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Fluidized bed desliming in fine particle flotation – Part III flotation of difficult to clean coal

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A B S T R A C T

A novel flotation system was used to process fine coal feeds supplied from coal preparation plants. The system consisted of an inverted fluidized bed arranged above a system of inclined channels. High fluidization (wash water) fluxes were imposed through a distributor enclosing the free-surface, producing strong positive bias of up to 2.4 cm/s, ideal for desliming. High gas fluxes of up to 2.6 cm/s, in excess of the flooding condition, were also imposed. The presence of the inclined channels prevented the entrainment of gas bubbles into the tailings stream. This paper, which is the third in a series, examines, for the first time, the hydrodynamic performance of this system on two actual plant feeds, each known to be difficult to wash. The first feed was a poorly liberated coal with particle size <260 μm and 69% feed ash. The second was a well liberated coal with nominal size <125 μm and 83% less than 38 μm. The product ash was shown to decrease significantly with an increasing fluidization flux to gas flux ratio. The single stage flotation system demonstrated a performance capable of matching the Tree Flotation Curve with some cases in fact surpassing this result.

1. Introduction

Froth flotation is used extensively in coal and mineral processing to recover and concentrate valuable fine particles. The valuable particles are made hydrophobic through the application of a collector, and their attachment and adhesion promoted using a high shear rate to effect both a collision, and then final adhesion with air bubbles. A frother is introduced to stabilize the air–water interface. The bubbles then rise up through the device to form a froth zone, allowing liquid drainage, releasing hydrophilic particles and some hydrophobic particles from the final froth product (Neethling and Cilliers, 2002). Additional water applied as drops at a sufficient rate from above the free-surface of the froth delivers a downwards positive bias flux, improving the product grade.

Conventional froth flotation suffers from incomplete recovery of the valuable particles due to (i) ineffective collisions between the ultrafine particles, typically below 10 μm, and the air bubbles (Miettinen et al., 2010), and (ii) the ease with which relatively coarse particles, several hundred microns, detach from the air bubbles (Goel and Jameson, 2012; Jameson, 2012). Bubble coalescence, which can arise for a multitude of reasons, can also lead to significant loss in product recovery. Moreover, the product retains fine hydrophilic gangue particles due to incomplete or non-uniform drainage and desliming of the froth product (Britan et al., 2009) or due to the entrainment of excessive liquid into the froth zone when a high gas flux is applied (Smith and Warren, 1989).

We have previously developed a fine particle gravity separator known as the Reflux Classifier (Galvin et al., 2009, 2010, 2012). This separator consists of a fluidized bed, with a system of parallel inclined channels mounted above. The technology is now deployed around the world in a range of fine coal and mineral processing applications. Froth flotation can, in part, be thought of as a gravity separation process, in which rising air bubbles segregate from the liquid. We have therefore applied our recent advances in gravity separation to the field of flotation, in turn inverting the Reflux Classifier, to produce the Reflux Flotation Cell shown in Fig. 1.

The Reflux Flotation Cell is fully enclosed at the top by a fluidized bed distributor, with a central port used to continuously discharge the bubbly overflow product. The inverted fluidization provides a basis for delivering uniform wash water, and hence counter-current washing of the product. A downcomer, consisting of a sleeved sparger, is used to introduce the feed particles and air bubbles at a high shear rate (Johnson and Gershey, 1991; Kracht et al., 2008), formed in the annulus around the sparger tube, thus providing efficient bubble particle interaction and collisions, and attachment and adhesion of the hydrophobic particles. The gas flux is run at levels that, ordinarily, would lead to flooding of the system. However, the incorporation of the system of parallel

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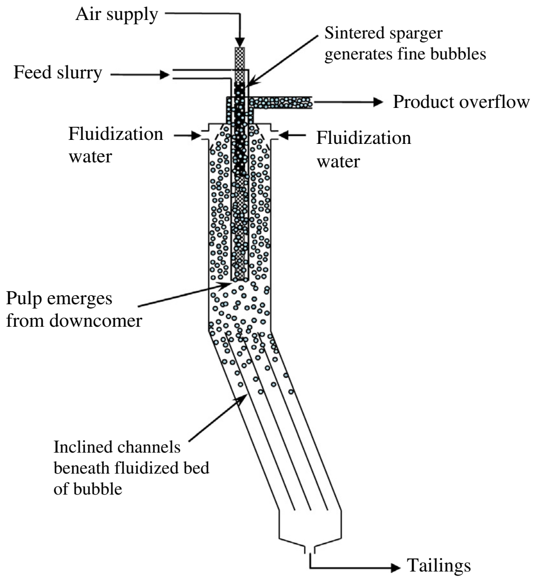

Fig. 1. Schematic representation of the Reflux Flotation Cell used in the study.

inclined channels below the main vertical cell prevents the transport of the gas bubbles to the tailings discharge at the base of the vessel. Thus, the upper system is permitted to flood and hence form spherical, extremely wet "foam" with a bubble volume fraction of order 0.5. In comparison, the volume fraction of bubbles in the pulp zone of a conventional cell typically lies within 0.02–0.33 (Gorain et al., 1995). Moreover, this new system is run in the absence of a froth zone, and thus there is relatively little tendency for coalescence. The system is thus more resilient to the effects of the (fluidization) wash water, providing a strong basis for driving efficient counter current washing of the bubbly mix, and hence efficient desliming.

