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Development of online soft sensors and dynamic fundamental model-based process monitoring for complex sulfide ore flotation

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ABSTRACT

Complex sulfide ores are difficult to process and often require multi-stage sequential flotation. Process outputs such as grade and recovery in each stage are affected by various sub-processes in the system, and it is crucial to monitor the performance in order to maximize the production. In this work, we have proposed and implemented a dynamic monitoring scheme using fundamental modeling and an online soft sensor network for real-time measurements of grade and recovery. Dynamic fundamental models for lead and zinc recovery were developed to represent the multi-stage rougher flotation for lead-zinc sulfide ores. A soft sensor network was built to measure the grade and recovery in real-time using support vector machine classification and regression on multivariate image data. A factorial design with feed particle size, collector dosage in the lead rougher flotation stage, and collector dosage in the zinc rougher flotation stage as the design variables was used to obtain diverse process conditions for validation. Successful validation at the entire range of process conditions demonstrates the potential of the technique for use in process control and monitoring applications. Changes in the collector dosage were monitored in the lead and zinc rougher flotation stages using state and parameter estimates of the fundamental model structure. The process monitoring framework can be extended to monitor other key variables in the process.

1. Introduction

Froth flotation is the most used separation process in the mineral industry (Nguyen and Schulze, 2003; Wu et al., 2016) and is used to separate the ore into valuable mineral concentrates and tailings (gangue minerals) based on physicochemical principles (Yalcin and Kelebek, 2011; Kawatra, 2002; Wang et al., 2016). The process is driven by the difference in the surface hydrophobicity between the value and gangue minerals. In most cases, the value mineral is rendered hydrophobic using a chemical reagent known as the collector, which has a direct impact on the process outputs (grade and recovery). Froth flotation is a multi-phase process with gas flowing through the slurry to initiate the attachment of hydrophobic particles to the bubbles (Kawatra, 2002; Finkelstein and Lovell, 1972).

Flotation has been practiced for the beneficiation of sulfide ores for over 100 years (Somasundaran, 1980). With the recent advances in the technology, it is now possible to concentrate poor quality complex sulfide ores through fine grinding (Kohad, 1998). Most of the research has been focused on improving the types and dosage of reagents used in sulfide ore flotation (Barbaro, 2000). Thiol-type collectors (e.g., xanthates) have generally been accepted and employed for the separation of complex sulfide ores (Barbaro, 2000). Various researchers have studied the adsorption effects of Xanthates on the minerals (Barbaro, 2000; Little et al., 1961; Page and Hazell, 1989). It was found that the Xanthates can float all sulfide minerals and are thus not selective towards specific minerals found in the sulfide ores; hence, the process requires the use of other reagents such as modifiers or depressants to achieve the differential flotation of different sulfide minerals (Barbaro, 2000; Finkelstein and Alllison, 1976). Lead–zinc sulfide ores are among the common sulfide ores that use flotation for beneficiation. Flotation of these sulfide ores is accomplished using multi-stage differential flotation. Several flotation cells are used to separate and recover galena (lead sulfide, PbS), followed by floating sphalerite (ZnS) in a sequential manner (Basilio et al., 1996). Various disturbances may be present and cause the separation process to deviate from its desired state of maximum possible grade and recovery. For instance, kinetic studies for the lead-zinc sulfide ore flotation have reported that the sphalerite shows certain floatability towards the end of galena flotation and reduces the lead concentrate grade and zinc concentrate recovery (Basilio et al., 1996). The presence of copper activates sphalerite during the grinding (Fisher and Tokich, 1943), thus reducing the separation efficiency further. Depressants are added to inhibit the sphalerite activation.

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Bubble-particle attachment, dependent on these chemical reagents, is an important process for the ultimate objective of mineral separation, and any disturbance in collector or reagent addition or its quality has a direct impact on the concentrate grade and recovery by affecting the attachment. Other than the chemistry-based factors, there are several operational and feed-based variables that need to be manipulated and monitored to achieve the desired separation (Kawatra, 2002; Popli et al., 2015). Disturbances in feed particle size, feed density, feed grade, air flow rate, or pH are relatively common during operation. These disturbances influence the process and can degrade the product quality and move the operation away from the optimized state. It is therefore of great importance to develop in-depth fundamental process knowledge and monitor the attachment, detachment and transport sub-processes to maximize the grade and recovery without upsetting the operation. It is also important to understand the importance of these operational variables and their relationship to lead and zinc recovery to achieve effective process control.

Various attempts have been made to model the flotation processes and develop an accurate mathematical treatment. The majority of the studies deal with fitting first order kinetic models to the experimental data (Asghar et al., 2015; Kracht et al., 2005; Wills, 1997). First principles models have also been studied for the flotation process. The early first principles models were based solely on the pulp phase; later, many models were proposed for the froth phase by considering it as an important component (Arbiter and Harris, 1962; Harris et al., 1963; Harris and Rimmer, 1966; Lynch et al., 1974). Ventura-Medina and Cilliers (2002) introduced the plateau border to describe the froth in the flotation process. Compartment-based models divide the process into various compartments and develop mathematical relations for inter-compartment processes (Fuerstenau et al., 2007; Bascur, 2000; Popli et al., 2015; Alves dos Santos et al., 2014). Some of these sub-processes include attachment between a bubble and particles to form an aggregate, detachment of a particle from the bubble-particle aggregate, entrainment of a particle from the pulp phase to the froth phase without being attached to a bubble and drainage of a detached particle from the froth to the pulp phase (Bascur, 2000; Popli et al., 2015; Alves dos Santos et al., 2014). The majority of these models are valid only at steady-state and their inability to connect various sub-processes has made them unsuitable for the control and monitoring purposes. In this study, we propose a compartment-based model that includes theoretical dependence of various operational and feed variables to sub-processes in both the lead and zinc rougher flotation stages of flotation for a Pb-Zn sulfide ore. These sub-processes were further connected to the lead and zinc concentrate recovery by developing dynamic equations for those relations.

