MODEL-BASED CONTROL OF COLUMN FLOTATION: TOWARD INDUSTRIAL APPLICATION AND REAL-TIME OPTIMIZATION

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ABSTRACT

The metallurgical performance of the column flotation process is determined by the concentrate grade and recovery. Although the former can be continuously measured using an on-stream analyzer, the latter must be estimated by a material balance calculation based on seldom verified steady-state assumptions. Consequently, the automatic control and optimization of flotation columns should be performed using secondary variables having a strong influence on the metallurgical performance, such as froth depth, gas hold-up or bubble surface area flux and bias. The aim of this paper is to present a model-based automatic control strategy using froth depth and bias measurements obtained from virtual sensors developed at Laval University. Preliminary pilot plant results on two-phase (water–air) and three-phase system (water–minerals–air) will be presented and eventual industrial implementation of such a strategy as well as the possibility of achieving effective real-time optimization from bias and froth depth measurements will also be discussed.

INTRODUCTION

Flotation columns have been widely studied and used in mineral processing for about twenty years. Although a great deal of work has been accomplished to understand the influence of different variables such as froth depth ($H$), bubble surface area flux ($S_b$) and bias ($J_b$) on the metallurgical performance, the measurement of some of these variables is still difficult to be performed – except at the laboratory level – because in most cases, no commercial device yet exists.

As a result of this, it is almost impossible to achieve neither efficient control nor optimization of the process at the industrial level, even in open-loop operation. This paper aims at presenting a simple control strategy of froth depth and bias. Description of the sensors used to achieved measurements, preliminary pilot plant results for froth depth control, eventual industrial applications and possibilities for process optimization are also treated.

BACKGROUND

Froth depth and pulp-froth interface position measurements provide the same information about the flotation column operation. Current measuring methods generally attempt to locate the pulp-froth interface instead of directly measuring the froth depth. The pulp-froth interface position is important from a metallurgical point of view because it determines the relative importance of the cleaning and the collection zones. In this paper, both expressions will be used indiscriminately.
Many techniques have been proposed in the past for froth depth measurement. The most common ones are summarized by Finch and Dobby (1990) and some further developments are presented by Bergh and Yianatos (1993) and del Villar et al. (1995a, 1995b, 1999). All these methods use the difference of a physical characteristic, such as specific gravity, temperature or conductivity, between the pulp and the froth to locate the pulp-froth interface position. Even though the principles behind these methods are fairly simple, some of them have encountered important operating problems that limit their accuracy. Nevertheless, methods based on the use of a float or pressure gages (one to three) are commonly used and seem to be precise enough for day-to-day process supervision.

New techniques using temperature or conductivity profiles have shown promising characteristics for industrial applications. Besides being very accurate, the gathered information can also be used for inferring the bias as indicated hereafter. Conductivity profile probes have been successfully tested by Gomez et al. (1989), Bergh and Yianatos (1993) and del Villar et al. (1999). Moreover, important improvements have been introduced since their inception, namely in what concerns the conductivity profile scanning time, which has improved from one minute (Gomez et al., 1989) to less than one second (del Villar et al., 1999).

The bias is another important variable for the column flotation process optimization since it is highly correlated to the concentrate grade for a given reagent dosage and $S_b$. Defined by Finch and Dobby (1990) as “the net downward flow of water through the froth” or by its equivalent “the net difference of water flow between the tailings and feed” (mass balance calculation around the collection zone), the bias can be qualitatively interpreted as the fraction of the wash water flow really useful for froth cleaning. The wash water flow rate is more often used since simpler, but it does not correlate well to the concentrate grade and recovery. In fact, it also includes the fraction of wash water flow short-circuited to the concentrate which is not used for froth cleaning.

Accurate bias measurement with common devices (flow meter and density meter) is difficult to achieve because a steady-state assumption has to be made to obtain the bias from a mass balance calculation (Finch and Dobby, 1990). Moreover, error propagation resulting from the use of four instruments (two flow meters and two density meters) to infer a rather small value, leads to high relative standard deviations (Finch and Dobby, 1990). These facts justify the interest of developing an alternative method.

