Effects of particle size on lignite reverse flotation kinetics in the presence of sodium chloride

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ABSTRACT

The purpose of this study was to investigate the effect of particle size on lignite reverse flotation with a focus on reverse flotation kinetics in the presence of sodium chloride. Six flotation kinetic models were applied to data from the tests using the 1stOpt statistical analysis software package to estimate the relationship between the flotation rate constant, the maximum ash flotation recovery and the particle size. Within the range studied, the best reverse flotation performance was obtained at a grinding fines (-74-μm size fraction) content of 42.34% with a concentrate ash content of 11.30% at 65.29% combustible recovery after 20 min of flotation time. The results show that all kinetic models except the classical first-order flotation kinetic model gave excellent fits to the experimental data under various grinding fines contents and various size fractions. The high flotation rate constant was limited to a narrow particle size range. The maximum flotation rate constant was obtained at a grinding fines content of 42.34% and with the $-250 + 150$ μm fraction. We concluded that the reverse flotation of lignite in the presence of sodium chloride can be described with the first-order and second-order models. Furthermore, the reverse flotation performance as a function of particle size was further evaluated using the reverse flotation efficiency index. We found that the -425-μm size fraction with a grinding fines content of 42.34% resulted in the greatest index value compared with the investigated narrow size fractions at any given flotation time.

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1. Introduction

Froth flotation is a physico-chemical separation process based on the attachment of hydrophobic particles to an air bubble. The actual flotation process is highly complex and involves three phases (solids, water, and air bubbles) with numerous subprocesses and interactions [1–3]. 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 [4,5]. Therefore, the general mathematical flotation models for flotation that incorporate both a recovery and a rate function can completely describe flotation time–recovery profiles.

Since the initial flotation model was reported in the 1930s, numerous researchers have studied the kinetics of flotation. Batch flotation test data in the literature have established that the flotation process follows the general mathematical flotation model under reasonable operating conditions [6–10]. However, the order and the rate constant vary with the flotation conditions, such as the particle size and size distribution, the air flow rate, the reagents used, the operating parameters, etc. [11–15]. Different models have been proposed to simulate flotation kinetic behaviour in the literature [8,16]. These models can be separated to three categories according to previous

studies [5,7–15]: (1) empirical models, (2) probability models and (3) kinetic models. In this paper, we focus only on kinetic models because empirical models are specific to their environment and usually involve a trial-and-error feedback approach to optimisation, whereas probability models can be reduced to kinetic models within certain constraints.

The particle size distribution has been reported to affect the flotation kinetics to a great extent [17,18]. Numerous researchers have studied the aspects of flotation kinetics while paying special attention to particle size [19–24]. However, many of these studies are mainly based on the direct flotation process. In the direct flotation process of coal or lignite, the combustible material is usually transferred to the froth with the gangue mineral left in the pulp or tailings. In contrast, gangue minerals have been reported to transfer the flotation froth during the reverse flotation process [25,26]. As we all know, lower rank coals are more hydrophilic, particularly lignite, which is difficult to float in the traditional manner even using a high reagent dosage because of higher oxygen functional groups, such as hydroxyl, carbonyl and carboxyl [27,28]. However, very little work has been done in lignite reverse flotation, particularly flotation kinetic. Furthermore, flotation kinetic studies are generally employed to evaluate the flotation performance before the flotation time and the flotation circuit to be adopted for any new mineral or coal are decided. Thus, in this study, the evaluation of flotation kinetics is based on the recovery of gangue minerals rather than combustible materials in lignite

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reverse flotation. Previous research has been focused primarily on direct flotation, whereas studies on the flotation behaviour of gangue minerals in lignite reverse flotation have been relatively few, particularly with respect to the aspects of flotation kinetics as a function of particle size.

On the other hand, several theories have been proposed to explain the enhancement of mineral flotation in salt solutions: (1) the inorganic electrolytes destabilise the hydrated layers surrounding the mineral particles and reduce the surface hydration of particles, which in turn increases the efficiency of the attachment of valuable mineral particles to air bubbles [29]; (2) the inorganic electrolytes compress the electrical double-layer between and reduce the zeta potential of bubbles and particles [30,31]; and (3) the inorganic electrolytes could produce an abundance of fine bubbles, thus preventing bubble coalescence and increasing froth stability [32,33]. In order to improve the floatability of gangue, sodium chloride (NaCl) was selected as a soluble salt in this study.

Therefore, in the present paper, to further understand the role of particle size in the lignite reverse flotation process in the presence of sodium chloride (NaCl), a lignite sample was separated via the reverse flotation technique using different grinding fines contents and different particle size fractions. We selected six kinetic flotation models to evaluate the effect of particle size on lignite reverse flotation kinetic parameters. In addition, the reverse flotation performance was evaluated on the basis of the reverse flotation efficiency index.

2. Experimental

2.1. Materials and sample preparation

A lignite sample obtained from Alberta, Canada, was used in this investigation. The as-received sample was crushed to a particle size of -2 mm. The product was then blended, divided into 100 g charges, placed in plastic bags and stored in an icebox until required for grinding and reverse flotation tests. The moisture content of the prepared lignite sample was 22.46%, and the ash content was 15.19% on a dry basis. The proximate and ultimate analyses results for the sample are given in Table 1.

