



# Reducing the entrainment of clay minerals in flotation using tap and saline water

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## ABSTRACT

High gangue entrainment is a major problem in fine particle flotation. In this study, the entrainment of kaolinite Q38 in flotation was examined in tap and saline water. High molecular weight polyethylene oxide (PEO) was used to reduce the entrainment of kaolinite Q38 by enlarging the size of kaolinite particles in flotation. It was found that PEO reduced the entrainment significantly in flotation using tap water, but in saline water, the effect of PEO was less pronounced. The aggregation behaviour of kaolinite Q38 particles in the absence and presence of PEO and its effect on the entrainment of kaolinite Q38 were studied by the in-situ measurement of flocs and the size of enlarged particles, settling tests and the measurement of froth stability in flotation. It is interesting to find that PEO did flocculate kaolinite Q38 particles and enlarge their sizes in flotation despite high agitation. However, the reduction of the entrainment of kaolinite Q38 in flotation was dependent on the type of flocs formed and froth stability which can be modified by electrolytes in water and a high addition of PEO.

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## 1. Introduction

Flotation which exploits the difference in wettability on valuable and gangue mineral surfaces, is an important technology to concentrate minerals. However, flotation becomes more and more difficult as a result of the need to treat fine and ultrafine mineral particles. One challenge in the flotation of fine and ultrafine mineral particles is the high gangue entrainment resulting in low concentrate quality. Fine hydrophilic gangue particles are easily dragged by the interstitial liquid film between air-bubbles and enter the froth layer with liquids in flotation, resulting in mechanical entrainment. It is the primary recovery mechanism for gangue, especially fines [1].

Trahar [2] and Smith and Warren [3] found that mechanical entrainment became significant for particles smaller than about 30  $\mu\text{m}$ , and it was proportional to the recovery of water into froth products. The severe mechanical entrainment of fine gangue mineral particles has been observed in many flotation testing programs [4,5]. For example, in the bulk flotation of copper and lead, the recovery of non-metallic gangue minerals as well as pyrite and sphalerite was increased from about 5% for 40  $\mu\text{m}$  particles to 20–30% for 10  $\mu\text{m}$  particles [4].

Clay minerals usually occur at less than 2  $\mu\text{m}$  in the flotation of coal, oil-sands and base metal minerals no matter whether fine grinding is used or not [6]. It is expected that clay mineral particles are easily entrained into froth layers and cause high gangue entrainment in froth flotation as a result of the fine size. Arnold and Aplan [7] found that the addition of bentonite to tap water with MIBC (a frother in

flotation) gave a more persistent froth in coal flotation, leading to higher entrainment with the poorer quality of coal products. Industry practices indicate that the flotation of highly clayey ores is impossible presently. Highly clayey ores have to be blended with normal ores at a small proportion before flotation [8,9].

Besides clay minerals, saline water that has been widely used in mineral flotation plants as a result of the scarcity of fresh water may cause the high entrainment of fine gangue minerals in flotation. It is well documented that many salts inhibit bubble coalescence [10,11]. Therefore, saline water may generate more stable froth leading to higher gangue entrainment than fresh water. Wang and Peng [5] decoupled the entrainment and entrapment of gangue minerals in coal flotation and found that saline water increased the entrainment across all the size range and the increase in entrainment was more evident for gangue mineral particles smaller than 38  $\mu\text{m}$  compared to deionised water.

Research carried out by Cao and Liu [12] and Liu et al. [4] showed that the entrainment of fine and ultrafine particles in flotation was reduced by enlarging their sizes using either inorganic depressants to coagulate fine gangue mineral particles [12], or high molecular weight polymers to flocculate them [4]. Recently, Gong et al. [13] demonstrated that high molecular weight PEO successfully reduced the mechanical entrainment of quartz in the batch flotation of artificial mixtures of chalcopryrite–quartz. When PEO was applied in the flotation of a copper–gold ore, the entrainment of quartz was reduced as well corresponding to improved copper and gold recovery. Gong et al. [13] used a Photometric Dispersion Analyser (PDA) to investigate the flocculation/dispersion behaviour of quartz, chalcopryrite and their mixtures in the presence of PEO. PDA is a sensitive technique developed to monitor the aggregation state of particle suspensions [14]. In their tests, Gong et al.

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[13] used a certain amount of minerals smaller than 20 µm and water circulated through the flow cell of the PDA so that the flocculation/dispersion state of suspensions was monitored and correlated with the entrainment in flotation. It was found that PEO was selectively adsorbed on quartz particles and enlarged their sizes. The quartz flocs that were large enough to overcome the fluid drag were therefore less recovered by entrainment [11].

Over the last several decades, polymeric flocculants have gained wide use in thickening and dewatering for solid–liquid separation processes in the mining industry because they can bond colloidal particles together to form sediment flocs [15]. Due to the specific layered structure with charged layers and active edges, clay minerals can easily interact with molecules and ions [16]. Bridging and charge neutralisation are commonly encountered mechanisms in the flocculation and dewatering of clay mineral dispersions using high molecular weight non-ionic polymers or polyelectrolytes [17]. The polymeric flocculants normally used in industry as dewatering aids are polyacrylamide (PAM)-based [18], polyacrylate [19], and starch-based [20–22] etc. High molecular weight non-ionic polyethylene oxide (PEO) is also employed as flocculants of clay mineral dispersions [23,24]. According to Mpofu et al. [25], PEO produces better inter-particle bridging, greater settling rate and higher floc compaction behaviour upon shear than PAM. Besides, the presence of some divalent cations improves the flocculation efficiency of high molecular weight polymers on clay minerals [26]. In this current study, PEO was examined to reduce the entrainment of kaolinite Q38 in flotation using saline water. For comparison, tap water was tested in parallel.

