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Entrainment in froth flotation: The degree of entrainment and its contributing factors

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ABSTRACT

In froth flotation, the degree of entrainment affects the concentrate grade and it is often assumed to be only a function of particle size in models. Literature suggests that other variables might also have a significant impact on the degree of entrainment. In this study, a factorial batch flotation experiment using a mixture of liberated chalcopyrite and two liberated gangue minerals, quartz and hematite, was performed to investigate the effects of these other variables (including impeller speed, gas flow rate, froth height and the specific gravity of gangue mineral) on the degree of entrainment. Results show that the degree of entrainment varied significantly as the flotation test conditions changed. Particle density and the interaction between gas flow rate and froth height had a statistically significant effect on the average degree of entrainment measured for the entire test. The degree of entrainment also significantly changed with flotation time throughout each experiment. It is hypothesised that these effects are a consequence of the degree of entrainment being affected by the weight of particles (not just their size) because of its effect on particle settling as well as the froth structure which provides varying resistance to particle drainage. It is concluded that models for the degree of entrainment that incorporate only particle size are not sufficient to predict gangue recovery and concentrate grade in an industrial application.

1. Introduction

Entrainment is a mechanical transfer process by which mineral particles suspended in water enter the flotation froth, move upwards, and finally leave the flotation cell with the mineral particles recovered by true flotation. It plays a critical role especially in the processing of ores with a large proportion of fine gangue particles [8,12]. The quality of final products in mineral flotation is often greatly influenced by entrained gangue materials.

Entrainment is generally taken as a two-step process: in step 1, mineral particles ascend upwards into the froth phase from the region just below the pulp/froth interface, and in step 2, the entrained particles in the froth are transferred to the concentrate launder with water. These two steps are strongly dependent on the processes occurring within both the pulp and froth phases [17]. As a result, the recovery by entrainment is related to the state of solids suspension in the pulp, the drainage in the froth phase as well as the recovered water.

A classification function has been proposed to describe the drainage in the froth [10]:

$$CF_i^f = \frac{(\text{mass of free gangue per unit mass of water})\text{concentrate}}{(\text{mass of free gangue per unit mass of water})\text{top of pulp}} \quad (1)$$

where CF_i^f is the classification function representing the drainage in the froth phase, subscript i represents the particle size and superscript f represents the froth phase.

Similarly, a classification function has been proposed to describe the state of solids suspension in the pulp [24]:

$$CF_i^p = \frac{(\text{mass of free gangue per unit mass of water})\text{pulp}}{(\text{mass of free gangue per unit mass of water})\text{tailing}} \quad (2)$$

where superscript p represents the pulp phase.

Taking the classification effects in both the pulp and the froth into account, the overall classification effect can be determined by:

$$ENT_i = CF_i^p \cdot CF_i^f \quad (3)$$

where ENT_i is the degree of entrainment representing the overall classification effect in both the pulp and the froth (for particle size i).

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ENT_i can be used directly for the estimation of gangue recovery by entrainment by the combination of these two classification effects. The recovery by entrainment is virtually the water recovered corrected by the degree of entrainment. There are two models of gangue recovery by entrainment that are commonly seen in the literature (see Eqs. (4) and (5)) ([7,11,13]):

$$R_{ent,i} = \frac{ENT_i \cdot R_w}{1 + R_w \cdot (ENT_i - 1)} \quad (4)$$

$$R_{ent,i} = ENT_i \cdot R_w \quad (5)$$

where $R_{ent,i}$ is the recovery by entrainment and R_w is the water recovery.

However, the boundary conditions for applying these models in industrial applications are not specified in the literature. Eq. (4) was derived from the definition of gangue recovery (based on the mass of the gangue in the concentrate and the feed), water recovery (based on the mass of the water in the concentrate and the feed) and *ENT* (based on the mass of solids and water in both the concentrate and the tailing). Hence, it can deliver a very precise value of gangue recovery by entrainment. Eq. (5) is a simplified form of Eq. (4) that can be used either when water recovery is below 30% or for ultrafine particles regardless of the water recovery. This is demonstrated in Fig. 1 which shows the gangue recovery calculated using these two equations for different water recovery and degree of entrainment values.

There is a debate whether a minor change in the degree of entrainment will change the gangue recovery and the concentrate grade significantly in industrial applications, and hence whether it is necessary to pay special attention to the degree of entrainment. Despite this, some research has been carried out on the degree of entrainment and its influencing factors. In froth flotation, particle properties and operating conditions are always of great importance in the mechanical entrainment process. These factors change the processes occurring in the pulp and the froth which result in a change either in the water recovery or in the degree of entrainment. Among these factors, the degree of entrainment is always size dependent with coarse particles exhibiting a low degree of entrainment ($ENT_i \rightarrow 0$) and the fine particles exhibiting a high degree of entrainment ($ENT_i \rightarrow 1$). Particles smaller than 50 μm are generally known to be recovered more easily by entrainment (Savassi et al., 1998).

