeling with group contribution models Validation based on material balance
Level III	Final design	Operational conditions Equipment design