Another approach validated by Uribe-Salas et al. (1991) consists in using a conductivity balance calculation. Known as the "rule of additivity", its final expression:

$$ J_b = J'_t \left( \frac{K'_f - K'_c}{K'_f - K'_w} \right) - J'_c \left( \frac{K'_c - K'_w}{K'_f - K'_w} \right) $$

(1)

involves the knowledge of the tail ($J'_t$) and concentrate ($J'_c$) water flow rates as well as the conductivity of wash water flow ($K'_w$) and those of the feed ($K'_f$), tail ($K'_t$), and concentrate ($K'_c$) water flows. This method is rather limited to steady-state laboratory scale tests.
Moys and Finch (1988) have reported the existence of a relationship between the bias and the temperature profile along the column. An equivalent relationship between bias and conductivity profile has been introduced by Xu et al. (1989) and later detailed by Uribe-Salas et al. (1991). Pérez and del Villar (1996) have proposed a neural network modeling approach to obtain a mathematical representation of the relationship between the conductivity profile and the bias. The use of this sensor for automatic control have been presented by del Villar et al. (1999) and Milot et al. (2000) for a two-phase laboratory column operation.

**EXPERIMENTAL APPARATUS**

The pilot flotation column used in this work is 7 m height (23’) and 5.25 cm (2’’) diameter. The column is instrumented with flow meters for feed, tails, wash water and air, as well as with a conductivity profile sensor (eleven 11-cm spaced stainless rings) and conductivity cells on the feed and wash water flows. Local control loops are implemented to regulate feed, tails, wash water and air flow rates. The tests described in this paper were performed on a two-phase system (water – air, no solids) and a three-phase system (water – minerals – air). The feed pulp was composed of an iron ore containing approximately 10 % silicates and a reverse flotation was targeted (silicate flotation). All experiments were conducted at 20 % to 30 % solids. Feed conductivity was adjusted using NaCl for the two-phase experiments.

**Froth Depth Measurement**

The pulp-froth interface position is measured using semi-analytical method based on the conductivity profile along the column developed by Grégoire (1997). As described by Desbiens et al. (1998) and del Villar et al. (1999), this approach replaces the previous search of the inflection point of the conductivity profile using a neural network algorithm, thus eliminating the extensive experimentation required for the training of the neural network. In the current method, the various pairs of electrodes (each pair corresponds to a conductivity cell) are sequentially activated to avoid secondary currents and the corresponding conductivity value is calculated through a very precise electronic circuit. The scanning of the whole set of electrodes takes less than one second.

Grégoire’s technique is based on the assumption that the resistance of the cell containing the pulp-froth interface is a weighted average of those immediately above (in the froth zone) and below (in the pulp zone). The measurement is achieved in two steps. First, an algorithm locates the cell containing the interface (highest conductivity change). The actual froth depth is then calculated from the conductivity of this cell and that of the immediately adjacent ones (below and above). Figure 1 compares the sensor measurements to the observed values (in a transparent column).
Although Grégoire’s algorithm is very accurate, it fails with high conductivity feeds (above 1200 µS/cm). In these cases, the conductivity profile is very steep below the interface and a larger conductivity change may occur at the bottom of the sensor (near the feed inlet) as compared to that where the interface is really located. This change results from the important difference in conductivity between the feed (above 1200 µS/cm) and the wash water flow rates (between 100 and 200 µS/cm). This problem can be easily solved by taking into account the slope of the conductivity profile before the "discontinuity" in the calculation algorithm. As shown in Figure 2, the froth phase conductivity is quite constant so that the absolute value of the slope near the interface tends to infinity.
For the operation with a three-phase system, similar results were obtained. However, the reliability of the measurements seem compromised when the electrodes clogged-up after a few hours of operation. In those cases, errors of about 5 cm were experienced. More tests are being conducted at different operating conditions to evaluate the progression of the error with time and to study how it can be avoided.

**Bias Measurement**

Bias measurement is achieved using the neural network modeling technique developed by Pérez and del Villar (1996). The only “physical” measurements required are those made by the froth depth probe, some flow rates and the conductivities of the feed and wash water flows. This black-box modeling approach has the great advantage of providing an easy-to-get and effective model from the experimental data. On the other hand, the model has no physical meaning and is dependant on the network structure, the initial state of the interconnection weights and the experimental data. Moreover, the calibration of neural network requires an extensive experimental program. Nevertheless, the method remains very interesting as it is demonstrated in the following paragraphs. As for the froth depth, the bias measurement is completed in less than a second.

