Grade-Recovery prediction of an operating plant using flotation model and operating conditions

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Abstract

A transient flotation model for the purpose of flotation control has been proposed in this paper, which describes the operation from one steady state to other steady state when influential process variable (such as reagent addition, air flow rate, level etc.) change during operation. The proposed model assumes first order kinetics of floating species under specified process conditions. During transition, the material with rate constant $K_b$ (before condition) and volumetric solids hold-up $m_{h,b}$ will start depleting in the system and a material with rate constant $K_a$ (after condition) and volumetric solids hold-up $m_{h,a}$ starts building up till all the material with rate constant $K_a$ is completely depleted. This will influence the change in the grade and recovery of the process.

In order to verify the model, detailed plant campaigns were done under steady state on a lead zinc ore plant, components assays were analyzed for various streams (% Pb, % Zn and % Fe), mass balance performed. Regression relations were built from partial campaign data by relating local influential operating variables with their solid flow split, water flow split and Pb flow split. These relations were linked to flotation model to simulate the effect of operating variables on grade and recovery of the plant. The framework presented in this paper is equally applicable to phosphate mineral flotation.

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1. Introduction

At macro scale, flotation models can be of two kinds: either based on phenomenological models or data driven input-output models (like fuzzy logic, neural network etc.). The phenomenological models take into account the sub-processes and hydrodynamics that are responsible for flotation of each individual mineral in the bank of cells depending on the conditions maintained. This is done by considering flotation rate constant as the environment dependent variable, the value of which decides the rate of flow of individual mineral to the concentrate stream. If the feed were to be divided into “n” number of species, each of the species will have a rate constant. If there is selectivity in the process (like preferable flotation of phosphate bearing minerals over the rest) then those minerals which have got greater selectivity will have a higher rate constant than the rest.

The rate constant depends on the plant operating conditions and thus decides grade and recovery of mineral species of concern. It is essential in any flotation plant to have a bare minimum grade and recovery from the final output stream (as decided by the techno-economics of the plant) and therefore control actions are essential to be taken aptly to meet this objective for any disturbances that occur in the plant operation like changes in feed mineralogy, head grade, water quality etc or operational changes.

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such as changes in throughputs, pulp density, grind size, air flow rates, reagent dosages etc. in order to move the grade-recovery curve towards higher side as shown in Figure 1. Normally pulp levels of the cells, reagent dosages and aeration rates are used as the ways of increasing or decreasing the rate constants and bring in changes in grade-recovery of the plant.

So it is essential to capture the variation of rate constant as a function of operating conditions as well as disturbance variables. For establishing such relationships for each bank of the plant, plant campaigns need to be conducted under varied operating conditions to characterize the circuit behaviour. From the reconciled data of the campaign runs, and by using appropriate model, k’s are evaluated for each species of the bank for each of the plant campaign run. Following this regression equations relating rate constant (or flow split factors) of each individual bank or sub-bank need to be developed as a function of operating conditions (related to that bank). Once such relationships are established for each bank of the plant, they become the keys for controlling each flotation bank in the narrow window of variable’s permissible operation. Set points for reagent dosages, aeration rate and pulp levels can be set for desired grade and recovery by prioritizing the controllable variables (such as pulp levels, reagent dosages, aeration rates etc.). Any change in the set point of controlled variable is reflected in changes in rate constant, and hence changes in flow rates, grade and recovery of that bank and hence shift the conditions of the downstream banks. A mathematical model will capture this change in rate constant and predict the new state of flotation plant performance, which is focus of this paper.

2. Mathematical Model

For the purpose of control, we build a transient flotation model as below. The rate of change of holdup in a bank of flotation cells can be written as

$$\frac{dH(t)}{dt} = \frac{dm_b(t)}{dt} + \frac{dW_F(t)}{dt}$$

(1)

where

- $H_b$ is volume holdup of pulp in the bank of cells, m$^3$
- $m_b$ is volumetric solids holdup in the pulp phase of the bank of cells, m$^3$
- $W_F$ is volumetric water holdup in the pulp phase of the bank of cells, m$^3$

