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The behaviour of mineral matter in fine coal flotation using saline water

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HIGHLIGHTS

- ▶ Saline water increased the recovery of mineral matter in coal flotation.
- ▶ The increase in entrainment was more pronounced for fine particles.
- ▶ Entrapment played a more important role in de-ionised and saline water.
- ▶ Saline water significantly increased the entrapment of fine mineral matter.
- ▶ Saline water enhanced particle aggregation associated with entrapment.

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ABSTRACT

In this study the behaviour of mineral matter in the flotation of a fine coal sample using saline water was investigated. For a comparison, de-ionised water was tested in parallel. It was found that saline water increased the recovery of mineral matter while increasing the combustible recovery. By calculating the degree of entrainment in the flotation of the coal sample and also the ash after combustion, coupled with the froth image analysis and rheology measurements of froth and pulp suspensions, the entrainment and entrapment of mineral matter in coal flotation were examined. Compared to de-ionised water, saline water increased the entrainment across the size range and the increase in entrainment was more pronounced for particles smaller than 38 μm. However, entrapment played a more important role in recovering mineral matter smaller than 38 μm in coal flotation using both de-ionised and saline water. Saline water significantly increased the entrapment through enhancing the aggregation of coal particles.

1. Introduction

Coal mining is an important business in Australia supplying coal to produce 85% Australia's electricity. 54% of the coal mined in Australia is also exported, mostly to Eastern Asia. In the last few years there has been a distinct change in the water quality used in coal preparation plants within Australia due to stringent policy on the amount of saline water which a mine can discharge into the local river system. As a result, most coal mines have introduced water re-use as a conventional practice. One of the consequences of increased water re-use is a concomitant increase in the salinity of water on the sites and subsequently in flotation. A number of studies have been conducted to investigate coal flotation using saline water. In general, saline water increases combustible recovery compared to fresh water [1–5]. However, these studies have not taken into account the behaviour of mineral matter in saline water. With the depletion of coal resources, more and more low-grade and difficult coal deposits are being processed and the role of saline water in recovering mineral matter in coal flotation becomes important.

It is known that the recovery of particles by flotation is a function of true flotation and mechanical entrainment. In mineral flotation the pulp of solid particles in water is conditioned with collectors (a type of surfactants) to render value minerals hydrophobic, while gangue minerals remain hydrophilic. Air is then injected into the pulp to form bubbles that collide with particles. Hydrophobic particles tend to attach to the bubbles and the bubble–particle aggregates are then transported to the pulp/froth interface at the top of the pulp and eventually enter the froth launder as the concentrate. This process is called true flotation. However, mechanical entrainment of particles taking place when particles are dragged by the interstitial liquid films between air bubbles always occurs in parallel with true flotation and is the primary recovery mechanism for gangue, especially fines [6]. Due to its unselective nature and the fact that gangue minerals are generally abundant in the ore, the recovery by entrainment may have a significant detrimental effect on the concentrate grade.

Entrainment in flotation can be considered as a two-step process, including the transfer of the suspended solids in the top of

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the pulp region just below the pulp–froth interface to the froth phase and the transfer of the entrained particles in the froth phase to the concentrate [7]. The first step of entrainment is via (i) hydraulic boundary layers surrounding air bubbles [8], (ii) the wades of bubble clusters [9], and (iii) water entrapment by the continuous transport of bubbles into the froth layer [10]. The water flow rate into the froth phase is inversely proportional to the bubble diameter [11]. The reduced bubble size in saline water due to the inhibition of bubble coalescence [12–14] may promote more water to flow into the froth phase and therefore higher particle entrainment. The presence of the froth phase in a flotation cell provides certain time for the water and the entrained particles to drain back to the pulp phase before the froth enters the concentrate. The transport of gangue minerals in the froth phase is strongly affected by the structure of the froth and the bubble size. Small-bubbled and closely-knit froth is likely to enhance the entrainment of gangue minerals [15].

It has been found experimentally that the amount of gangue minerals recovered is intimately related to the amount of water recovered [6]. The relationship between the water recovery and gangue recovery is linear over most of the region of interest. When this linear relationship is extrapolated, it produces a zero intercept on the water recovery axis for very fine particles. The slope of the linear portion of the relationship increases with decreasing the particle size. It is often refer to as the degree of entrainment (*ENT*) which is normally calculated by the equation [16]:

$$ENT_i = \frac{\frac{\alpha_{ij}^c \cdot m_i^c \cdot X^c}{1-X^c}}{\frac{\alpha_{ij}^p \cdot m_i^p \cdot X^p}{1-X^p}} \tag{1}$$

where a is the mineral assay, m is the mass fraction, X is the solids concentration (% solids), subscripts i and j represent the particle size fraction and mineral, respectively, and superscripts p and c represent the pulp phase and the concentrate, respectively. Eq. (1) uses the water as a reference to define the classification effect of the drainage of entrained particles in the froth phase. Savassi et al. [17] predicted the following boundaries of *ENT* in relation to the particle size d_i (μm):