The effectiveness of the bias sensor depends on the richness of the information present in the experimental data. Therefore, it is essential to carefully program the experiments to ensure that the information is well structured, diversified and that the confusion between main effects (i.e. effects of a single variable or combined effects of small group of variables) is avoided. To cover a wide range of experimental conditions with the fewest number of tests, a fractional factorial experimental design has been chosen. The five chosen factors for a two-phase system (only water and air, no solids) are: the air ($J_\text{g}$), feed ($J_\text{f}$) and wash water flow rates ($J_\text{w}$), the froth depth ($H$) and the feed conductivity ($K_\text{f}$).

The validation of neural network model for the two-phase system was accomplished using a new data set composed of 17 repeated tests of the original design. Figure 3 compares the predictions made by the sensor and the "reconciled" values of the calibration and validation data sets. It can be seen that the sensor may be really effective when used within its calibration range. The reconciled reference bias was obtained from mass and conductivity balance calculations. The data reconciliation was achieved using the flow rates and conductivity measurements (mean values for a 10-minute steady state observation window).

A new batch of tests is currently running to perform a calibration in the three-phase system and to evaluate the possibility of using a water-only calibration, which is easier to perform than a pulp-based calibration, for bias measurement in an industrial scale column.
CONTROL STRATEGY

Decentralized control strategies based on froth depth and bias are simple to implement because coupling between inputs (tail and wash water flow rate) and outputs (bias and froth depth) occurs only in one direction (del Villar et al. 1999). In other words, wash water flow rate influence both bias and froth depth, whereas tails flow rate only influence the froth depth, the bias remaining unaltered. It is then possible to tune the controllers as if the process was composed of two independent SISO systems, froth depth controlled by tails flow rate and bias controlled by wash water rate, this latter variable also acting as disturbance on the froth depth loop. This disturbance could be avoided by the introduction of a decoupler. Figure 4 schematically presents such a control structure.

Predictable disturbances are monitored variables such as feed and gas flow rates while unpredictable disturbances include unmonitored variables and modeling errors. It is clear that the impact of predictable disturbances could be decreased by the addition of feed forward control actions.
Identification

Like most processes, column flotation behaviour is dependant of the prevailing operating conditions. For example, the tails flow rate influence on froth depth is dependant on the air flow rate value (Desbiens et al. 1998). As a result, the performance of linear controllers (e.g. PI) may decrease drastically if the operating conditions move away from those used for identification. Aiming at obtaining a linear model between froth depth and froth depth, some preliminary tests have been conducted in the three-phase system around the following reference points: \( J_f = 1 \text{ cm/s}, J_g = 1 \text{ cm/s}, J_w = 0.3 \text{ cm/s} \) and \( H = 60 \text{ cm} \).

Obviously, the position of the interface (H) depends on the pulp level in the column and behave as a integrating process. Figure 5 shows the data collected during the identification tests for the three-phase system along with the model obtained. To cope with the non-zero operating points and with the slowly ascending drift clearly visible in Figure 5, deviation values (with respect to a straight line fitted to raw data) (Ljung, 1999) were used for identification purposes.

The Laplace-domain transfer function of the obtained model is given by:

\[
G_H(s) = \frac{h(s)}{j_t(s)} = \frac{K_h}{s} = \frac{0.324}{s} \tag{2}
\]

where \( h(s) \) and \( j_t(s) \) respectively represent the froth depth and the tailing flow rate centred around the reference operating condition. The positive gain results from the fact that H is measured from the top of the column (froth depth).
Controller Tuning

A close-loop time response method was chosen to tune the controller. From a PI transfer function given by:

\[ G_c(s) = \frac{K_c (1 + T_s s)}{T_s s} \]  

the closed-loop transfer function becomes:

\[ H(s) = \frac{K_c K_v (1 + T_s s)}{T_s s^2 + K_c K_v (1 + T_s s)} = \frac{(1 + T_s s)}{1 + T_s s + \frac{T_s s^2}{K_c K_v}} \]

Figure 5. Identification test & linear modelling.
As result of the relative position of the zero and the poles, it is impossible to avoid an overshoot in the response when the system is submitted to a set point step change. This is always the case when an integrator is present in both the process and the controller. For this reason, the desired closed-loop dynamics are selected as:

\[ H_{ref}(s) = \frac{(1+T_1s)}{(1+T_2s)(1+T_3s)} \]  

(5)

where \( T_1 > T_2 > 0 \). The corresponding tuning parameters must be:

\[ K_c = \frac{T_1 + T_2}{T_1T_2K_v} \]  

(6)

\[ T_i = T_1 + T_2 \]  

(7)

The overshoot to a set point step change can be eliminated by adequately filtering the set point.