A transient model for the flotation process between any two steady state operations can be built by assuming the kinetics of the flotation to follow a first order rate equation. During the transition state, at time $t \rightarrow 0^+$, evident as a result of changes in the influential operating or input variable(s), the material with rate constant $K_b$ (for the before condition of the step change) and volumetric solids holdup $m_{b,b}$ will start decreasing its concentration and a material with rate constant $K_a$ (for the after condition of the step change) and volumetric solids holdup $m_{b,a}$ starts building up till all the material with rate constant $K_b$ i.e., $m_{b,b}$ is replaced by $m_{b,a}$. Thus overall change in solids volumetric holdup in the pulp phase can be written as
\[
\frac{dm_{b}(t)}{dt} = m_F - K_b m_{h,b}(t) - K_a m_{h,a}(t) - \lambda_b m_{h,b}(t) - \lambda_a m_{h,a}(t)
\]

(2)

where \(m_F\) is the instantaneous volumetric solids flow rate in the feed stream; \(K_b\) and \(K_a\) are steady-state flotation rate constants for before and after step change conditions; \(m_{h,b}(0)\) and \(m_{h,a}(0)\) are steady state volumetric solids holdup in before and after steady states; \(\lambda\) is reciprocal of steady state mean residence times of the pulp holdup for before and after step change conditions. (Note: \(m_b = m_{h,b} + m_{h,a}\))

We assume that the rate constant for flotation of water species is proportional to that of floatable solids by a factor of \(f_w\), and hence

\[
\frac{dW_b(t)}{dt} = W_F - (K_b m_{h,b}(t) + K_a m_{h,a}(t))f_w - \lambda_b W_{h,b}(t) - \lambda_a W_{h,a}(t)
\]

(3)

Adding equations (2) and (3) gives:

\[
\frac{dH(t)}{dt} = m_F + W_F - (K_b m_{h,b}(t) + K_a m_{h,a}(t))(1 + f_w) - \lambda_b H_{b}(t) - \lambda_a H_{a}(t)
\]

(4)

Since the level controllers maintain a constant pulp level in the bank of cells under steady state operation (whether before or after steady state condition),

\[
\frac{dH(t)}{dt} = \frac{dH_a(t)}{dt} = \frac{dH_b(t)}{dt} = 0
\]

(5)

and hence

\[
\lambda_b = \frac{m_{F,b} + W_{F,b} - K_b m_{h,b}(0)r_{w,b}}{H_b}
\]

(6a)

\[
\lambda_a = \frac{m_{F,a} + W_{F,a} - K_a m_{h,a}(0)r_{w,a}}{H_a}
\]

(6b)

where \(r_w = (1 + f_w)\); \(\lambda_b\) and \(\lambda_a\) are reciprocals of steady state mean residence times of the pulp holdup in before and after step change steady states. Also [1-3]

\[
m_{h,b}(0) = \frac{m_{F,b}}{(K_b + \lambda_b)}
\]

(7a)

\[
m_{h,a}(0) = \frac{m_{F,a}}{(K_a + \lambda_a)}
\]

(7b)

From Eq. (2), the decrease in the concentration of \(m_{h,b}(t)\) in the pulp with marching time is

\[
\frac{dm_{h,b}(t)}{dt} = -K_b m_{h,b}(t) - \lambda_b m_{h,b}(t)
\]

(8)

Solving Eq.(8) with the initial condition \(m_{h,b}(t) = m_{h,b}(0)\) at \(t = 0\) gives

\[
m_{h,b}(t) = m_{h,b}(0) * \exp[-(K_b + \lambda_b)t]
\]

(9)
Also from Eq. (2), the increase in the concentration of \( m_{h,a}(t) \) in the pulp with marching time is

\[
\frac{dm_{h,a}}{dt} = m_{F,a} - K_{a} m_{h,a} - \lambda_{a} m_{h,a}
\]

Solving Eq. (10) by substituting the value of \( m_F(t) \) from Eq.(2a) and with the initial condition of \( m_{h,a}(t) = 0 \) at \( t = 0 \) gives

\[
m_{h,a}(t) = \frac{(m_{F,a})}{(K_{a} + \lambda_{a})} [1 - \exp\left(-(K_{a} + \lambda_{a})t\right)]
\]

The rate constants can be related to the transient flow-split factor, \( S(t) \), as

\[
S(t) = \frac{K_{b} * m_{h,b}(t) + K_{a} * m_{h,a}(t)}{m_{F,a}}
\]

The above equations can be applied to each individual bank of cells for rougher, scavenger and cleaner sections and integrated to predict the transient behaviour of the circuit.