Real-time or online process measurements are another vital component to complete a monitoring and control framework. Grade and recovery are the key measurements for the flotation processes. Traditional offline procedures of obtaining the grade measurements using analytical methods in the laboratory are not suitable for dynamic operations due to their long sampling and measurement times. Recently developed online sample analyzers (online X-ray Fluorescence) have been implemented in various plants to measure the grade with better response time. However, their high maintenance, high initial cost, inaccurate data, and difficulty in calibration demand a better solution for process control purposes (Duchesne, 2010; Popli et al., 2015). Additionally, experienced operators also rely on the qualitative assessment of the visual features of the froth such as color, texture, and stability. However, this assessment is not quantitative, and it is difficult for the operators to understand the process conditions or the root-cause for certain setbacks in the operations (Aldrich et al., 2010; Popli et al., 2015). It is known that two similar looking froth images can have different extracted features using machine vision, unnoticeable by even the experienced operators (Aldrich et al., 2010). In the last 25 years, several researchers have exploited the relationship between the froth image structure and corresponding mineral grade (Pryor, 1965; Aldrich et al., 2010; Barbian et al., 2007; Bonifazi et al., 2000; Holtham and Nguyen, 2002; Leiva et al., 2012; Moolman et al., 1996; Popli et al., 2015). Image processing algorithms have been applied to extract various static (color, texture, etc.) and dynamic features (froth mobility, speed, stability, etc.) followed by their application in control systems (Brown et al., 2001). Most of the research in flotation control and implementation in the industry is focused on using single variables such as froth velocities or color to control the product quality (Runge et al., 2007). Recently, multivariable analysis has been proposed for the flotation control and information extraction using image features (Duchesne, 2010). Modern developments in machine vision for flotation have led to the development of various commercial packages to extract and measure the image features. These packages include METCAM FC (SGS), VisioFroth (Metso® Minerals), FrothMaster™ (Outotec), and PlantVision™ (KnowledgeScape Inc) (Popli et al., 2015). We have previously attempted to correlate the image features obtained by VisioFroth to key process measurements for pure minerals and synthetic mixtures (Popli et al., 2015). In this work, we extend our studies to a real complex sulfide ore with multi-stage flotation. The concentrate grade is inferred with image features and supplied to a mass balance framework for inference of recovery. A robust structure is proposed for multi-stage flotation circuits. VisioFroth is chosen for the studies due to its common usage in the Canadian mining and oil industries.

The objective of this work is to develop a process monitoring scheme using fundamental models and online measurements from a soft sensor network for complex lead-zinc sulfide ores. The fundamental model was updated in real-time using online process measurements and state and parameter estimation. Factorial design of experiments (DOE) was used to generate a set of multi-stage flotation operating conditions using two levels of each of three factors: the dosage of Xanthate collector in the lead stage of flotation, the dosage of Xanthate collector in the zinc stage of flotation, and the particle size distribution of the feed. The monitoring framework was used to estimate the rate of attachment in real-time and identify disturbances introduced in the collector dosage. Furthermore, to demonstrate other applications of the image-based soft sensor network, results from factorial DOE were used to analyze the effects of design variables on online process measurements.

2. Experimental methods

2.1. Materials: Feed sample and reagents

Feed samples in the form of lead-zinc sulfide ore were obtained in the crushed form from the Red Dog Mine, Alaska. X-ray diffraction was used to analyze the feed ore and identify the minerals present as galena (lead sulfide), sphalerite (zinc sulfide), pyrite (iron sulfide), quartz (silicon dioxide), and barium oxide. Galena and sphalerite were the value minerals to be recovered while pyrite and quartz were identified as the gangue minerals. Lead and zinc content in the feed ore were found to be 3.52% and 18.12%, respectively, using atomic absorption spectroscopy (AAS) and classic zinc titration. A comminution circuit was designed for 500 g of the homogenized sample. A jaw crusher and wet ball mill (65% solid density) were used to obtain two types of feed streams with different particle size distributions of P_{80} at 35 μm and 75 μm, respectively. Particle size distributions were measured using a Mastersizer 3000 and are presented in Fig. 1. The feed streams have median particle sizes (P_{50}) of 18.4 μm and 47.1 μm, respectively.

Rougher flotation of lead and zinc ores requires several chemical reagents for efficient separation. Lime (CaO) was used to modify the pH of the slurry to the specific pH requirements. Potassium ethyl xanthate ($C_3H_5KOS_2$, KEX) was used as a sulfide collector for both lead and zinc stage flotation. Methyl isobutyl carbinol ($C_6H_{14}O$, MIBC) was used as a frother in both stages for stabilizing the froth. Depressants are the reagents that inhibit the flotation of certain minerals by controlling metal ion activation. Activators enhance the conditions for the interaction of