In this study, Particle Vision Measurement (PVM) and Focused Beam Reflectance Measurement (FBRM) instruments were installed in the flotation cell to measure the enlarged size of clay minerals by PEO under dynamic flotation conditions. In the previous studies, the enlarged size was measured ex-situ and then correlated with the decrease in gangue mineral flotation recovery. This does not reflect the true size that necessitates the reduction of fine gangue entrainment in flotation. This study will provide a guideline to apply in-situ measurements of PVM and FBRM and polymeric flocculation in flotation to reduce fine gangue mineral entrainment in industry practice.

## 2. Material and methods

### 2.1. Raw material

Kaolinite Q38 was purchased from Sibelco Australia Limited Company, South Australia. Quantitative XRD analysis shows that kaolinite Q38 contains 85 wt.% kaolinite with 11 wt.% muscovite and 4 wt.% quartz. The same clay sample was tested previously [27]. Murray and Lyons [28] and Du et al. [29] indicated two types of kaolinite, well crystallized and poorly crystallized. Q38 belongs to the latter. Low crystallized kaolinite particles are poorly ordered and have more complex surface structures and higher specific surface areas than the well crystallized counterparts, as identified by SEM [29].

PEO with a molecular weight of 8 million was purchased from Sigma–Aldrich. The fresh stock solution of PEO was prepared at a concentration of 1 g/L daily. Tap water and saline water were used in flotation. Saline water was made in the laboratory and the chemical composition is shown in Table 1. The same saline water was used to simulate the bore water used in nickel flotation plants in Australia, and tested in the flotation of coal and nickel ores in the laboratory producing significantly different results compared to fresh water [30,31]. The ionic strength of the saline water is 1.8 mol/kg in comparison

**Table 1**  
The composition of saline water (mg/L).

Na <sup>+</sup>	K <sup>+</sup>	Ca <sup>2+</sup>	Mg <sup>2+</sup>	Cl <sup>-</sup>	SO <sub>4</sub> <sup>2-</sup>
20,000	940	400	5100	32,000	23,000

**Table 2**  
The composition of tap water (mg/L).

Na <sup>+</sup>	K <sup>+</sup>	Ca <sup>2+</sup>	Mg <sup>2+</sup>	Si <sup>4+</sup>	Cl <sup>-</sup>	SO <sub>4</sub> <sup>2-</sup>	CO <sub>3</sub> <sup>2-</sup>
48.6	3.16	25.4	17.3	2.98	105	42.3	58

with the ionic strength of 0.7 mol/kg in normal seawater [32]. The composition of tap water used in this study was analysed by ICP and listed in Table 2. MIBC (Methyl Isobutyl Carbinol) and diesel, industrial grade, were used as frother and collector, respectively. They are widely used in coal flotation plants [5]. Other chemical reagents used in this study such as different salts were purchased from Sigma–Aldrich and used directly without further purification.

### 2.2. Batch flotation

Batch flotation of kaolinite Q38 was conducted by using a 1.5 L JK batch flotation cell. Prior to flotation, 100 g kaolinite Q38 was well dispersed in either tap water or saline water in the flotation cell for 20 min. Then kaolinite slurry was conditioned with PEO at various dosages, diesel (240 g/t) and MIBC (160 g/t) for 2 min with each reagent addition at an agitation speed of 950 rpm. The solid percentage in the flotation cell was about 6.6%. NaOH was used to adjust pulp pH to 8.5 in the flotation cell. These conditions were the same in the previous study on coal flotation in the presence of clay minerals [5]. In flotation, the froth was scraped every 15 s and four concentrates were collected after cumulative times of 1, 2.5, 5, 10 min. Flotation concentrates and tailings were then filtered, dried at 80 °C, and weighed for recovery calculation. Kaolinite Q38 recovery in these tests was considered as a result of entrainment since diesel does not float kaolinite minerals by true flotation.

### 2.3. PVM and FBRM measurement

Particle Vision Measurement (PVM, model PVM 800, Lasentec Inc., USA) and Focused Beam Reflectance Measurement (FBRM, Lasentec D600L) instruments were installed in the flotation cell to measure the size and morphology change of the enlarged clay particles by polymeric flocculants. They are able to measure particle sizes in the range of 0.25–1000 µm. PVM is a probe-based high resolution in-situ video microscope providing images of clay flocs as they exist in a process. It uses six independent laser sources to illuminate a fixed area within the slurry. Light scattered back towards the probe is used in conjunction with a CCD element to produce an image. The image has a field of view of 1700 µm × 1300 µm, with 0.67 mm of the pixel size on the CCD array, allowing image resolution down to approximately 5 µm. The software allows up to 10 images per second to be stored. These images help validate particle shapes and give an indication of particle dimension and structure [33]. The measurement principle of FBRM is based on backward light scattering [34]. A laser beam is coupled to an immersible probe via an optical fibre. This laser beam is deviated from the probe's central axis in a rotational movement with a constant velocity. When this laser beam intersects with a particle, light scattering occurs. A certain fraction of the light is scattered back into the system. This back scattered light is coupled via a beam splitter to a second filter and conducted to a detector. The FBRM probe measures chord length, ground in a chord length distribution, rather than the actual sizes (i.e. diameters) [35]. Chord is supposed to be a fraction of the particle size. Hence, there should be no chord above the maximum particle diameter in the system. The results can be used for qualitative analysis. When flocculation occurs, the chord length value increases. Conversely, when the suspension becomes more dispersed, the chord length decreases. The chord length value is a sensitive indicator of the flocculation or dispersion state of suspensions.

Fig. 1 shows the setup of FBRM/PVM in the flotation cell at the conditioning stage. The FBRM and PVM probes were positioned across from each other and inserted to the flotation cell 5 cm below the pulp level.

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