3. Plant Description

In order to simulate the model, a base metal ore plant was considered for data collection, which treated 4500 tpd of ore, wherein Pb minerals were floated first followed by Zn minerals (by way of differential flotation). Grinding was done using three parallel circuits consisting of a rod mill, operating in open circuit followed by closed ball-mill and two-stage-cyclone classification circuit. The secondary cyclone overflow, comprising 80% passing 63 micron particles fed the lead flotation circuit and lead tail was feed to the zinc flotation circuit. In this paper, we restrict our analysis to lead flotation circuit only.

4. Plant campaign

For capturing the plant behaviour, design of experiments (DOE) plan with partial factorial involving all influential variables was made. However, strict implementation of the DOE was not successful owing to deterioration in grade and recovery of the plant under some restricted conditions set by DOE plan that was noticed at the beginning of the implementation. So plant campaigns were conducted under operating conditions in consultation with plant personnel by suitably modifying some of the DOE variables.

The plant campaigns were done during July-December, 2000 and essence of this is still applicable in today's context as well. The plant was stabilized for four hours, which is the residence time of the flotation circuit (both lead and zinc circuits), under the set operating conditions of influential variables before commencing the sampling of the various streams.

The feed rate to the lead conditioner tank from the secondary cyclone overflow, fed from the three grinding circuits was also stabilized by the grinding-circuit-controller for a fixed throughput rate and feed size distribution consistency. During plant campaign samples of various streams were collected and analysed for % solids, pulp density, assays (namely %Pb, % Zn and %Fe). Air flow rates to different flotation banks, reagent dosages additions at various locations were also recorded during campaign.

5. Data reconciliation and water balance

All the campaign data of various stream-assays were reconciled for mass balance using PREDICT software, developed at Tata Research Development and Design Centre (TRDDC), Pune, India. This gave the missing flow rates and assay values across the circuit. Approximately there were 45 campaigns. The reconciled data was examined for consistency and if there were problems in the estimation of missing flow rates and assays, the assaying was redone from the stored samples and data was reconciled. Otherwise, in case of ambiguity the campaign data was discarded from further analysis.

From reconciled data of flow rates and measured % solids and pulp density values, water balance of the circuit was optimized by considering the water additions at various launder locations. Although water additions at various locations were not measured for each run, the information on approximate range of water additions was considered during optimization.

Grade-Recovery relationship for all the campaigned runs of lead circuit is shown in Figure 2. Basically it shows a scattered plot with wide variation in grade and recovery of lead concentrate, showing that operational variables have a large effect on the lead circuit performance. Some of the runs show very low-grade and low-recovery and some of the runs show high-grade and high-recovery, as depicted by the circles in the figure. There are also runs with high-grade and low-recovery. This figure shows that there is an opportunity for plant control for optimum Grade-Recovery. However the basis for such an approach is techno-economics of the plant operation, which should decide the optimum grade-recovery of the plant under given set of operating conditions.
6. Model Application

To demonstrate the application of the model, we have restricted to the analysis in this paper to Pb beneficiation circuit only. Two types of models were studied: (a) steady state model predicting the grade and recovery of the plant using split factors (b) transition model predicting the dynamics involved from one steady state to the other under the influence of operational change.

6.1 Steady state Model

This model will be based on split factors that can infer flotation rate constant of the operation as well as can be related to the local influential variables. Physical values of split factors are obtained from reconciled campaign data.

Since the model was built only for single bank of cells in our previous discussion, the first step is to integrate rougher, scavenger and cleaner circuits along with the recycle streams under steady state conditions in order to understand the behaviour of the circuit from split factors pertaining to individual bank of cells, namely, solid material, species of interest (say Pb component) and water. This exercise will integrate flow rates of solid material, Pb component as well as water across the circuit. The second task would be to obtain reliable relationship between various split factors (mentioned above) and local influential variables of the bank. Last step would be the implementation of the model.

6.1.1 Integration of bank of cells through split factors

The circuit configuration of lead circuit is shown below in Figure 3. F1, F2 and F3 describe split factors of solid split from rougher combined feed (i.e., F+R1+R2) to rougher Concentrate C1, from rougher tails T1 to scavenger concentrate R1 and rougher concentrate C1 to final lead concentrate C2 respectively.
Solid mass flow balance across the circuit in terms of input flow rate, \( F \), and flow-split-factors, \( F_1, F_2 \) and \( F_3 \) yields:

\[
\text{Combined Rougher feed} = \frac{F}{(1-F_1)(1-F_2)+F_1F_3} \tag{13}
\]

\[
C_1 = \frac{F_1F_3}{(1-F_1)(1-F_2)+F_1F_3} \tag{14}
\]