Many studies have also shown that the degree of entrainment is influenced by the particle density [2,5,10,15,21]. However, the extent to which it affects the degree of entrainment is unresolved. Bisshop [2], for example, who measured the degree of entrainment of different gangue minerals found that particle density significantly affected the degree of entrainment. However, the work of Johnson [10] showed that the degree of entrainment of different gangue minerals in an industrial rougher flotation cell was similar, which suggested that the effect of particle density was less significant than that of other factors. This latter conclusion was supported by Savassi [18]. It should be noted that the effect of particle density is often influenced by the effect of particle size, and requires further investigation where the influence of particle size is specifically excluded.

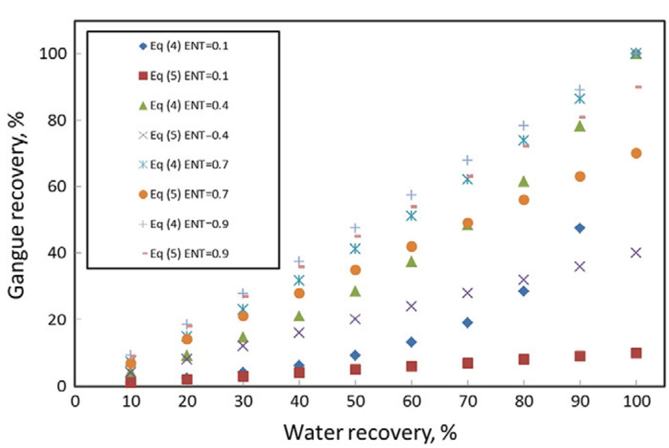

Fig. 1. Gangue recovery at different water recoveries and *ENT* values.

Gangue recovery by entrainment is significantly affected by gas flow rate and froth height, although the importance of these two factors compared with other influencing factors is still poorly understood. It is often thought that these two parameters affect the recovery by entrainment by changing the residence time and therefore the time available for water and particle drainage [25].

Recent studies have also demonstrated a change in the recovery of gangue minerals by entrainment with changes in the impeller speed [1,3]. Impeller speed can greatly change water recovery which in turn affects the gangue entrainment, but it is still not clear whether the degree of entrainment is affected by the impeller speed and its interaction with other variables.

The literature contains several models which can be used to evaluate and predict the degree of entrainment. However, these models which incorporate different influencing factors cannot predict entrainment for industrial applications [22]. One main reason is that little work has been done on the identification of the key drivers of the degree of entrainment. It should be noted that, whatever model is developed, one requirement for a good model is that it should describe the basic phenomena and account for all factors affecting the response significantly [2].

In this study, therefore, batch flotation tests were performed to identify the key drivers of the degree of entrainment using a mixture of liberated chalcopyrite as a valuable mineral and two liberated gangue minerals, quartz and hematite. The aim was to develop fundamental knowledge that is currently lacking to enable modelling of the degree of entrainment in industrial flotation applications.

2. Experimental

2.1. Materials and reagents

The flotation feeds to the experiments were created artificially by mixing pure chalcopyrite with pure gangue minerals. Quartz (SG = 2.65) and hematite (SG = 5.26) purchased from Geodiscoveries were used to investigate the effect of specific density of gangue minerals on the degree of entrainment. Sodium hydroxide (NaOH) was used to adjust the pH of the slurry to 9.5. Sodium ethyl xanthate (SEX), used as the collector, was supplied by Qingdao Lnt Chemical LTD. The collector dosage used in the flotation tests was 50 g/t of the feed. The frother used in the flotation experiments was Dowfroth 250 that was supplied by Chemical Dictionary Online. The concentration of the frother was kept at 10 mg/L. These reagents were prepared daily prior to the flotation tests using Brisbane tap water.

2.2. Flotation tests

Pure chalcopyrite, quartz and hematite samples were crushed to below 3.35 mm using a laboratory jaw crusher and then split to create numerous samples of 53 g, 1530 g and 1530 g, respectively. These weights were chosen so that, when combined, they resulted in a 1 wt.% copper feed grade and 37 wt.% solids in the flotation cell. Chalcopyrite samples were stored in a freezer to avoid oxidation.

Prior to each flotation test, a sample of chalcopyrite and one of the gangue minerals were ground separately to produce the appropriate feed particle size distribution. The chalcopyrite sample was ground with water (35 wt.% solids) in a rod mill operated at a speed of 76 rpm to obtain 80% particles passing 106 μm.

The gangue minerals were ground to a particle size of P80 = 70–80 μm, a size similar to that in typical flotation plants. This resulted in