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Optimizing flotation bank performance by recovery profiling

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ABSTRACT

This paper uses the first-order fully mixed model to argue that operating a bank of cells with a flat cell-by-cell recovery profile yields maximum separation between two floatable minerals with constant relative floatability for a target bank cumulative recovery. The bank optimization problem thus translates into a local problem of selecting cell manipulated variables, such as air rate, to reach that recovery profile. Some properties of the bank that emerge from the analysis are discussed. Recovery profiling appears to contribute to the success of air profiling recently reported.

1. Introduction

Flotation circuits are arrangements of stages which typically comprise several cells in series referred to as a line, row or bank. The series arrangement reduces short circuiting and provides for transport to approach plug flow and thus minimizes retention time for a target recovery (Gupta and Yan, 2006). There is, however, no clear guidance how to operate a bank to maximize mineral separation.

Xstrata Brunswick Division tested various strategies of distributing (profiling) air to the final (fourth stage) Zn cleaner bank of seven cells. It was found that an increasing profile gave the best performance (down-the-bank grade-recovery relationship) (Cooper et al., 2004). The increasing air rate profile was adopted on all four cleaner stages with total bank air adjusted to achieve target bank recovery; and it remains the practice. Other operations subsequently demonstrated that air profiling can generate significant performance gains (Gorain, 2005; Hernandez-Aguilar and Reddick, 2007; Smith et al., 2008; Hernandez-Aguilar, 2010; Hadler et al., 2010).

Analysis of the Brunswick case concluded that the improvement was due to reduced entrainment of non-sulphide (non-floatable) gangue in the first cells in the bank because the low air rate restricted water recovery. There was no difference in relative floatability of the two floatable minerals, sphalerite and pyrite, and thus it appeared there was no impact on their separation. Air profiling, however, could be considered as recovery profiling, the different air profiles distributing material differently down the bank, which opens the question addressed in this paper: does the recovery profile influence separation of floatable minerals? We address the question as an optimization problem.

2. Optimization of a bank performance to separate two floatable minerals

Two floatable minerals A and B are considered. The optimization problem is formulated to maximize the (technical) separation efficiency (Schulz, 1970), i.e., cumulative recovery of mineral A minus cumulative recovery of mineral B, for a target cumulative recovery of mineral A.

Making the common assumption of first-order flotation kinetics and fully mixed isolated cell, the recovery of mineral A and B in cell j can be expressed as follows:

$$R_{A_j} = \frac{k_{A_j} \cdot \tau}{1 + k_{A_j} \cdot \tau} \qquad R_{B_j} = \frac{k_{B_j} \cdot \tau}{1 + k_{B_j} \cdot \tau} \tag{1}$$

where k_{A_j} and k_{B_j} are the first-order flotation rate constants for mineral A and B respectively and τ is the average residence time of a particle in the flotation cell.

By rearranging Eq. (1), the relative rate constant (relative floatability, Gaudin (1957)) S_j can be expressed as a function of recovery of minerals A and B in cell j as follows:

$$S_j = \frac{k_{A_j}}{k_{B_j}} = \frac{R_{A_j}}{1 - R_{A_j}} \cdot \frac{1 - R_{B_j}}{R_{B_j}} \tag{2}$$

Cooper et al. (2004) found that relative floatability of sphalerite and pyrite was not dependent on the operational conditions ($S_j \sim 2 - 3$) and was approximately constant along the bank. Based on this, the

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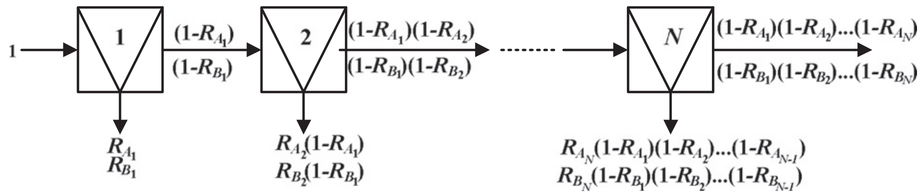

Fig. 1. Flotation bank composed of N cells.

relative floatability is assumed to be constant for all cells in the bank, i.e., $S_j = S$, $j = 1,\ldots,N$. Then, for a given recovery of mineral A in cell j, the recovery of mineral B in that cell is given by:

$$R_{B_j} = \frac{1}{\left[1 + S \cdot \frac{(1-R_{A_j})}{R_{A_j}}\right]} \quad (3)$$

