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Predictive control of the bubble size distribution in a two-phase pilot flotation column

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ABSTRACT

Among the gas dispersion properties affecting flotation column behavior, the bubble size distribution (BSD) is one of the most important. Its control could positively contribute to optimize the metallurgical performance. Experimental tests are carried out in a laboratory flotation column working with air and water. The objective is to regulate the BSD to a desired distribution set-point. BSD is measured in real-time using an image analysis method and a dynamic non-linear model (Wiener) for BSD, based on a log-normal distribution, is identified. Finally, a constrained model predictive controller is designed to control the BSD. The proposed approach leads to good control results, thus confirming the possibility to use this strategy to optimize the valuable mineral recovery by adequately selecting the BSD for a given particle size distribution.

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1. Introduction

Flotation is a mineral processing method that separates minerals based on the difference of hydrophobicity. In the case of a flotation column, the process consists in injecting air bubbles into a column vessel (typically 12–14 m height) where ground ore slurry is introduced at approximately 2 m from the top. Air is dispersed into bubbles at the bottom of the column through a sparging manifold. Prior to its introduction into the flotation column, the slurry is conditioned with chemical reagents called collectors that render the surface of selected minerals hydrophobic, or in other words inducing attraction with air. Particles exhibiting hydrophobic surfaces thus attach to the rising air bubbles. These bubble-particle aggregates then rise to the top of the column forming a froth phase rich in the selected minerals. The overflowing froth at the top of the cell (usually the valuable product) is the concentrate. Hydrophilic mineral particles, which do not attach to the flow of rising bubbles, settle and exit the column at the bottom port and form the tailings.

Performance in flotation is determined by the grade and recovery of the valuable mineral. Grade is usually measured by an X-ray on stream analyzer. Recovery can be estimated by a steady state material balance which means that it cannot be used for dynamic control purposes. Moreover on stream analyzers are designed to sample from different points of the flotation circuits, causing a significant measurement delay (Holtham and Nguyen, 2002). This delay can make the use of the measurement difficult for online control purposes. Therefore, recovery and grade are often controlled indirectly by instead regulating secondary variables such as gas dispersion properties.

The three main objectives when operating a flotation column are (McKee, 1991): (1) to stabilize circuit performance by minimizing the frequency and severity of erratic operation, (2) to achieve target grade and recovery set-points, and (3) to maximize the economic performance of the circuit.

The interaction between rising bubbles and particles is at the heart of the flotation process. One way to improve the flotation process performance would certainly be to adjust the bubble size distribution with respect to the particle size distribution (Heiskanen, 2000; Gorain et al., 1995). However, implementing this strategy requires to measure and control the whole bubble size distribution rather than just an average bubble size value. Indeed, theoretically an infinite number of distributions can give the same average value but of course they would not lead to the same flotation behavior.

Wishing to control a distribution instead of an average value occurs in many processes such as the flocculent control in paper

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machines (Yi et al., 2011), the control of the 2D and 3D flame distribution systems (Sun et al., 2006), the molecular weight control in polymerization processes (Yue et al., 2004), among others. For most processes, the product quality is better expressed by some variable distribution rather than its mean.

Classical linear stochastic control does not solve the problem of controlling the shape of the distribution instead of their moments (Jazwinski, 1970). One of the first journal papers about distribution control was published in 1996 by Kárný (1996), where the necessity of controlling the whole distribution rather than just one parameter for stochastic processes was pointed out. Some theoretical structures for the design of the controller are discussed, based on the minimization of the Kullback–Leibler distance (a maximum likelihood method), assuming a linear Gaussian state-space model. This approach is theoretical, but then provided new guidelines for future research.

Wang et al. (2008) classify stochastic distribution into three different groups:

- output probability density function control using input–output models;
- minimum entropy control for non-Gaussian stochastic systems;
- output probability density function control using neural networks.

The choice of one of these methods depends principally on how the PDF (probability density function) is modelled. Parametric and semi-parametric methods are considered when the control of the PDF is desired.

Forbes et al. (2004) model the PDF using Gram–Charlier (GC) basis functions and calculate the analytical solution for GC components. Then, the target PDF is achieved by the design of a constant feedback gain control.

Another strategy consists in dealing with the probability potential. This concept is driven by Fokker–Planck–Kolmorov (FPK) equations, where a partial differential equation describes the PDF time evolution (Crespo and Sun, 2002). This method can be used on systems that can attain the exact desired output PDF in steady-state, leading to impractical feedback control otherwise.