\[
C_2 = \frac{FF_1F_3}{(1-F_1)(1-F_2)+F_1F_3} \tag{15}
\]

\[
T_1 = \frac{F(1-F_1)}{(1-F_1)(1-F_2)+F_1F_3} \tag{16}
\]

\[
T_2 = \frac{F(1-F_1)(1-F_2)}{(1-F_1)(1-F_2)+F_1F_3} \tag{17}
\]

\[
R_1 = \frac{F(1-F_1)F_2}{(1-F_1)(1-F_2)+F_1F_3} \tag{18}
\]

\[
R_2 = \frac{FF_1(1-F_3)}{(1-F_1)(1-F_2)+F_1F_3} \tag{19}
\]

Similarly, lead flow balance across the circuit in terms of input lead-flow-rate, (i.e., \( F^* \text{feed Pb}\% \)), and lead flow split factors, \( S_1, S_2 \) and \( S_3 \) can be developed, mainly to assist in Pb recovery calculations across the circuit. Using recovery and solid flow rates, grades across the circuit can be calculated.

For water flow balance, water flow rate entry points \( W_1 \) and \( W_2 \) respectively to scavenger launder and cleaner circuits have to be considered along with feed water flow rate, \( WF \).

6.1.2 Relationships between operating parameters and split factors

Nine relationships were established between the nine flow split factors (3 for rougher circuit consisting of solid flow split, Pb flow split and water flow split; 3 for scavenger circuit and 3 for cleaner circuit) and their local influential variables through multivariate regression.

Figure 3. Simplified flow sheet of lead flotation.
Figure 4 shows actual and predicted split factors (from the built multivariate relationship) for rougher, scavenger and cleaner circuits.

6.1.3 Steady-state model simulation

By incorporating the split factors obtained from influential parameters, it is possible to get the flow-rates of solid, water and grade and recovery of Pb (using Eqs. (13)-(19) plus additional ones). Figure 5 (a)-(b) show the comparison of actual and predicted results for grade and recovery under steady state simulations. Figure 5 shows that the approach is aptly depicting the flotation performance under steady-state simulations.

Now, by using the model, effect of influential variables on grade recovery of any particular run can be seen by varying each variable within its permissible limits. Figure 6 shows the effect of individual variable on Run #1 on grade-recovery pattern (by keeping all other variables constant as per the run). This is the effectiveness of steady state model to infer influence of operating variables on plant performance.
6.2 **Transient Model**

Generally, the many of the influential variables are changing simultaneously in a plant and to control the situation for a good grade-recovery, a transient model depicting the plant behaviour with time is essential. A transient model between any two steady state operation can viewed from the model discussed earlier in this paper, which gets reflected in its flow split factor (Eq. 12). Once the transient behaviour of the flow-split factors is known, we can couple them together in a similar manner to Eqs (13)-(19) with transient input variables, such as solid throughput and water additions to mimic the circuit behaviour.

Suppose we assume that all conditions of Run #20 were set to Run #7 simultaneously at t=0. We can mimic the circuit behaviour as shown below. As discussed earlier, the model assumes that Pb species flotation with rate constant $K_b$ will change to rate constant $K_a$ and the volumetric solids hold up $m_{h,b}$ under Run #20 will deteriorate and $m_{h,a}$ under Run #7 starts building up. Figure 7 shows this phenomenon for Rougher bank of cells.
Figure 6. Effect of influential variables on grade-recovery of Run #1 (varied one at a time). Eye represents Run #1.

Figure 7. Build up of new floating species when the influential variables in rougher bank of cells change from Run #20 to Run #7 at t=0.
This will suggest that the solid flow split factor of the rougher cells will change gradually from Run #20 value to a new value as shown below in Figure 8.

![Figure 8. Change in solid flow split factor, when Run #20 conditions change to Run #7 conditions.](image)

Applying all nine flow-split-factors and then integrating them together will describe transient behaviour circuit. The following figures shows how the final concentrate grade and recovery fall as a result of the shift in influential variables.

![Figure 9. Fall in final concentrate grade, when Run #20 conditions change to Run #7 conditions.](image)
7. Conclusions

A flotation transient model that influences the grade and recovery of the plant, through its operational variables is proposed. The steady state model considers constant split factors of solid, water and component of interest while the transient model considers these split factors to be dynamically changing. The dynamic split factors are in turn related to first order flotation rate constant and volumetric concentration of floatable species. The significance of the model is highlighted for operational benefit. The model approach can be applied to any industrial flotation circuit.

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