Consider the flotation bank composed of N flotation cells depicted in Fig. 1. The optimization objective is: for a given target cumulative recovery of mineral A, find the cell-by-cell recovery profile of mineral A which maximizes the separation efficiency. This can be expressed mathematically as follows:

$$\mathbf{Max}_{R_{A_1},R_{A_2},\ldots,R_{A_N}}\ E = \left(R_A^C - R_B^C\right) \quad (4)$$

subject to the following set of equality constraints:

$$\begin{aligned} R_A^C &= R_{A_1} + R_{A_2} \cdot (1 - R_{A_1}) + \cdots \\ &\quad + R_{A_N} \cdot (1 - R_{A_1})(1 - R_{A_2}) \cdots (1 - R_{A_{N-1}}) \\ R_B^C &= R_{B_1} + R_{B_2} \cdot (1 - R_{B_1}) + \cdots \\ &\quad + R_{B_N} \cdot (1 - R_{B_1})(1 - R_{B_2}) \cdots (1 - R_{B_{N-1}}) \\ S &= \frac{R_{A_j}}{1 - R_{A_j}} \cdot \frac{1 - R_{B_j}}{R_{B_j}}, \quad j = 1,\ldots,N \\ R_A^C &= R_{target} \end{aligned} \quad (5)$$

and inequality constraints:

$$\begin{aligned} 0 \leqslant R_{A_j} \leqslant 1, \quad j = 1,\ldots,N \\ 0 \leqslant R_{B_j} \leqslant 1, \quad j = 1,\ldots,N \end{aligned} \quad (6)$$

where R_A^C and R_B^C are the cumulative recoveries of mineral A and B in the bank and R_{target} is the target cumulative recovery of mineral A.

To gain insight into the optimization problem, a bank composed of one, two and three cells is first analyzed. Then, the analysis is extended to the general problem consisting of a bank of N cells. The general optimization problem is formulated in the dynamic programming framework.

2.1. One-cell bank

This case does not entail any optimization problem since the end constraint $R_A^C = R_{target}$ completely determines the solution, i.e.:

$$R_{A_1}^* = R_{target} \quad (7)$$

where superscript * stands for optimal. Fig. 2 shows the separation efficiency of the cell as a function of recovery of mineral A for different relative floatability. There is a maximum in separation efficiency for a given relative floatability and that as separation becomes harder (decreasing relative floatability) the optimum operating point shifts towards lower recoveries. Since the end constraint imposed for the cumulative recovery in the cell fixes the recovery, the maximum separability is not attained at a target recovery (illustrated for R_{target} = 0.9).

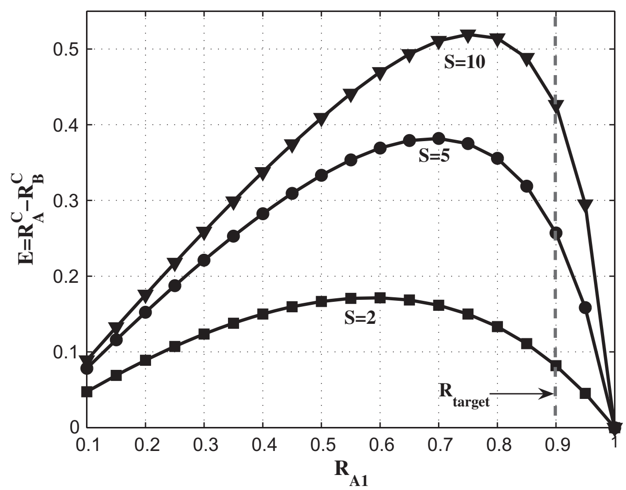

Fig. 2. Separation efficiency of the one-cell bank as a function of recovery of mineral A for different relative floatability.

2.2. A two-cell bank

In this case, two degrees of freedom are available to solve the optimization problem, i.e, R_{A_1} and R_{A_2} the cell recovery of mineral A in the first and second cell of the bank respectively. Figs. 3 and 4 show the separation efficiency of the bank as a function of the recovery of mineral A in the first cell at a given relative floatability for a target cumulative recovery of 0.9 and 0.75 respectively. Regardless of target bank recovery, the optimal solution is obtained when the cell recoveries (based on feed to the cell) are equal, i.e., $R_{A_1}^* = R_{A_2}^* = 0.684$ for target recovery of 0.9 and $R_{A_1}^* = R_{A_2}^* = 0.5$ for target recovery of 0.75. Three other features are: the optimal

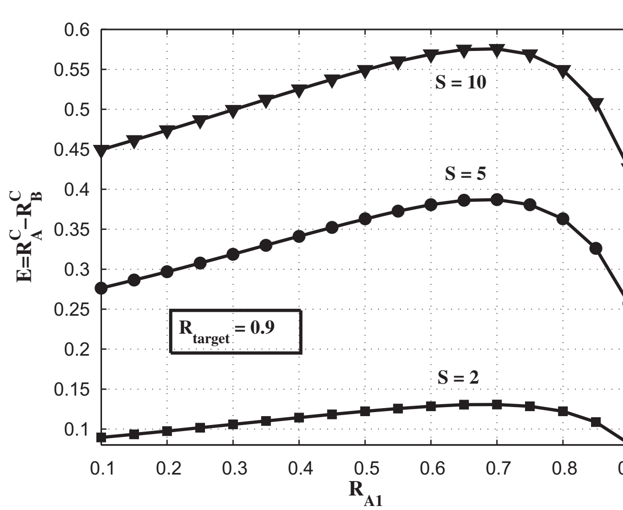

Fig. 3. Separation efficiency of the two-cell bank as a function of recovery of mineral A in the first cell for different relative floatability and a target cumulative recovery of 0.9.