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The difference in flotation kinetics of various size fractions of bituminous coal between rougher and cleaner flotation processes

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ABSTRACT

In order to investigate the difference in flotation kinetics of various size fractions of bituminous coal between rougher and cleaner flotation processes, clean coal was collected as a function of time in both rougher and cleaner flotation processes. The size composition of clean coal was then analyzed. Six flotation kinetic models were applied to the modeling of data from the flotation tests by using MATrix LABoratory software. The relationship between flotation rate constant, maximum combustible recovery and particle size was also studied. The results show that the maximum flotation combustible recovery and flotation rate are obtained with an intermediate particle size both in the rougher and cleaner flotation processes. The combustible recovery and flotation rate are higher in the cleaner flotation process than that in the rougher flotation process. Except the classical first-order flotation kinetic model, the other five kinetic models gave an excellent fit to the flotation data. The rougher flotation process can be described using the first-order and second-order models while the cleaner flotation process can only be described using the first-order model. It is found that the first-order model with rectangular distribution of floatability provides the best fit of the experimental data obtained from both the rougher and cleaner flotation processes among the tested models.

1. Introduction

Flotation is a physico-chemical separation process based on the difference in surface properties between valuable minerals and gangues. Flotation kinetics can be described using the mathematical models which incorporate both a recovery and a rate function, since the flotation process is theoretically considered as a time-rate recovery process [1–3]. Furthermore, flotation kinetics models are generally applied to evaluate the flotation tests.

The first flotation model was proposed in the 1930s [4]. Subsequently, numerous works about the kinetics of flotation process were reported [3,5–9]. The flotation kinetics models of quite a few flotation processes have been established based on the test data from batch flotation tests or industrial tests under reasonable operating conditions. The effects of flotation parameters including particle size and size distribution, reagents type and dosage, air flow rate, pulp density, and wash water rate on the flotation kinetics in a flotation cell or column were studied [10–14]. A great number of flotation models have been proposed to investigate flotation kinetic behavior [1,6–15]. These models have conveniently been defined in three categories: (1) empirical models, (2) probability models, and (3) kinetic models [16]. This paper will consider only kinetic models according to the previous studies [1–3].

A single-stage circuit is commonly applied in coal flotation, i.e., rougher flotation process [17]. Therefore, almost all the previous studies on kinetics of coal flotation are based on the single-stage flotation process. However, flotation products that consistently fulfill requirements cannot be obtained using the single-stage flotation process in some cases, e.g. treating poorly floatable coal and producing super-clean coal. In fact, multi-stage coal flotation process is favored in reducing the ash content of clean coal by eliminating the hydraulic entrainment and selectively rejecting lower hydrophobic particles [18–20]. Furthermore, there are a number of multi-stage flotation circuits in the treatment of metallurgical coking coal and production of super-clean coal [17,21–22]. Therefore, the kinetics of multi-stage coal flotation process should also be studied. However, little attention has been devoted to the flotation kinetics of cleaner stages or multi-stage flotation circuits. The difference in the flotation kinetics between rougher and cleaner stages has not been adequately investigated in the past.

In this study, the particle size distribution of collected clean coal in various flotation stages both in rougher and cleaner processes was analyzed, and six kinetic flotation models were selected to test their applicability for various size fractions of coal both in rougher and cleaner flotation stages. In addition, a major attempt of the paper was to discuss

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the differences in the flotation kinetics of various size fractions between rougher and cleaner flotation process.

2. Experimental

2.1. Materials

A bituminous coal sample obtained from Yunhe Mine of Shangdong province, China, was used in this investigation. The sample was screened to pass 500 μm. The particle size distribution of the coal sample is given in Table 1, and the proximate and ultimate analyses of the coal sample are given in Table 2. The ash content of the coal sample was 33.57% on an air dry basis. The sample had 53.00% fine particles with sizes below 45 μm with an ash content of 43.63%. It indicated that the coal sample had many fine coal particles with high ash content.

2.2. Flotation tests

In the flotation experiments, kerosene and DL-2-Octanol (DLO) were used as the collector and frother, respectively. The flotation water used in the experiments was tap water, and the chemical composition was shown in Table 3.

The flotation tests were divided into two parts: (1) rougher flotation tests; and (2) cleaner flotation tests. The rougher flotation tests were performed in a 1.5-L Denver flotation cell. In each test, 150 g of coal sample was mixed with 1 L tap water in the cell and was agitated for 2 min at an impeller rotation speed of 1800 rpm. Then, kerosene (1750 g/t) was added to the pulp and conditioned for 2 min. Subsequently, the DLO (300 g/t) was added to the pulp and conditioned for 0.5 min. After the conditioning process, tap water was added to increase the volume of pulp in the cell up to 1.5 L, and the air was introduced into the cell at a flow rate of 4.17 L/min. The pulp was floated for 200 s, and tap water was added to maintain a constant pulp level when it was necessary. The froth was collected by using an automatic froth collector at a rotation speed of 30 r/min. Products were obtained in the rougher flotation tests: clean coal and tailings.

