Minerals Engineering 92 (2016) 9–20

Contents lists available at ScienceDirect

Minerals Engineering

journal homepage: www.elsevier.com/locate/mineng

The concentrate ash content analysis of coal flotation based on froth images

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ARTICLE INFO

Article history:
Received 26 November 2015
Revised 16 February 2016
Accepted 17 February 2016
Available online 23 February 2016

Keywords:
Coal flotation
Ash content
Concentrate
Froth
Images

ABSTRACT

Ash content is a vital indicator for coal flotation performance. Froth plays an important role in determining flotation concentrate grade and there are strong correlations between the concentrate froth and the ash content. Therefore, the research in the correlations is of great importance for further flotation prediction and control. In this paper, flotation experiments were conducted at different frother dosages and froth depths using a flotation column. It was found that there were relations between the ash content, yield and water recovery of the concentrates. Variables of froth property such as the average gray value, the homogeneity, the burst bubble parameters and the height over weir were extracted from video images and were analyzed to explain the flotation results. The connections between the variables and the concentrate ash content were analyzed.

1. Introduction

Ash content is a significant indicator of coal industry as coal products must satisfy the requirements for various applications. In coal preparation, the performance of the gravity separation of bulk particles is usually better than that of the flotation of fine particles, so the ash content of flotation concentrate must be strictly controlled to maximize the financial profitability. Traditionally, operators of flotation could only adjust parameters timely according to their experience (Moolman et al., 1996; Hätönen, 1999; Holtham and Nguyen, 2002; Aldrich et al., 2010; Shean and Cilliers, 2011). The exact results of coal flotation performance could only be tested after the long-time processing of sampling, filtrating, drying, sample preparing and burning to ash. It is too late to adjust the flotation parameters after obtaining the result of concentrate ash content. Once the disturbances of flotation input appear, amounts of concentrate could not meet the requirement of ash content by the delayed adjustment. While in base metal applications, X-ray fluorescence (XRF) analyzers are used for on-line assaying the elemental contents in the flotation streams which is important to effective flotation control (Wills and Napier-Munn, 2006; Shean and Cilliers, 2011). However, the relevant research can be scarcely found in coal flotation area. The timely, accurate and applicable measurement of the concentrate ash content is rather challenging.

Among the methods to detect or predict the ash content of coal, the prediction by froth features is the most applicable one for timely and repeatable requirements. High temperature ashing method is used as the standard method due to the accuracy and stability, but it is time-consuming. Other methods such as double γ-ray transmission method (Tang et al., 1998; Yazdia and Esmaeilnia, 2003; Zhu and Zhang, 2004) and neutron analysis method (Cheng, 2005; Sibiya et al., 2014) are relatively accurate and quick, but they are costly and very harmful to the environment. As a result, these methods are not widely used. Recently, image processing of flotation froth is used to predict and analyze the flotation concentrate grade and satisfactory results can be obtained (Shean and Cilliers, 2011).

Some froth variables can be obtained with the help of froth images and used to analyze the relation with concentrate grade, such as air recovery (Moys, 1984; Barbian et al., 2005, 2006, 2007; Zheng et al., 2006a; Hadler and Cilliers, 2009; Hadler et al., 2010) and bubble burst rate (Morar et al., 2012a, 2012b). Air recovery represents the fraction of the air that overflows the cell as unbroken bubbles.

$$\alpha = \frac{Q_{out}}{Q} = \frac{\zeta \times v_f \times h_w \times w}{Q} \quad (1)$$

where Q_{out} is the volumetric flowrate of air leaving the top surface of the froth as unbroken bubbles, Q is the volumetric flowrate of air introduced in the column, ζ is the fraction of air in the overflowing

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http://dx.doi.org/10.1016/j.mineng.2016.02.006
0892-6875/

froth, v_f is the velocity of the bubbles on top of the froth, h_w is the height of the froth overflowing at the weir and w is the weir lip length. The higher α refers to the lower the loss of air by bubble breakage and the higher the froth stability. $(1-\alpha)$ represents the fraction of bubbles bursting on the froth surface. Its correlations with concentrate grade were found in copper and platinum flotation. Bubble burst rate could also characterize the froth stability which also relates to the concentrate grade in copper and platinum flotation (Morar et al., 2012a, 2012b). The bubble burst rate was extracted by comparing two consecutive frames after segmentation and aligning the images. It was supposed to burst if the ratio of the bubble size from the first frame to the average area of the intersecting bubbles is greater than a threshold (Morar et al., 2012a). In coal flotation, Qu et al. (2013) investigated the links between air recovery, froth stability and coal flotation performance. It was found that there is a strong correlation between the air recovery and the dynamic froth stability which was determined by measuring the maximum froth height in a non-overflowing froth column. At a fixed aeration rate (hydrodynamic condition) and various MIBC concentrations, a strong correlation between air recovery and coal flotation performance was also observed.