The crushed samples were ground with a ball mill (ADVAN-TEC, No. 5C). The rotation speed was maintained at 400 rpm, and the grinding time period ranged from 1 to 11 min. The effect of the grinding time on the fines is presented in Fig. 1. The results show that the yield of the -74-μm size fraction increased from 12.99% to 72.30% as the grinding time was increased from 1 min to 11 min, and the ash content of the -74-μm size fraction decreased from 21.77% to 14.25%. The grind fineness increased slowly when the grinding time was longer than 7 min. For size classification in narrow size intervals, the grinding product collected after 3 min of grinding time was screened into five narrow size fractions: $-425 + 250$, $-250 + 150$, $-150 + 74$, $-74 + 45$ and -45 μm.

Dodecylamine hydrochloride (DAH, $C_{12}H_{28}ClN$, ≥99%) was used as a surfactant or collector, corn starch (($C_3H_{10}O_5)_n$, M.W. 162.15, lab grade) was used as a coal depressant and 4-methyl-2-pentanol (MIBC, lab grade) was used as a frother. Sodium chloride (NaCl, lab grade) was selected as a soluble salt. To increase the solubility of
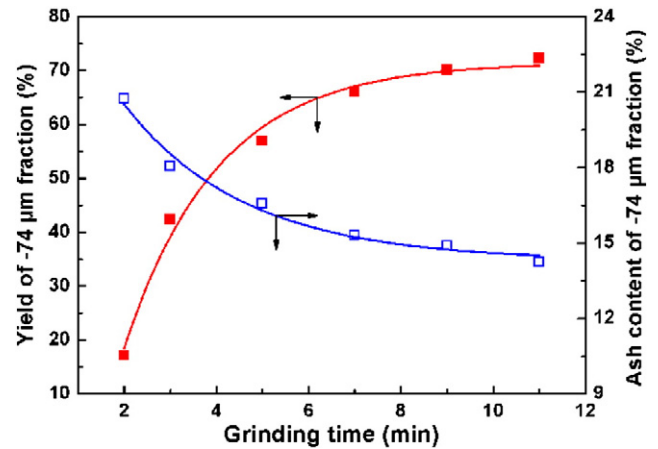

Fig. 1. Effect of the grinding time on the grinding fineness.

the corn starch, we prepared a 1% causticised corn starch solution (corn starch:NaOH = 4:1, wt.%). All water used in the experiments was distilled.

2.2. Reverse flotation tests

The reverse flotation tests were performed in a 1-L Denver flotation cell at a solids concentration of 8%. In each test, a lignite sample was mixed with 500 ml 0.3 M NaCl solution in the cell and was agitated for 5 min at an impeller rotation speed of 1600 rpm. Then, starch (2500 g/t), DAH (5000 g/t) and MIBC (200 g/t) were added to the slurry in succession. The conditioning time for each reagent was 3, 2 and 1 min, respectively. After the conditioning process, the desired NaCl solution (0.3 M) was added again to increase the volume of pulp in the cell to 1 L, and the slurry was stirred for an additional 4 min. Subsequently, air was introduced into the cell at a flow rate of 1.35 L/min. Distilled water was added as necessary to maintain a constant pulp level, and the pulp was then floated for 20 min. The froth was collected at 1, 3, 6, 12 and 20 min. All tests were conducted at the pH value of natural pulp. Impeller rotation speed was operated at 1600 rpm in each flotation test. The flotation concentrate (a combustible material that does not transfer to the flotation froth) and the tailings (a gangue mineral that transfers to the flotation froth) were filtered, dried, weighed and submitted to ash content determination according to the ASTM method. The ash and combustible recoveries were calculated from the following equations:

$$\text{Ash recovery}(\%) = [M_T A_T / M_F (100 - A_F)] \times 100 \tag{1}$$

$$\text{Combustible recovery}(\%) = [M_C (100 - A_C) / M_F (100 - A_F)] \times 100 \tag{2}$$

The reverse flotation efficiency index derived from Hancock's efficiency formula [34] was used to evaluate the reverse flotation performance in this study. Only when the ash content of the concentrate is more than the tailings, namely, a reverse flotation process, is employed, the reverse flotation efficiency index value is greater than zero. Thus, the bigger the index value is, the more excellent the reverse flotation performance. The formula is given as follows:

$$\text{Reverse flotation efficiency index}(\%) = [M_T (A_T - A_F) / A_F (100 - A_F)] \times 100 \tag{3}$$

where M_C is the weight of the concentrate (%), M_T is the weight of the tailings (%), M_F is the weight of the feed (%), A_C is the ash content of the concentrate by weight (%), A_T is the ash content of the tailings by weight (%) and A_F is the ash content of the feed by weight (%).

Table 1
Proximate and ultimate analyses results for the lignite sample.

Proximate analysis (wt.%, ad)				Ultimate analysis (wt.%, daf)					O/C	H/C	LHV$_{ad}$ (MJ/kg)
M	A	V	FC	N	C	H	S	O			
22.46	11.78	45.86	19.90	1.28	69.22	4.53	0.71	24.25	0.26	0.39	15.99

ad = Air dry basis; daf = dry ash-free basis; M = moisture content; A = ash content; V = volatile matter; FC = fixed carbon; LHV = low heating value.