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Nonlinear modeling of the relationship between reagent dosage and flotation froth surface image by Hammerstein-Wiener model

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A R T I C L E I N F O

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A B S T R A C T

Due to the frequent and random disturbances to flotation banks, reagent dosages are frequently changed to stabilize the flotation process at a desired level to obtain an expected grade and recovery. It is widely accepted that the froth surface after a reagent change is the essential process output, corresponding to reagent dosages for a current chemical condition (that also can be characterized by the froth surface). Based on this causal relationship, the froth surface can be controlled to any expected stable state by changing reagent dosage. Therefore, a Hammerstein-Wiener based causal model that models bubble size distribution (the image feature used to characterize froth appearance) and reagent dosage as a nonlinear relationship was developed. Since existing watershed algorithms are ineffective in segmenting the highly reflective zinc bubble images, a novel illumination modeling-based marker watershed method was proposed. A log-normal distribution model was used to fit the bubble size distribution, and then a nonlinear model between bubble size distribution and reagent dosage was approximated by a wavelet-based Hammerstein-Wiener model. The proposed methods have been validated through comparative experiments for a lead–zinc flotation plant in China.

1. Introduction

52838351147445Direct froth flotation is a mineral processing method used to selectively separate hydrophobic valuable minerals from hydrophilic minerals. Specific reagents are added to the slurry prior to the flotation process to accentuate the differences in surface properties of the desired mineral and gangue minerals, allowing better separation in terms of selectivity and recovery. The performance in this process is determined by the grade and recovery of the valuable minerals. In practical flotation operations, the reagent dosage, interface level, inlet air flow rate, and pH of the slurry are manipulated to ensure an expected concentrate grade (Liu and MacGregor, 2008; Aldrich et al., 2010; Shean and Cilliers, 2011; Cao et al., 2013). However, due to frequent and random disturbances to the flotation banks, the reagents are frequently changed to stabilize the flotation process at a desired level to achieve the required grade or recovery.

Lead-zinc froth flotation is a typical two-stage sequential flotation process, as shown in Fig. 1 that is a schematic of a lead-zinc flotation plant located in China. In the first step, sphalerite is ensured to be nonfloatable. Galena flotation collectors and the frother are conditioned before galena flotation. During lead flotation, the sphalerite is rejected into the tailings. In the second flotation step, the sphalerite is activated with copper sulfate (activator) in the zinc flotation conditioner, and the activated slurry is transported to the first zinc rougher flotation bank. The froth and tails are the feed to the cleaner bank and zinc rougher bank I, respectively. If the flotation conditions in the first zinc rougher bank can be stabilized, the conditions in subsequent flotation banks will also be stable. Therefore, the first zinc rougher bank is the primary control object. The flotation process involves the interactions of three phases (gas, liquid, and solid), often modelled using intricate mathematical relations based on offline measurements or lab analyses. It is generally agreed that the first paper regarding flotation kinetics was published by Zuniga in Chile (Zuniga, 1935). He had applied the differential equation of chemical reaction kinetics to portray the flotation rate and observed that the flotation recovery is an exponential function of flotation time. In 1984, a bubble generation model was proposed by Schulze (1984), in which the bubble diameters could be calculated from the surface tension at the liquid/vapor interface and the energy dissipation rate at the bubble generation zone. The first principle model for particle/bubble collision, particle adhesion, and particle detachment was proposed by Luttrell and Yoon (1992) and Yoon and Mao (1996). However, a kinetic model linking the operating variables (reagent dosage, interface level, inlet air flow rate, and slurry pH) to flotation performance (concentrate grade and recovery) in an actual lead-zinc flotation process plant has been difficult to develop due to the lack of effective on-line measurement equipment.

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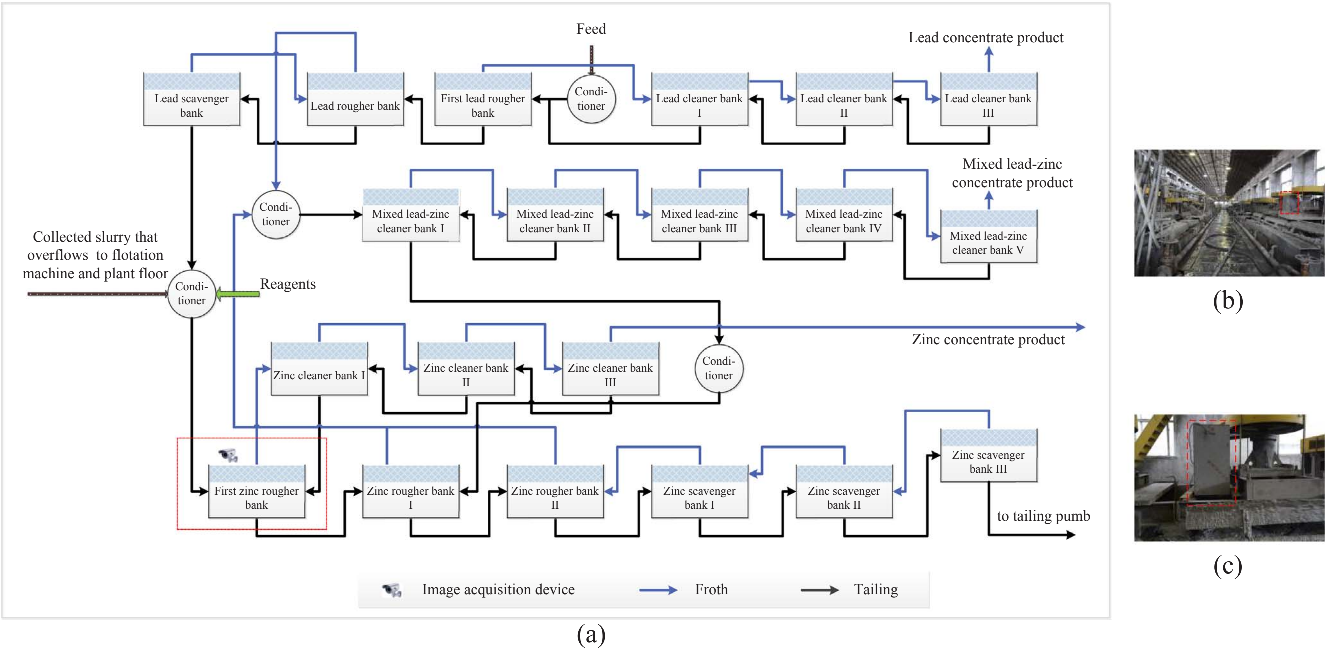

