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Kinetic modeling and optimization of flotation process in a cyclonic microbubble flotation column using composite central design methodology

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ABSTRACT

In this work, a composite central design with five levels and four variables was employed to model and optimize the batch flotation kinetic process in a cyclonic microbubble flotation column (FCMC). 30 sets of batch flotation rate tests were executed at different conditions of pulp concentration (X_1), frother dosage (X_2), flow rate of circulation pulp (X_3) and froth depth (X_4). It was observed the maximum flotation time (t_{max}) obtained in tests fluctuated wildly under different conditions. Statistical analysis based on the model fit and stability was performed to discriminate six kinetic models. The response surface methodology was used for the identification and development of significant relationship between process variables. Statistical analysis indicated that the modified Kelsall model was the optimal kinetic model for characterizing the flotation process. Analysis of variance results revealed that the effect of X_1 was significant for all process responses. X_4 was found as a significant independent factor for the two response variables of t_{max} and the ultimate combustible recovery (ε_∞) of the optimal kinetic model. X_3 had a significant influence on the parameter of the optimal kinetic model (the fraction of flotation components with the slow rate constant). Furthermore, the maximum flotation time and ε_∞ were significantly influenced by the interaction between X_1 and X_4. Based on the result of optimization it was found that the desired ultimate combustible recovery with an appropriate flotation time was obtained from the flotation process with a given range of experimental variables (X_1: from the intermediate levels to the higher levels; X_2: the intermediate level; X_3: 220 g/t and X_4: 25.00 mm). There was an acceptable relationship between predicted and actual values with one of the optimal conditions ($Adj.\ R^2 = 0.9971$). The response surface methodology was effective for predicting and optimizing the batch flotation process of FCMC.

1. Introduction

Froth flotation has been used industrially for years to separate valuable minerals from their associated gangue constituents (Yuan et al., 1996). Flotation is a physio-chemical separation which is affected by many factors such as degree of liberation, surface properties, dosage of flotation reagent, etc., and with many operating variables (Cilek, 2004). For coal fines below 0.5 mm in size, froth flotation is one of the most effective methods to separate the ash forming mineral matter and the carbonaceous materials (Polat et al., 2003). It is well known that column flotation has many advantages over conventional mechanical flotation process, including simplicity of construction, no moving parts, low energy consumption, low operating and maintenance costs, higher recovery and product grade, etc. (Mathieu, 1972; Beasley et al., 1985). During the last three decades, column flotation has been extensively studied and various columns have been developed, including the Leeds column, the Microcel column, the packed column, the Flotaire column, the hydrochem column, the Jameson column and cyclonic microbubble column (Li et al., 2003).

Cyclonic microbubble flotation column technology (abbreviated as FCMC)was developed and patented by China University of Mining and Technology, in which flotation column and centrifugal force field are combined to enhance the efficiency of separation for coal fines (Liu, 2000; Xie et al., 2005). Over 350 FCMCs with different capacities has been available for various applications in different coal preparation plants (Jiang et al., 2001; Li et al., 2003; Xie et al., 2014). There is a cone at the bottom of FCMC comparing with other kinds of flotation columns, which offers a centrifugal force field. The middling pulp is pumped into the nozzle and shoots out as a jet flow at high speed, after which the pulp is forced into the centrifugal force field in the tangent direction at a rapid velocity (Li et al., 2012). Due to the combination of flotation theory and cyclonic force field mechanism, rough

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Table 1
Comparison of concentrate quality between FCMC and flotation cell in coal flotation %.

Coal preparation plant	Flotation cell		FCMC		$A_{ad, required}$
	A_{ad}	$A_{ad, 0.045 mm}$	A_{ad}	$A_{ad, 0.045 mm}$	
San Hejian, Jiangsu Prov.	10.96	13.87	8.45	11.43	8.50
Zhang Xiaolou, Jiangsu Prov.	11.09	14.65	8.97	10.89	9.00
Xing Tai, Hebei Prov.	11.17	14.61	8.25	10.75	8.50
Pan Xi, Shandong Prov.	12.88	16.73	10.02	13.97	10.50
Gu Cheng, Shandong Prov.	10.92	14.98	9.09	10.84	9.50
Longgu, Shangdong Prov.	8.70	13.35	8.42	12.54	8.50
Wang Lou, Shandong Prov.	11.24	14.81	8.91	11.09	9.00
Jin Jia, Guizhou Prov.	12.95	13.88	10.47	12.83	10.50
Wo Bei, Anhui Prov	10.97	13.96	9.59	11.38	10.00
Ling Shi, Shanxi Prov.	11.22	14.98	9.43	13.99	9.50

beneficiation, primary separation and scavenging are completed in order in a single unit.

FCMC has some advantages over the conventional mechanical flotation cell in fine and ultrafine coal. As shown in Table 1, FCMC performs well in the separation of −0.045 mm size fraction compared to flotation cell. The ash of −0.045 mm fraction of clean coal of FCMC is 0.81–4.14% lower than that of flotation cell. Therefore, flotation column produces an overall clean coal product that has ash content 0.28–2.92% lower in comparison with flotation cell.