For a close-loop time response specification (final value ± 5%) of about 100 s, \( T_1 \) and \( T_2 \) may be fixed at 14 s. Thus, the PI parameters are:

\[ K_c = \frac{T_1 + T_2}{T_1T_2K_v} = \frac{14 + 14}{(14)(14)(0.324)} = 0.441 \]  

(8)

\[ T_i = T_1 + T_2 = 14 + 14 = 28 \text{ s} \]  

(9)

**Results**

This controller was tested on the three-phase system. Figure 6 shows a set point step change at \( t = 126 \text{ s} \) and two feed flow rate step disturbance at \( t = 590 \text{ s} \) and \( t = 708 \text{ s} \). Wash water and air flow rates were kept constant during the test. As expected, the froth depth set point is reached in 100 s. The regulation performance is satisfactory regarding feed flow rate disturbances since froth depth remains near its set point.

**EVENTUAL INDUSTRIAL APPLICATIONS**

The conductivity-based froth depth probe has shown to be very accurate, fast and robust. It requires low-maintenance and has a very low cost. Although the results with a three-phase system are not available at the time this article was written, previous tests (Pérez-Garibay and del Villar, 1997) have indicated that the same probe can provide good estimates of the bias, a variable which is not measured by any existing device. The implementation of such device in an industrial column could significantly improve the understanding of the relationship between bias and froth depth and the column metallurgical performance. This could lead to great possibilities for automation an in-plant optimization of the flotation column process.
If we consider a step further in the improvement of the process control, bias and froth depth measurements could establish the basis to support a hierarchical control strategy. Since flotation columns are often over-dimensioned and consequently, less affected by external perturbations, it is legitimate to question the interest of implementing such a strategy. The answer could be found in the interest of industries to improve their metallurgical performance, to increase productivity and to decrease production costs, targets difficult to reconcile with the current control practice. In fact, this one generally rely on an insufficient information about critical operating variables (besides froth depth) and a choice of set points rather based on the intuition and operating easiness instead of technical considerations.

Figure 7 illustrates the principle of a hierarchical control structure applied to column flotation. After the regulation of all flow rates (tertiary variables) with local SISO control loops, the following step is to implement a stabilizing control strategy, like the one presented in this paper, with the aim of regulating secondary variables (bias, froth depth and $S_b$) having a strong influence on the metallurgical performance. At this stage, it might be necessary to implement a multivariable controller that allows to reach and maintain secondary variable set points (stabilizing control).
Tertiary variables:
feed, wash water, concentrate, tail and gas flow rates

Secondary variables:
froth depth, bias, gas holdup, $S_b$

Primary variables:
grade & recovery

**Time scale**
- hour or day
- minute
- second

**Type of control**
- Real-time optimization
  - multivariable
- Stabilizing
  - monovariable & multivariable
- Local loops
  - monovariable

**Figure 7. Hierarchical control strategy applied to column flotation.**

Set points of the secondary variables control loops could be either fixed manually or by an on-line optimization algorithm (real-time optimization) to obtain the desired concentrate grade and recovery for some given production objectives in term of productivity or production costs. In both cases, the relationship between the secondary variables and the metallurgical performance must be known.

As previously mentioned, the bubble surface area flux ($S_b$) is another key variable for the flotation metallurgical performance (Gorain et al., 1996; Heiskanen, 2000). Successful estimation of $S_b$ using a conductivity probe for gas hold-up measurements and the drift flux analysis (Dobby et al., 1988) for bubble diameter estimation has been achieved for a lab-scale column (Li et al., 2001). Such a device will be soon be integrated to the experimental set-up to evaluate the potential of this variable for metallurgical control purposes.

**CONCLUSION**

The froth depth and bias sensors based on the conductivity profile along the upper section of a flotation column have undoubtedly an interesting potential to improve the understanding of the process and to facilitate its optimization. Preliminary results for froth depth control are encouraging. Next step will be to implement feed forward actions to anticipate froth depth disturbances from feed, wash water and air flow rates and to add a bias controller. Then, an evaluation of the degree of non-linearity of the process will be carried out aiming at obtaining controllers independent of the operating points. Finally, such a control structure will make possible the systematic study of the effect of bias and froth depth on the metallurgical performance.
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