Pigeon et al. (2011) critically discuss the GC and the FPK methods to analyze the performance for specific shapes of PDFs, showing that FPK models obtained by minimizing the integral squared error gives better results than minimizing the GC coefficients. They also conclude that a switching linear controller has a better performance than a polynomial controller in either case (FPK and GC).

Jian-Qiao (2006) proposes a method based on Itô differential equations and stochastic calculus to model stochastic processes. The controller hierarchically regulates the process moment equations. In a case study, the first two moments (mean and standard deviation) are used to generate the control equation.

One alternative to the PDF parametric modelling is investigated by Wang et al. (2008). This method uses B-spline neural networks to calculate a semi parametric decomposition of the PDF. The resulting PDF is a linear combination of a group of B-splines multiplied with a weighting vector (Wang, 1999, 2000, 2002; Wang et al., 2008). The weights are used to generate a discrete-time system (autoregressive moving-average model with exogenous inputs), and an optimal control is designed to track the target PDF. This strategy is able to control multi-modal distributions since the inclusion of the weight vector can generate practically any distribution in the desired interval (Wang et al., 2008; Wang and Boyd, 2009).

Maldonado (2010) suggest a similar strategy to Wangs, using Gaussian mixture models instead of B-splines to represent BSD in flotation. This modelling strategy is a simplified method assuming fixed means and standard deviations for each kernel component. By doing so, only the weights for each distribution have to be estimated with an expectation–maximization algorithm. The problem of controlling the BSD is formulated as an optimization problem whose cost function aims to minimize the geometric distance between the system output and the target distribution.

In a previous work (Riquelme et al., 2015), a Wiener model is developed to predict the BSD based on a parametric function (log-normal PDF). This model will be used here to control the bubble size distribution in a laboratory flotation column, using a model predictive controller (MPC).

The objective of this research project is to evaluate the influence of BSD on the flotation performance indices (concentrate grade and recovery). Obviously, to do so, it must be possible to keep the bubble size distribution to a desired constant value. Thus, its control (described in this paper) is required and will allow various experiments to answer questions such as:

- All other parameters being constant, what are the relationships between flotation performance indices and BSD?
- Are the flotation performance indices significantly improved if BSD is optimally selected according to the particle size distribution?

It is not claimed that the proposed control strategy and instrumentation are directly suitable for industrial applications. However, it is certainly a successful step in that direction.

The article is organized as follows. Section 2 describes the air–water flotation column set-up employed in this research. Bubbles are produced with a frit-and-sleeve sparger that allows the variation of the bubble size by manipulating a shearing water flow rate. Section 3 introduces the BSD measurement and its identification with a Wiener model. This non-linear dynamic model predicts the log-normal distribution of the bubble diameters in terms of two input signals (superficial gas velocity set-point and superficial shearing water velocity set-point). Section 4 details the constrained MPC design to regulate the BSD, based on the previous Wiener model. Section 5 presents and discusses some control results. The last section concludes the paper.

2. Experimental set-up

A schematic representation of the experimental set-up is presented in Fig. 1. The laboratory flotation column is made of 5.08 cm diameter acrylic tubes for a total height of 7 m. Two peristaltic pumps are used for injecting the feed at the middle of the column and for extracting the tailings at the bottom flow. Tailings and concentrate streams are recirculated to a common reservoir containing the feed solution, i.e. tap water and F150, a frothing agent that stabilizes the froth. The frother concentration was set at 15 ppm.

Air bubbles are generated with a stainless-steel frit-and-sleeve sparger located at the bottom of the column. The frit-and-sleeve sparger (Fig. 2), consists of a porous cylinder surrounded by a sleeve forming a gap through which water is injected, shearing the air injected through the sparger to generate small bubbles (Kratch et al., 2008). This sparger allows the modification of the bubble size by manipulation of the shear-water flow rate through the gap. This means that bubble size can be varied independently of the air flow rate, i.e. it provides an extra degree of freedom for controlling the bubble size distribution. The gas flow rate is controlled by a mass flow controller and the shearing water flow is regulated by manipulating the speed of a gear pump with a proportional-integral controller. The set-point of these two loops, J_G (superficial gas velocity set-point, cm/s) and J_L (superficial shear-

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