$$d_i \to \infty \Rightarrow ENT_i \to 0$$

$$d_i = 0 \Rightarrow ENT_i = 1$$

These boundaries are consistent with the measurements in industry flotation cells indicating that smaller particles correspond to greater *ENT* and the *ENT* is normally smaller than 1 due to the higher specific gravity and faster drainage of gangue minerals than water [6,7,16]. However, Eq. (1) does not distinguish entrainment from physical entrapment between particles in the froth attached to air bubbles. From literature, physical entrapment occurs in three circumstances in mineral flotation and may result in a higher recovery of gangue minerals and calculated *ENT* value than expected from the entrainment. Firstly, entrapment occurs when the thickness of the froth lamellae and Plateau borders reduces to a value similar to or less than the particle size [18]. At such a condition, the free drainage of the particles may cease. Secondly, the flotation of composite particles without complete liberation of gangue minerals from value minerals is another type of entrapment, contributing to the recovery of non-floating particles [16]. Thirdly, the occlusion of gangue minerals within the flocs or aggregates of hydrophobic value minerals attributes to entrapment as well [19].

In coal flotation, aggregation among coal particles has been reported [19]. The degree of aggregation increases as a function of hydrophobicity of the coal particles and the amount of the oily collector present in the system. Pawlik et al. [20] attributed the aggregation of hydrophobic coal particles to the hydrophobic forces which occur over a broad pH range, while the aggregation of hydrophilic coal particles to van der Waals interactions when the zeta potential values were near zero (e.g., around the iso-electrical point). Aggregation in coal flotation means entrapment of mineral matter in the aggregates of coal particles. Polat et al. [21] observed that the primary size distribution of the coal sample was much greater in the flotation cell as a result of aggregation compared to the size distribution of the same coal dispersed using chemical and mechanical dispersion methods, corresponding to entrapment of mineral matter and a higher ash recovery.

In this study, the behaviour of mineral matter in coal flotation using saline water in terms of entrainment and entrapment was examined. For a comparison, de-ionised water was also tested.

2. Materials and methods

2.1. Raw materials

A coal sample obtained from a coal mine was tested in this study. It is thermal coal with about 25 MJ/kg Calorific value, 0.4% sulphur content, 6% humidity and 15% ash content. XRD analysis of this sample is indicated in Table 1. The mineral matter includes quartz, kaolinite, calcite, ankerite, siderite, pyrite and bentonite minerals with bentonite minerals being predominant consisting of 9.1% of the sample. The concentrate of the amorphous phase is 86.8%. The combustible content of the coal is about 85%. The coal sample was crushed to a size of −2.36 mm before grinding and flotation. De-ionised water and saline water were used. Saline water was made in the laboratory by adding certain amounts of a number of salts in 50 dm^3 de-ionised water. The chemical composition of the saline water is shown in Table 2. Similar saline water was used previously in the flotation of coal and produced significantly different results to fresh water [22]. The water was well mixed before the use to ensure similar concentrations of salts for each experiment. The de-ionised water used in this study has the resistivity of 35 Ω m. MIBC (Methyl Isobutyl Carbinol) and diesel, industrial grade, were used as frother and collector, respectively. They are widely used in the flotation plants in Australia including the one where the coal sample was obtained.

2.2. Grinding and flotation

100 g crushed sample was ground in a laboratory stainless steel rod mill at 33.3% solids to obtain 80% particles passing 75 μm. The size distribution of the mill discharge measured by a Laser Diffraction Malvern Mastersizer (Model No. MSX14) is shown in Fig. 1. Half of the particles after grinding were smaller than 30 μm. This matches the size of the flotation feed in the plant where the coal sample was obtained. SEM analyses showed that mineral matter was liberated from coal particles after grinding. After grinding the pulp was transferred to a 1.5 dm^3 JK Batch Flotation Cell and then conditioned with collector (240 g/t) and frother (160 g/t) at an agitation speed of 950 rpm. The solid percentage in the flotation cell was about 6.5%. In flotation, four concentrates were collected after cumulative times of 1, 2.5, 5, and 10 min. When de-ionised water was used, flotation was operated at an air flow rate of 3.0 L/min at which normal flotation was observed. However, when saline water was used, an air flow rate of 3.0 L/min caused significant overflow and normal flotation was not possible. This reflects the industry practice where flotation is operated differently in fresh and saline water. In this study, the air flow rate was reduced to 1.6 L/min to ensure no overflow in the flotation using saline water, and therefore the behaviour of mineral matter in fine coal flotation using de-ionised and saline water was compared under normal flotation instead of exactly the same conditions. The flotation froth was scraped every 15 s.