The availability of mathematic model is an essential requirement for the optimization and operation of automation of the flotation process (Luttrell and Yoon, 1983). Traditionally, the cumulative recovery of minerals being floated in the concentrate is undoubtedly proportional to the flotation time. In essence, the flotation process can be considered as a time-rate recovery process (Sripriya et al., 2003). Therefore, mathematic flotation models incorporate both a recovery and a rate function can completely describe flotation time-recovery profiles. They provide an excellent tool to evaluate flotation tests (Shean and Cilliers, 2011). It is vital for achieving the automation of the flotation process that the occurrence of the process can be predicted accurately by suitable mathematic model.

In this study, batch flotation rate tests were carried out based on the central composite design (CCD). The availability and validity of six kinetic models listed in Table 2 were measured to discriminate the optimal kinetic model by statistical analysis. Surface response methodology was applied to evaluate significant relationships between experimental variables and responses and optimize response variables of flotation process.

2. Materials and methods

2.1. Coal sample

The coal sample was collected from a coal preparation plant (Datong, China). The sample was screened at 0.5 mm. The product was then blended, divided into charges of different weight, placed in plastic bags and stored in a deep freezer until required for kinetic tests. Size distribution and ash analysis of the sample are provided in Table 3.

Table 3
Size and ash distributions of the coal sample.

Size (μm)	Wt (%)	Ash (%)
−500+250	20.26	18.95
−250+125	21.29	18.15
−125+74	4.91	18.81
−74	50.51	25.82
Total	100.00	22.45

2.2. Experimental system

Fig. 1 is the schematic and actual diagram of FCMC. The system consisted of stirred-tank, a feed pump, the flotation column, a circulation pump, a bubble generator, a tailing tank for discharging gangue, an overflow port for collecting concentrate and a pressure gauge for controlling circulation pressure. The diameter of the flotation column was 100 mm, and peristaltic pumps were use as the feed and circulation pump. Models of the feed and circulation pump were BT/601S with a diameter 18 mm hose (LEAD FLUID Technologies Inc, Baoding, China,) and TL00-700M with a diameter 82 mm hose (Tianli Fluid Industrial Equipment Factory, Wuxi, China), respectively.

A self-aerating bubble generator was used to generate microbubbles in which circulating middling pulp was pumped into the nozzle and shoots out as a jet flow at high speed. Air was drawn in due to the negative pressure induced by jet-flow. The slurry exiting the bubble generator was fed into the cyclone section at the bottom of the column. The froth depth (H) was adjusted by the altitude difference between the tailing tank and the concentration froth overflow weir, and the reject was discharged from the tailing tank based on law of equilibrium in connected vessels in continuous test. In this batch flotation study, the tailing was not withdrawn from the tailing tank until the last concentrate was collected. Further water was added from the tailing tank to keep the pulp level constant.

Batch flotation tests were executed in the experimental system. All tests were carried out at pH = 7.0 and at room temperature. The coal sample was conditioned with tap water in a stirred-tank conditioner for 3 min. The impeller speed of stirred-tank conditioner was 180 rpm. Then, the collector dosage (kerosene) was added into the pulp to enhance the hydrophobicity of coal fines and was allowed to condition for 3 min. The frother dosage (sec-octyl alcohol) was then added and a further 1 min of conditioning was performed. Afterwards, pulp was fed through the feed pump with the flow of 2.30 L/min at approximately two-thirds of the total height from the bottom of the column. The circulation peristaltic pump was started when the level of

Table 2
Description of applied flotation kinetic models.

No.	Model	Formula	Remark (Jowett, 1974; Dowling et al., 1985; Bu et al., 2016)
1	Classical first-order model	$\varepsilon = \varepsilon_\infty[1-e^{-K_1 t}]$	This model has been reported to predict values best when the recovery is especially low.
2	First-order mode with rectangular distribution	$\varepsilon = \varepsilon_\infty\{1-\frac{1}{Kt}[1-e^{-K_2 t}]\}$	This model has been reported to be the best of all models tested to fit experimental data because the rectangular distribution of flotabilities gives an added flexibility.
3	Second-order model	$\varepsilon = \frac{\varepsilon_\infty^2 K_3 t}{1+\varepsilon_\infty K_3 t}$	Two parameter expression describing the flotation of a monodisperse feed with particles having a constant floatability.
4	Second-order mode with rectangular distribution	$\varepsilon = \varepsilon_\infty\{1-\frac{1}{K_4 t[1n(1+K_4 t)]}\}$	Similar to model 2, this model assumes that flotation components are rectangular distribution. The fit to the experimental data and the confidence intervals become increasingly worse as the fractional recovery approaches 1.0.
5	Fully mixed factor model	$\varepsilon = \varepsilon_\infty[1-\frac{1}{1+t/K_5}]$	This model assumes that flotation components are exponentially distributed which gives an added flexibility over the classical first-order model and enables it to fit the observed values very well.
6	Modified Kelsall model	$\varepsilon = \varepsilon_\infty[(1-\varphi)(1-e^{-K_f t})+\varphi(1-e^{-K_s t})]$	This model is a discretized distribution that describes the fractions and rate constants of fast and slow-floating of combustible matter.

Note: ε—fractional combustible recovery at time t (%), ε_∞—fractional ultimate combustible recovery (%), K_n— rate constants, $n = 1, 2, 3, 4$ (min^{-1}), K_f—fast flotation rate constant (min^{-1}), K_s— slow flotation rate constant (min^{-1}), φ—fraction of flotation components with the slow rate constant.