This is the third in a series of papers concerned with the hydrodynamics of the Reflux Flotation Cell. In part I (Dickinson and Galvin, 2014) the device was investigated using a gas–liquid feed system, and then using feed slurry consisting of fine hydrophilic silica of particle size range between 5 and 22 μm. This work demonstrated the potential to operate at extreme gas flux levels, while maintaining a relatively low liquid split to overflow. For example, in the presence of a fluidization wash water flux of 1.1 cm/s it was possible to operate with a gas flux of 0.8 cm/s, generating a bubble surface flux of 144 m^2/m^2 s using bubbles 0.340 mm in diameter. Under these conditions the system achieved better than 97% desliming of the ultrafine silica, and better than 99% when the gas flux was lowered to 0.5 cm/s and fluidization flux increased to 2.7 cm/s.

In part II (Galvin and Dickinson, 2014) the device was fed with a model flotation feed, consisting of equal portions of fine hydrophobic coal (<260 μm) previously recovered by flotation, and ultrafine hydrophilic particles of silica ($\ll$63 μm). Again the system was shown to withstand extreme conditions in the level of the applied fluidization wash water flux and the imposed gas flux. A regime map was presented in order to illustrate the vast operating zone. At relatively low wash water fluxes the combustible recovery was close to 100% across the full range of conditions, and the product grade, defined by the ash %, was about 8.1%, significantly better than the 10.1% ash in the original flotation product. At an extreme wash water flux, and low gas flux, selective recovery of the coal particles was achieved, with the combustible recovery reduced to about 75%, while the product ash % was reduced to 4.0%. By comparison, the lowest product ash obtained from the Tree Flotation method was 5.4% with the combustible recovery at a low of 23.6%.

The present work was concerned with the application of this novel flotation device to actual industrial feeds. Clearly, the system performed remarkably well on very well defined feeds consisting of fine hydrophilic silica. However, it was still unclear whether this performance could be translated to cover the presence of more realistic conditions involving ultrafine clays, and poorly liberated feed particles. Thus the feeds used in this study were selected because of the significant challenge they presented. The first feed contained very high levels of fine clays and minerals, with the overall feed ash at 69%, and 79% ash in the −38 μm particle size fraction. The fine coal, having a top size of 260 μm, also exhibited poor liberation. The second feed also contained very high levels of clays and minerals, with 55% ash. In this case the feed, which had a top size of ∼125 μm, was well liberated, however the portion of particles less than 38 μm was in excess of 83%.

These feeds contained hydrophobic particles that were capable of attaching to air bubbles. Thus they were clearly floatable, and hence there was no fundamental issue associated with the system chemistry. This was most appropriate because the benefits of the Reflux Flotation Cell are fundamentally hydrodynamic in nature. However, these coals were deemed hard to wash due to the extreme levels of clays and mineral matter, and their ultrafine sizes. It was also known that conventional flotation had failed to deliver acceptable product ash levels.

2. Theoretical

It is important to realise there is a subtle but significant theoretical difference between applying wash water at the boundary of the foam compared to injecting the wash water just beneath the upper boundary (Dickinson and Galvin, 2014). Thus the boundary condition for wash water addition is a complex matter. Typical flotation practice involves the spraying of wash water from a distance above the free-surface of the foam. However, in the Reflux Flotation Cell fluidizing wash water is added via a distributor enclosing the top vertical section of the cell, and has previously been shown to function as if it were injected deep beneath the free-surface of the rising foam (Dickinson and Galvin, 2014). This permits effective desliming by imparting the downward flow of the wash water, counter current to the rising foam, leading to positive bias.

Consider the steady state flow of bubbles and liquid in a vertical flotation column. We will define all system inputs and outputs as positive in value, and all vector quantities as positive in the upward direction, apart from the bias flux, j_b, which is, by convention, positive in the downward direction. The effect of hindered settling on the bubble velocity can be described by the equation given by Richardson and Zaki (1954),

$$V_s = V_t(1-\theta)^n \tag{1}$$

where V_t is the terminal velocity of a rising bubble of a given diameter, d_b, θ the volume fraction of bubbles, and n a scaling constant. Using Eq. (1), together with one-dimensional Drift Flux theory (Wallis, 1969), Dickinson and Galvin (2014) derived the well-known relationship between the gas flux, j_g, and the volume fraction of bubbles, θ_b, in the foam rising above the level of water injection,

$$\frac{V_{sb}}{j_g} = \frac{(1-\theta_b)}{n\theta_b^2} \tag{2}$$

and the liquid flux, j_f, rising up with the foam,

$$\frac{j_f}{j_g} = \frac{(1-\theta_b)}{\theta_b} - \frac{(1-\theta_b)}{\theta_b^2 n} \tag{3}$$

Using a simple flux balance, they derived an equation for describing the zone below the wash water injection point, where the bubble volume fraction is θ_w. That is,