The cleaner flotation tests were also performed in a 1.5-L Denver flotation cell, and the feed of which was the froth product of rougher flotation. The operating parameters of cleaner flotation tests were the same to those of rougher flotation tests. In each cleaner flotation test, the rougher flotation concentrate was poured into the cell and was agitated for 1 min at an impeller rotation speed of 1800 rpm. No flotation reagents were added to the pulp. Then, tap water was added to increase the volume of pulp to 1.5 L, and air was introduced into the cell at a flow rate of 4.17 L/min. The flotation time and froth collection time were the same to those of rougher flotation tests. Two products were obtained in the cleaner flotation tests: further clean coal and cleaner tailings.

The final froth products from the rougher flotation tests and the cleaner flotation tests were both divided to 5 products according to the collection periods: 0–20 s, 20–40 s, 40–80 s, 80–120 s, and 120–200 s. All products including flotation concentrate and tailings were filtered, dried, weighed and analyzed for the ash content. In addition, each product was screened into five narrow size fractions: −500 + 250, −250 + 125, −125 + 74, −74 + 45, and −45 μm. The ash content of the products and the combustible recovery of the flotation were obtained. The combustible recovery was calculated from Eq. (1):

$$\textit{Combustible}\ \text{recovery}\% = [W_C(100-A_C)]/[W_F100-A_F] \times 100 \quad (1)$$

where W_C is the weight of the concentrate (%), W_F is the weight of the feed (%), A_C is the ash content of the concentrate by weight (%), and A_F is the ash content of the feed by weight (%).

2.3. Flotation kinetic models

In this investigation, six flotation kinetic models were selected to study the flotation performance of various size fractions in rougher flotation and cleaner flotation processes, as shown in Table 4. The cumulative combustible recoveries of various size fractions after 20, 40, 80, 120, and 200 s of flotation time were fitted using the six kinetic models. The narrow size fractions included −500 + 250, −250 + 125, −125 + 74, −74 + 45, and −45 μm. The MATrix LABoratory (MATLAB) software (Version 7.0) was used to simulate the flotation rate constant (K), the maximum combustible recovery (ε_∞), and the correlation coefficient (R^2) based on the nonlinear least square optimization method. MATLAB is one of the most powerful and advanced numerical calculation software. Nonlinear least squares optimization has been widely used in the non-linear regression, curve fitting and optimization of nonlinear model parameters.

3. Results and discussion

3.1. Flotation kinetics of various size fractions in rougher flotation process

The flotation time-combustible recovery of various size fractions in rougher flotation process are shown in Fig. 1. The combustible recovery of the flotation increased initially and then decreased with the increase of particle size, and the maximum combustible recovery in the rougher flotation process was obtained with the −250 + 125 μm size fraction. It indicated that the maximum combustible recovery was obtained with an intermediate particle size in the rougher flotation process. Similar findings were also reported by other researchers [23–25].

Flotation is a physic-chemical separation process, in which hydrophobic particles are captured by air bubbles and eventually reported to the froth product. This process is determined by three most critical steps including the particle–bubble collision, attachment, and detachment [3,25–26]. It is well known that particle size is an important parameter in flotation process, and a high process efficiency of froth flotation is typically limited to a relatively narrow particle size range [23–29]. However, outside this range, the recovery drops significantly, whether it is at the fine or the coarse end of the size spectrum [28]. The low combustible recovery of fine particles is mainly because of the poor collision and attachment between the fine particles and air

Table 1
Particle size distribution of bituminous coal sample.

Size fraction (μm)	Mass (%)	Ash content (%)	Cumulative undersize	
			Yield (%)	Ash contend (%)
500–250	14.68	22.85	100.00	33.57
250–125	13.44	21.83	85.32	35.41
125–74	6.69	20.53	71.88	37.95
74–45	12.19	22.82	65.19	39.74
−45	53.00	43.63	53.00	43.63

Table 2
Proximate and ultimate analyses of bituminous coal sample.

Proximate analysis (wt, %, ad)				Ultimate analysis (wt, %, daf)					LHV_{ad} MJ/kg
M	A	V	FC	C	H	O	N	St	
1.21	33.57	25.76	39.46	80.85	5.46	10.85	1.12	0.88	19.89

ad = Air dry basis; daf = Dry ash-free basis; M = Moisture content; A = Ash content; V = Volatile matter; FC = Fixed carbon; LHV = Low heat value.

Table 3
Conductivity and chemical composition of the tap water (mg/L).

Conductivity (mS/cm)	Ca^{2+}	Mg^{2+}	Na^+	K^+	Cl^-	HCO_3^-	SO_4^{2-}
0.36	54.7	16.6	15.4	3.4	24.7	13.9	5.4