Fig. 1. Schematic of lead-zinc flotation. (a) Schematic of lead-zinc flotation; (b) flotation circuit; (c) image acquisition device that consists of an industrial camera, high-frequency light source, and a waterproof cover mounted on the first zinc rougher bank.

It has been established that the froth is the essential process output that responds to process inputs, such as reagent flow rate, interface level, inlet air flow rate, and pH of the slurry under the current chemical conditions (particle loading). The pH of the slurry is adjusted in the ball mill process. The interface level is mainly adjusted in the scavenger bank. The inlet air flow rate is mainly adjusted in the cleaner bank. In the first zinc rougher bank, the interface level, inlet air flow rate, and pH of the slurry are barely adjusted. The purpose of our study is to develop a dynamic causal model to simulate the relationship between the reagents and froth in a first zinc rougher bank. Once this causal model is established, the froth can be easily stabilized at a stable state or adjusted to any new state by changing the reagent dosages under guidance from the model (Liu and MacGregor, 2008; Aldrich et al., 2010; Shean and Cilliers, 2011; Zhu et al., 2014). Although this causal process is notoriously difficult to model from first principles, knowledge-based systems can be used to simulate this process effectively by providing process knowledge.

There are two key points in the construction of a flotation causal model. The first one is the characterization of the froth surface. Concentrate grade is the most important parameter of the froth, and the froth appearance is the most intuitive representation of the froth. Concentrate grade can be measured reliably by an X-ray fluorescence analyzer, but the analyzer relies on a steady-state material balance, which strongly limits its use for real-time grade analysis. Furthermore, since an X-ray fluorescence analyzer is expensive to purchase and maintain, the analyzers are often designed to analyze process streams collected from many flotation banks. With only one analyzer to analyze multiple flotation banks, there will be significant measurement delays (20 min in the plant described in Fig. 1 (Liu and MacGregor, 2008). Therefore, in practical reagent dosage changes, the control of reagents is based on human observation of the froth surface. In recent years, machine vision-based froth flotation analysis has attracted great interest from both academic and industrial researchers (Zhu et al., 2014; Bergh and Yianatos, 2011). In the previous work undertaken by Wang and Neethling (2009), the relationship between the surface and internal structure of dry foam was studied using a simulation approach. In their study, an empirical formula characterizing the surface film size and the size of bubble was proposed:

$$\begin{cases} f\left(\frac{r_s}{r}\right) = \frac{3.54(r_s/r)^{4.61}}{1+\exp(47.96(r_s/r-1.08))}, & (unconstrained\ surfaces) \\ f\left(\frac{r_s}{r}\right) = \frac{3.51(r_s/r)^{4.67}}{1+\exp(56.34(r_s/r-1.08))}, & (constrained\ surfaces) \end{cases} \quad (0)$$

where r_s is the surface film size, and r is the surface bubble radius. Therefore, the film size distribution observed at the froth surface can be used as a proxy for the bubble size distribution in flotation process modeling.

In bauxite flotation, we built a working condition recognition system based on froth images, which achieved on-line flotation process monitoring (Zhang et al., 2016). Liu et al. (2013) proposed an online operational status recognition method for quality evaluation of reagent addition based on adaptive learning of the dynamic bubble size distribution. To predict the metallurgical performance of a batch flotation system, He et al. (2013) combined bubble size, froth velocity, froth color, and froth stability to construct a neural network predictive system.

Generally, the froth surface appearance can be described by image texture (Zhang et al., 2016; He et al., 2013), bubble speed (Núñez and Cipriano, 2009; Jahedsaravani et al., 2014), bubble loading (Farrokhpay, 2011; Barbian et al., 2005), and bubble size obtained through image segmentation (Jahedsaravani et al., 2014; Mehrshad, 2011; Zhou et al., 2010). It has been established that the bubble size distribution (BSD) is the most significant indicator reflecting the working conditions in a flotation cell (Barbian et al., 2005; Hunter et al., 2008; Farrokhpay, 2012; Xie et al., 2016). In this study, the BSD is selected to characterize the froth surface. With direct application of watershed transformation to the froth image, the image will be seriously over-segmented. In recent years, attempts have been made to improve the effectiveness of watershed marker extraction. The function of the high-frequency light source mounted on the surface of a first zinc rougher flotation bank is to produce a high light spot on each bubble surface. These high light spots are extracted and used as markers in the watershed transform. For example, Hunter et al. (2008) proposed a clustering-driven method to extract watershed markers. In this method, Fuzzy C-Means is introduced to separate froth pixels from edge pixels first. Then, morphological operations are used to remove image noises (Zhou et al., 2010). Mehrshad and Massinaei (2011) proposed an adaptive marker selection method. Wu et al. (2016) extracted the