Some other froth variables relating to the concentrate grade are extracted and directly applied to establish or train models such as regression model, neural network or support vector machine. These froth features are mainly bubble size, froth velocity, froth color and froth stability. Jahedsaravani et al. (2014) extracted froth features by image processing in the batch flotation of a copper sulfide ore. The relationships between the froth features and concentrate grade were successfully modeled using the neural networks. Marais and Aldrich (2011) estimated the platinum flotation grades and recoveries from froth image data. It was shown that grades and recoveries can be reliably estimated from a number of different features by use of linear and nonlinear models. The similar research was also conducted in other fields, such as iron flotation (Mehrabi et al., 2014), zinc flotation (Kaartinen et al., 2006) and bauxite flotation (Cao et al., 2013). In coal flotation area, Hargrave et al. (1996) found that the gray level has correlations with flotation performance. Wang et al. (2001) developed the relationship between the features of froth image and indicators of coal flotation concentrate. Citir et al. (2004) calculated the average bubble diameter in each image for coal flotation by image processing off-line. The relationship between the mean bubble diameter and the cumulative grade was described by the linear fitting functions.

The reason why concentrate grade can be predicted by froth property is not very clear at current stage. But it can be interpreted to a certain extent by the interaction between particles and bubbles (Ventura-Medina and Cilliers, 2002; Barbian et al., 2007). Hydrophobic particles that attach on the bubbles enter the froth phase. They may detach from the bubble lamellae when bubble burst or coalesce occur. The detached particles then enter the Plateau border, where three lamellae meet. The liquid of the froth is mainly in the Plateau borders, as well as the entrained hydrophilic particles. The liquid, hydrophilic particles and detached hydrophobic particles in the Plateau border may drain back to the pulp. Drainage could reduce the entrainment and it also causes the bubble coalescence or burst. Hence, froth features could reflect the concentrate grade. In addition, particle properties have significant influence on froth property (Johansson and Pugh, 1992; Ventura-Medina et al., 2004; Barbian et al., 2007; Aktas et al., 2008; Cole et al., 2010; Tang et al., 2010; Farrokhpay, 2011; Wang et al., 2014, 2015). Particle size and hydrophobicity affect the froth stability and water recovery very much in coal flotation (Liang et al., 2015). In return, froth properties such as stability, mobility, water content under different conditions can also affect the particles that are loaded on the bubble lamellae or entrained in the plateau borders (Ventura-Medina and Cilliers, 2002; Shi and Zheng, 2003; Zheng et al., 2006b; Barbian et al., 2007; Farrokhpay, 2011; Wang and Peng, 2014; Haffner et al., 2015; Razavi et al., 2015; Wang et al., 2015). It can be summarized that there are complex interactions between the particles that determines the concentrate grade and the bubbles that determines the froth properties. However, the understanding of the complex three-phase froths is far from unambiguous (Morar et al., 2012a) at current stage.

There is little research concerned concentrate ash content analysis by froth images in coal flotation. In this research, the concentrate ash content was analyzed at different frother dosages and froth depths. Froth property variables relating to the concentrate ash content were proposed to explain the flotation results. The average gray value of flotation froth at different flotation time was used to analyze the concentrate ash content and the froth overflowing speed. The homogeneity was proposed to characterize the bubble size in coal flotation froth, the images of which were difficult to segment under small error. The texture homogeneity was analyzed as a function of offset to estimate the froth bubble size at different frother dosages and flotation time. The height over weir was studied individually as a function of time. The fluctuation range and frequency features were interpreted by the burst bubble size and overflow velocity. Bubble burst parameters were also investigated to analyze its correlations with ash content.

2. Experimental

2.1. Materials

Coal sample was obtained from a flotation feed stream in a coal preparation plant in Linhuan, China. The size analysis of the flotation feed was shown in Table 1.

Table 1 shows that the fraction of the particles finer than 74 μm is the dominant fraction which constitutes nearly half the total sample. The ash content increases with the size decreases. This could be explained by the fact that the gangue minerals are easily to degrade and much secondary slime is produced during the separation process.

2.2. Flotation experiments

A pneumatic flotation column of 1 L was designed to conduct the flotation experiments. No agitation is applied in the flotation column, so relative peaceful froths which are favorable for the extraction of froth properties could be obtained. 60 g of coal were used in each batch flotation with 1 L of tap water. Kerosene and 2-octanol were used as the collector and the frother. The dosage of the collector was 330 g/t consistently, while the frother dosage increased from 27 g/t to 206 g/t. The slurry was first conditioned in a 1.5 L XFD flotation cell for 2 min. Then the collector was added and another 2 min of conditioning was kept before adding the frother. The slurry conditioning was stopped 30 s after the frother was added. Then the slurry was poured into the flotation column. One camera (Canon PC1331) was set on an iron shelf above the flotation column and another camera (Nikon D7100) was set on the camera tripod on the side of the flotation column. The frame rates of the cameras above and on the side are 30 and 29 frames per second

Table 1
Sieving results of the coal sample finer than 500 μm.

Size (μm)	Fraction (%)	Ash content (%)
500–250	20.68	12.92
250–125	18.59	22.84
125–74	14.39	29.97
−74	46.34	36.82
Total	100.00	28.29